# Twin-Control: A New Concept Towards Machine Tool Health Management

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## ABSTRACT

Twin-Control (http://twincontrol.eu/) is a new concept for machine tool and machining process performance optimization. It is based on a new simulation model that integrates the different aspects that affect machine tool and machining performance. This holistic approach will allow a better estimation of machining performance than single featured simulation packages, including lifecycle concepts like energy consumption and end-life of components.

This theoretical representation of the machine is complemented with real process data by the monitoring of the most important variables of the machining process and machine condition. This monitored information, combined with the developed models, is used at machine level to perform model-based control actions and/or warn about damaged components of the machine tool. In addition, a fleet-level data management system is used for a proper health management and optimize the maintenance actions on the machine tools.

## 1. INTRODUCTION

Europe is the world's largest manufacturer of machine tools, but this position is threatened by the emergence of Asian countries. However, Europe has world-class capabilities in the manufacture of high-value parts for such competitive sectors like aerospace and automotive and this has led to the creation of a high-technology, high-skill industry. European machine tool builders, part manufacturers and other agents have to work together to increase the competitiveness of European manufacturing industry.

Simulation tools are currently a key complement to European machine tool industry expertise in order to increase competitiveness. In fact, according to Industry 4.0 (Kagermann et al., 2013) modeling plays a key role in managing the increasing complexity of technological systems. A holistic engineering approach is required that spans the different technical disciplines and providing an end-to-end engineering across the entire value chain. However, the different software packages are focused in a single feature related to machine tool or machining process. In the last years, so called Virtual Machine Tool packages have appeared that offer similar solutions based on the interpretation of G-code to check machine tool movements according to the programmed tool path and kinematics with the purposes of training and process checking, including collision avoidance. However, none of these packages deals with aspects like dynamics, machining processes or lifecycle estimation. As noted by Abdul-Kadir et al. (2011), "the developed tools are still not capable of supporting an inclusive simulation package". In addition, the more and more important lifecycle concepts like energy consumption and component end-life and degradation are not always present in machine tool builders and part manufacturer's calculations.

Because machining process performance is related to the combination of the different phenomena, it can be concluded that there is a need to integrate the most important effects in a common simulation environment.

Another key principle of Industry 4.0 is to increase the knowledge of the process obtained through monitoring (Lee et al. 2015). This knowledge can be applied, for example, for process control (Denkena et al. 2014) and maintenance

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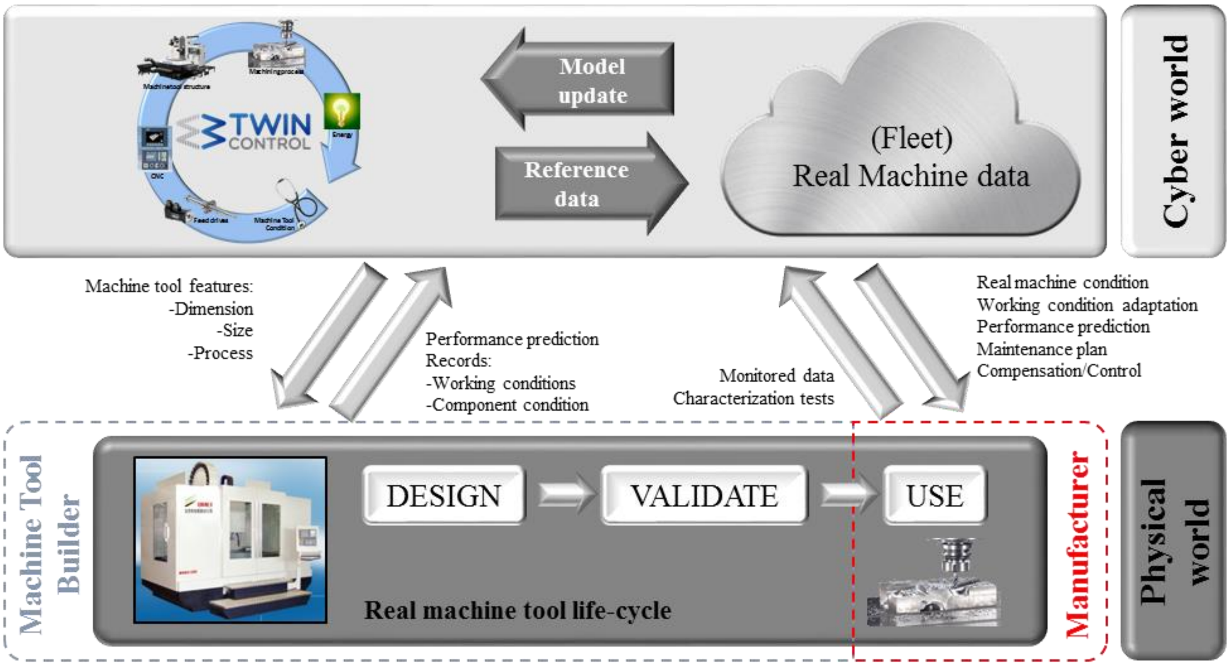

Figure 1. Twin Model concept used in Twin-Control project.

actions optimization (Alzaga et al. 2014). The combination of models and process monitoring will be useful not only in the development and design stages, but mainly during the production stage in order to check that production is running smoothly, detect wear and tear without needing to halt production or predict component failure and other disruptions.

Twin-Control (http://twincontrol.eu/) is a novel concept for machine tool and machining process performance optimization. It combines a holistic simulation model, integrating most important features of machine tools and machining process, with monitoring and data management capabilities.

This paper is composed of four sections. The first one presents the introduction and context of this research. The second one introduces Twin-Control concept. The third chapter presents an overview of the technical solution architecture of Twin-Control. Finally, the fourth chapter presents the conclusions and the future steps.

## 2. TWIN-CONTROL CONCEPT

Twin-Control will use a Twin Model concept for the development of the simulation tool (Figure 1). The Twin Model concept is based on a combined application of the Cyber and Physical worlds, following the Cyber Physical System (CPS) concept. The Cyber world consists in the computation, communication, and control systems. The Physical world is composed by the natural and human-made systems governed by the laws of physics.

In this project, the Virtual Manufacturing System resulting from the combination of the different theoretical models that cover different aspects of the manufacturing process corresponds to the Cyber world, together with the cloud based data management part, where machine fleet data is managed. The Physical world corresponds to the real machine that performs the real manufacturing process.

The Cyber world will make use of real machine tool and process data through all its life cycle. The Virtual Manufacturing System will be created by combining the correspondent theoretical models according to machine tool design and process specifications. During part manufacturing, the holistic simulation model will be updated according to machine tool real condition using data obtained through monitoring and additional characterization tests designed for this purpose. This way, the Virtual Manufacturing System will be able to predict current machine/process performance in an accurate way.

In the same way, the simulations outputs obtained with the new Twin-Control tool will be useful through all machine tool life cycle. In the machine tool design stage, Twin-Control will be an extraordinary tool to predict the performance of projected machine tools. The same occurs with the process design, providing accurate estimation of cycle times and resultant part accuracy allowing a quick optimization procedure. By applying Twin-Control, validation stage will be minimized due to set-up time reduction.

Finally, during machine tool usage period, process will be under control by the monitoring of the most important variables and the compensation actions to be performed through machine tool's CNC. According to machine tool health management, both local and fleet level tasks will be implemented. On the one hand, spindle temperature and power consumption will be monitored on machine level to control spindle's condition. On the other hand, additional variables of the most important components of the machines will be also monitored and managed at fleet level. The collected data will be combined with simplified versions of the simulation models in order to enhance predictions.

## 3. ARCHITECTURE DEFINITION

Two separate application environments have been clearly defined: simulation, linked to a theoretical representation of the machine tool and the process; and Monitoring and Control, linked to a real representation of the machine tool and the process. The fleet-based knowledge acts as a link between both representations by managing the real machine data (machine tool state, usage conditions, etc.) at a fleet level and using it to improve the accuracy of the simulation models. In the same way, simplified versions of the simulation part and results will be used in the real part to enhance monitoring and control activities.

### 3.1. Simulation Operation Mode

Devoted to machine tool and process design and optimization. The application of complex theoretical models leads to very accurate estimations of process performance, allowing its optimization. Due to computational costs, this operation mode is oriented to offline simulations executed in a conventional PC. The link with the real world is obtained, in one direction, by the usage of the fleet level knowledge stored in the cloud (model update, validation using monitored data…) and, in the other direction, by uploading simulated results and parameters to the cloud ("reference" machine values).

The core of the simulation model is a Virtual Machine Tool module based on machine tool's finite element (FE) model that integrates the toolpath simulation and process effects (Figure 2). This integration leads to a complete understanding of machine tool dynamic performance during real machining processes and will allow the prediction of the most important features like surface roughness, form errors, etc.

By using the results of the Virtual Machine Tool, some complementary features will be studied through additional models. Next to surface topics, energy efficiency of the simulated process and end-of-life estimations of the most critical elements could be provided.

End-of-Life module will be in charge of the determination of the end-of-life of typically problematic machine tool components like bearings, linear guidelines and screw drives. Based on the predictions of the integrated Virtual Machine Tool model, which will be able to estimate operating conditions of these elements, an accurate prediction of their end-of-life will be made based on the methods defined in the well-established standards defined by the International Standard Organization for each component: bearings (ISO, 2007), linear guidelines (ISO, 2004), and screw-drives (ISO, 2006).

The energy efficiency module will be in charge of the determination of the energy consumption of machine tools. To gain a most widely transparency, the energy consumption will be observed on a component level. This will lead to the possibility to design energy efficient machine tools and processes. The Simscape model library to be developed will be the basis for the configurator. The physical input parameters are obtained from data sheets: if detailed characteristic curves are available, they are directly used for simulation; if less information is available, the behaviour will be modelled.

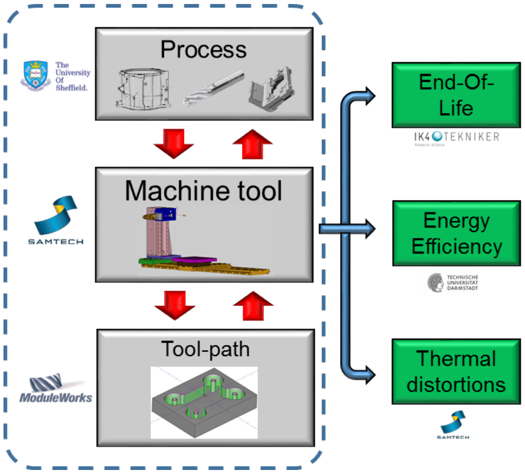

Figure 2. General overview of the Simulation Operation mode architecture.

By using the estimations provided by its different modules, Twin-Control will provide the chance to optimize the process by adapting the toolpath and/or cutting conditions. In addition, the analysis of the results provided by Twin-Control could be used to make changes at machine tool level (including clamping).

### 3.2. Monitoring and Control Operation Mode

The most important variables of the machine tool and machining process performance will be monitored and managed at machine and fleet level. This operation mode is aimed to be executed in the machine tool control for visualization purposes.

For monitoring purposes, ARTIS Genior Modular will be installed in the machines. This device allows direct exchange of CNC data at high real-time rate. Depending on the CNC model installed in the machine, CANOpen or Profibus communication protocol can be applied.

Additionally, an ARTIS OPR unit – Offline Process Recorder – will be used and connected via Ethernet to the Genior Modular to store the real-time data capturing and also to receive OPC data in non real-time as a second data source. The OPR will push real-time and OPC data to the Remote or Local service hosting the fleet-based database. In addition, Genior Modular and OPR could exchange real-time information using CANOpen, e.g. in case of critical alarm information remotely detected inside the fleet-based database.

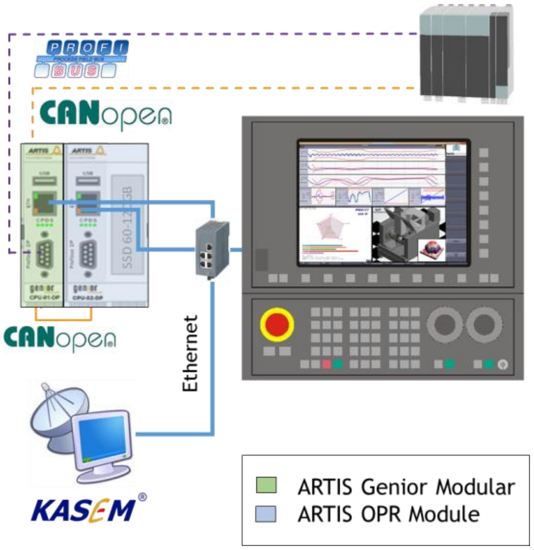

Figure 3. Monitoring architecture diagram.

The real-time local data management system will allow implementing process monitoring capabilities that will be used to safeguard production. Spindle torque monitoring on all machines will be used to detect abnormal behavior during processing. This could be sudden action in case of tool breakage, delayed stop in the case of tool breakage during tapping operation or tool wear events.

A new energy monitoring system that avoids the extensive use of hardware (hall) sensors will be also implemented, leading to a drastic reduction in investment costs for an energy monitoring solution on component level. To do that, Simscape models developed for the Simulation Operation Mode will be embed in ARTIS Genior Modular (Figure 4). Using real CNC sensor data, the module will be able to determine energy consumption per component.

Health assessment of the most important components of the machine tools will be done at local level applying two approaches:

- Continuous monitoring of some available variables. For example, continuous monitoring of spindle temperature. If spindle temperature increases, it could be related with anomalous performance. The monitored data, together with some limits provided by the user, could be used to provide warnings or suggest.
- Characterization test: A periodic test procedure will be defined to characterize machine tool condition and compare it to reference conditions (Prado et al. 2014). The proposed monitoring hardware will be used to monitor these tests and manage the data at local level.

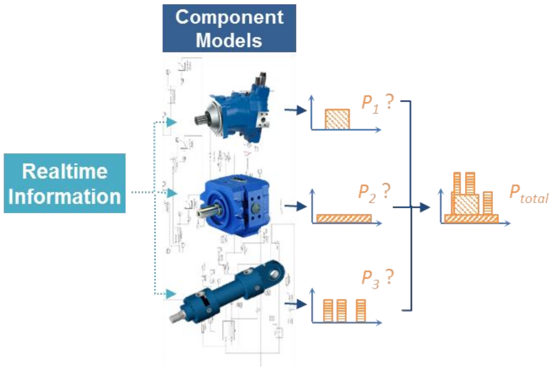

Figure 4. Model-based energy consumption estimation.

All signals will be visualized in a central HMI solution (Figure 5), each signal in a window on its own. HMI will be enhanced by including PlugIns of additional features like fleet-level knowledge reports or graphical representation of simulation results.

Figure 5: ARTIS HMI, showing anomalous process performance, integrated in smartphone.

## 3.3. Fleet-based data management

From Twin-Control point of view, fleet refers to a set of machine tools of different owners and builders. A fleet can be viewed as a population consisting of a finite set of units (individuals). Fleet's units must share some characteristics that enable to group them together according to a specific purpose. By considering domain specific attributes, fleet-wide approach of data management allows to analyze data and information through comparison according to different point of view of heterogeneous units (e.g. compare condition index of similar equipment in the different location, compare different system health trend for the same operation…). Fleet-wide approach provides a consistent framework that enables coupling data and models to support diagnosis, prognostics and expertise through a global and structured view of the system and enhances understanding of abnormal situations. Fleet management raises issues such as how to process large amount of heterogeneous monitored data (i.e. interpretable health indicator assessment), how to facilitate diagnostics and prognostics of heterogeneous fleet of equipment (i.e. several technologies and usage) or how to provide key users with an efficient support to decision-making throughout the whole asset lifecycle. Towards this end, a complete guide (model, method and tool) is needed to support such processes (i.e. monitoring, diagnostics, prognostics…) at the scale of the fleet.

In addition to individual modeling and health monitoring, it is necessary to provide fleet-wide facilities. Towards this end, the platform integrates semantic modeling that allows gathering and sharing, at fleet wide, data, models and expertise from the different systems and equipment. The approach of fleet based data management, depicted in Figure 6, is built around a global methodology that allows guiding the proactive strategy definition all along the asset lifecycle. It provides a consistent framework that enables coupling data and models to support diagnostics, prognostics and expertise through a global and structured view of the system and enhances understanding of abnormal situation (i.e. system health monitoring level).

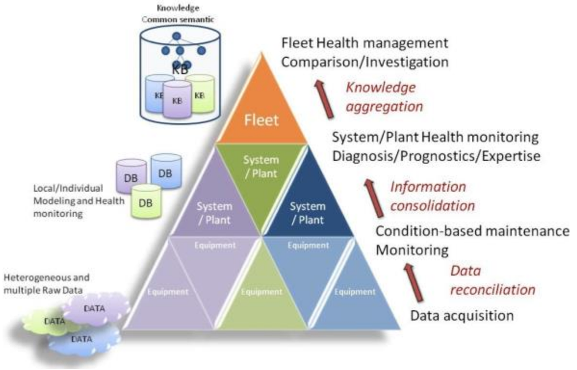

Figure 6: Hierarchical approach of the proactive fleet management (Monnin et al. 2011)

Starting from the definition of the system functioning in relation to its environment, the formalization of the system malfunctioning analysis is then considered. The corresponding knowledge (i.e. functioning and malfunctioning models) is incrementally built within a knowledge-based system that supports a structured and hierarchical description of the fleet. This formalization enables to reduce the effort for data consolidation within system health management as well as for knowledge aggregation within fleet health management, since it enhances understanding of the impacts between and within levels.

The fleet level data management platform proposed for the Twin-Control project is based on KASEM® (Knowledge and Advanced Service for E-Maintenance) (Léger, 2004). It is a collaborative e-Maintenance platform, integrating engineering, proactive maintenance, decision making and expertise tools (Prado et al. 2014) and used in former Power-OM project http://power-om.eu/.

### 3.3.1. Health assessment

Health assessment functionality consists of the correlation of various information computed by the fleet platform to evaluate the health status of one machine and health status of machines set. Health assessment is mainly based on a rating principle of different features:

- Key Performance Indicators (KPI): These indicators allow users to have a synthetic view of an equipment, a machine or a fleet of machines. They are computed at the equipment and then they are aggregated to build higher-level indicators. Aggregation of equipment KPI gives machine KPI, and aggregation of machine KPI gives the fleet KPI.
- Drift detection: this functionality is necessary to have early detections of machine non-nominal behaviors. Early detection is based on residual analysis of the difference between observed behavior and reference behavior. Early detection allows generating proactive alerts in order to anticipate fault occurrences and then to avoid machine tools stops. Detection can be done on operating points but also on transient behaviors. Figure 7 depicts an early detection of a temperature transient drift according to spindle speed level. In this case, detection is based on a thermal model learned by the fleet platform.

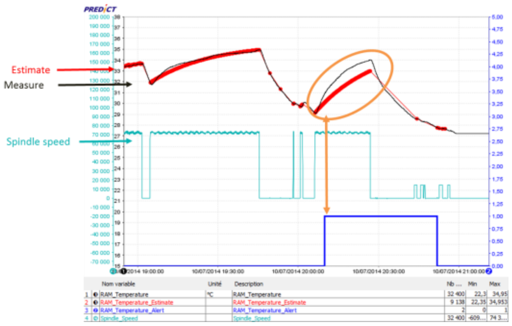

Figure 7: Example of drift detection on temperature measurement

- Machine references: To detect behavior drifts it is necessary to have reference behaviors, the fleet platform are able to learn references but also to use references extracted from the simulation environment. In this case, it will take advantage of the simulation models developed within Twin-Control project.
- Machine Tool characterization tests: The periodic execution of the test procedure will allow obtaining a

good source of information that reflects the condition of the different components of the machine tool without process effects.

A score is assigned to each component of the health status, and then scores are merged to compute the health status. This principle allows a graphical representation of machines health status on radar plot. Several machines can be overlaid to make a fleet comparison as depicted in the left part of Figure 8.

#### 3.3.2. Event's sequences analysis

Events include both alarms from local monitoring and alerts from fleet drift detection. This module will be in charge of the interpretation of events sequences, i.e. the interpretation of frequency and order of the events. Information about event types and the time stamps of their occurrence will be used to analyze the time series data and thus finding dependencies between different alarms. Generic causal models, i.e. models shared by all machines of the fleet, will be used during the analysis. A causal model represents the relationship between the different event types. These causal relationships can be used to recognize an event sequence on a given period. Once the sequence is identified, causal models allows to identify the sequence root cause (diagnosis) but also to know what could be the next event (prognostic) of the sequence.

This module will use event sequences as signatures of machine situations. For each machine, past situations will be stored in the knowledge base with generic label in order to build the fleet experience feedback and thus to improve event's sequences analysis.

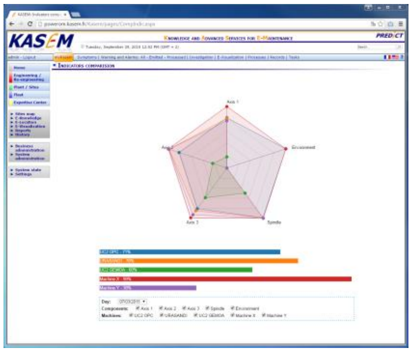

Figure 8: Graphical representation of machine health status in KASEM®.

#### 3.3.3. Remaining Useful Life (RUL) estimation

Based on the algorithms developed for the Simulation Operation Mode, which use theoretical working cycles to estimate end-of-life of critical components, a Remaining Useful Life (RUL) calculation module will be implemented in the fleet level management system by taking into account the real machine tool usage conditions.

#### 3.3.4. Platform portal and outputs

For the purpose of accessibility, all the functions of the platform are available through a web portal. Results can also be made available directly on site by means of report for instance that can be sent (e.g. by mail) to the users and/or displayed on machine local HMI through ARTIS PlugIn. The platform web portal will provide HMI to support decision making for diagnosis activities, to visualize knowledge base information with dynamics dashboards and static reports.

In addition, a functionality of data and knowledge extraction will be developed for both manually and automatically download information from platform to simulation environment and local monitoring environment.

## 4. CONCLUSIONS AND FUTURE LINES

Twin-Control (http://twincontrol.eu/) is a new concept for machining process performance optimization, including health assessment of the machine tools. Monitored data is combined to advanced simulation models to enhance the knowledge of the process. Apart from local level management, monitored data will be managed at fleet level. Local servers will be

Twin-Control project is currently in its early stage. In the next months, research work on the different modules (Simulation and Monitoring) will be carried out. This work will be continued by the integration of all the modules on a single platform. One of the highlights of this project is the possibility to validate the developed tool in two scenarios of the most important sectors of the European industry: Aerospace and automotive. In order to feed the fleet level data management system with the highest amount of data, monitoring activity will start on summer 2016. For the fleet level database, local servers to gather and manage the data collected in the machines at each use case will be installed.

## ACKNOWLEDGEMENT

The work presented in this paper is part of the research work still in progress in the project Twin-Control, funded under H2020 under grant agreement no. 680725, as part of the Factories of the Future initiative.

## REFERENCES

Abdul-Kadir, A., Xu, X., Hämmerle, E. (2011) *Virtual Machine Tools and Virtual Machining—A Technological Review*. Robotics and Computer-Integrated Manufacturing 27, 494–508.

Alzaga A., Konde E., Bravo I., Arana R., Prado A., Yurre C., Monnin M., Medina-Oliva G. (2014). *New technologies to optimize reliability, operation and maintenance in the use of Machine Tools*. Euro-

Maintenance conference, 5-8 May 2014, Helsinki, Finland.

Denkena, B., Fischer, R., Euhus, D., Neff, T. (2014). *Simulation based Process Monitoring for Single Item Production without Machine External Sensors*. 2$^{nd}$ International Conference on System-Integrated Intelligence: Challenges for Product and Production Engineering, Procedia Technology, Volume 15, 341-348.

International Standards Organization (ISO) (2004). Rolling bearings -- Linear motion rolling bearings -- Part 1: Dynamic load ratings and rating life. In ISO, *ISO14728-1:2004.* Genève, Switzerland: International Standards Organization.

International Standards Organization (ISO) (2006). Ball screws -- Part 5: Static and dynamic axial load ratings and operational life. In ISO, *ISO3408-5:2006.* Genève, Switzerland: International Standards Organization.

International Standards Organization (ISO) (2007). Rolling bearings -- Dynamic load ratings and rating life. In ISO, *ISO281:2007*. Genève, Switzerland: International Standards Organization.

Kagermann, H., Wahlster, W., Helbig, J., (2013). *Recommendations for implementing the strategic initiative INDUSTRIE 4.0*. Report. National Academy of Science and Engineering (Acatech), Germany.

Lee, J., Bagheri, B., Kao, H.-A. (2015) *A Cyber-Physical Systems architecture for Industry 4.0-based manufacturing systems*. Manufacturing Letters, Volume 3, January 2015, Pages 18–23.

Léger J-B. (2004). *A case study of remote diagnosis and emaintenance information system.* Keynote speech of IMS'2004, International Conference on Intelligent Maintenance Systems, Arles, France.

Monnin, M, Leger, J-B., Morel, D. (2011). Proactive facility fleet/plant monitoring and management, in Proceedings of 24th International Congress on Condition Monitoring and Diagnostics Engineering Management, 29th May – 1st June, Stavanger, Norway.

Prado, A., Alzaga, A., Konde, E., Medina-Oliva, G., Monnin, M., Johansson, C.-A., Galar, D., Euhus, D., Burrows, M., Yurre, C., (2014) *Health and Performances Machine Tool Monitoring Architecture*. E-maintenance conference, from 17th to 18th of June 2014, in Luleå, Sweden.