Editorial

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Biographical notes: José Ríos is currently a Visiting Professor in the DiK Department at TU Darmstadt. He holds an Associate Professor position in the Department of Mechanical Engineering at the Universidad Politécnica de Madrid, where he earned his Doctoral degree in Mechanical Engineering in 1997. He has focused his work on the digital manufacturing area, and on techniques, standards and software systems involved. He has participated in projects related to digital manufacturing, CAD/CAM/PLM, information modelling, KBE and design integration. He was a visiting scholar at Penn State University, USA, a visiting researcher at Cranfield University, UK and was the Spain representative to the ISO TC 184/SC4 for two years. He is a member of the IFIP TC5 WG5.1 Global Product Development for the Whole Lifecycle.

Reiner Anderl earned his Dr.-Ing. degree in Mechanical Engineering in 1984 at the Universität (TH) Karlsruhe. Since 1993, he is a Professor and the Head of the Computer Integrated Design Department (DiK) at TU Darmstadt. From 2005 until 2010, he served as the Vice-President of TU Darmstadt. He was an Adjunct Professor at Virginia Tech, USA, and Visiting Professor at UNIMEP, Piracicaba, Brazil. He is a full member of WiGeP (Eng.: Scientific Society for Product Development) and of ACATECH (Eng.: National Academy of Science and Engineering). He is also the Chairman of the Scientific Advisory Board of ‘Plattform Industrie 4.0’. Since 2017, he is the President of the Academy of Sciences and Literature, Mainz. He has authored and co-authored more than 300 publications.

Peter Pelz earned his Dr.-Ing. degree in Mechanical Engineering in 2000 at the Technische Universität Darmstadt. From 2003 to 2006, he was the Manager for Advanced Development by the company, Vibracoustic AG & Co. KG. Since 2006, he is a Professor and the Head of the Institute of Fluid Systems Technologies (FST) at TU Darmstadt, where he leads the research on sustainable system design, cavitation and generic flows in turbo machinery and systems, and urbanisation and infrastructures. Since 2013, he leads the Research Collaborative Centre 805 on control of uncertainty in load-bearing systems in mechanical engineering. Since 2015, he is an active member and German representative to the CEN/TC 156/WG 17. Since 2019, he is a deputy speaker in the consortium NFDI4Ing Development of Research Data Infrastructure for Engineering Sciences.

We are pleased to present a special issue of the *International Journal of Product Lifecycle Management*, entitled 'Uncertainty in the digital twin context'. This special issue is part of an effort to encourage the submission of works dealing with uncertainty quantification, modelling and management within the product lifecycle community. It corresponds also to a dissemination task within the collaborative research project number 57157498 – SFB 805, that deals with uncertainty within the mechanical engineering context, and which is funded by the German Research Foundation (Deutsche Forschungsgemeinschaft – DFG). In this project, one of the objectives is to manage uncertainty along the product lifecycle, from development to usage.

The management of uncertainty along the product lifecycle is a complex and daunting aim that is widely acknowledged both in industry and academia. The current trend in achieving digital twins make that aim even more significant, since a larger amount of data acquired from the physical domain, which implies the measurement of physical magnitudes or quantitative properties, must be integrated into a digital domain to assist in predictive and decision-making processes. In engineering, it is widely accepted that three elements: nominal value of the magnitude, measurement unit, and uncertainty of the measurement; constitute the result of a measurement. In general terms, the creation of a digital twin demands integrating measured data into the models created during the development and design phase and using measured data to create manufacturing-related models (as-manufactured, as-fabricated or as-built), maintenance-related models (as-maintained) and usage or operation-related models (as-operated).

Measured data from tests, conducted on test specimens, scale models and prototypes, are used in different models created in the development and design phase, to estimate properties and performance of the product through multiple rounds of convergent and progressive iteration. Design margins of key requirements and design parameters are reduced and adjusted along those iterative tasks. Ultimately, estimated properties and performance are used to impose product mandatory specifications along the design phase. The outcome of the development and design phase is a set of linked models (e.g., as-specified, as-designed, as-tested, as-planned and as-prepared) that conform a digital master.

Part of the mandatory specifications, which include nominal values and tolerances or min-max values of ranges, must be fulfilled by manufacturing. Along the manufacturing phase, both process-related measured data and product-related measured data are used to monitor the execution of the manufacturing itself and to assess and validate the manufactured product against mandatory specifications. Obvious though it may seem, we still would like to point out that the uncertainty of the measurements conducted on a manufactured product must be lower than the tolerance intervals defined during the design phase. The aim of creating an as-manufactured 3D model is to represent the geometric deviations caused by the manufacturing processes and use the model to perform simulations. In that sense, the as-manufactured 3D model should improve the accuracy of the results obtained when using as-designed 3D models to perform those simulations. However, literature emphasises that uncertainty of measured data and of reconstructed 3D geometric models are frequently unknown.

During the product operation phase, data are also captured as part of in-service monitoring solutions. These measured operational data are relevant, for instance, to monitor the product against possible failures, when developing smart products, and to perform simulations of the whole product or failure simulations of critical components. The in-service monitoring data are part of as-operated models. Making explicit the uncertainty of the measured in-service conditions is relevant, since the objectives of using in-service data are various, e.g., reduce the uncertainty derived from adopting worst-case scenarios and assumptions during the design phase, or act as input to perform adaptive and responsive tasks.

This special issue was initially conceived to address uncertainty related aspects such as: information models for the representation of uncertainty, uncertainty in industrial information systems, uncertainty propagation when implementing model-based systems engineering methods, impact of physical domain data uncertainty when using robust design and resilience design techniques, uncertainty and predictions derived from applying machine learning techniques on product-related or process-related data acquired from the physical domain, and uncertainty and conflicting data sources in data fusion environments. Reality shows that initial limits run the risk of becoming too narrow, and we are pleased to state that was the case for this special issue. The accepted submissions provide a scope wider than initially envisaged. The content of this special issue is structured into three parts attending to the specific digital field where the uncertainty is considered. Part 1 brings an industrial contribution on the field of quality information standards. Parts 2 and 3 bring research contributions on the field of data induced conflicts and sensing machine elements (SME), and on the field of digital engineering integration and change management, respectively.

The first work of this special issue presents, with an industrial-oriented perspective, an approach to help quality engineers in addressing uncertainties in the data used to assess the quality of manufactured products. Kramer and Campbell present a brief introduction to the ANSI and ISO standard quality information framework (QIF) and to its model-based quality workflow. QIF integrates a product model-based definition with measurement planning, measurement results, and measurement statistics. Then they discuss in detail how QIF deals with different types of uncertainty that arise when performing a dimensional measurement process, e.g., about the accuracy of nominal values, about measurement units, about the identity and accuracy of measurement devices, whether measurement devices are calibrated and used properly, about data file integrity, and about the algorithms and software used to analyse measurement data. The relevance of the work presented by Kramer and Campbell is also emphasised by the fact that QIF is being used with other digital thread information technologies such as ISO 10303 (STEP) and ANSI MTConnect to facilitate the creation and integration of digital twins.

The benefits derived from the digital twin implementation, depend on incorporating ‘true data’ from the physical domain into the digital one. However, in general, the problematic of the trueness of measured data is wider in the case of monitoring and operating data than in the case of dimensional measurement. In the case of monitoring, operating or testing data, typically, the gathered data are the result of measurements conducted by means of a variety of sensors which are part of a measurement subsystem. The uncertainty due to data induced conflicts is relevant in this scenario. The identification of false readings from sensors is important, since it helps to solve data inducted conflict situations. Analytical redundancy methods are frequently used to address failure detection situations such as data inducted conflicts. Mastering data-induced conflicts is the aim of the work from Öztürk et al. They propose the concept of soft-sensor to establish a redundancy without adding additional physical sensors into an existing system. A soft-sensor is the combination of a physical sensor and a model, which describes the relation between an already measured auxiliary quantity and the target quantity of interest. In their contribution, Öztürk et al. present an approach that combines a digital twin with uncertainty propagation, conflict detection, conflict processing and conflict visualisation techniques. Their solution was tested on a technical system with a variety of sensors. In their work, they illustrate that data-induced conflicts, emerging from redundant observation of multiple comparative quantities, can be used for the detection of sensor and model errors. In their solution, they propose a visualisation method in the form of a conflict matrix, which can help the user to isolate the cause of errors, using a colour code, by limiting the number of potentially faulty sensors.

The next contribution deals with the acquisition of data from the physical domain by means of machine elements that incorporate a sensor function, called SME, to feed digital twins with in-situ acquired data. Hausmann et al. discuss and illustrate a classification of measurement locations (in-situ and ex-situ), with the corresponding sensing elements, based on the complexity of the required transfer path of the quantity of interest and the prevailing uncertainty. When applying the robust design method to the design of a system that comprises a measurement subsystem, one of the aims is to eliminate or reduce the uncertainty of measurement. The selection of the measurement location is relevant to address that aim. With this idea, an in-situ measurement means that the physical magnitude of interest is measured directly at its place of origin. On the contrary, an ex-situ measurement means that the physical magnitude of interest is measured in a location different from its place of origin. SME require a reduced structural change and are a promising solution for performing in-situ measurements and reducing the measurement uncertainty. Potentials and challenges of in-situ measurement and its corresponding uncertainty in a digital twin context are discussed by the authors.

The creation along the product lifecycle of digital twins requires the implementation of digital engineering approaches, which in turn, relies on the integration of a variety of industrial software solutions and methods, for instance, product lifecycle management (PLM) and model-based systems engineering (MBSE). The work from Menshenin et al. analyses the MBSE and PLM integration from a system of systems (SoS) perspective and applies two of the methods used in systems engineering [design structure matrix (DSM) and technology readiness level (TRL)] to better understand their nature, quantify their epistemic uncertainty, and propose possible solutions aiming to reduce the complexity and uncertainty when integrating them. In their approach, they analyse the integration of three different data models or ontologies: object-process methodology (OPM, a systems paradigm and language to model and specify a system and create conceptual models), core product model (CPM, a product information modelling framework for PLM) and manufacturing process management (MPM, an information scheme to integrate product design information with product manufacturing process information). They analyse, by using DSM, the interfaces between OPM, CPM and MPM, which provides a basis to evaluate their structural complexity. Then they estimate, by using TRL, a technology risk of their integration. The structural complexity is considered as a significant contributor to the epistemic uncertainty in digital engineering implementation and integration.

The last contribution of this special issue deals with the uncertainty in a process digital twin. Engineering change management (ECM) plays a significant role along the product lifecycle. Depending on how far the product is in its lifecycle, more and more functions and resources might have to be involved, which results in uncertainty in planning and in executing processes. Shakirov et al. focus their work on the product development and design phase and introduce the concept of the digital twin for the ECM process to enable its continuous quantitative assessment and improvement of engineering process planning. They aim to improve the accuracy of the ECM modelling and to enable more precise predictions on process lead time and its uncertainty. In their work, they adopt as reference the ECM process defined by the German Association of the Automotive Industry (VDA), propose combining past information of as-executed processes and learning curves, create a discrete-event simulation model (as-designed process model), and execute simulations to estimate activities duration and their uncertainty. The as-designed process model can be continuously refined by incorporating actual data measured during the real process execution, leading to states of the process based on as-executed data. Ultimately, the project management team is expected to benefit from more precise engineering change planning.

Finally, we would like to thank all who kindly submitted their papers for this issue and Professor Alain Bernard, Editor-in-Chief of the *International Journal of Product Lifecycle Management*, for his kind help and support. We are also indebted to the *International Journal of Product Lifecycle Management* editorial office and the publishing and production teams at Inderscience Publishers for their assistance in preparation and publication of this issue.