

# Sintesi della tesi

Hybrid modeling to support the smart manufacturing: concepts, theoretic contributions and real-case applications about Hybrid and Wisdom-based Systems

The main motivation of the research is the desire to investigate hybrid systems and their application in the manufacturing sector. This thesis aims to propose a method or rather a framework for designing an information system that not only includes, but integrates different modeling techniques in order to optimize the stages of mapping the information flows of the system and describing the knowledge needed in order to achieve the awareness that can guide toward optimal choices. Such hybrid systems, i.e., hybrid model systems, turn out to be an interesting research topic as they are widely used even though the scientific literature provides neither a clear definition and comprehensive results regarding their benefits over single models and under different hybridization choices. Another important open research question specifically concerns system knowledge and, in particular, how to integrate so-called prior knowledge and how to structure a framework that provides for the addition of new knowledge sources over time.

The main scientific contribution that this work seeks to bring, therefore, is a proposal for a design method that promotes to the reader, or accentuates, hybrid thinking, that is, designing an information system by considering different models, separately and simultaneously, in order to obtain more reliable descriptions and predictions of the state of the system, ensuring greater resilience of the system as it is able to exploit the strengths of different prediction models. This certainly pushes research efforts toward the concepts of Enterprise Information Systems (EISs) and Knowledge-Based Systems (KBSs), and thus toward the study of how to use different information mapping techniques and different approaches of variables modeling (the main ones being data-driven and those based on laws of physics, analyzing how integrate human-driven ones, i.e., variables models based completely on manufacturing human know-how).

Hybrid modeling, considering different modeling techniques, aim to avoid the unscrupulous use of one single family of models that are often non-sustainable. It is unequivocal that the sustainable manufacturing needs an appropriate digital information system that has (or that is design with) an awareness of the enterprise's objectives and the impact of its use by the enterprise's resources. Today it is required that this awareness is increasingly comprehensive and effective, in other words, that it follows the 5.0 vision by making use (or being able to make use) of all 4.0 technologies. In order to guarantee the sustainability, an hybrid model has to consider the impact due to energy consumption or hardware production and installation, but often the non-sustainability is also due to maintenance costs or the inability of humans to use the system.

In detail, this thesis is a work dealing with (i) awareness Knowledge-Based Systems (KBSs) and (ii) hybrid systems as base concepts for designing a digital platform aiming of supporting a specific physical manufacturing environment. The model proposed by this work is based on these two concepts and, basically, it is a theoretical formalization of a digital platform belonging to a Cyber-Physical System (CPS) that uses hybrid models in order to achieve a 5.0 wisdom, i.e., in order to promote and follow a 5.0 awareness as digital component of information management for a generic 4.0 manufacturing system. The hierarchical structure of the 4 levels of Data, Information, Knowledge and Wisdom (DIKW) is proposed as a method capable of (i) making use of data-lakes, information flows and knowledge

processes to make conscious decisions, with wisdom for the precisely, and (ii) developing the concept of hybrid system by characterizing the 4 hybrid subsystems: hybrid data sources, DB and computer networks hybrid models, hybrid models for estimating state variables, and hybrid decision support methods.

The first chapter introduces the background of the author, the motivations and the aim of the research and the research question. This introduction allows, in a few pages, to understand the objective of the thesis and the associated research axes.

The second chapter describes the state of the art carried out starting from lean thinking and waste elimination, through the digital era of Industry 4.0, until today with the need to have and greater spread of awareness of these tools and their impact. This chapter is a quick introduction to the main manufacturing concepts on which this thesis is based: lean manufacturing from which is important to understand variables and methodologies to eliminate wastes, Enterprise Information Systems (EISs) focusing on ERP, PLM, MES and their integration, Industry 4.0 and its technologies, and finally the Industry 5.0 and the European manufacturing view.

The central chapter presents the methodological proposal in detail and it is a description of the proposed hybrid wisdom-based framework. It includes an analysis of manufacturing processes and the opportunities they offer for the proposed framework. After giving basic notions about agent-based system, DIKW-structures and hybrid modeling, the element of the framework, the agent, is presented with DIKW levels, the hybrid structure of which is subsequently discussed level by level. Finally, a proposal of framework evaluation metrics and the expected impacts in Industry 4.0 and Industry 5.0 is provided.

One case study is presented, and it is focused on the application of the framework to design a Tool Condition Monitoring (TCM) system for a Total Productive Maintenance (TPM). Results obtained with a real case application are provided on milling process: monitoring and optimize the changeover of the milling cutters using open data for results replication. The aims of the case study is to present a design methodology for predictive maintenance functionalities in a TPM CPS.

The theoretical contributions of this work are towards the concepts of hybrid systems, Industry 5.0 and DIKW structures for AI. Even if the single case study presented unfortunately fails to validate all the characteristics required for the general framework, it certainly contributes to various open points of research on hybrid systems. Considering the 6 categories to better integrate social and environmental European priorities into technological innovation and to shift the focus from individual technologies to a systemic approach, this work contributes for the most of them: only bio-inspired technologies and smart materials are difficult to apply for the proposed framework. The proposed work, therefore, can be considered with regard to:

- individualising Human-Machine Interaction, as agents in CPS modeled as a HW-system through the proposed framework;
- digital twins and simulation, as knowledge tools to be integrated with others as components of the hybrid system;

- data transmission, storage, and analysis technologies described in detail through the DIKW structure of the proposed framework;
- Artificial Intelligence structured as MAS where the intelligence is a cognitive back-warding process from data, through information and knowledge, until the wisdom making use at every level of hybrid modelling systems;
- technologies for energy efficiency, renewable, storage and autonomy that are considered by the 5.0 oriented wisdom that the framework guides to build.