Digital Twin for Maintenance Management
November 14th, 2023

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Introduction

Luca Fumagalli

POLITECNICO MILANO 1863 | SCHOOL OF MANAGEMENT Manufacturing Group

Luca Fumagalli is Associate Professor at Politecnico di Milano. He is Mechanical Engineer, graduated at Politecnico di Milano in 2006, and obtained PhD in Industrial Engineering at Politecnico di Milano in 2010.

He works on different research topics about production management, industrial services and in particular maintenance management related topics, with a specific concern on new technological solutions. His research activity has been related also with European research funded projects.

During his career, Luca Fumagalli has been visiting researcher or visiting professor at: Lorraine University (France), Universidad de Sevilla (Spain), VTT Research Center (Finland), University of Cincinnati (USA), Universidad Catolica de Valparaiso (Chile), Universidad de Los Andes (Colombia), Warsaw University of Technology (Poland).

Luca Fumagalli is coordinator of the Network of International Collaboration of Industry 4.0 Lab (www.industry40lab.org) at Department of Management, Economics and Industrial Engineering

industry40lab.org

Warsaw University of Technology is joining the International Collaboration Network of the Industry 4.0 Lab

Fumagalli, Luca

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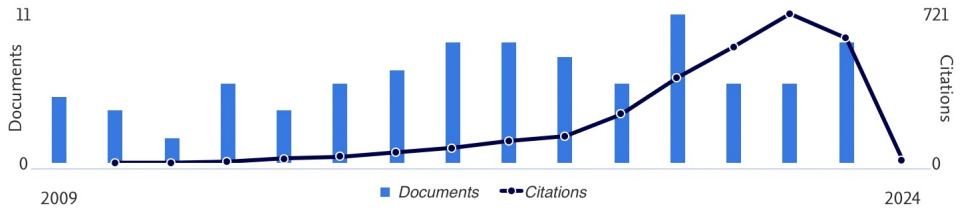
Document & citation trends



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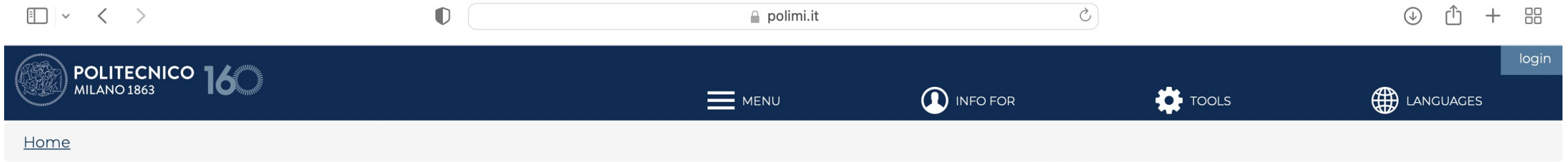

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QS EUROPE UNIVERSITY RANKINGS

THE POLITECNICO DI MILANO RANKS 47TH IN EUROPE AND 1ST IN ITALY

In the new QS University Ranking dedicated to Europe, the Politecnico di Milano achieves the **47th position**, entering the **Top 7% of the best universities** (which are 690 in the ranking).

Moreover, the Politecnico is confirmed as the first university in Italy. This result was made possible by important factors that contributed to achieving this position. The University ranks among the best universities in Europe and first in Italy in terms of **Employer Reputation**, an indicator that assesses employers' opinions on how universities train their graduates for the world of work.

The Politecnico is also awarded in **Academic reputation**, an indicator based on the responses to a survey distributed to thousands of academics who drew up the list of the most authoritative universities in their scientific discipline.

These data confirm Politecnico di Milano's outstanding results, ranking among the **world's top 20 universities** in **Design**, **Architecture** and **Engineering**, according to the QS World University Rankings by Subject 2023 published last March. In Design and Architecture, it ranks 8th and 10th. In Engineering, it ranks in the top 20 worldwide, coming in at 18th position.

The Campuses of Politecnico di Milano

POLITECNICO MILANO 1863

SCHOOL OF MANAGEMENT
Manufacturing Group

Milano campus

Simulation and Digital Twin… experience

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- Years 2000: course of Modelling of production and logistic systems for Industrial/Management Engineering

- 2016: first course at Industrial/Management Engineering with the use of Matlab (Matlab/Simulink)

- 2017:

Outline

Abstract

Keywords

References

Cited by (986)

ELSEVIER

Procedia Manufacturing

Volume 11, 2017, Pages 939-948

A Review of the Roles of Digital Twin in CPS-based Production Systems ☆

Elisa Negri, Luca Fumagalli, Marco Macchi

- 2020: Digital Twin Course for «Summer School» at Universidad de Los Andes (Colombia)

- 2022: Digital Twin Game at POLIMI Graduate School of Management for MBA courses

EVIDENCES OBSERVED IN PAST AND RECENT YEARS

What is Maintenance?

Maintenance is the dirty job!

Maintenance is the uncorfortable job!

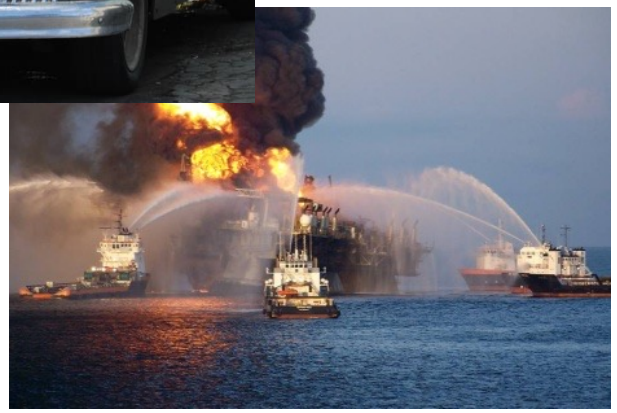
Maintenance is something related to bad products / equipment only!

Maintenance means disasters!

Maintenance is only a cost!

Maintenance is something to be left to technicians!

Maintenance is not important from a management point of view!



EVIDENCES OBSERVED IN PAST AND RECENT YEARS

What is Maintenance?

BUT:

Perfection does not exist!

Nothing is forever!

Everything must be maintained!

Good maintenance means safety, quality, cost reduction, competitiveness, enviromental care, ..

Maintenance can be a strategic asset!

Maintenance helps sustainability!

EVIDENCES OBSERVED IN PAST AND RECENT YEARS

Strategic importance of maintenance in manufacturing

Maintenance has slowly progressed towards higher recognition as a **source of value** for production systems, and a contributor to company's **productivity** and **profitability**. Changes in perception of maintenance are evident in the most recent years:

- Moving away from cost-centric models for maintenance planning that can lead to sub-optimal maintenance strategies;
- Need to quantify maintenance contribution to the organization's profitability and overall performance;
- Evidence of impacts on quality, efficiency and effectiveness of operations, thus leading to contribution to profitability of a manufacturing company.

Alsyouf, I. 2007. "The role of maintenance in improving companies' productivity and profitability." International Journal of Production Economics 105 (1):70-78.
Marais, K.B. and J.H. Saleh. 2009. "Beyond its cost, the value of maintenance: an analytical framework for capturing its net present value." Reliability Engineering & System Safety 94 (2): 644-657.
Maletič, D., M. Maletič, B. Al-Najjar and B. Gomišček. 2014. "The role of maintenance in improving company's competitiveness and profitability: a case study in a textile company." Journal of Manufacturing Technology Management 25 (4): 441-456.

EVIDENCES OBSERVED IN PAST AND RECENT YEARS

Looking at the past achievements …

- 1900 Handicraft production > Corrective maintenance
- 1920 Mass production > Preventive maintenance
- 1960 Industrial development > Diagnostics techniques

Second world war/logistics support
Apollo program / FMECA

- 1970 JIT-TQM > Productive maintenance/TPM
- 1980 Lean production > Productive maintenance/TPM

RCM program development

- 1980-90 Information systems in enterprises > CMMS
- 1990 Virtual enterprise > [Focus on core competences & ICT →] tele-maintenance
- 2000 Globalization > Outsourcing & maintenance engineering

- Maintenance initially conceived as a **technical function**; Maintenance lately transformed into an **engineering and management function**;
- **ICT** initially introduced **for management support** in general (CMMS), and lately enhanced **for service-support** (remote/tele-maintenance).

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- 2000 Globalization > Outsourcing & maintenance engineering
- 2010+ Digitalization > PHM (Prognostics & Health Management)

- **Digitalization** is associated with transformative concepts and methods that are widely leading to impacts in business and society.
- In the manufacturing context, **maintenance** is on top of the agenda for future developments in **digital applications** (digital maintenance, digital service).

Digitalization for modern maintenance: maintenance related concepts and their evolutionary path

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Computers in Industry 133 (2021) 103531

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Computers in Industry

Journal homepage: www.elsevier.com/locate/compind

Maintenance concepts evolution: a comparative review towards Advanced Maintenance conceptualization

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Smart maintenance
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E-maintenance
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Review

ABSTRACT

The implementation of Industry 4.0-like solutions for the maintenance of production assets is a relevant topic in the mainstream for researchers and industries around the world. As a matter of facts, the technology-based transformation of maintenance has been germinated since several years. In fact, the evolution of maintenance along with the development of the information and communication technologies has been studied in the literature since early 2000, and concepts like e-maintenance and intelligent maintenance have been largely addressed. Nowadays, smart maintenance and maintenance 4.0 concepts are getting popular in the Industry 4.0-based literature. While e-maintenance, intelligent maintenance, smart maintenance and maintenance 4.0 are similar concepts, they are not identical. From an evolutionary perspective, there has been little consideration on whether the definition, connotation, and technical development of the concepts are consistent in the literature. To address this gap, the work performs a qualitative and quantitative investigation of the scientific literature to clarify the relationship among the different maintenance concepts. A bibliometric analysis of publication sources, annual publication numbers, keywords frequency, and top regions of research and development establishes the scope and trends of the currently presented research. Critical topics discussed include the evolutionary path of the different concepts. Moreover, the evidence collected through a case study involving eight production companies are discussed to report the perspective of industry about advanced maintenance, may it be defined 4.0, smart, intelligent or e-maintenance. Finally, a definition of the advanced maintenance concept is given, proposed as an integral approach inheriting the knowledge from past developments of e-maintenance and intelligent maintenance concepts and more recent developments including smart maintenance and maintenance 4.0.

Contents

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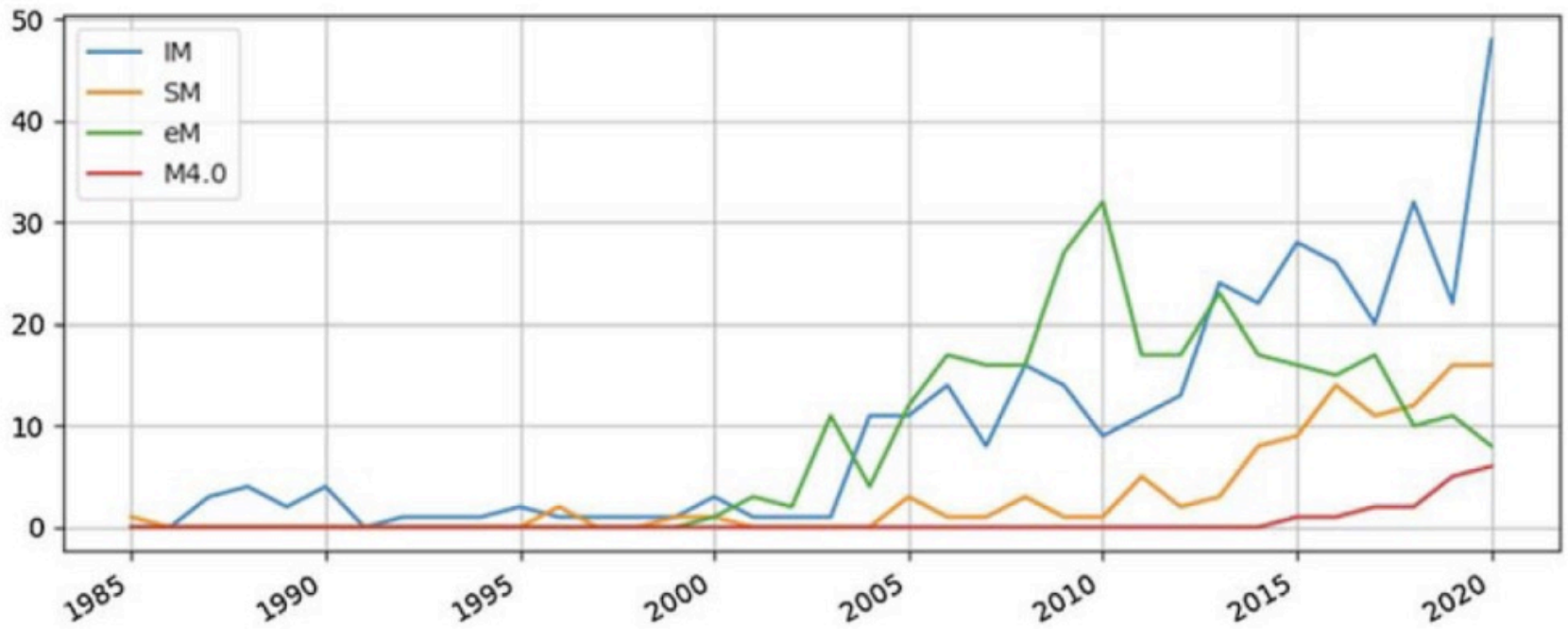
https://doi.org/10.1016/j.compind.2021.103531
0166-3615/

Highlights

- Investigation of the relationship among the different **maintenance related concepts** and their **evolutionary path**.
- We aim to define the concept of **advanced maintenance**, based on the state of the art of research and empirical evidence of practices.
- Research methods are systematic literature review, bibliometric analysis and multiple case study involving production companies.
- Advanced Maintenance is recognized as an approach **inheriting the knowledge from past developments of maintenance related concepts**.

EVIDENCES OBSERVED IN PAST AND RECENT YEARS

Looking at the past achievements …



- Intelligent Maintenance (IM)
- E-maintenance (eM)
- Smart Maintenance (SM)
- Maintenance 4.0 (M4.0)

Trend of different concepts: Annual publication volume (Scopus data base, period 1970-2020)

Roda, I., Macchi, M. Maintenance concepts evolution: a comparative review towards Advanced Maintenance conceptualization. Computers in Industry, Vol. 133, December 2021.

EVIDENCES OBSERVED IN PAST AND RECENT YEARS

Looking at the past achievements …

Total	Phase I 1985–2000	Phase II 2001–2010	Phase III 2011–2015	Phase IV 2016–2020
Keywords	Analytic Hierarchy Process, Fuzzy Logic, Information Systems, Decision Support Systems	Condition Monitoring, Diagnostics, Web Services, Prognostics	Fault Diagnosis, Condition Monitoring, Knowledge Management, Fault Detection	Industry 4.0, Internet of Things, Fault Diagnosis, Machine Learning
Concepts Percentage	76 % **IM** 19 % SM 5% eM	37 % IM 4 % SM 59 % **eM**	45 % **IM** 13 % SM 41 % **eM** 1 % M4.0	51 % **IM** 23 % SM 21 % eM 5 % M4.0
Paper number in Scopus	21 papers	236 papers	216 papers	290 papers
High Citation Papers	(Labib et al., 1998) (Deb et al., 1997) (Kobbacy et al., 1995)	(Lee et al., 2006) (Muller et al., 2008) (Tsang, 2002)	(Lee et al., 2015) (Kumar et al., 2013) (Chen et al., 2011)	(Selcuk, 2017) (Berredjem and Benidir, 2018) (Guillén et al., 2016a)

Different phases in the evolution of advanced maintenance concepts

- The evolution shows, since its early stage, that **decisional support and information systems** are emergent needs for advances in maintenance management.
- In the evolution, it is evident that the **maintenance practice** come along with the development of **ICT as enabler of advanced maintenance concepts**.

Roda, I., Macchi, M. Maintenance concepts evolution: a comparative review towards Advanced Maintenance conceptualization. Computers in Industry, Vol. 133, December 2021.

Towards a modern maintenance

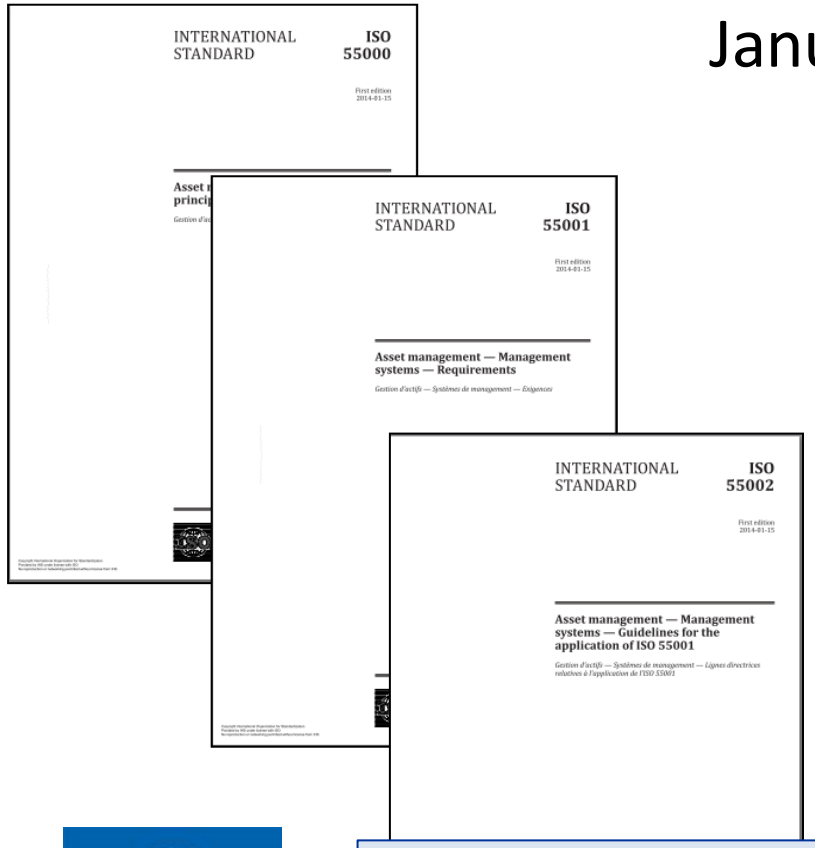
Maintenance is evolving due to the double-sided influence of digitalisation and Asset Management (AM).

- **digitalisation** is pushing maintenance to adopt Industry 4.0-like solutions towards diagnostic and predictive solutions for data-driven design improvements and services.

- the **Asset Management paradigm** requires maintenance to broaden its scope including strategy, risk management, safety and environment, and human factors towards value generation from assets.

Polenghi, A., Roda, I., Macchi, M., & Pozzetti, A. (2021). A methodology to boost data-driven decision-making process for a modern maintenance practice. Production Planning & Control, 1-17.

EVIDENCES OBSERVED IN PAST AND RECENT YEARS



January 2014: Release of the **ISO 5500x** body of standards

- **ISO 55000:** Overview on AM and terms and definitions
- **ISO 55001:** Requirements for an AM system
- **ISO 55002:** Guidelines for implementing ISO 55001

ASSET MANAGEMENT: "The coordinated activities of an organization to realize value from assets" (ISO 55000, 2014)

OPPORTUNITIES AND CHALLENGES IN THE RESEARCH AGENDA

A lot of challenges are open for lifecycle management of industrial assets, such as …

- **Cyber-physical assets** & **Digital Twins of physical assets** are still in a (very) early stage development; more experiences and use cases will be required, aimed to support the whole spectrum of relevant decisions in the asset-control activities.

- **Reliability & condition-based maintenance modelling** methodologies / methods should take advantage of the **new capabilities** made available by the Cyber-physical assets and Digital Twins, to extend their potential for decision support.

Digital Twin

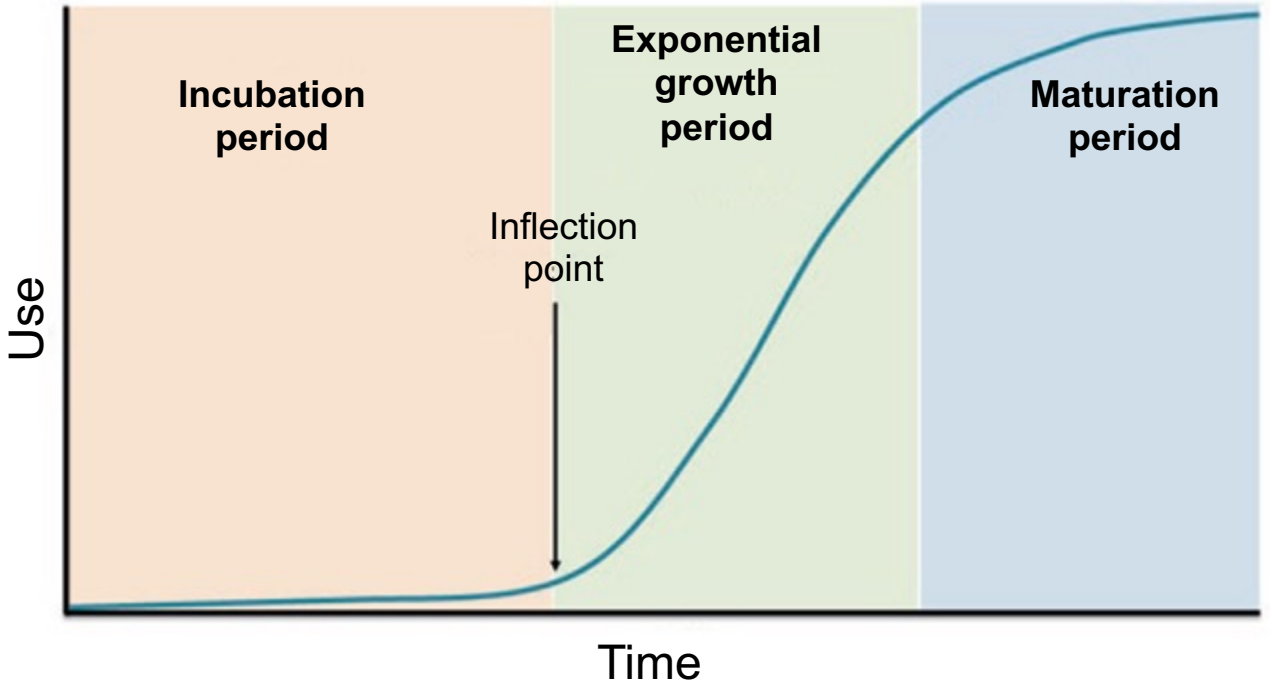
(the material of this section was kindly provided by prof. Giacomo Barbieri, Universidad de Los Andes, Bogotà, Colombia)

Another commercial invention?

The "concept" of modeling a physical object through software is present in various application domains. Various modeling tools and best practices have supported this approach long before the term “digital twin” became popular.

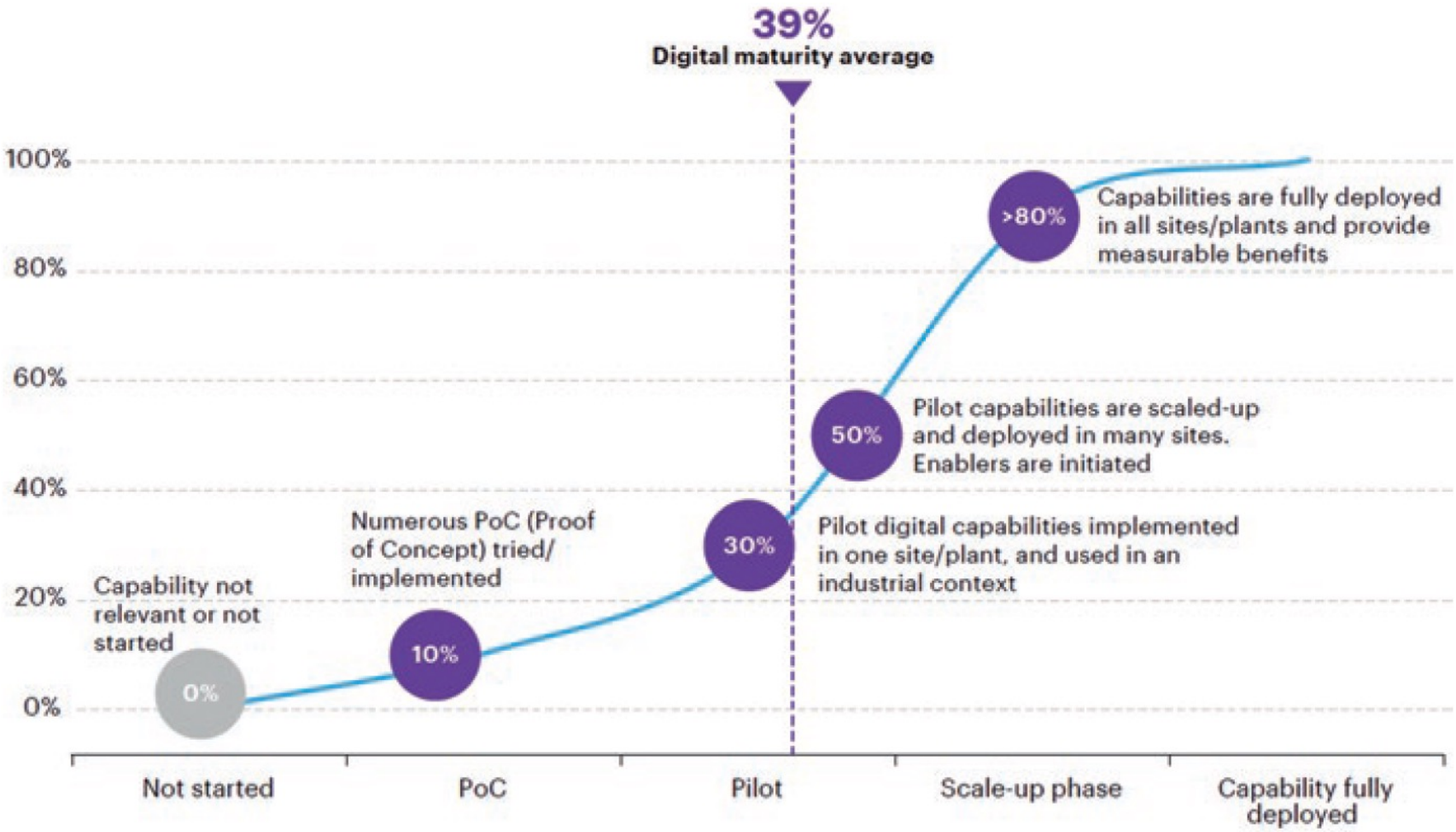
Rules

- ISO23247-1 (2022). Automation systems and integration — digital twin framework for manufacturing — part 1: Overview and general principles. Standard, International Organization for Standardization, Geneva, CH.
- DNV-RP-A204 (2020). Qualification and assurance of digital twins. Recommended practice, DNV.



Schmitt, L., & Copps , D. (2023). The Business of Digital Twins. In *The Digital Twin* (pp. 21-63). Cham: Springer International Publishing.

Digital Maturity Index



Research study conducted by Accenture that includes 600 manufacturing companies from around the world

Audit on 40 key digital capabilities for operations

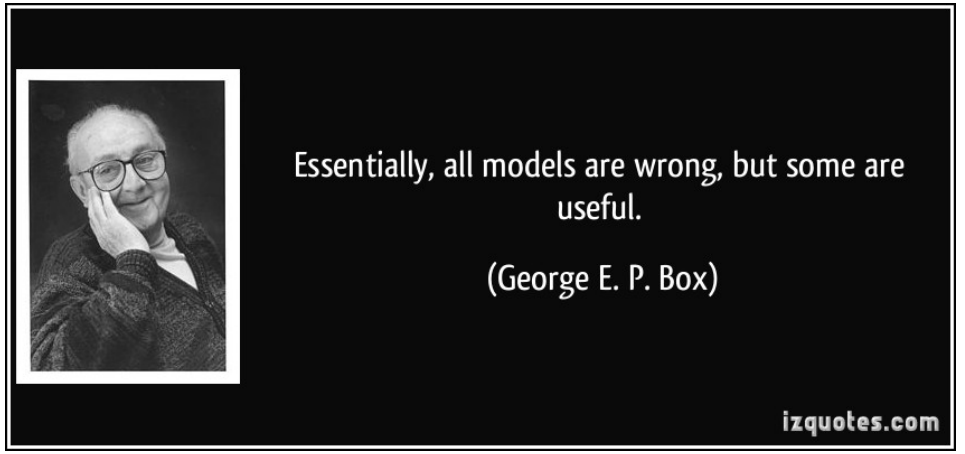
Blanchet M. (2023). The Dimension of Markets for the Digital Twin. In *The Digital Twin* (pp. 65-96). Cham: Springer International Publishing.

Models vs experimentation: approximations

All physical principles and their mathematical expressions applied to real-world situations are approximations of real behavior.

These approximations can, in individual cases, be good, fair or poor, but there is always some discrepancy between the modeled and real behavior.

Experiments are run on the real system and, when properly designed and executed, reveal the true behavior



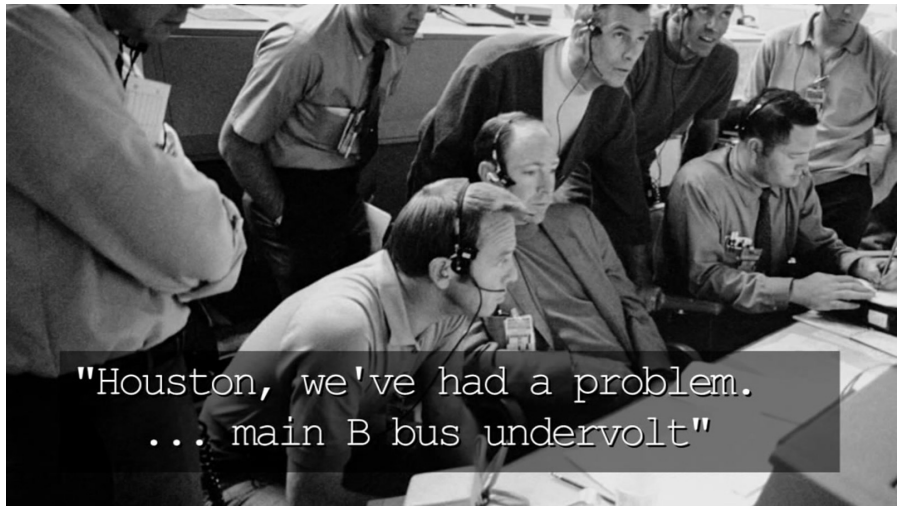
Models vs experimentation: times and costs

Experimentation, by definition, requires an investment in equipment suitable for the proposed study, plus laboratory space to host the experiment

However, modern simulation has an ever-higher cost.

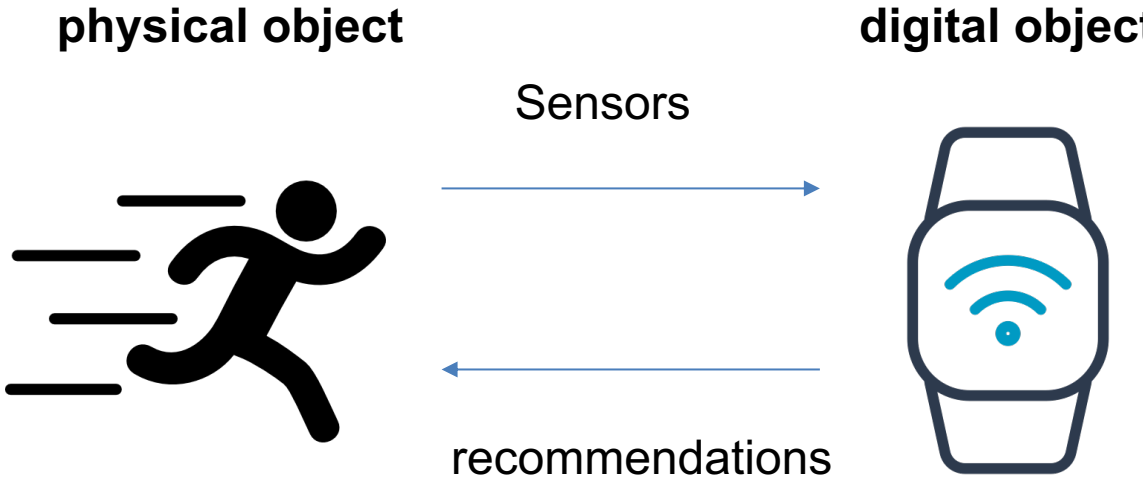
Examples of digital twins

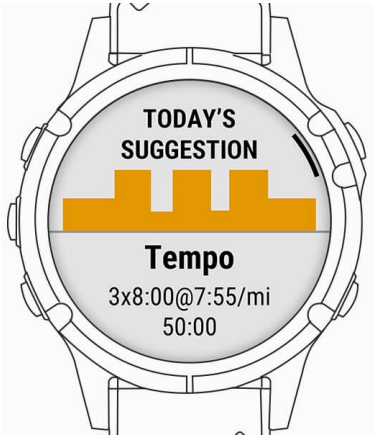
Physical twin to implement “ what-if ” scenarios through experimentation



Examples of digital twins

GPS
Heart rate
Blood oxygen saturation
Accelerometer
Thermometer
Gyroscope
Compass
barometric altimeter

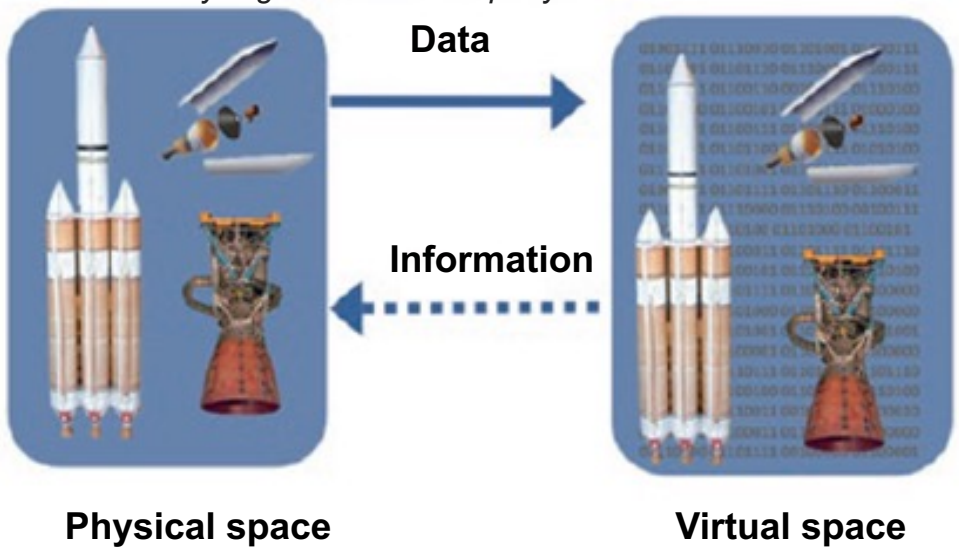




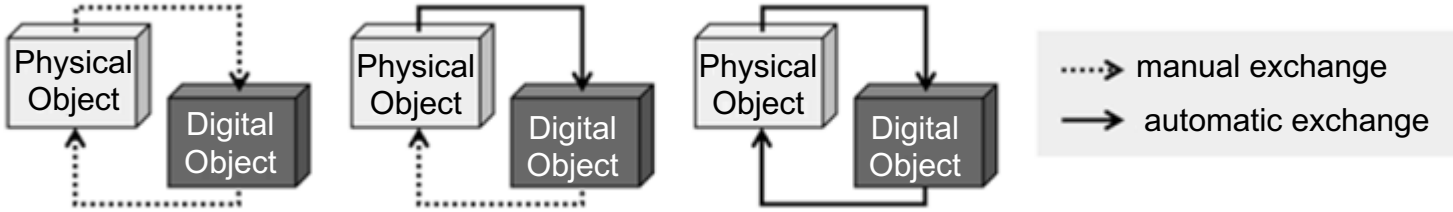
Recommendations based on historical data and intelligent algorithms

Digital twin

An Early Digital Twin Concept by Grieves and Vickers



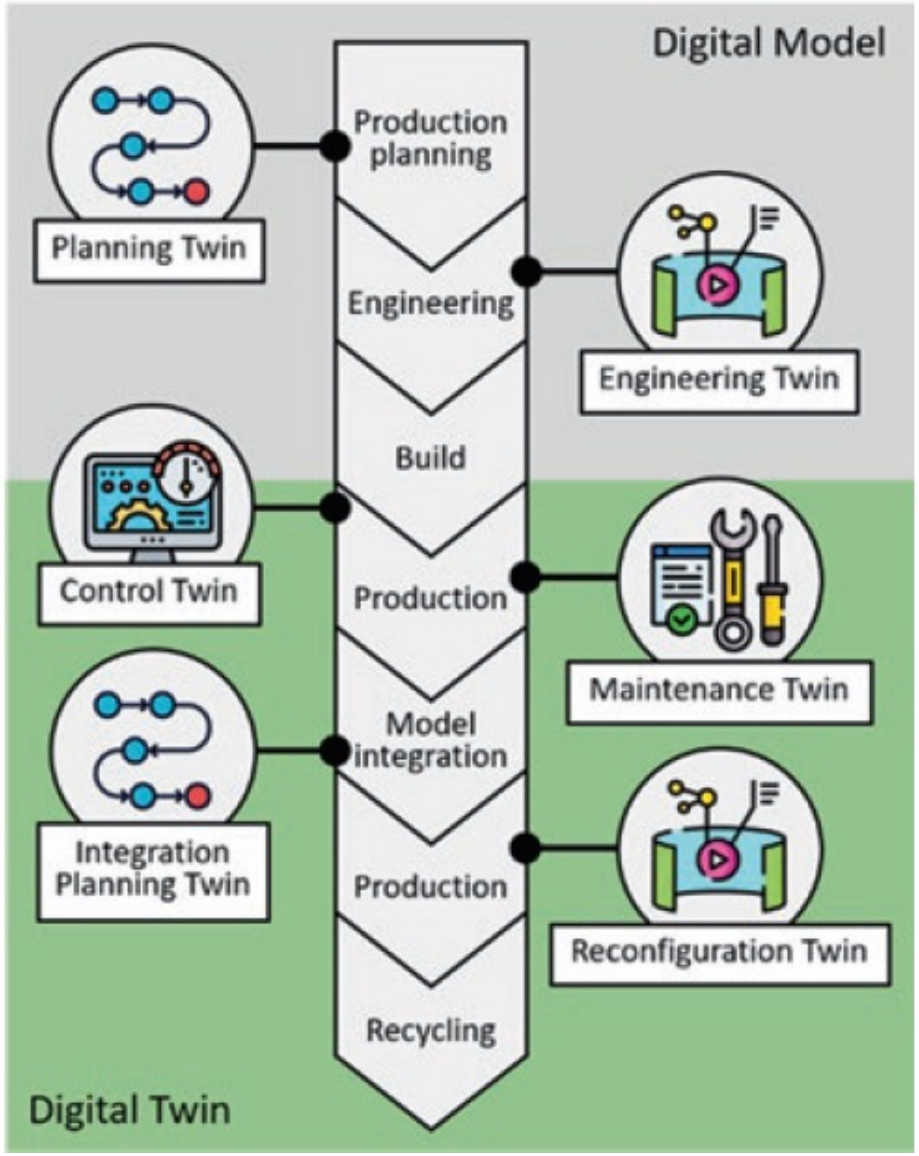
Characterized by the synchronization between the physical and digital object



Digital model of an object in the physical world developed for the purpose of studying, analyzing and predicting its behavior

Kritzinger , W., Karner , M., Traar , G., Henjes , J., & Sihn , W. (2018). *Digital twin in manufacturing : A categorical literature review and classification* . IFAC- Papers Online, 51, 1016–1022

Digital twin



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Digital Twin and Education in Manufacturing

Giacomo Barbieri, David Sanchez-Londoño, David Andres Gutierrez, Rafael Vigon, Elisa Negri & Luca Fumagalli

Chapter | First Online: 03 June 2023

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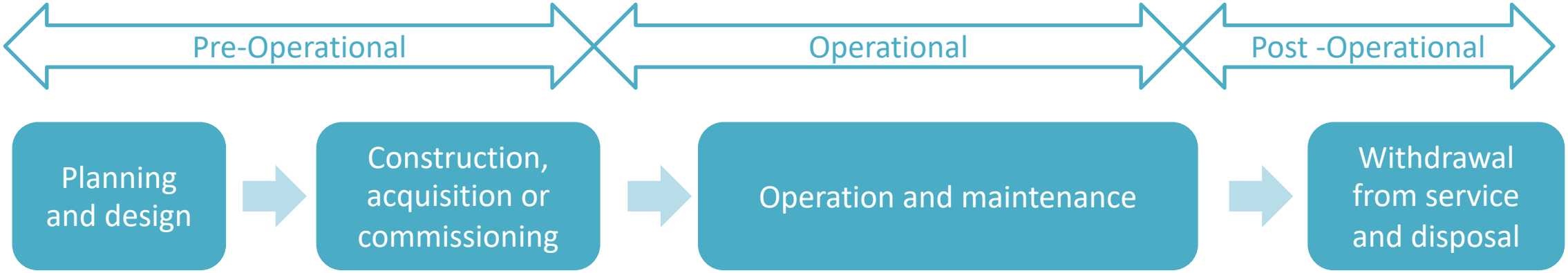
Digital Twin for Maintenance Management / Asset Management

Decision making in asset management

Determine which assets to create or acquire, and when

Ensure the required performance over the useful life of the assets

Manage decommissioning and disposal

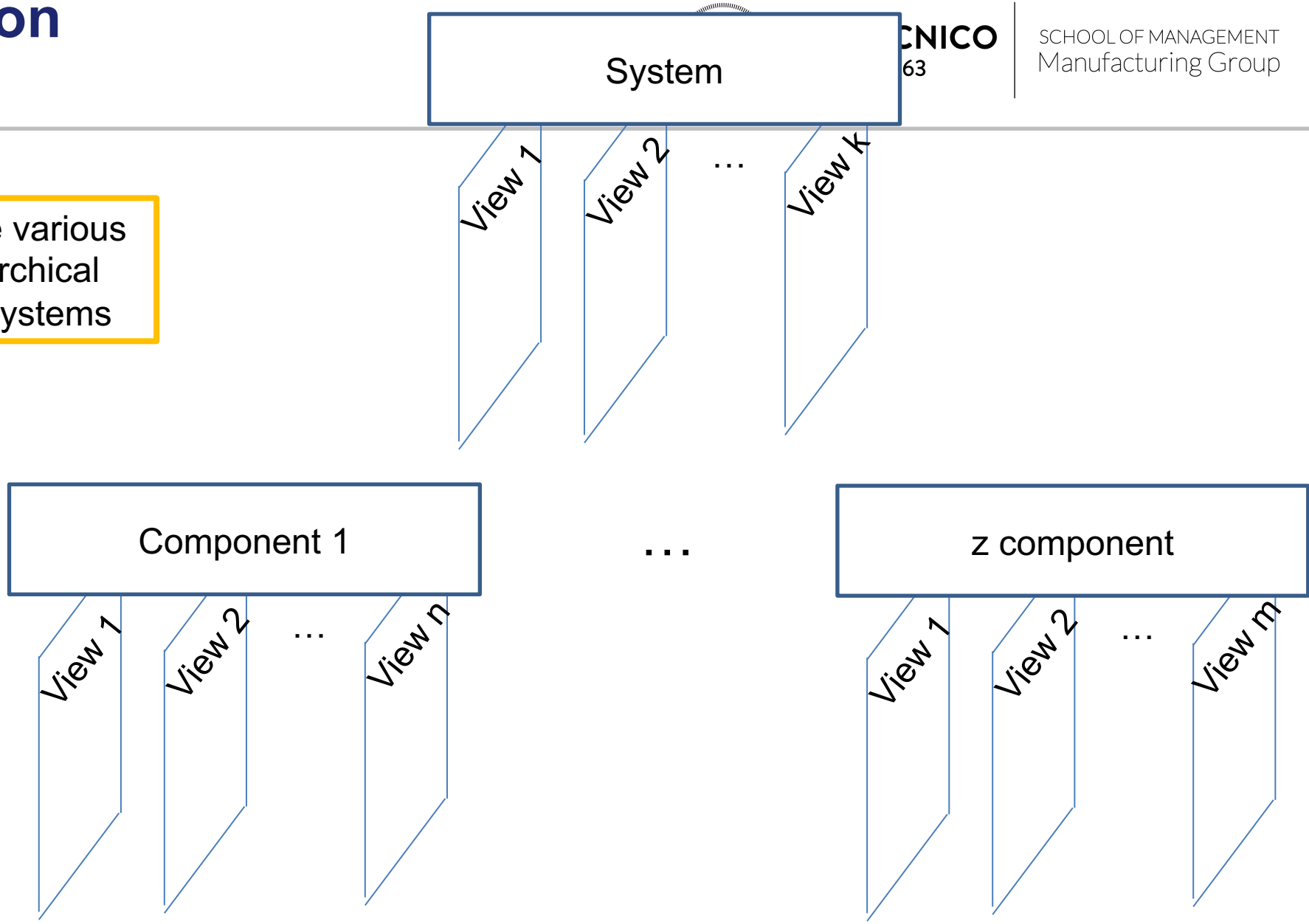


Decisions are not isolated : impact on other stages of the life cycle and on other assets

GFMAM. The Maintenance Framework, *Global Forum on Maintenance & Asset Management* , 2021

Approach based on Digital Twins

Integrate the models and the various facets of the different hierarchical levels of assets and asset systems

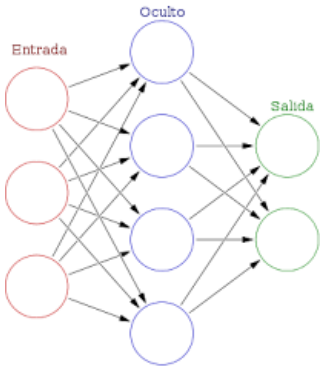


Crespi N., Drobot A., Minerva R. (2023). The Digital Twin: What and Why?. In *The Digital Twin* (pp. 1-20). Cham: Springer International Publishing.

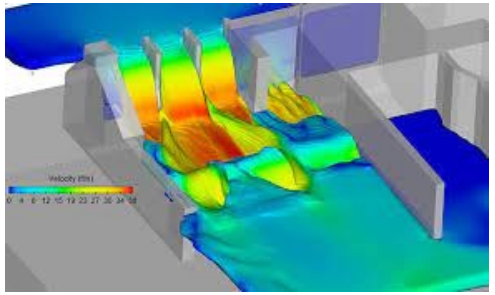
Digitization

Reduce development and testing costs , while expanding the number of "situations" that can be considered, assessed and evaluated

Data-driven models



Physics-based models



Crespi N., Drobot A., Minerva R. (2023). The Digital Twin: What and Why?. In *The Digital Twin* (pp. 1-20). Cham: Springer International Publishing.

OPPORTUNITIES AND CHALLENGES IN THE RESEARCH AGENDA

A reflection on future topics in the research agenda

Digital twins for lifecycle support of future intelligent manufacturing assets in complex systems

- Lifecycle planning & monitoring of manufacturing assets;
- Advanced condition monitoring, diagnostics & prognostics;
- Joint production & maintenance planning and control;
- Monitoring of manufacturing assets for their integrity management / life extension.

Digital twin for the asset life cycle

BOL - Design, Build & Commissioning

MOL - Operations & Maintenance

EOL - Decommissioning

Supporting the decision-making in the asset lifecycle

OPPORTUNITIES AND CHALLENGES IN THE RESEARCH AGENDA

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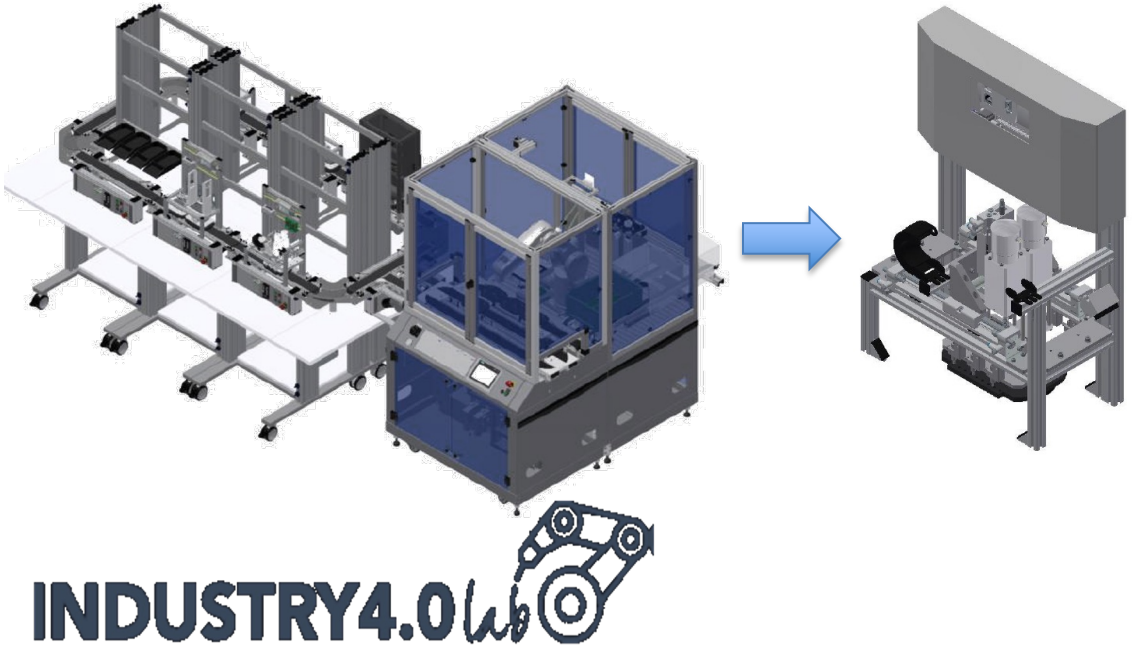
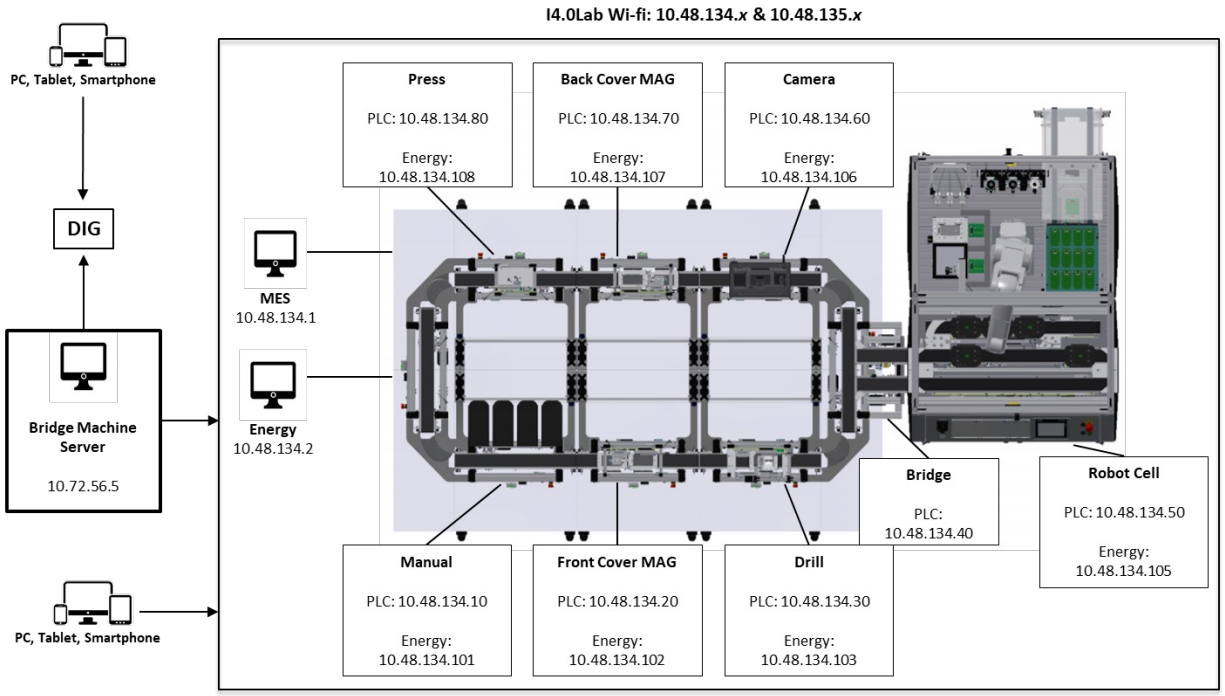
OPPORTUNITIES AND CHALLENGES IN THE RESEARCH AGENDA



Flexible manufacturing line & Critical machines

- Operation of different stations and equipment in the line
- Degradation of the drilling machine, in view of the evolution of its critical failure modes

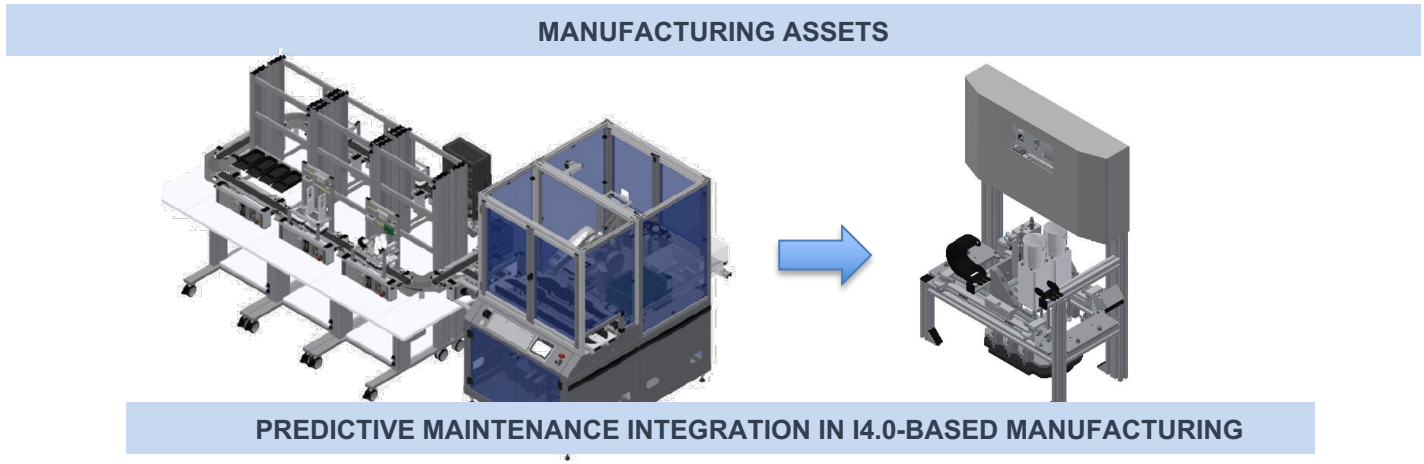
Machining & Assembling



Architecture of Industry 4.0 lab base ICT system (focus on Levels 0, 1, 2 of Enterprise-control system ref. (IEC) 62264:2003)

Extension of extant system with a Digital Twin-based decision making support

OPPORTUNITIES AND CHALLENGES IN THE RESEARCH AGENDA



Cattaneo, L., Polenghi, A., Macchi, M.. A framework to integrate novelty detection and remaining useful life prediction in Industry 4.0-based manufacturing systems, International Journal of Computer Integrated Manufacturing, 2021.

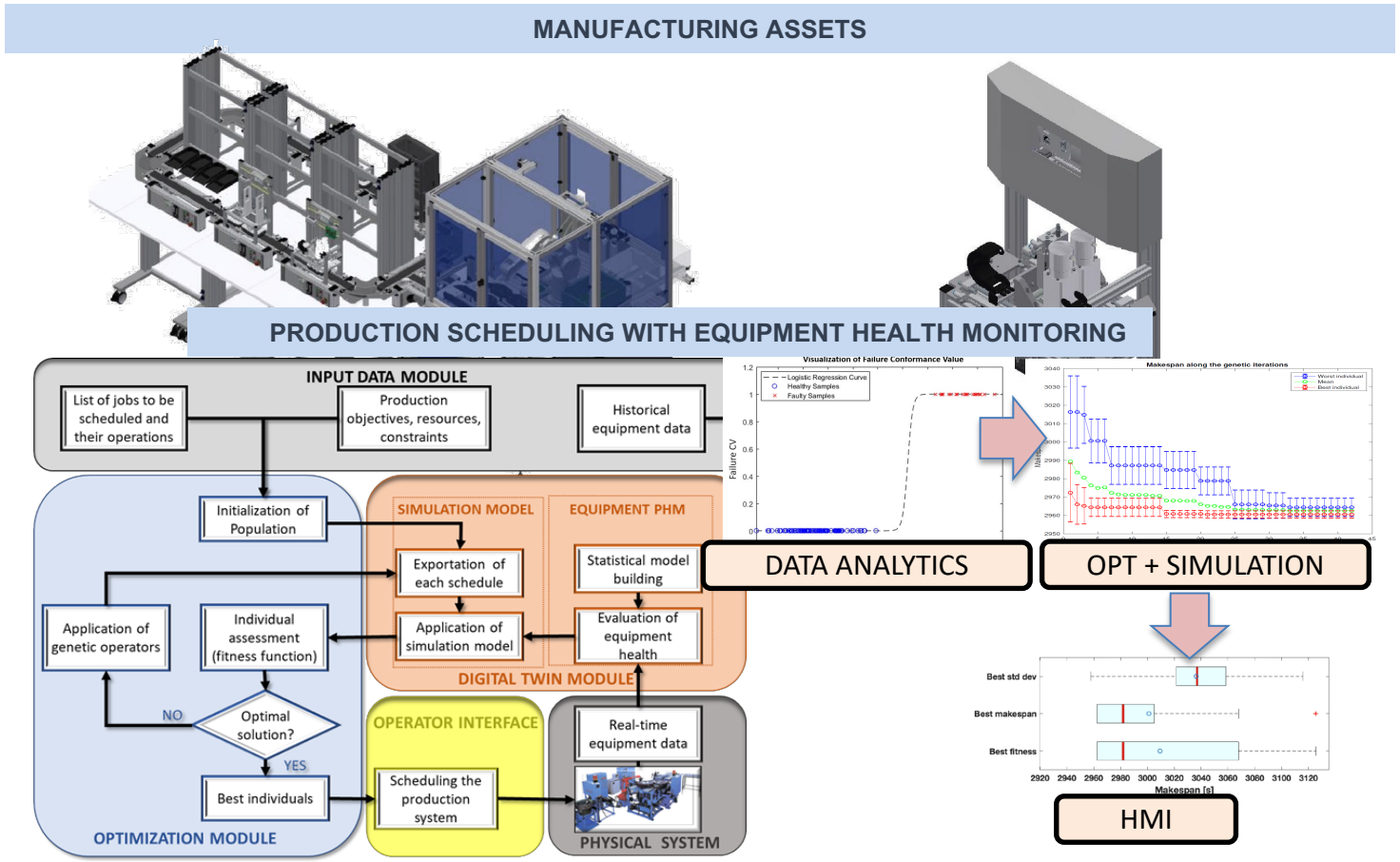
Opportunity

Advanced data analytics for CBM/PHM is developed through an **integration capability built upon a reference framework** providing guidelines and supporting **models** both from **process & data** viewpoints, while leveraging upon a **library of algorithms** to be exploited according to the boundaries and the case-related characteristics

Benefits

- Productivity and robust performance of the production line
- On-line control of the conditions of critical equipment through integrated predictive maintenance capabilities in the production line

OPPORTUNITIES AND CHALLENGES IN THE RESEARCH AGENDA



Negri E., Pandhare V., Cattaneo L., Singh J., Macchi M., Lee J., Field-synchronized Digital Twin framework for production scheduling with uncertainty, Journal of Intelligent Manufacturing, vol. 32, 1207-1228, 2021

Opportunity

Digital Twin to synchronize a Genetic Algorithm (GA)-based **optimization** of jobs scheduling, through a **Discrete Event Simulation** (DES) embedded with an **equipment health monitoring** built on data-driven approach, with the purpose to optimize **productivity measures with uncertainty** due to the operational risks related to machines downtime

Benefits

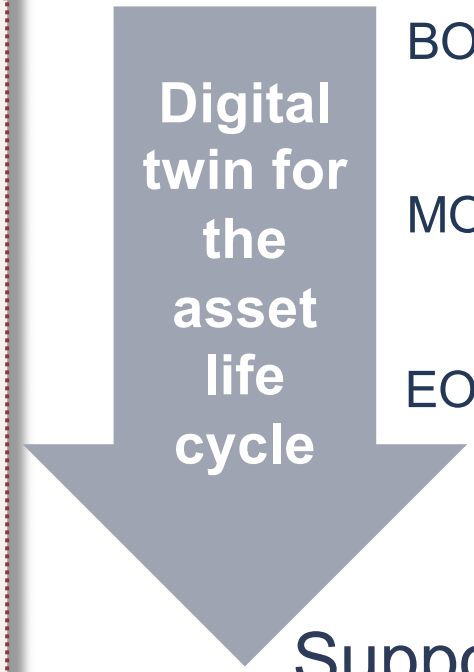
- Productivity and robust performance of the production line
- On-line control of the conditions of critical equipment in a joint preventive approach for robust scheduling

OPPORTUNITIES AND CHALLENGES IN THE RESEARCH AGENDA

A reflection on future topics in the research agenda

PHM for decision support framed in life cycle management

- Extended reliability and maintenance engineering, capable to exploit advanced data analytics for PHM inclusive of context-awareness on the process condition;
- Collaborative prognostics in social networks of industrial assets;
- Advanced data analytics for PHM framed within semantic data and ontology models of industrial assets & products.



BOL - Design, Build & Commissioning

MOL - Operations & Maintenance

EOL - Decommissioning

Supporting the decision-making in the asset lifecycle

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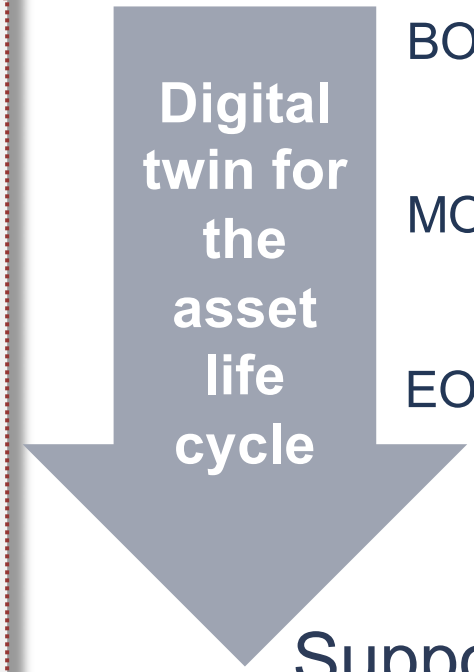

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Thank You!

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