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The role and function of maintenance is today subject to a profound transformation. Compared to past developments, it now attains a broader scope. Maintenance decisions are no longer addressing a narrow scope limited to technical and operational considerations. Instead, they are increasingly related to a comprehensive systems engineering approach, linked to extended enterprise and risk management considerations and adopting new technology, management and business perspectives. Hence, maintenance entails different processes and multi-disciplinary approaches, requiring the integration of a wide range of engineering and management-related methodologies, information and communication technologies, management philosophies, models and strategies, as well as considerations on business strategies and models. It is a value adding function for a range of industrial assets and products and is increasingly linked to complex product-service propositions, thus requiring increasing connectivity of involved entities, ranging from low level component and asset interactions, to higher level multi-stakeholder performance and service delivery considerations. This special issue provides evidence of the evolving transformation of the maintenance function, the breadth of activities contributing to it and the increasing impact that emerging information and communication technologies have on enabling such advancements. It comprises 11 contributions, which are revised and extended manuscripts, following the third International Federation of Automatic Control (IFAC) workshop on Advanced Maintenance Engineering Services and Technology (IFAC A-MEST'16) which took place in Biarritz, France, 19–21 October 2016. The contributions included in this issue are a clear reflection of the fact that the research agenda in maintenance engineering and management is currently integrating new topics and transforming traditional ones in view of the new challenges and needs for multi-disciplinary approaches.

The first two papers deal with different perspectives of risk management in maintenance services and production management.

- Liu et al. propose a new modelling technique based on an extended Bayesian approach to tackle uncertainty and risk modelling challenges raised by large-scale and complex real-world systems. The

Extended Object-Oriented Bayesian Networks (EOOBNs) approach taken adopts object orientation to enable the required flexibility in modelling scenarios for such complex systems, while retaining the same modelling structure for the entities of the modelled network. Adaptation mechanisms are included to take into account system dynamics when modelling machinery state evolution and its impact on productivity. The adoption of the EOOBN is illustrated on modelling a selected industrial process, that is, cement manufacturing. Overall, the modelling approach may facilitate risk management and decision-making in large-scale and complex systems.

- Erguido et al. provide a methodological approach for risk-based optimisation of after-sales maintenance services. The approach is concerned with the implementation of opportunistic maintenance strategies to identify a range of solutions, which represent different trade-offs between service level and costs. The multi-objective optimisation is performed by a variation of the popular non-dominated sorting (multi-objective) genetic algorithm NSGA-II. Simulation modelling is employed to handle the stochastic nature of processes involved in after-sales maintenance services and to evaluate the different strategies. Based on different considerations from the original equipment manufacturers' (OEMs) and users' needs and the analysis of the impact of uncertainty sources on the after-sales services, the proposed approach enables to assess the economic risk of the services to be offered. The whole system modelling is illustrated in a wind energy case study.

The transformation of the maintenance function in the context of asset and production management is the prime focus of the next four papers.

- Roda and Macchi propose a framework to integrate asset management (AM) in production companies. Taking into account concepts from the ISO 55000 AM standard, the framework consists of two dimensions, the asset life cycle and the hierarchical level of the asset control activities, and four founding principles namely life cycle, system, risk and asset-centric orientation, as levers relevant for the

integration. The framework is first defined based on literature analysis and then confirmed by industrial experts through the development of focus groups. An empirical investigation, through multiple case study analyses in Italy, allows to map the elements of the framework against the real mechanisms in industrial practice, eventually demonstrating the framework's validity and potential as a support to implement gap analysis on AM practices in production companies. The research findings are interesting for managers and engineers in this context to be aware of the main principles and dimensions required to structure an AM system.

- Do et al. investigate the use of energy efficiency (EE) as a key performance indicator for condition - based maintenance (CBM). Therefore, an EE-based CBM policy is developed. In particular, the energy efficiency indicator (EEI), defined as the amount of energy consumption to produce one output unit, is adopted for preventive maintenance decision-making: the EEI level, acting as the representative of the system health condition, is monitored at regular inspection times and is used to trigger preventive maintenance actions. A cost-benefit model, considering both the output performance benefit and energy cost, is also developed and employed to optimise a CBM policy. The approach is demonstrated on a case study of a laboratory scale production line, comparing EE-based CBM with conventional CBM, highlighting the benefits of introducing the EEI indicator.
- Internet of things-enabled connectivity is the key enabler for the vision of a Social Internet of Industrial Assets (SIIoIAs) by Hao et al. In SIIoIA, autonomous assets are proposed to act as collaborating (social) agents. The authors identify the building blocks of the SIIoIA and present a general architecture of the proposed social network. Subsequently, two illustrative examples of SIIoIA applications are presented. Overall, the paper introduces a framework to improve AM policies, based on collaborating industrial assets, allowing asset managers to have a much broader knowledge of their fleets of well-instrumented assets.
- Fasanotti et al. consider the maintenance services of geographically dispersed industrial systems via an innovative viewpoint, proposing an artificial immune system (AIS) agent-based maintenance management approach. Examples of how to apply this exploratory study approach on industrial problems, such as in a wastewater treatment plant and an oil/gas pipeline system, are provided. The study argues about the flexibility of AIS methodologies to be employed for diagnostic and prognostic functionality, coupled with the flexibility of a multi-agent architecture as enabler of a mix of autonomy and

distributed processing. The approach has potential in contexts with a large number of devices and assets, located in disparate geographic areas.

The next three papers deal with asset-level activities and are especially focussed on inspection, diagnostics, and prognostics and health management (PHM).

- Zhang et al. propose a PHM approach for improving the quality of remaining useful life (RUL) predictions of a proton exchange membrane fuel cell (PEMFC). While particle filter-based approaches for PHM are well established in the literature, including for PEMFC, the interest here is in combining this with a model-based approach that takes into account degradation recovery phenomena. Overall, the proposed method is applicable to fuel cell stacks under both stationary and quasi-dynamic operating regimes. The experimental results demonstrate the improvements in the prognostic performance, especially for long-term predictions.
- Assaf et al. study the degradation process of complex multi-component systems, with a particular focus on modelling degradation interactions between components. To this end, a general wear model is proposed where the degradation process of a component may be dependent on the operating conditions, the component's own state, and the state of the other components. This is combined with a methodology to extract health indicators from multi-component systems by means of a time-frequency domain analysis. The approach is demonstrated on a lab-based gearbox-accelerated life-testing platform, studying the impact of old-new component couplings in reduced life expectancy of new, healthy components in the multi-component system.
- The paper by Moustakidis et al. introduces a methodology for handling some of the challenges when applying thermography techniques for the inspection of composite structures commonly used for aircraft components. Focusing on lock-in thermography, the authors analyse the needs and introduce an approach for excitation invariant pre-processing of thermographic images. The proposed pre-processing techniques were demonstrated on testing composite samples with pre-determined defects. Whereas, thermography has been widely applied to aircraft component inspections, including composites, extending the applicability of such techniques critically depends on introducing invariances in any image pre-processing and therefore the paper is of added value to a growing body of literature in the field.

The final two papers address issues related to maintenance strategies and optimisation.

- Kathab et al. develop a new mathematical model for the condition-based selective maintenance problem (CBSMP). The formulation considers components with stochastic degradation, periodic inspection and imperfect maintenance. The proposed approach targets the identification of components which should be maintenance targets, while optimising the level of maintenance actions to be performed within time-limited scheduled breaks. Parameters impacting on the operational requirements of the maintained assets, such as the minimum required reliability to achieve the next mission, are taken into account. Simulation based degradation experiments are employed to show the applicability of the proposed model.
- Finally, Sera et al. adopt a case study approach to jointly address cost and value in a criticality-based analysis of risks for priority setting in preventive maintenance optimisation. The approach is explained step by step in the case study, dealing with gas network infrastructure. The provided example should be of considerable interest to practitioners, while the paper highlights the need for further work in the direction of identifying the right business and risk drivers for maintenance action prioritisation in a systematic, risk-based framework.

The breadth of the thematic coverage of the contributions in this special issue provides evidence that maintenance is becoming a comprehensive and multi-disciplinary business function. It increasingly capitalises on a blend of engineering and management activities, supported by rapidly evolving and maturing technology enablers, with a particular contribution from internet of things, advanced modelling and simulation, as well as various aspects of data analytics and machine learning, all contributing to a vision of smart and interconnected physical assets, as key constituents of the extended production and services ecosystems of the future. We therefore hope that, whether the focus is on component and asset-specific activities or all the way up to global maintenance service delivery and asset life cycle management, these contributed papers will be of added value and inspiration for further advancing the integration of maintenance engineering and management within a broader risk-based and life cycle-based maintenance strategy thinking.

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