DYNAMIC E-MAINTENANCE IN THE ERA OF SOA-READY DEVICE DOMINATED INDUSTRIAL ENVIRONMENTS

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The factory of the future will be heavily based on service oriented architecture approaches. Business continuity will need to be guaranteed as interactions in the shop-floor will be more complex and demanding. In parallel sustainable manufacturing is emerging as a new approach to address economical, environmental, and societal issues. In this context, maintenance will play a major role. In particular, an e-maintenance platform will have to deal with the emerging challenges, and take advantage not only of the latest technologies but also of new collaborative concepts that will be possible in the future factory. We discuss here the dynamic e-Maintenance in the era of SOA-ready device dominated industrial environments. Furthermore, we demonstrate how existing efforts in cross-layer SOA based enterprises in conjunction with e-maintenance platform can greatly enhance existing decision making processes supporting the transition towards sustainable manufacturing.

Keywords: service-oriented architecture, asset lifecycle management, open ICT cross-layer platform, e-Maintenance, web services, DPWS, dynamic asset discovery.

1 MOTIVATION

Industrial maintenance, is gaining significance [7] both within the academic and industrial community, as it develops from being considered a minor activity, towards a strategic task in operation management [14], thus being called asset lifecycle management. Moreover, maintenance is considered a major lever to be exploited to go towards sustainable manufacturing, where economical, societal, and environmental issues are properly considered [17]. Recently, the focus is on e-Maintenance, that is “maintenance support which includes the resources, services and management necessary to enable proactive decision process execution” [13] and that is considered the major pillar of e-Manufacturing. However, in order to implement effectively e-Maintenance applications for asset lifecycle management, several requirements need to be met, and this is a challenging task. One major need is the absence of an open ICT platform that can fully support e-Maintenance practices [13], taking also into consideration the latest concepts and technology trends such as the Service Oriented Architecture (SOA) approaches at device level.

The future factory will be dominated by SOA [4], which empowers us with new capabilities and enables the realization of sophisticated approaches based on the collaboration of devices, network services within the single enterprise and among enterprises. This is a key issue especially for the maintenance, as now the devices are not considered as simple passive black boxes, but active entities that can do self-monitoring, proactively inform third party services about their status or maintenance needs and therefore greatly enhance existing efforts for remote and autonomous maintenance.

Within the project SOCRADES (www.socrades.eu) we have developed a Service-Oriented Cross-layer infRAstructure for Distributed smart Embedded devices, which is an open approach for enabling among others the effective interaction and collaboration among all entities in future industrial domain, ranging from devices, engineering systems, enterprise systems, etc. SOCRADES is a platform for next-generation industrial automation systems that exploits Service Oriented Architecture (SOA) paradigm in a cross-layer way i.e. at the device, network and business application level. The SOA paradigm in our case is implemented through Web Services technologies even at the device level which enables the adoption of a unifying technology for all levels of the future enterprise, from sensors and actuators to enterprise business processes. In this way, different entities (whether they are services or devices) can subscribe and get the necessary information (event based infrastructure) while in parallel being agnostic to the actual implementation details.

The SOCRADES Integration Architecture (SIA) [10, 16] demonstrates how the close coupling of devices that host web services locally e.g. via the usage of Device Profile for Web Services (DPWS [2]) and OPC Unified Architecture (OPC UA [8]) can offer several advantages and ease close collaboration with enterprise applications. These SOA-ready devices can host intelligence and offer their functionality in a service oriented way. That, in conjunction with the overall platform functionality, has the potential to drastically change the way we design and deploy services within the industry, and has a significant impact on asset management and e-maintenance.

In this paper, we highlight how future industrial environments empowered by SOA platforms such as the SOCRADES one can support seamlessly and effectively e-Maintenance applications. In particular, since the SOCRADES platform bridges the communication gap between business applications (e.g. ERP) and shop floor applications (i.e. MES), it represents a useful support to implement the e-Maintenance applications envisioned in the literature [13], e.g. on-line maintenance, collaborative maintenance, etc. In particular, we stress how the features of the integrating platform that we propose [10, 15] (such as Service Discovery, Cross-layer Service Catalogue and Service Lifecycle Management) can be fully exploited in order to implement e-Maintenance practices such as real-time fault diagnosis/localization, predictive maintenance, intelligent support for maintenance decision making, etc. Some scenarios, related to asset lifecycle management, are analysed in order to better highlight the functionalities enabled by the platform, in the future sustainable manufacturing environment.

2 THE E-MAINTENANCE CONCEPT

E-maintenance is a variegate concept, which has been studied from different perspectives and with different aims [13]. Muller et al. [13] define: "Maintenance support which includes the resources, services and management necessary to enable proactive decision process execution. This support includes e-technologies (i.e. ICT, Web-based, tether-free, wireless, infotronics technologies) but also, e-maintenance activities (operations or processes) such as e-monitoring, e-diagnosis, e-prognosis, etc." The e-maintenance enables four main different maintenance strategies [13] such as:

- Remote maintenance;
- Predictive maintenance;
- Real-time maintenance;
- Collaborative maintenance.

Remote maintenance refers to the capability enabled by ICT developments to provide maintenance practices from anywhere e.g. third party entities outside the enterprise borders. Through remote maintenance applications, an operator may complete his/her task without having to be physically present where the asset is located. This aspect of e-maintenance has a significant impact in terms of cost, downtime, quickness of reaction, and of effectiveness of maintenance intervention, since experts on specific field may be more easily consulted from anywhere without the need to physically be present. Moreover, it dramatically affects business models that should be applied in order to provide the customer with maintenance services.

Predictive maintenance (or condition-based maintenance) considers the adoption of models and methodologies to analyse real-time data coming from the monitored assets in order to provide optimized maintenance interventions. Predictive maintenance is the latest evolution of maintenance and reliability engineering, which aims to minimize failure in order to guarantee the appropriate asset operation. This relevant aspect of e-maintenance needs hardware and software components available at shop floor level (for example a watchdog agent [5]). These components collect data, analyse them, and provide bottom-up alters to force maintenance interventions.

Real-time maintenance focus on the reduction of the time delay between the moment when an event occurs on the shop floor (i.e. a failure of a machine) and the moment when that information is transmitted to the operator/responsible. This allows increasing reactiveness of enterprise in terms of maintenance activities. This maintenance strategy is included in the more comprehensive real-time enterprise concept, which addresses in the same way the reduction of information time delay, but in a more general scope, by looking at all the information related to the shop floor status, i.e. Work-In-Process, machines utilization, etc.

Finally, Collaborative maintenance refers to the capability enabled by e-maintenance concepts to allow collaboration among different areas of the enterprise (intra-enterprise collaboration) and among different enterprises (inter-enterprise). In particular this aspect is interestingly connected with another stream of research that addresses collaboration in the industrial automation domain, in what is called the Collaborative Automation Paradigm [3]. As a matter of fact both in automation and maintenance domain, when looking at collaboration similar issues are shared such as reduction of information interfaces, seamless communication, security, etc. Moreover, since e-maintenance is strictly connected to e-manufacturing [11], there is a need for an effective coordination among separate facets of manufacturing management, such as production, maintenance and business activities. Nowadays, this coordination is still underdeveloped and one of the main reasons is the lack of open tools that could support it.

One of the most relevant challenges when implementing e-Maintenance concepts is related to the lack of an integrating information and communication infrastructure [1, 11–13]. A seamless infrastructure that may support management and control of industrial operations (including maintenance) and connect them in real-time to the higher level layers (i.e. business layer) is the main issue to be addressed in order to go towards e-maintenance applications.

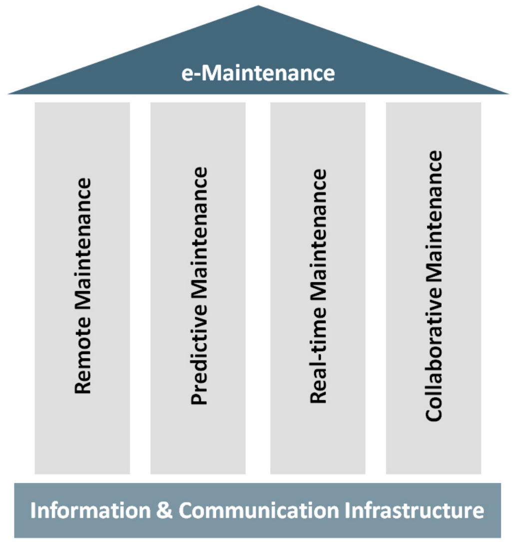

Figure 1. e-Maintenance: Basis and main pillars

Hence, we consider the four maintenance strategies highlighted before as the main pillars of the e-maintenance approach. An appropriate information and communication infrastructure represents the basis that supports e-maintenance strategies. This concept is represented in Fig. 1. Due to the relevance of the topic and the impact on the overall e-maintenance concepts, in this paper we decided to address the issue of information and communication infrastructure. In the next section, we define the requirements that such an infrastructure should present in order to be exploitable in the e-maintenance context.

3 INFORMATION AND COMMUNICATION INFRASTRUCTURE REQUIREMENTS

We selected the following requirements starting from previous research conducted within SOCRADES project [10, 15]. These requirements are considered critical for future industrial environments and are directly coupled with the e-maintenance concepts:

- Interoperability: several e-maintenance platform are based on proprietary technologies [13], which implies higher costs and slow market adoption, since implementation costs and time are required. In order to effectively support Collaborative, Real-time, and Remote Maintenance this infrastructure should be able to support open communication among different actors (i.e. collaborative), in different layers (i.e. interoperable) and in a timely manner in the enterprise information system (i.e. real-time), and through the adoption of different tools and technologies globally distributed (i.e. remote). One way could be to adopt a common language that reduces the need for interfaces among different systems: the aim is to have a common basis for seamless operation of standard functions such as discovery, description, addressing, invocation, etc.

- Scalability and flexibility: due to rapidly changing market and to on-going trend towards flexible and adaptive factories [9], there is a need for scalable platforms in order to effectively support all the pillars, even with changing conditions, such as for example, number and/or type of asset(s) monitored. Indeed, it is expected [6] that future factories will be composed by reconfigurable machines that will increase the level of dynamic behaviour shown at shop floor level. This dynamicity needs to be supported even in terms of maintenance through an appropriate scalable and flexible e-maintenance platform.

- Security: an open infrastructure where rapidly changing business processes and collaboration among companies at several layers occur in an e-maintenance context (in particular considering Collaborative, Remote and Real-time Maintenance) needs to support security. The openness and heterogeneity of such systems is requiring a different security approaches from that of traditional systems and architectures. These security architectures must be flexible enough to tailor themselves to application-specific security requirements, but also to be customizable for policy/compliance.

- Device to Business Integration (D2B Integration): Device manufacturers are increasing the amount of embedded software and also sophistication of their products. Therefore, new capabilities emerge on the shop floor and enable devices to actively participate in business applications by providing information from their domains and/or acquiring information from enterprise level (e.g.: devices can directly trigger an event in the business process and affect its execution [15]). An e-maintenance platform should consider this requirement and adopt a common approach to represent information among heterogeneous systems. This requirement is important to support in particular predictive maintenance and real-time maintenance.
- Distributed management: we see a trend in the shifting of intelligence and processing tasks towards the field level devices. In order to fully exploit remote and collaborative maintenance, a distributed infrastructure is required that does not only consider hierarchical control as this constrains the opportunities enabled by heterogeneous, distributed, and autonomous interaction among single elements (e.g. operators, devices, watchdog agents [5], etc.). Moreover, this requirement can inherently add flexibility and scalability to the system by reducing the number of centralized points.
- Semantics: due to the relevance of ontology in e-maintenance context [13], the information infrastructure should be able to inherently support knowledge processing. This is core for implementing effective collaboration among heterogeneous actors. Indeed, this requirement enables collaboration through formal description of elements and relationships in industrial maintenance domain.

On the base of these requirements, in the next section we describe the technologies that we consider to adopt in order to implement an effective e-maintenance platform. Moreover, in section 5 a description of the platform and of its components is proposed, with an evaluation based on the requirements identified.

4 SOA-READY DEVICES

Web services are used mainly in enterprise environments to support interoperable e.g. machine to machine (M2M) interaction while hiding the details of the implementation at each end-point. Enterprise applications use web services as basic blocks to create more sophisticated services e.g. to glue together cross-organizational functionality. Several standards exist, but most of them do not assume embedded systems as an implementation platform. In the past, there have been efforts (e.g. Jini, UPnP) to integrate devices into the networking world and make their functionality available in an interoperable way. The latest one, coming from UPnP and attempting to fully integrate with the web-service world, is DPWS [2], which defines a minimal set of implementation constraints to enable secure web service messaging, discovery, description, and eventing on resource-constrained devices. DPWS is an effort to bring a web services on the embedded world taking into consideration its constrained resources. Several implementation of it exist in Java and C (www.ws4d.org, www.soa4d.org), while Microsoft has also included a DPWS implementation (WSDAPI) by default in Windows Vista and Windows Embedded CE.

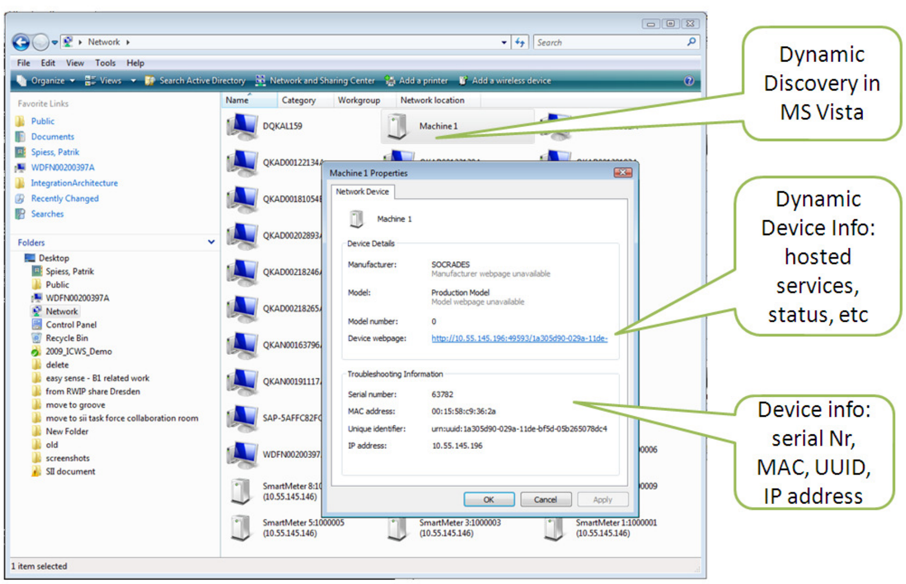

Figure 2. Asset management: dynamic device discovery and info e.g. status, hosted services, serial number, etc.

Emerging standards like DPWS and OPC UA [8] assume (web) services running within the devices. The key idea is to provide interoperability and easiness of integration of devices, focusing exclusively on the functionality they offer at the shop floor and not on the device-specific implementation as such. As the device now can provide variety of information about itself as well as dynamic information about its status and the services it hosts, new approaches can be applied e.g. in the asset management. We can clearly see in Fig. 2 that any device with the DPWS stack can already be dynamically discovered, and information such as serial number, MAC address, IP address, model number, Unique ID (UUID), etc can be obtained. Furthermore there is a standard way to access the functionality on the device and e.g. control it, or obtain its health status. Since now the device can provide this information in a standard way via web services, other devices or services in an e-maintenance platform can subscribe to the events it creates. In case of a failure, the e-maintenance platform is notified. This is a clearly paradigm shift towards an event-based infrastructure, where information can be dynamically discovered and be fed to the interested parties only.

5 E-MAINTENANCE PLATFORM

The purpose of an e-maintenance platform is to coordinate maintenance information shared among different actors (devices, plant managers, external partners, business managers, decision support systems, etc.), and provide the basic tools for decisions to be made. In the context of sustainable manufacturing, e-maintenance platforms are needed in order to make proper decisions (i.e. with accurate and near real-time information), taking into consideration all the relevant components of the production process and their respective impact. Since in maintenance domain, impact on sustainability often depends on timely reaction to unexpected events (e.g. a timely identification of failures that causes higher CO_2 emissions, may reduce environmental impact), e-maintenance platform emerges as a core support also for sustainable manufacturing. As depicted in Fig. 3, the e-maintenance platform provides its functionalities that in our case are easily realizable due to the usage of the SOCRADES Integration Architecture [16] (SIA). SIA allows seamless interaction among devices and services hosted at different layers (e.g. at device, network or enterprise system).

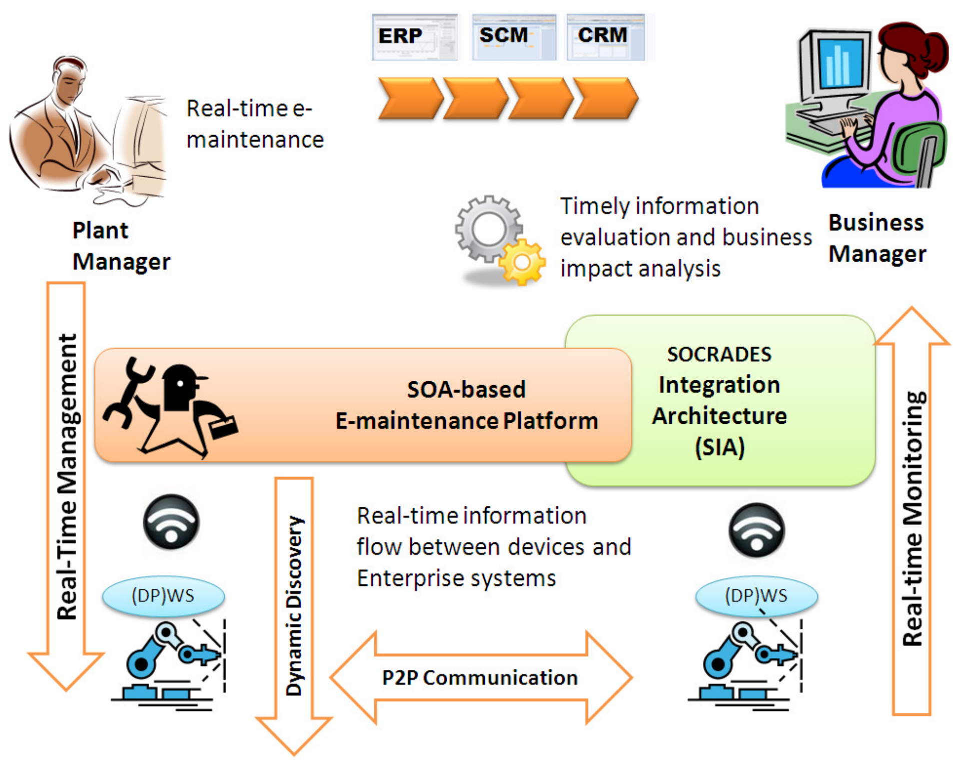

Figure 3. The e-Maintenance platform in the future shop-floor empowered by cross-layer SOA

Real-time Monitoring is possible and as an event-based infrastructure is used, this is done only when needed. Furthermore, via SIA and the web services on devices, management functions (soft control) can be directly done at device level. These two fundamental functionalities (i.e. monitoring and management) are used by the e-maintenance platform, to be combined in more sophisticated service behaviour. As an example, device status can be monitored or an event can be raised by the device itself. As now partial business logic can be hosted on the device, a direct mapping can be done and the e-maintenance platform knows which parts of the business process are affected. Immediately, automated tickets can be issued, e.g. a remote evaluation of the health status, exchange of the device, or even an order to the ERP system for a repair task to the nearest worker in the field. The e-maintenance platform can provide timely information that can be analysed by a Decision Support System (DSS) and, therefore, can predict or take sophisticated actions on the shop-floor with the goal of maintaining the business continuity.

Peer-to-Peer communication among the devices leads also to increased flexibility, as a malfunction device, with the help of the maintenance platform can identify and delegate part of its functionality to devices that host a similar set of services necessary to realize the tasks that are pending on the malfunctioning device.

It is clear that the e-maintenance platform can be empowered with new capabilities and deal with dynamically arising situations by using discovery and an event based infrastructure. Furthermore, as the communication is done in a standardized way e.g. via Web Services, interoperability is enhanced, while integration costs are lower than in legacy systems.

5.1 Real-time Monitoring

In Real-time Monitoring, SOA-ready devices provide information on their status to the higher level systems, through a bottom-up communication approach. Information is communicated on an event basis (and not on a pull schedule) and can be propagated across several layers that support SOA interaction. Raw basic data (e.g. temperature in an industrial oven) or processed information (e.g. expected time to failure derived from condition-based analysis) can be generated and delivered by the device itself as now it hosts logic and computational capabilities locally. Through the e-maintenance platform, information can be conveyed to heterogeneous agents, e.g. plant manager responsible for shop floor operation or business manager, who need fine-grained information from the shop floor level.

Since seamless and real-time information can be obtained through cross-layer SOA, new knowledge can be potentially created anywhere by composing in a Lego-like way the services offered at device, network and enterprise level. Real-time Monitoring is particularly relevant in the context of sustainable manufacturing, where quick reactions to unexpected events need to be provided, in order to minimize economic, environmental and societal security risks. In the context of Real-time Monitoring, the e-maintenance platform is responsible for conveying information even beyond the company borders e.g. when device health monitoring is outsourced. Heterogeneous actors (operators, managers, etc.) may subscribe/unsubscribe for obtaining Real-time Monitoring of specific SOA-ready devices, therefore, extreme flexibility can be obtained both in term of devices monitored and of actors interested in monitoring.

5.2 Real-time Management

Real-time Management focuses traditionally on top-down approaches to control and manage shop floor devices. Maintenance operators or plant managers may implement their decisions directly on the device, through e-maintenance platform. For example, a plant manager may directly switch off a specific machine, ask for a maintenance intervention and meanwhile reroute production flow on other machines; all this can be done in a seamless and transparent way thanks to the adoption of cross-layer SOA for the e-maintenance platform. In order to implement this, a repository of devices (i.e. service repository) needs to be provided at the e-maintenance level so that higher level systems (owned by plant manager, business managers, etc.) may retrieve the requested devices and perform a specific action through service invocation. This functionality is already provided for our case via the SIA, and the developers of services for the e-maintenance do not have to deal with the complexity or the specifics of the infrastructure - they rather use SOA techniques to request the necessary info from the SIA platform. It is clear that the e-maintenance platform now goes beyond specific network borders, or even geographical ones, and therefore real-time view on global scale can be achieved. Real-time Management in combination with real-time analytics may provide a better overview of the assets, their status and be able to start preventive measures or timely react to emerging problems. Furthermore, the usage of the timely generated info can be fed to Decision Support Systems that may help the managers on their perspective decisions, also by presenting alternatives and simulating possible scenarios. Finally, through real-time management, decision makers are provided with an overall picture of the manufacturing plant that could support sustainable directions. For example, reduction of emissions through proper maintenance intervention and minimization of dangerous failures, through appropriate analysis of fine-grained data coming from the shop-floor, could be exploited.

5.3 Dynamic Discovery

Dynamic Discovery is a specific feature enabled by the SOA-ready devices. Indeed, since devices implement SOA specifications such as the WS-Discovery (that exists in DPWS) can now be seamlessly discovered without the need for explicit registration. Furthermore, the services can also be dynamically discovered and used, which really brings the benefits of service-oriented approaches to the lowest levels of the industrial environments. In practice, this means that if a new device is added to the production systems, it is automatically recognized by the e-maintenance platform, registered and monitored. As such we avoid the possibility for mistakes, and keep always up to date the mapping between the real world and the business one in the asset management systems. Being able to get dynamically accurate info about the devices and their services, can help prevent or timely identify conflicts that otherwise would be discovered only after a problem arises e.g. production halt.

5.4 P2P Communication

As depicted in Fig. 3, another functionality that can now be realized is the peer to peer communication among heterogeneous devices. Devices using web services (e.g. DPWS) are able to directly communicate among each other. This allows decentralization of management, and enhances collaborative scenarios where several devices cooperate e.g. for decision making. For example, considering a redundant production system composed by two single identical machines: one machine that has just entered a failure mode may verify the actual operation of the other identical machine, in order to decide the priority level of the maintenance intervention request to be sent to e-maintenance platform level. As such, partial failures of a device may result that it uses the same service offered by a nearby device, and continue its operation. This enables us to have a more reliable shop-floor with increased uptime, thus reinforcing the business continuity goal.

5.5 Cross-company communication

Cross-company communication is already a reality, but constrained at enterprise level only. However, now the real-time connection to the devices will enable them to interact or inform actors over the company level, for their status. As such, malfunctioning of a device that may result in production slowdown, may have an impact on the performance of a production line in another company, which expects input from the first one. Communication can now be done directly e.g. via common trusted third party service providers, that may simply couple the two companies for the specific business case. As this can now be directly communicated, we avoid costly communication links by propagating the info on all above enterprise layers in both companies. Synergies can be identified and information that was too costly to be obtained in a timely manner can now flow into cross-company applications and services. This approach is very well suited for dynamic and short-lived interactions that can be set up, exploited and removed as easy as a simple composite service.

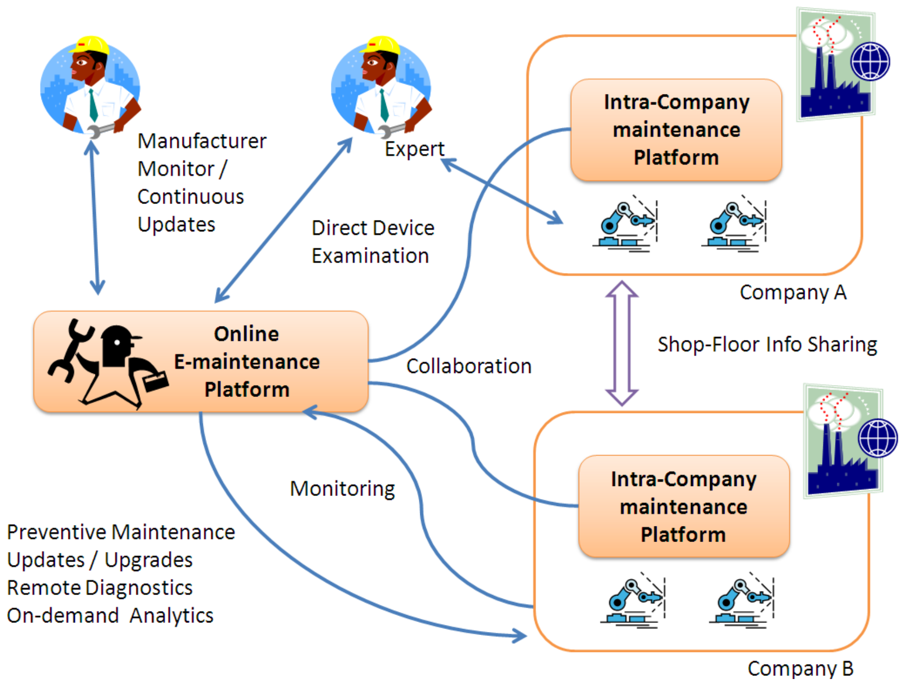

Figure 4. Remote continuous outsourced cross-company e-maintenance

Cross-company collaboration allows us to realize new functionality and innovate at services offered. Especially in case outsourcing of maintenance, specialized partners can now bring in their expertise and monitor remotely the devices at the shop-floor and maintain them. Assets that the company operates on may in future not be owned by the company as such, but instead be provided to them over specific service level agreements (SLAs) e.g. a production line with uptime 99% - how this is achieved and its maintenance is responsibility of the service provider. As a result, companies can now focus more on their core business, while service level agreements can regulate shop-floor performance that matches better the business process goals, but not how this is achieved, which is responsibility of the e-maintenance partner. This can facilitate the development of new business models based on remote maintenance service delivery through e-maintenance platform.

6 E-MAINTENANCE EFFECT IN DECISION MAKING PROCESS

As we have discussed so far, there are several benefits that can be brought with the introduction of a SOA based e-maintenance platform. The most important one is that business continuity can be enhanced. Business continuity describes a mentality or methodology of conducting day-to-day business. This assumes that critical business functions must be available to business partners and suppliers, and a way to do that relates to minimizing downtime which is part of the goals of an e-maintenance platform. By being able to directly access information, propagate it at different layers, endorse predictive and collaborative maintenance approaches, significant contributions can be made to the several steps of the business continuity process.

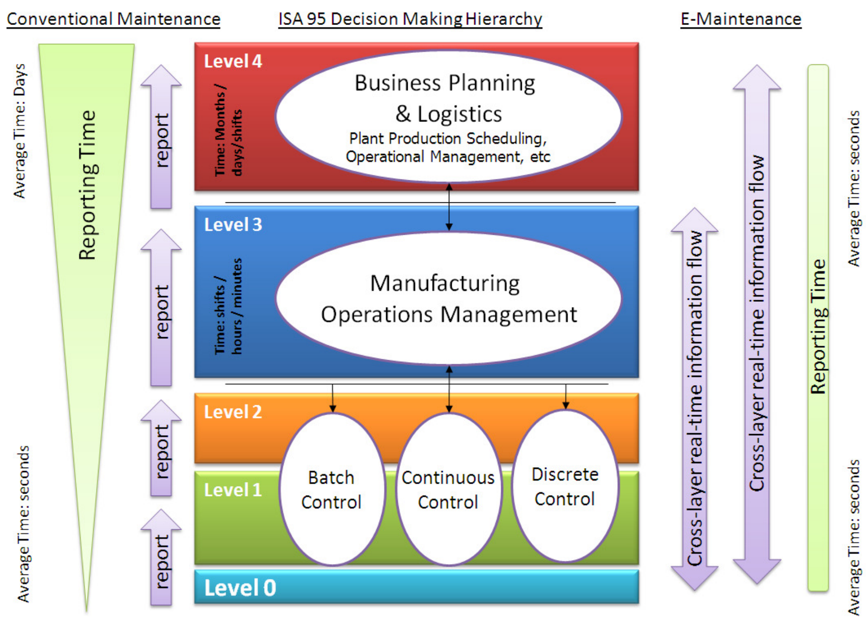

Figure 5. Timely reporting with e-maintenance

Fig. 5 depicts in the centre the decision making hierarchy according to the ISA-95 standard. Today the biggest problem is interaction among the different levels and integration of the information generated. As depicted on the left side of Fig. 5, currently the reporting done is segmented and hierarchical. Furthermore, the information flow is too slow, which can be even translated into days until it reaches the business level.

The adoption of an e-maintenance platform can have a significant impact. Apart from the other benefits of SOA and the explicit ones discussed in previous sections, now we can realize cross-layer integration and information flow. This leads to collaboration among the different layers in a peer-to-peer way without necessarily having to go through the whole hierarchy. In practice, that means that an enterprise service can directly be informed by a device e.g. an MES system on possible problems that directly affect a business process. This results in reduced time of reporting and timely dissemination of information at the appropriate and interested parties only via the event-based infrastructure.

6.1 Conclusions

We have investigated the benefits (in terms of e-Maintenance applications) coming from the adoption of a SOA-based platform that integrates business and shop floor level, through web services technologies. The whole approach demonstrates that SOA-ready devices can further empower e-Maintenance capabilities and pave the way for better business continuity, and more sustainable manufacturing. Since e-Maintenance will gain importance in factory of the future, this enforces the relevance and value of the proposed platform for next-generation industrial systems. It is clear that the SOA-empowered e-maintenance platform can provide a significant business advantage with respect to the timely information delivery to the interested parties. Furthermore, new business models can be realized that are service-driven, employing outsourced expertise and predictive maintenance. If implemented properly, enterprises and collaborators will benefit from the increased asset management, optimal performance and seamless integration.

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7 REFERENCES

[1] Campos, J.: Development in the application of ict in condition monitoring and maintenance. Computers in Industry 60, 1–20 (2009)

[2] Chan, S., Kaler, C., Kuehnel, T., Regnier, A., Roe, B., Sather, D., Schlimmer, J., Sekine, H.,Walter, D.,Weast, J., Whitehead, D., Wright, D.: Devices profile for web services. Microsoft Developers Network Library (2005)

[3] Colombo, A.W., Jammes, F.: Integration of cross-layer web-based service-oriented architecture and collaborative automation technologies: The SOCRADES approach. In: Proc. of the 7th IEEE International Conference on Industrial Informatics (INDIN 2009) (2009)

[4] Colombo, A.W., Karnouskos, S.: Towards the factory of the future - a service-oriented cross-layer infrastructure. in the book ICT Shaping theWorld, A Scientific View, ETSI, John Wiley and Sons Ltd ISBN: 9780470741306 (2009)

[5] Djurdjanovic, D., Lee, J., Ni, J.: Watchdog agent - an infotronics-based prognostics approach for product performance degradation assessment and prediction. Advanced Engineering Informatics 17, 109125 (2003)

[6] European Commission: Manufuture: A vision for 2020. Report of the High Level Group 1(92-894-8322-9) (November 2004)

[7] Garg, Amik, Deshmukh, S.G.: Maintenance management: literature review and directions. Journal of Quality in Maintenance Engineering 12(3), 205– 238 (2006). DOI 10.1108/13552510610685075. URL http://dx.doi.org/10.1108/13552510610685075

[8] Hannelius, T., Salmenpera, M., Kuikka, S.: Roadmap to adopting opc ua. In: Proc. 6th IEEE International Conference on Industrial Informatics INDIN 2008, pp. 756–761 (2008). DOI 10.1109/INDIN.2008.4618203

[9] Jammes, F., Smit, H.: Service-oriented paradigms in industrial automation. IEEE Transactions on Industrial Informatics pp. 62–70 (2005)

[10] Karnouskos, S., Baecker, O., de Souza, L.M.S., Spiess, P.: Integration of soa-ready networked embedded devices in enterprise systems via a cross-layered web service infrastructure. In: Proc. of the IEEE Conference on Emerging Technologies & Factory Automation (ETFA), pp. 293–300 (2007). DOI 10.1109/EFTA.2007.4416781

[11] Koc, M., Ni, J., Lee, J., P., B.: Introduction of e-manufacturing. In: Proceedings of the 31st North American manufacturing research conference (NAMRC), Hamilton, Canada (2003)

[12] Kumar, U.: System maintenance: Trends in management and technology (2008). URL http://dx.doi.org/10.1007/978-1-84800-131-2_47

[13] Muller, A., Crespo, Iung, B.: On the concept of e-maintenance: Review and current research. Reliability Engineering & System Safety 93(8), 1165–1187 (2008). DOI 10.1016/j.ress.2007.08.006. URL http://dx.doi.org/10.1016/j.ress.2007.08.006

[14] Pinjala, S.K., Pintelon, L., Vereecke, A.: An empirical investigation on the relationship between business and maintenance strategies. International Journal of Production Economics 104(1), 214–229 (2006). URL http://ideas. repec.org/a/eee/proeco/v104y2006i1p214-229.html

[15] de Souza, L.M.S., Spiess, P., Guinard, D., Koehler, M., Karnouskos, S., Savio, D.: SOCRADES: A web service based shop floor integration infrastructure. In: Internet of Things 2008 Conference, Zurich, Switzerland (March 26-28, 2008)

[16] Spiess, P., Karnouskos, S., Guinard, D., Savio, D., Baecker, O., de Souza, L.M.S., Trifa, V.: SOA-based integration of the internet of things in enterprise services. In: Proceedings of ICWS 2009 (IEEE International Conference on Web Services). Los Angeles, California, USA (2009)

[17] Seliger G. Kim, H-J. Kernbaum S. Zettl M.: Approaches to sustainable manufacturing. Int. J. Sustainable Manufacturing, (1), (1/2), 2008.