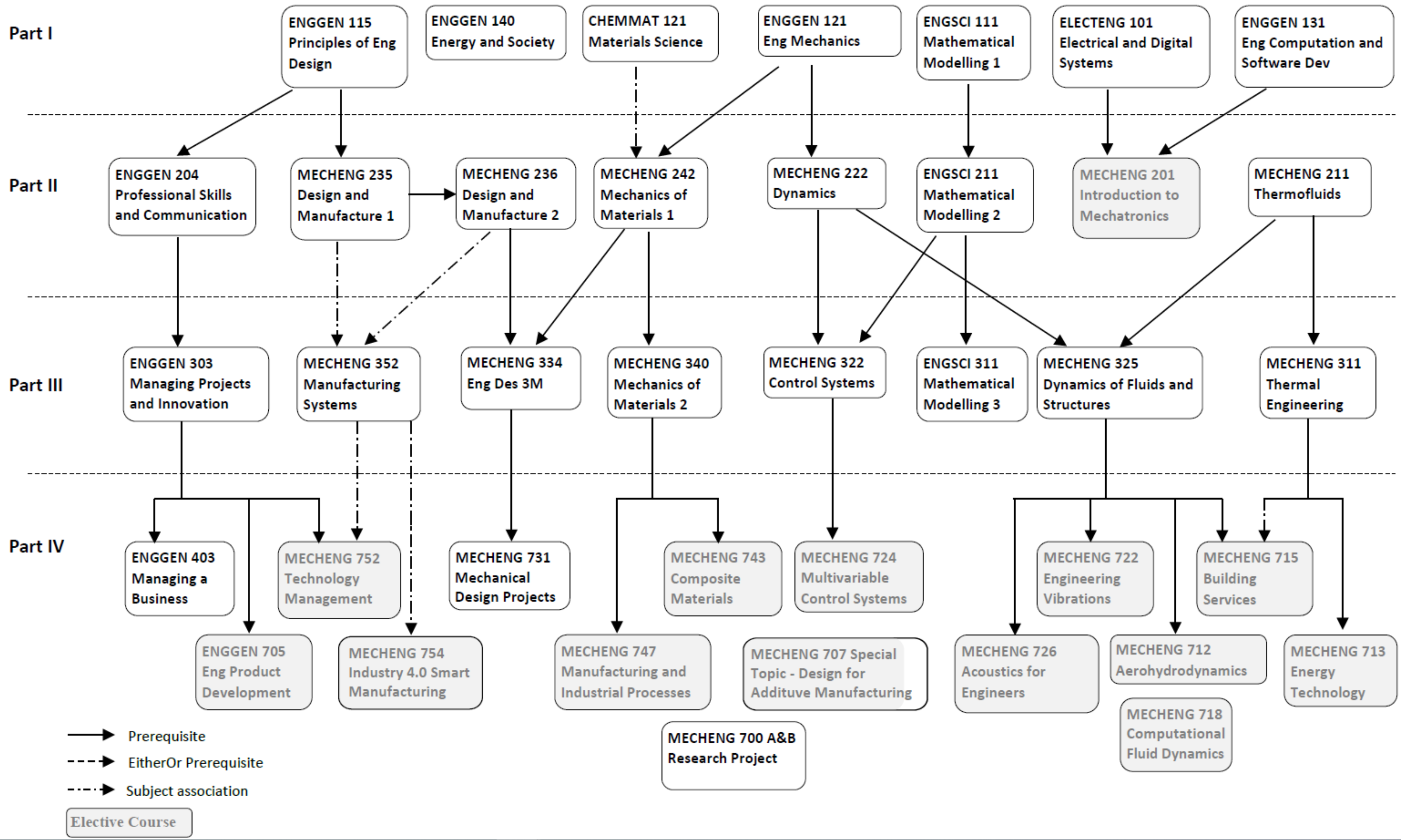
MECHENG 754

Industry 4.0 Smart Manufacturing (2022)

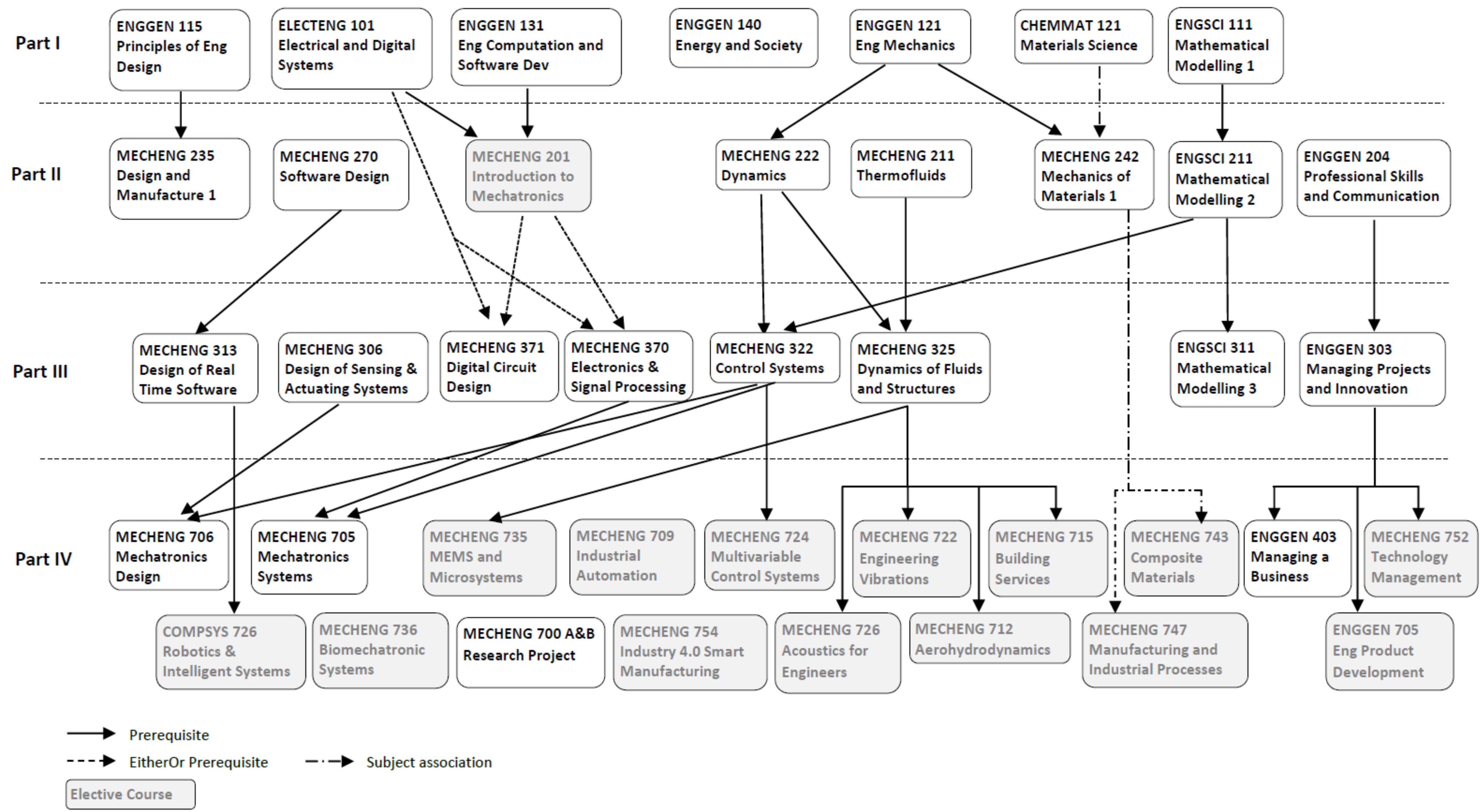
MECHENG 753

Advanced Industry 4.0 Smart Manufacturing (2022)

BE(Hons) Mechanical Programme 2022



BE(Hons) Mechatronics Programme 2022



MINISTRY OF BUSINESS, INNOVATION & EMPLOYMENT
HĪKINA WHAKATUTUKI

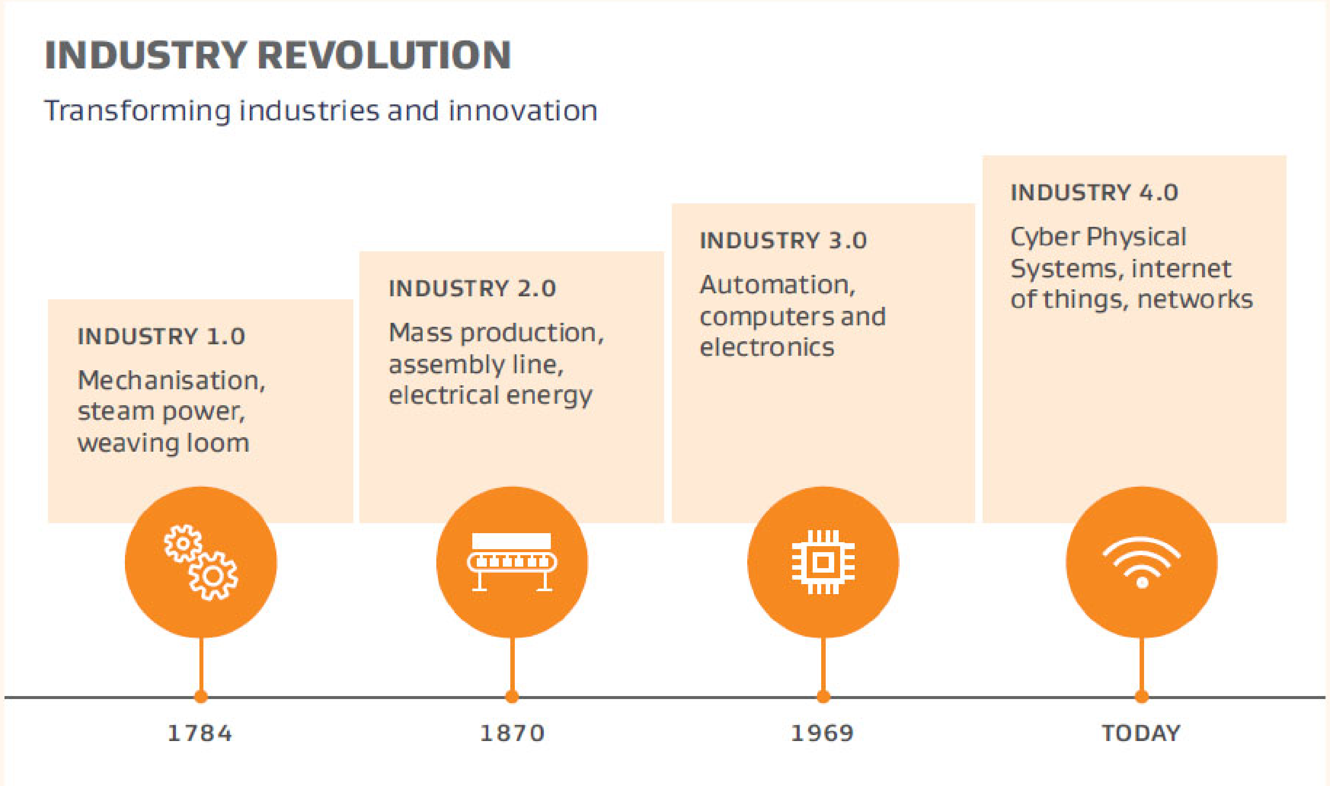
June 2022

Why this elective?

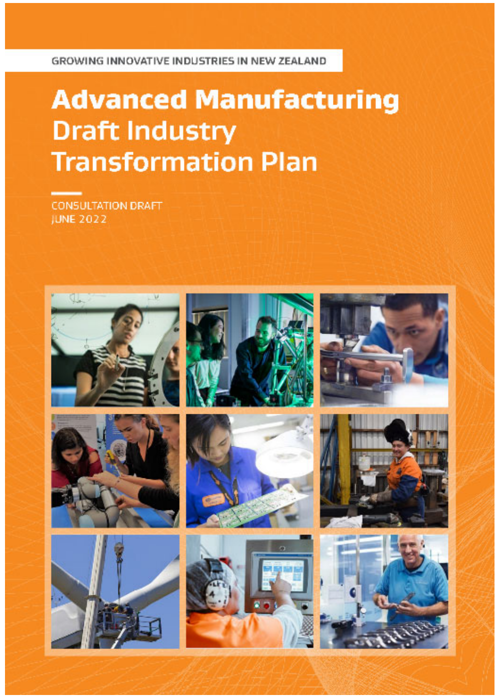
Key priorities to drive growth and transformation:

- improving understanding and perceptions of advanced manufacturing
- increasing investment in advanced technologies and processes to lift productivity and wages
- making innovation, R&D and science work for advanced manufacturing
- attracting and developing a diverse high-skilled and high-wage workforce
- creating a leading sustainable circular net-zero emissions sector
- enhancing global connectivity and opportunities

https://www.mbie.govt.nz/have-your-say/advanced-manufacturing-industry-transformation-plan/



In practice Industry 4.0 allows advanced manufacturing processes to be optimised by being digitally connected (the "internet of things"), improving use of data including sensors, incorporating automation and robotics, digital manufacturing (e.g. 3D printing and additive manufacturing), as well as digital twins, artificial intelligence and virtual reality. It is important to appreciate that it also includes advances in business and production processes, often with small changes yielding significant benefits.



https://www.mbie.govt.nz/have-your-say/advanced-manufacturing-industry-transformation-plan/

An international perspective

Course	Country
Smart Manufacturing and Automation with Industry 4.0	Germany
Industry success in the era of industry 4.0	Singapore
Digital transformation and Industry 4.0	UK
Digitalization and Industry 4.0	Sweden
Digital Transformation	USA
Implementing Industry 4.0: Leading Change in Manufacturing and Operations	USA
Business Success in the Industry 4.0 Era	Australia
Industry 4.0- How to revolutionize your busineess	Hongkong

Course staffing

- Block 1: Industry 4.0 introduction and the fundamentals

  (Xun Xu: xun.xu@)

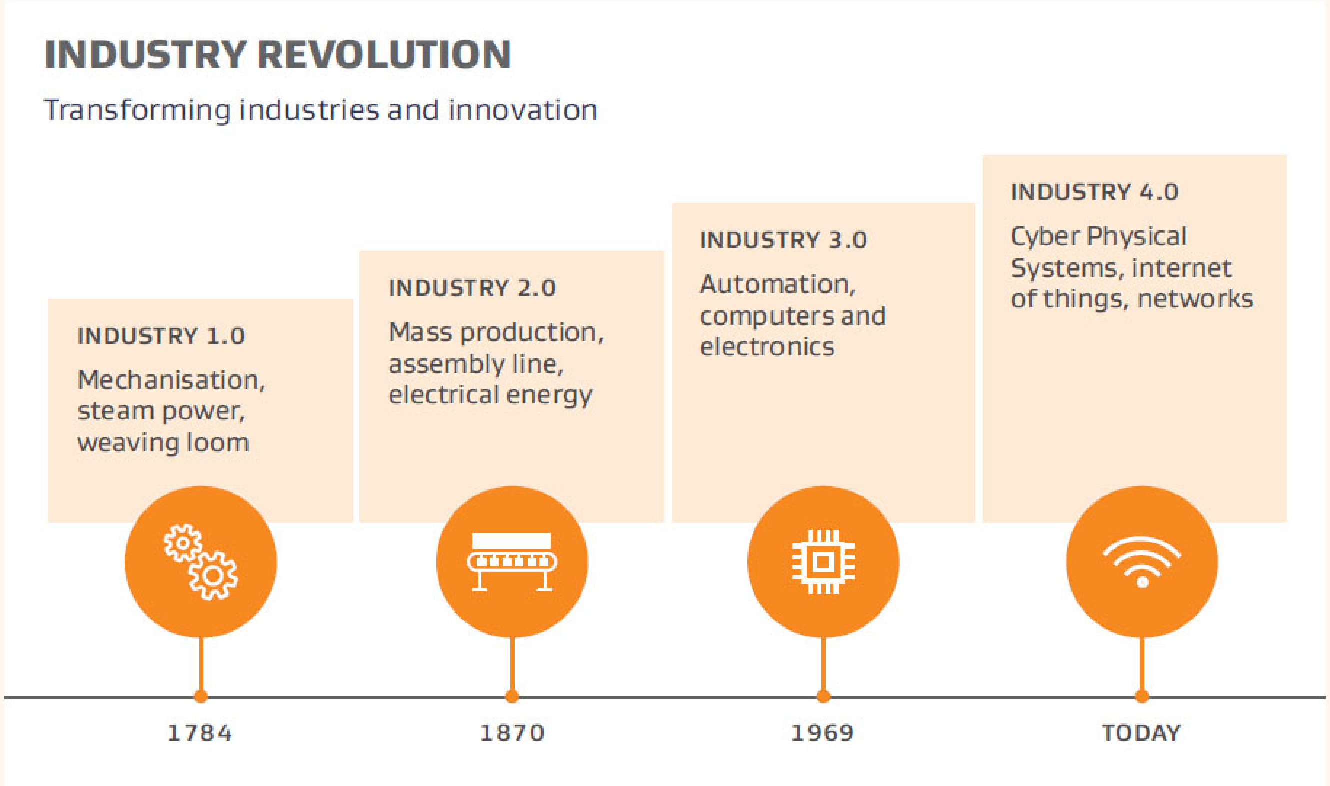
- Block 2: Industrial Internet of Things and data analytics

  (Yuqian Lu: yuqian.lu@)

- Block 3: Digital Twin technology and its applications

  (Jan Polzer: jan.polzer@)

MINISTRY OF BUSINESS, INNOVATION & EMPLOYMENT
HĪKINA WHAKATUTUKI



In practice Industry 4.0 allows advanced manufacturing processes to be optimised by being digitally connected (the "internet of things"), improving use of data including sensors, incorporating automation and robotics, digital manufacturing (e.g. 3D printing and additive manufacturing), as well as digital twins, artificial intelligence and virtual reality. It is important to appreciate that it also includes advances in business and production processes, often with small changes yielding significant benefits.

https://www.mbie.govt.nz/have-your-say/advanced-manufacturing-industry-transformation-plan/

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Learning Outcomes

- Understand the fundamentals of Industry 4.0 for smart manufacturing
- Understand some of the tools and models for measuring Industry 4.0 Readiness
- Gain appreciation of some specific tools for SMEs
- Demonstrate an understanding of the tools of the Industrial Internet of Things and data analytics
- Understand and apply digital twin technologies in manufacturing settings

Course details

- **Lectures:**
  - Monday 5.00-6.00pm, 260-004
  - Thursday 12.00-1.00pm, 260-004
  - Friday 1.00-2.00pm, 260-003 (maybe used as a tutorial/discussion session)
- **Assessments:**
  - MECHENG 754: 3 x assignments (20%, 20%, 15%) and exam (45%)
  - MECHENG 753: 3 x assignments (20%, 20%, 15%), report (20%) and exam (25%)
- **Workload expectations**
  - 15-point course
  - ~ 150 hours of study: 24-36 hours of lectures + 114-126 hours of independent study
- **Challenges**
- **Student feedback** – anytime, but a.s.a.p
- **Academic integrity**
- **Course materials**

Topics in Weeks 1-4

- Introduction to Industry 4.0
- Industry 4.0 Technology Readiness Assessment
- Digital Manufacturing Solutions for SMEs
- Basics of Industrial Communications

UNIVERSITY OF AUCKLAND
Waipapa Taumata Rau
NEW ZEALAND

https://profiles.auckland.ac.nz/xun-xu

← all experts

ABOUT RESEARCH OUTPUTS RESEARCH TEACHING & SUPERVISION

PROFESSOR

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Professor
Mechanical Engineering

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ENGINEERING BLOCK 5 - Bldg 405, 5 GRAFTON RD, AUCKLAND CENTRAL, AUCKLAND, 1010, New Zealand

Media

Collaboration Network

Apply To Study

BIO

I joined the Department of Mechanical and Mechatronics Engineering, The University of Auckland, in 1996 after obtaining a Ph.D. from the University of Manchester (then UMIST), UK. Since then, I have been working at the University of Auckland as a Lecturer, Senior Lecturer, Associate Professor, and now Professor. My teaching at the Department cuts across several fields, e.g., mechanical engineering design, manufacturing systems, advanced manufacturing technology, manufacturing information systems, advanced CAD/CAM/CNC and Industry 4.0.

My main research focuses on computer-aided design, process planning and manufacturing, particularly STEP-compliant CNC (STEP-NC), cloud manufacturing, smart manufacturing, and Industry 4.0. I set up the first Industry 4.0 laboratory in New Zealand, Laboratory for Industry 4.0 Smart Manufacturing Systems (LISMS) (https://lisms.auckland.ac.nz/), and lead one of the top research teams (IIMS (http://www.mech.auckland.ac.nz/en/about/ourresearch/researchareas/manufacturingsystems/IIMS.html) research group) in the world working in the field of STEP-compliant design and manufacturing.

Distinctions/Honours:
- Fellow, ASME (American Society for Mechanical Engineers)
- Fellow, EngNZ (Engineering New Zealand)
- "Highly Cited Researcher" 2020, Clarivate, WoS (https://recognition.webofscience.com/awards/highly-cited/2020/)
- "World's Top 2% Scientists", 2019,2020,2021, Standford University
- The 20 Most Influential Professors in Smart Manufacturing, SME. (https://www.sme.org/technologies/articles/2020/june/the-20-most-influential-professors/) Read the complete published issue here (https://www.qgdigitalpublishing.com/publication/?m=&l=1&i=660144&p=0).
- Winner of the inaugural RCIM Best Paper Award 2018 (https://www-sciencedirect-com.ezproxy.auckland.ac.nz/journal/robotics-and-computer-integrated-manufacturing/about/awards)
- Winner of the RCIM Best Paper Award 2021 (https://www-sciencedirect-com.ezproxy.auckland.ac.nz/journal/robotics-and-computer-integrated-manufacturing/about/awards)

ASME Best Organizer of Symposium & Sessions Award (BOSS Awards), ASME Manufacturing Engineering Division (MED), 2014, 2017

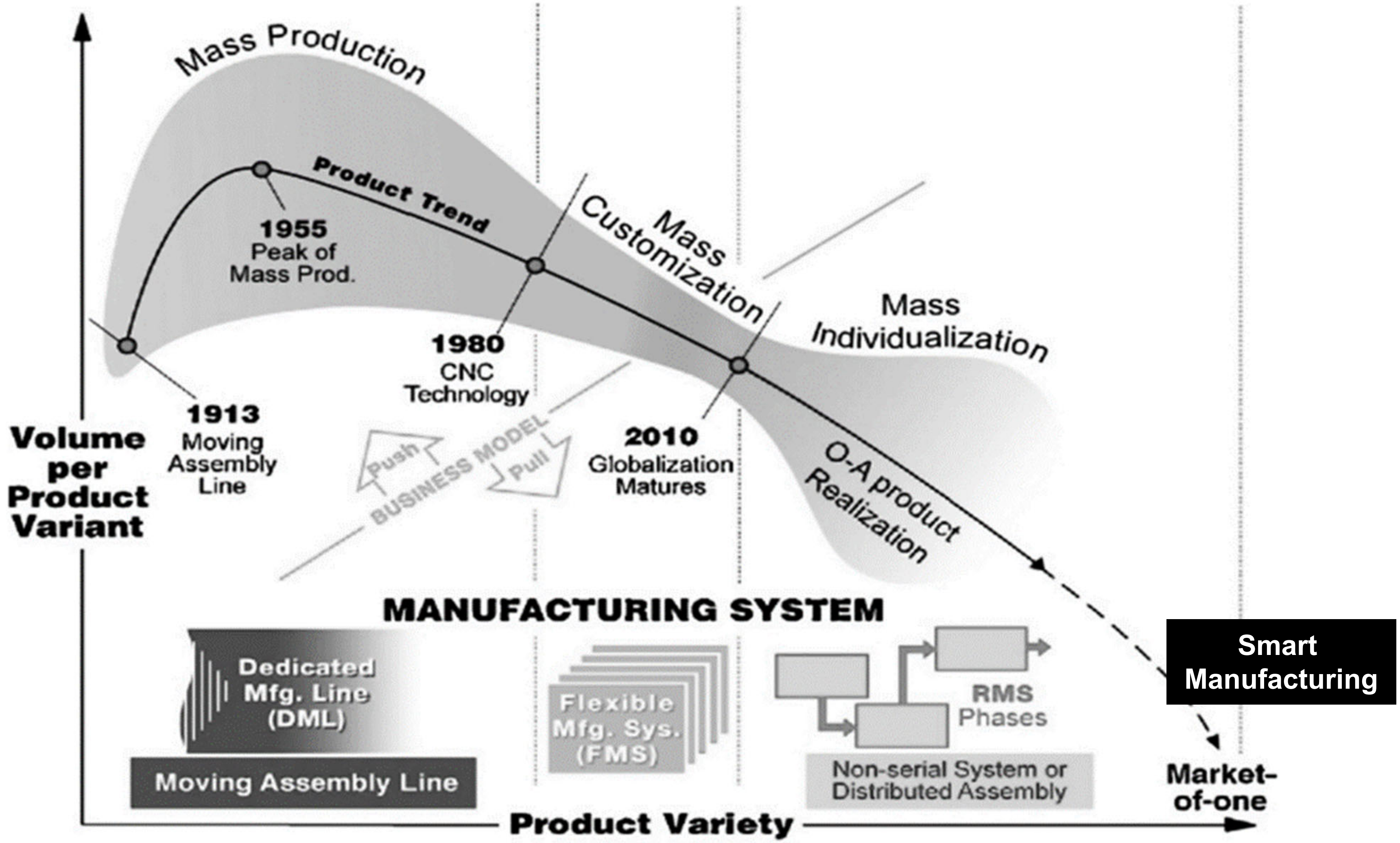
A new course on Industry 4.0: "Industry 4.0 Smart Manufacturing (https://courseoutline.auckland.ac.nz/dco/course/MECHENG/754/1225)"

UNIVERSITY OF AUCKLAND APPOINTMENTS

- **Professor**
  Faculty of Engineering, Mechanical Engineering, New Zealand

Introduction to Industry 4.0

Transformation of manufacturing approaches



Koren, Y. 2010 The global manufacturing revolution: product-process-business integration and reconfigurable systems: John Wiley & Sons, Inc.

New era of Information Technology

- Globalisation and decentralisation
- Data explosion; Big data
- Data vs. Information
- Internet of Things (IoT) and Connectedness
- Industrie 4.0
- Cyber-physical System

Forschungsunion
Wirtschaft und Wissenschaft begleiten die Hightech-Strategie

acatech
NATIONAL ACADEMY OF SCIENCE AND ENGINEERING

Securing the future of German manufacturing industry

Recommendations for implementing the strategic initiative INDUSTRIE 4.0

Final report of the Industrie 4.0 Working Group

April 2013

SPONSORED BY THE
Federal Ministry of Education and Research

Smart Service Welt

acatech
NATIONAL ACADEMY OF SCIENCE AND ENGINEERING

SMART SERVICE WELT

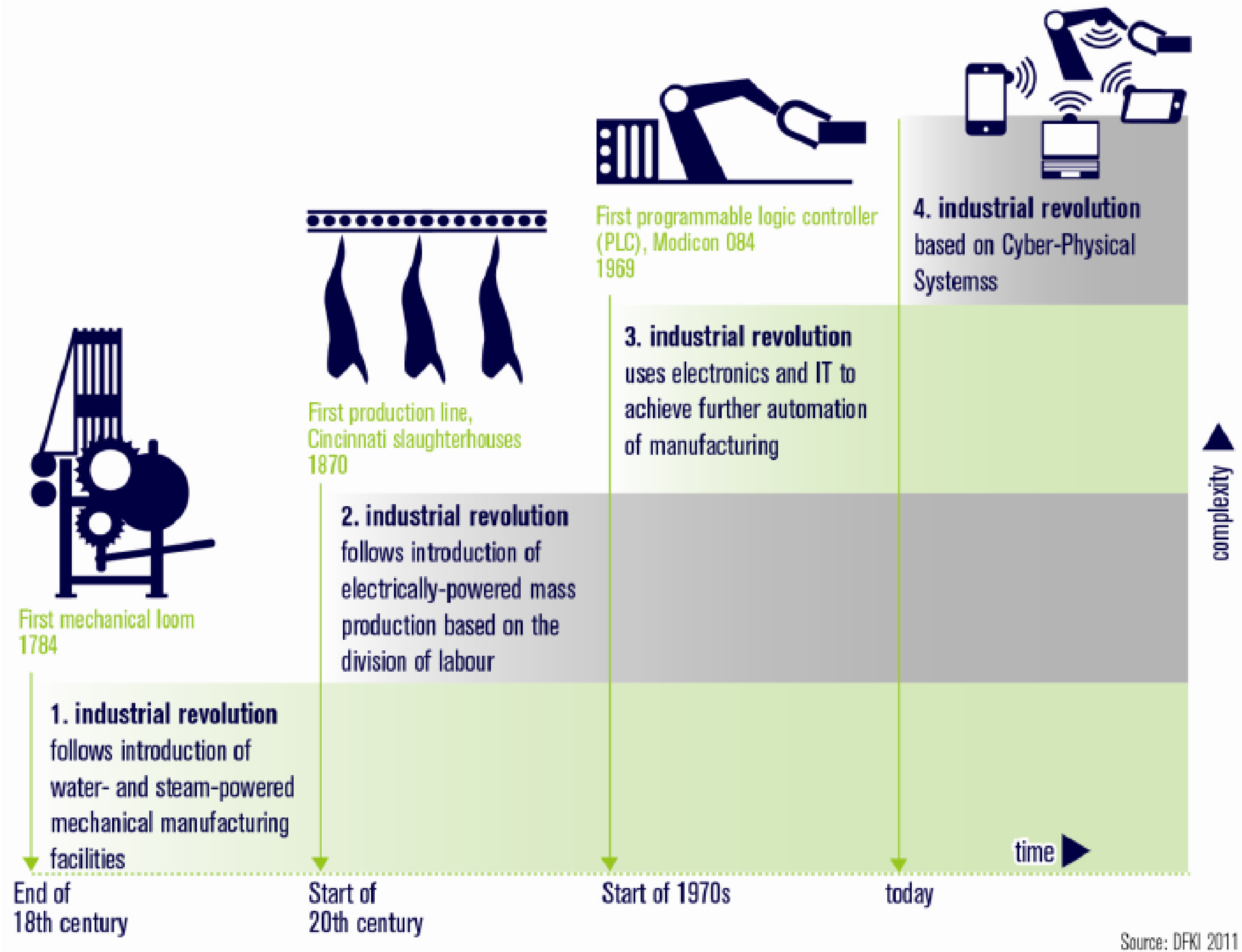
Recommendations for the Strategic Initiative Web-based Services for Businesses

FINAL REPORT
LONG VERSION

March 2015

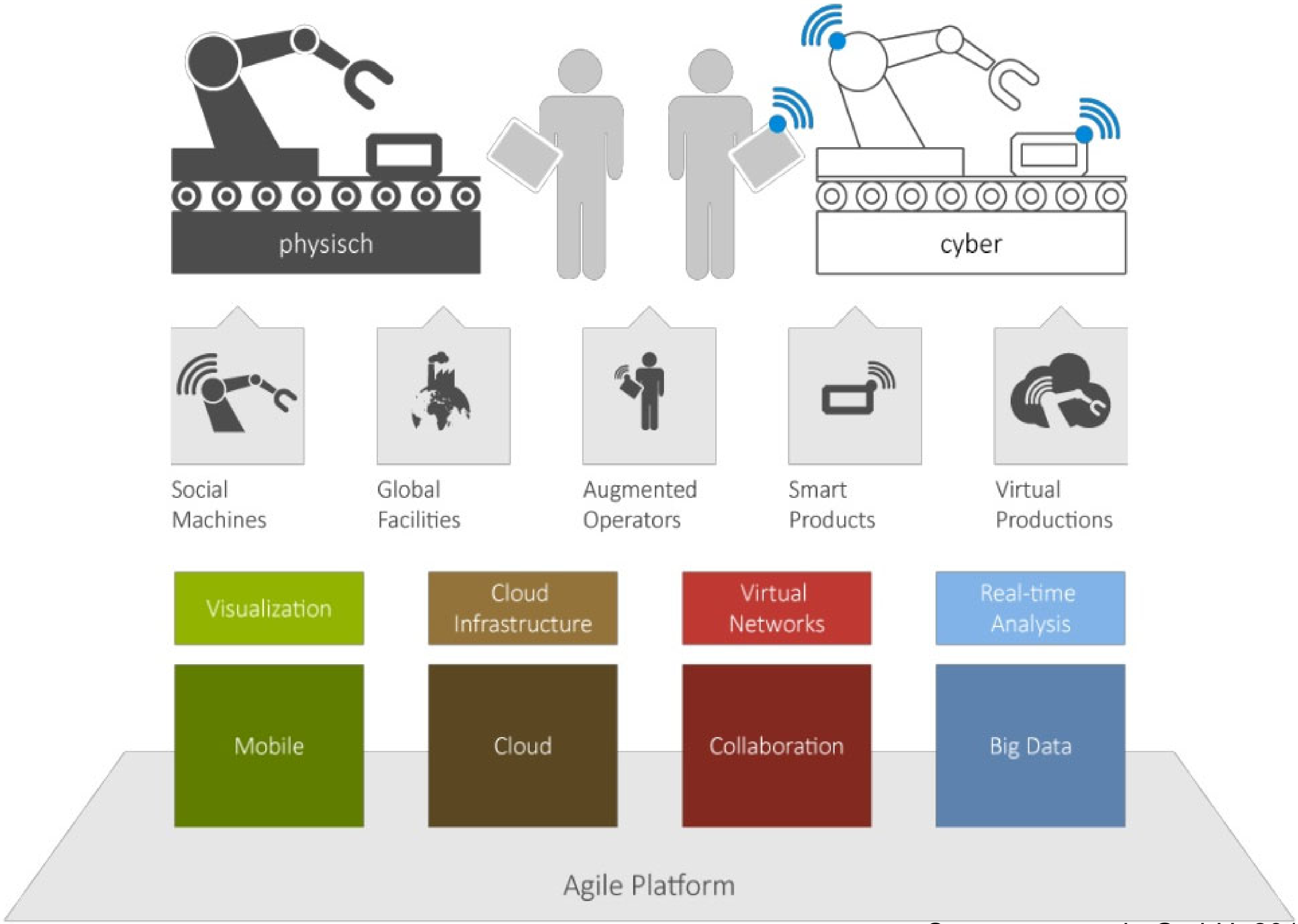
Supported by:
Federal Ministry for Economic Affairs and Energy

From Industrie 1.0 to Industrie 4.0 - the German vision



cf. achatech

Components of Industrie 4.0



Source: axxessio GmbH. 2014

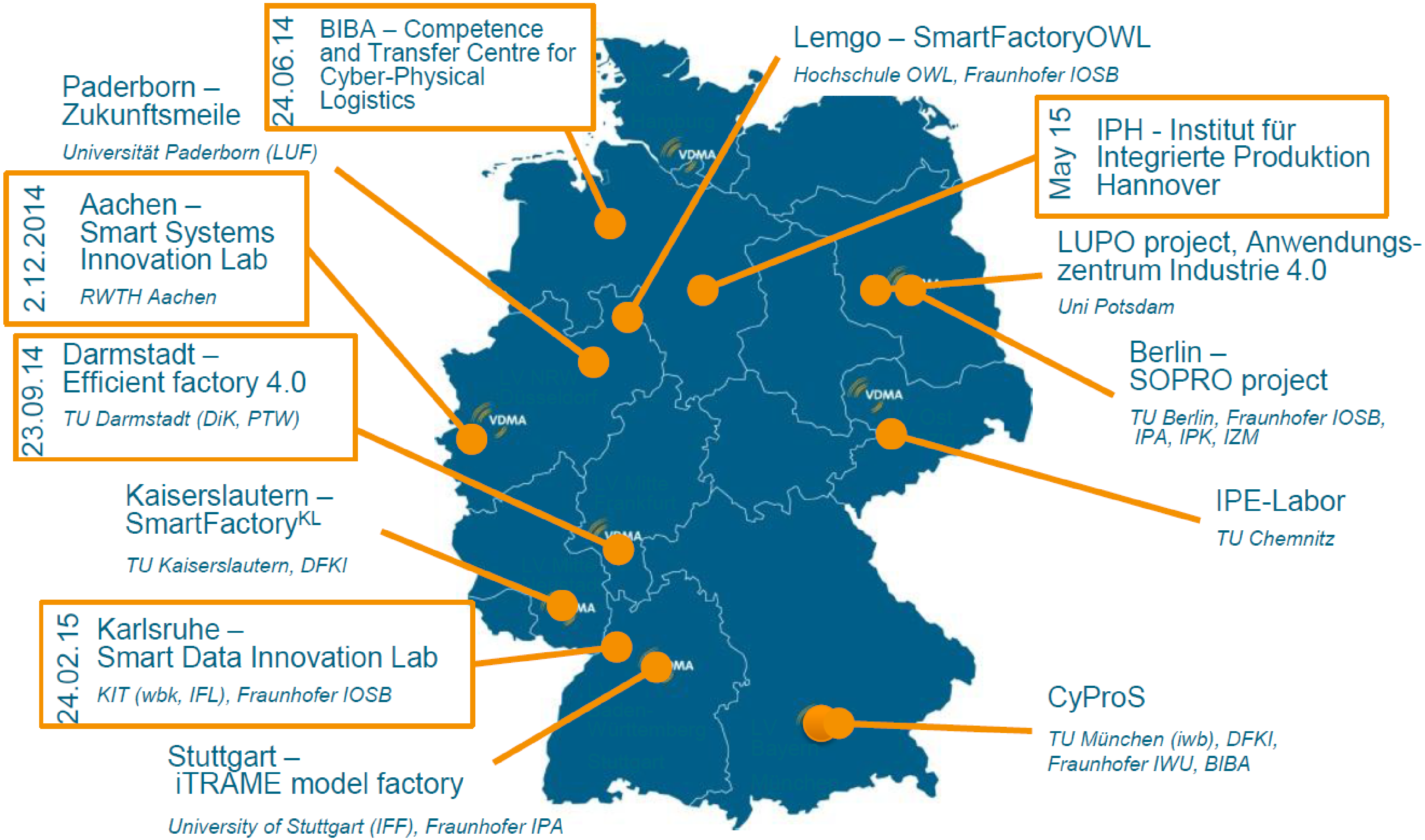
Industrie 4.0

- Originated from a project in the high-tech strategy of the German government (2011)
- A collective term embracing a number of contemporary automation and manufacturing technologies, e.g.
  - Cyber-Physical Systems (CPS) and digital twins
  - Internet of Things (IoT)
  - Industrial Internet of Things (IIoT)
  - Internet of Services (IoS)
  - Data analytics
  - AI

Germany's dual strategy: becoming a leading market and supplier

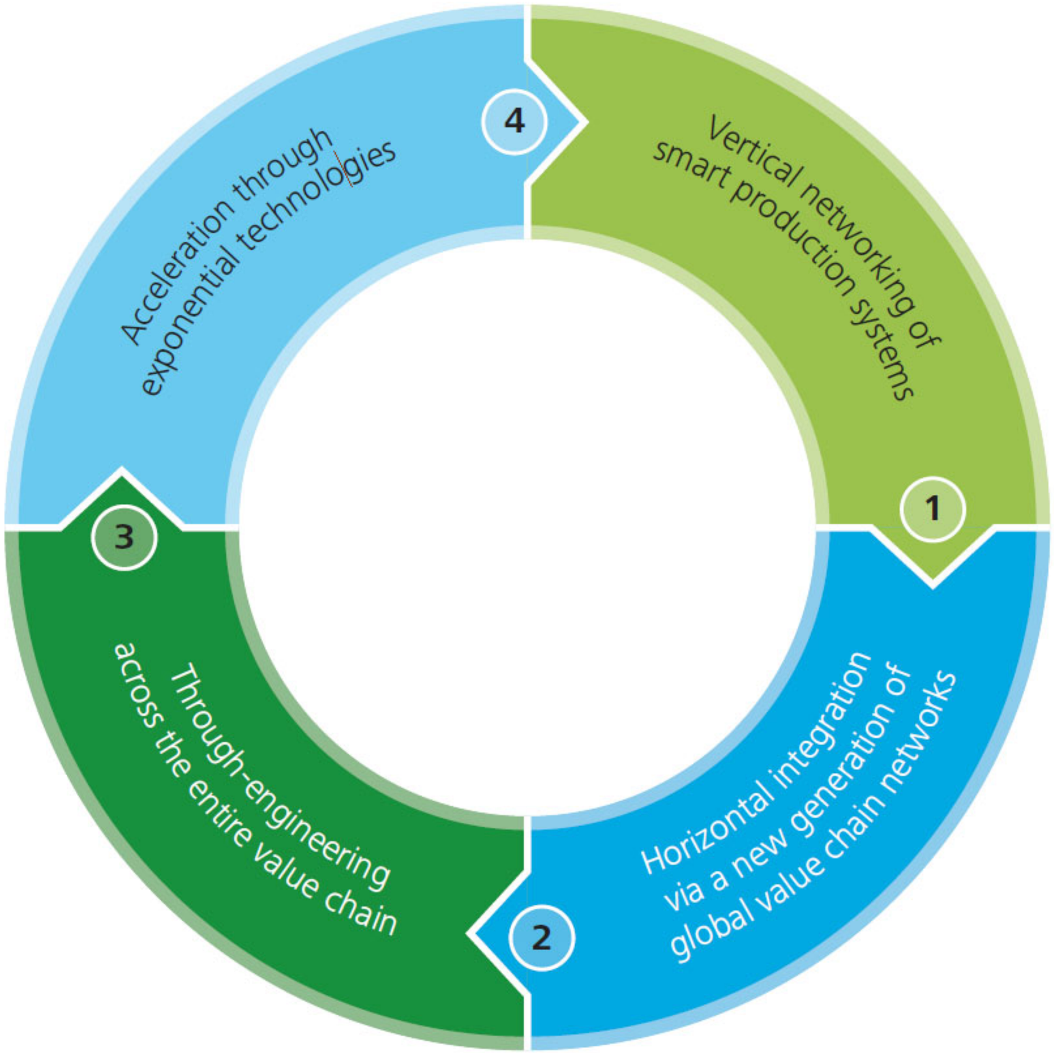
- Leading market
  - strengthen German manufacturing industry by improving the efficiency of domestic production.
- Leading supplier
  - develop Industry 4.0 technologies (e.g. CPS) to offer significant opportunities for exporting technologies and products.

I4.0 learning factories and I4.0 projects in Germany



VDMA (Verband Deutscher Maschinen- und Anlagenbau, German Engineering Federation)

Four main characteristics of Industry 4.0



Arbeitskreis Industrie 4 .0: Umsetzungsempfehlungen fur das Zukunf tsprojekt Industrie 4.0. April 2013. Eric Openshaw, Craig Wigginton, John Hagel, John Seely Brown, Maggie Wooll and Preeta Banerjee: The Internet of Things Ecosystem: Unlocking the Business Value of Connected Devices. Deloitte, 2014

Vertical networking of smart production systems

Mainly through cyber-physical production systems (CPPSs)

- Rapid response to changes in demand or stock levels and to faults
- Customer-specific and individualized production
- Extensive use of smart sensing technology
- Resources and products are networked and tracked in real-time
- Resource (materials, energy and human) efficiency

Horizontal integration via global value chain networks

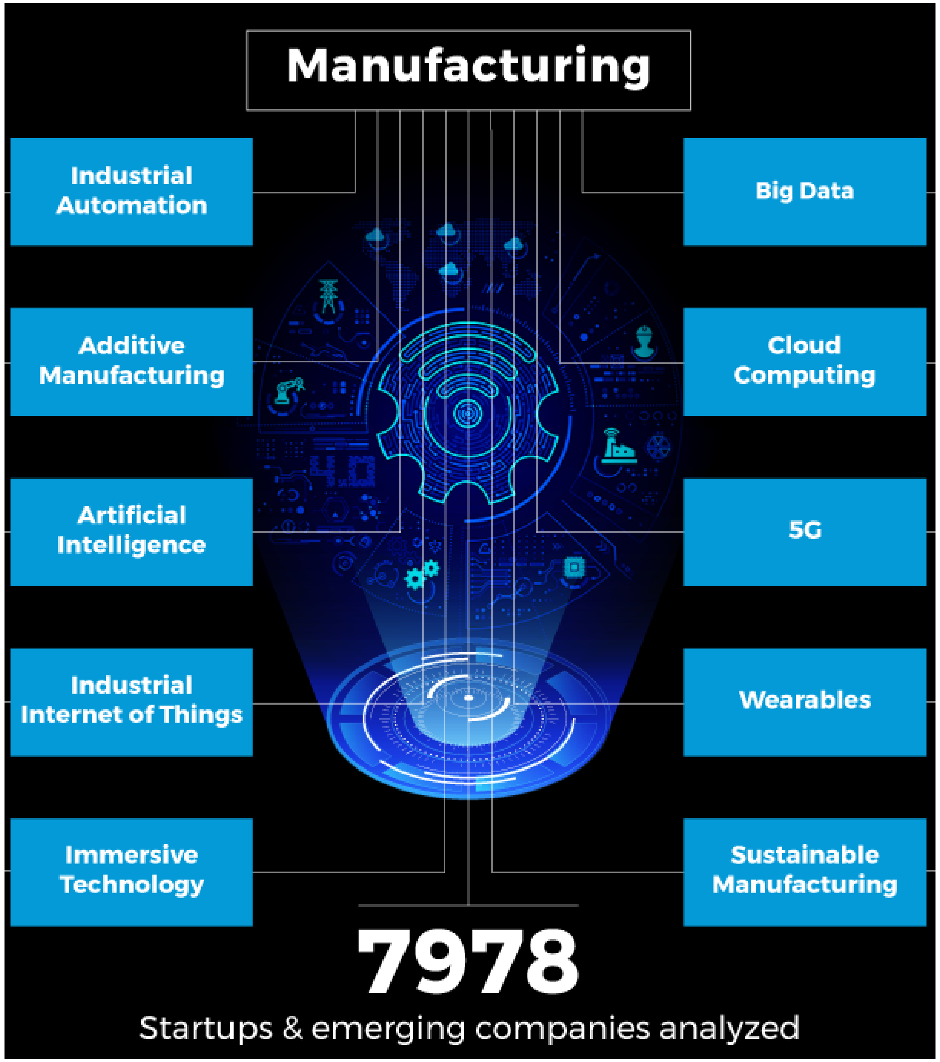
- Real-time optimized, integrated and resilient networks
- From inbound logistics through warehousing, production, marketing and sales to outbound logistics and downstream services
- History of any product is logged and can be accessed at any time – the concept of 'product memory'
- Horizontal integration of both customers and business partners
- Generation of completely new business models and new models for cooperation

Through-engineering across the entire value chain

- Engineer the full life cycle of a product (design-development-manufacture-services)
- Further extension of CAD/CAPP/CAM/CAE integration
- New synergies between product development and production systems

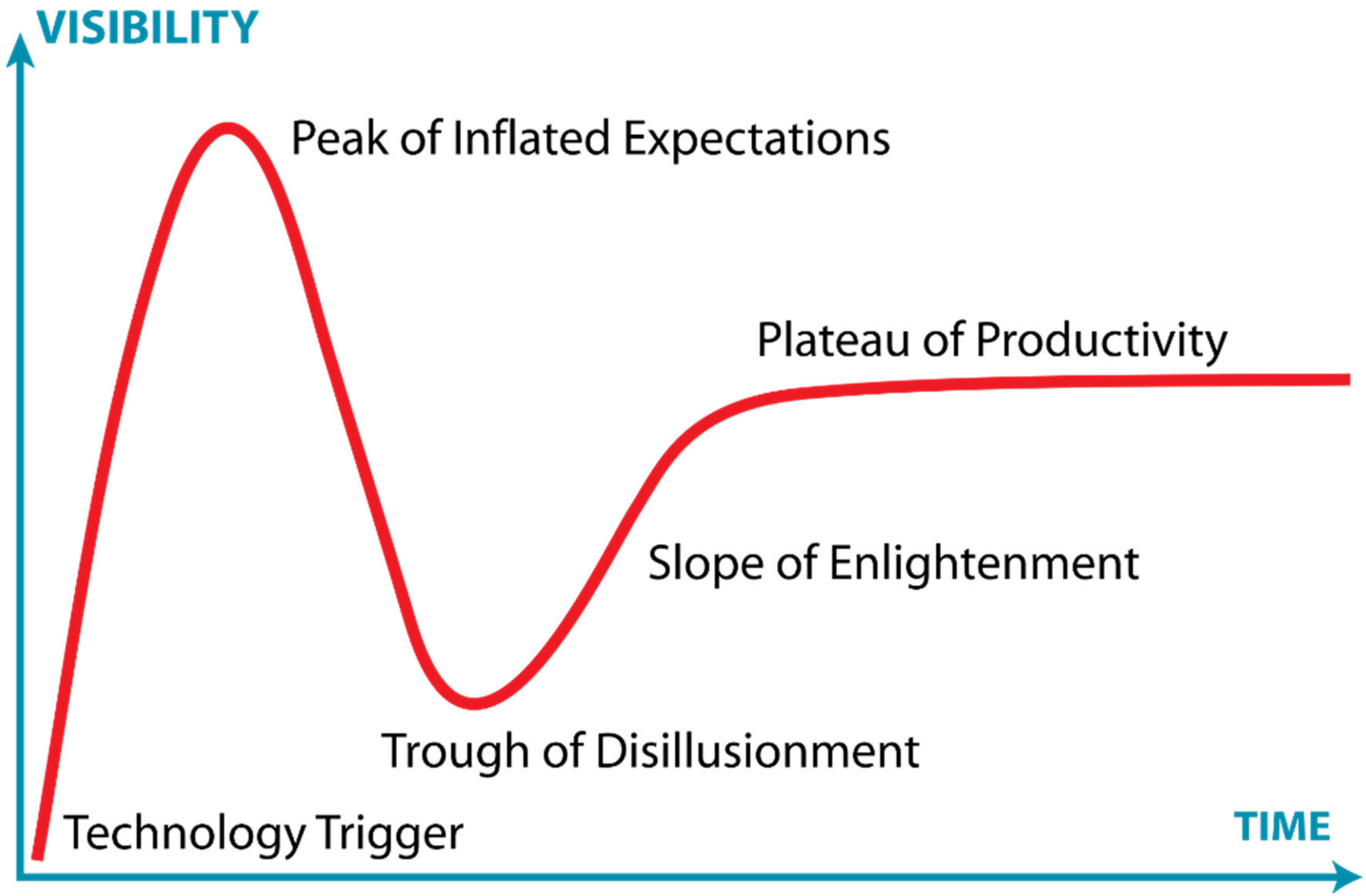
Acceleration through exponential technologies

Exponential technologies as an accelerant or catalyst to allow individualized solutions, flexibility and cost savings.

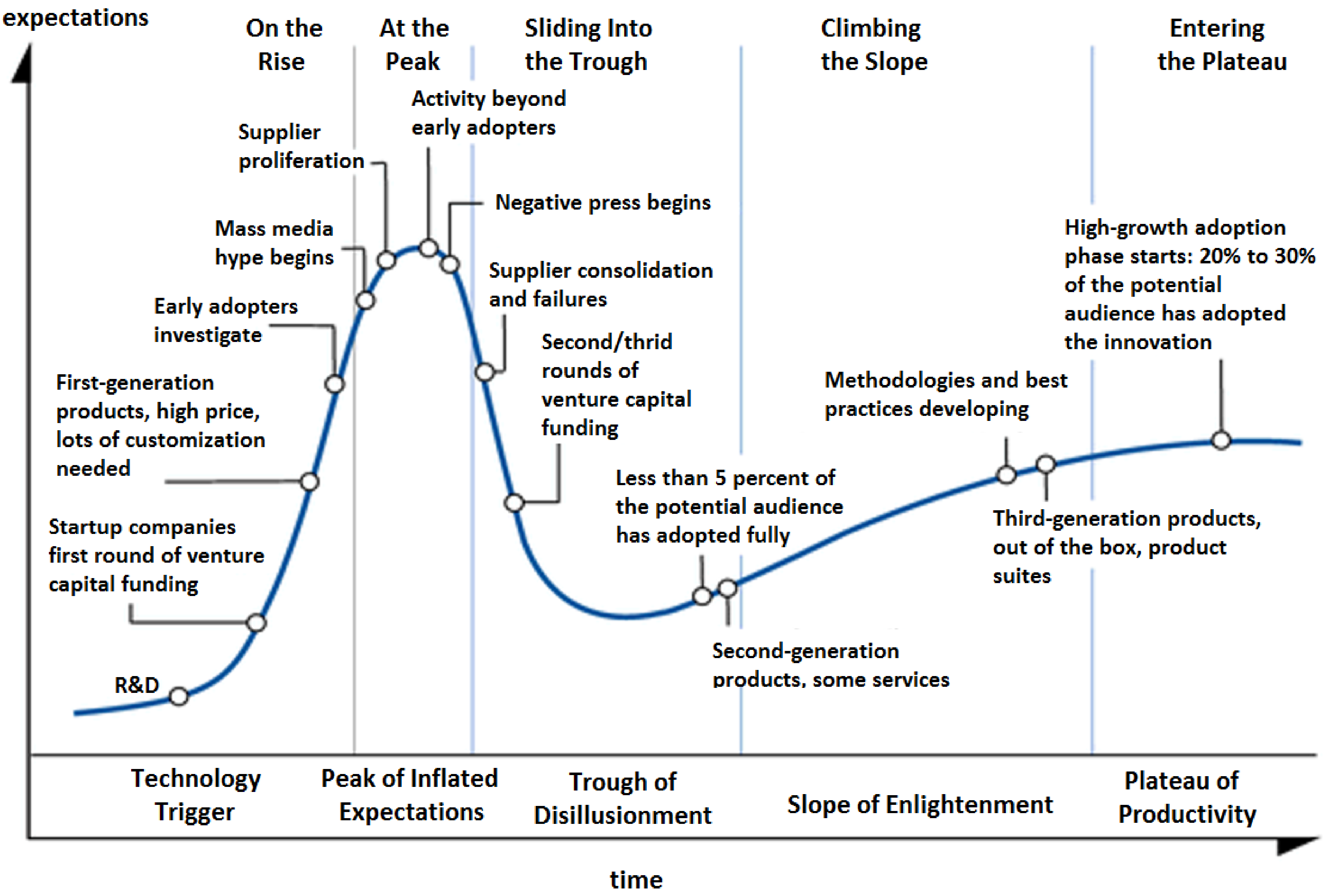


https://www.startus-insights.com/innovators-guide/manufacturing-trends-innovation/

Gartner's Hype Cycle for Emerging Technologies

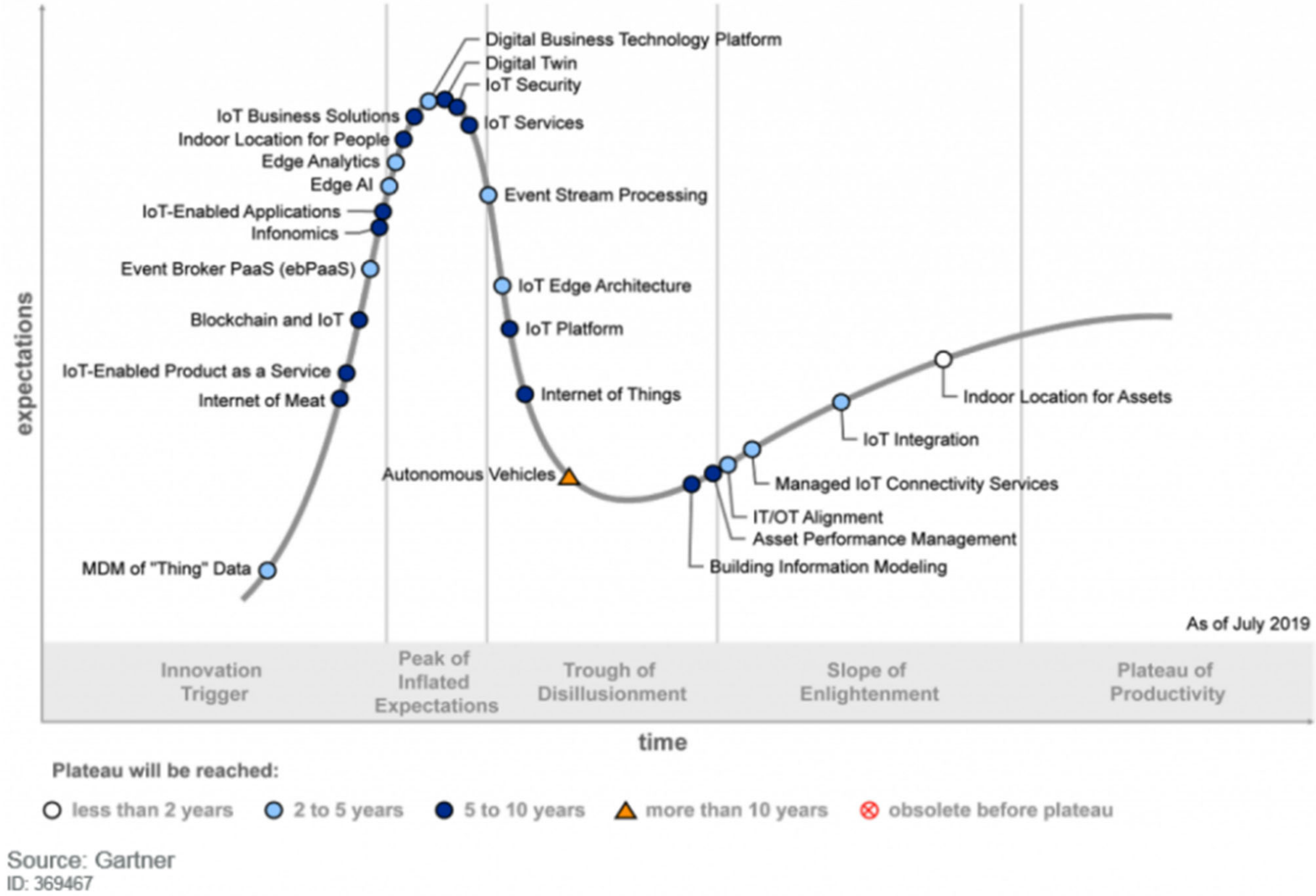


Source: By Jeremykemp at English Wikipedia, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=10547051

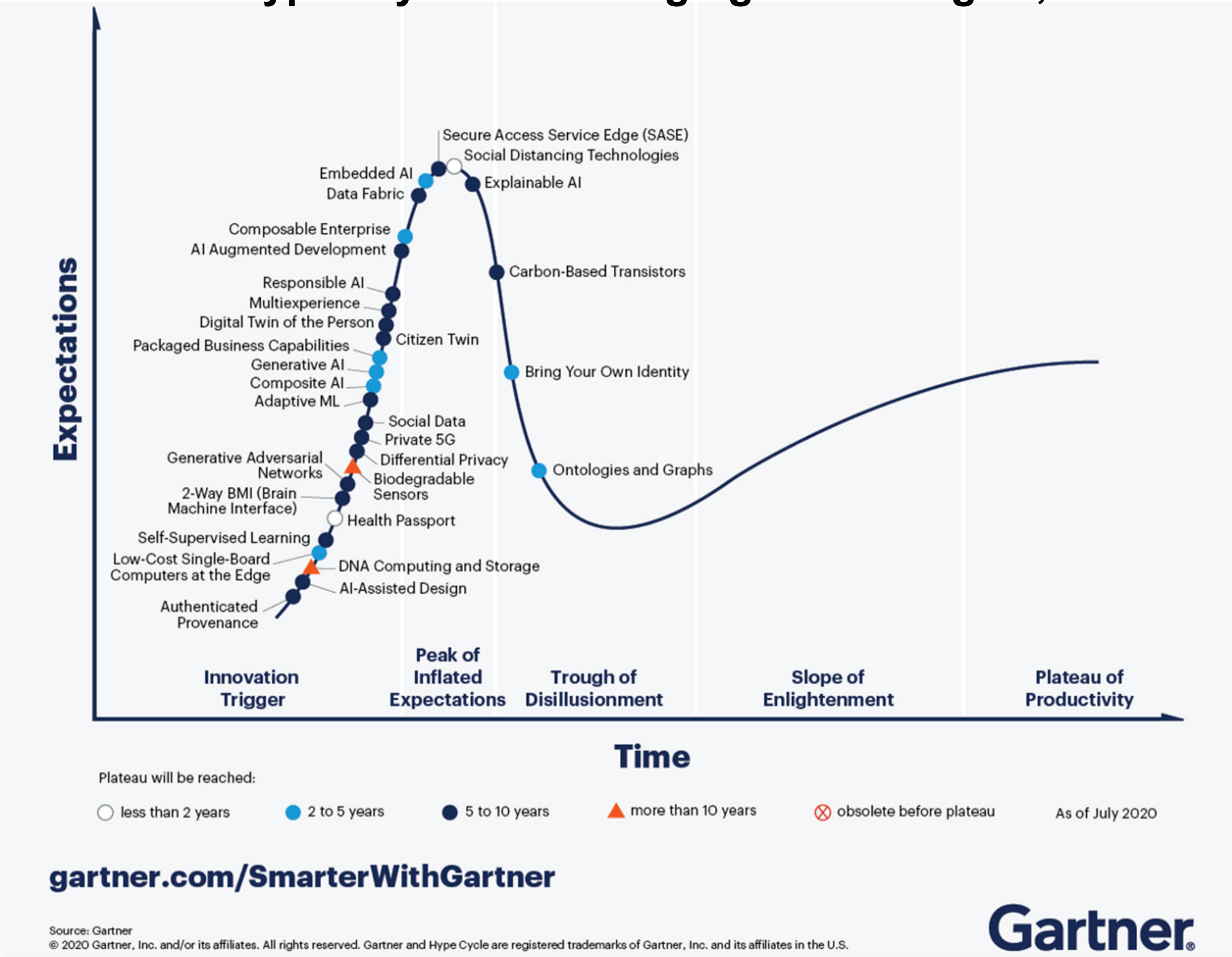


expectations
On the Rise
At the Peak
Sliding Into the Trough
Climbing the Slope
Entering the Plateau
Activity beyond early adopters
Supplier proliferation
Negative press begins
Mass media hype begins
Supplier consolidation and failures
Early adopters investigate
Second/thrid rounds of venture capital funding
High-growth adoption phase starts: 20% to 30% of the potential audience has adopted the innovation
Methodologies and best practices developing
First-generation products, high price, lots of customization needed
Less than 5 percent of the potential audience has adopted fully
Third-generation products, out of the box, product suites
Startup companies first round of venture capital funding
Second-generation products, some services
R&D
Technology Trigger
Peak of Inflated Expectations
Trough of Disillusionment
Slope of Enlightenment
Plateau of Productivity
time

Gartner Hyper Cycle for Internet of Things, 2019



Gartner Hyper Cycle for Emerging Technologies, 2020



Industrie 4.0 in a hype cycle

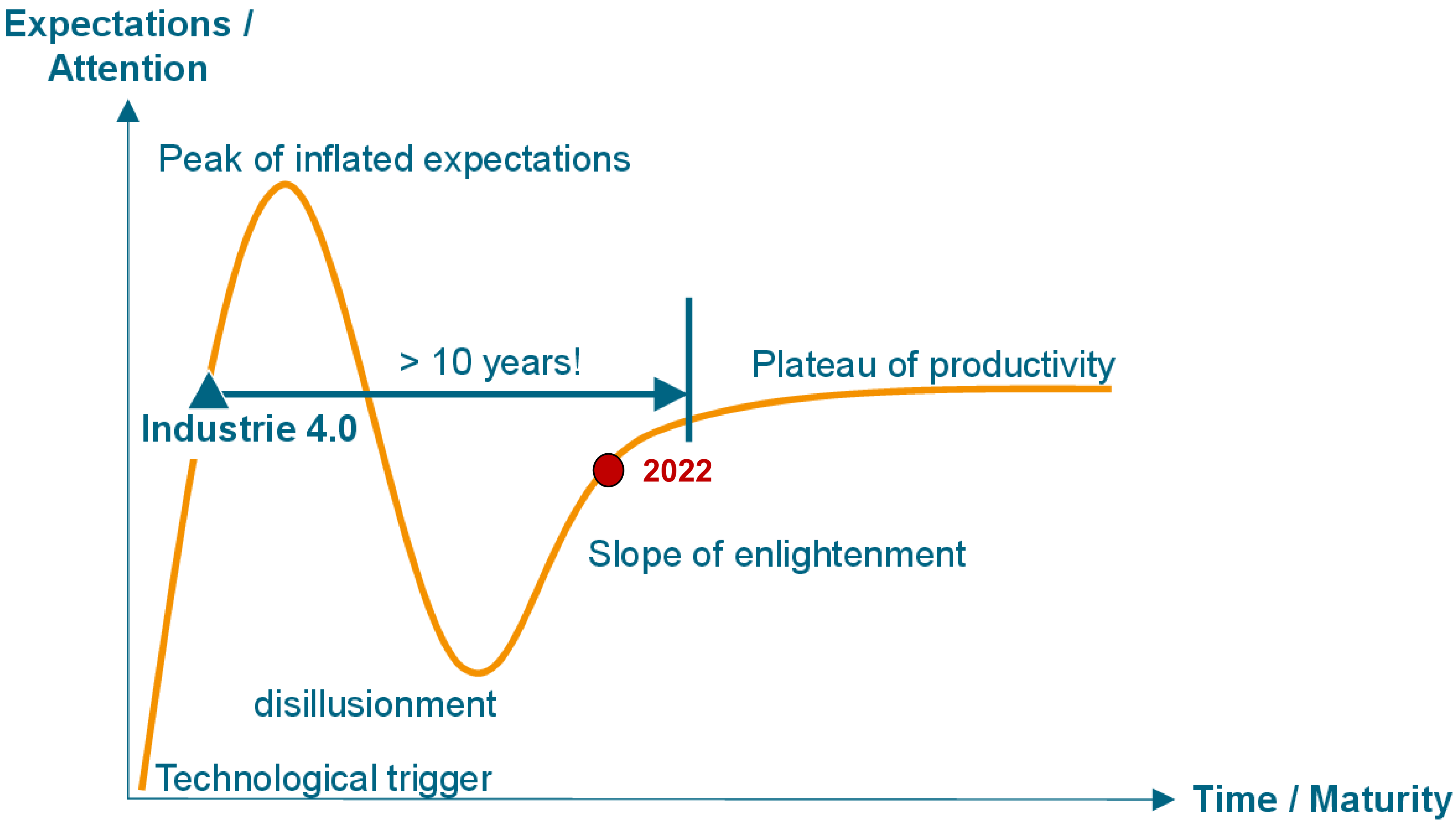
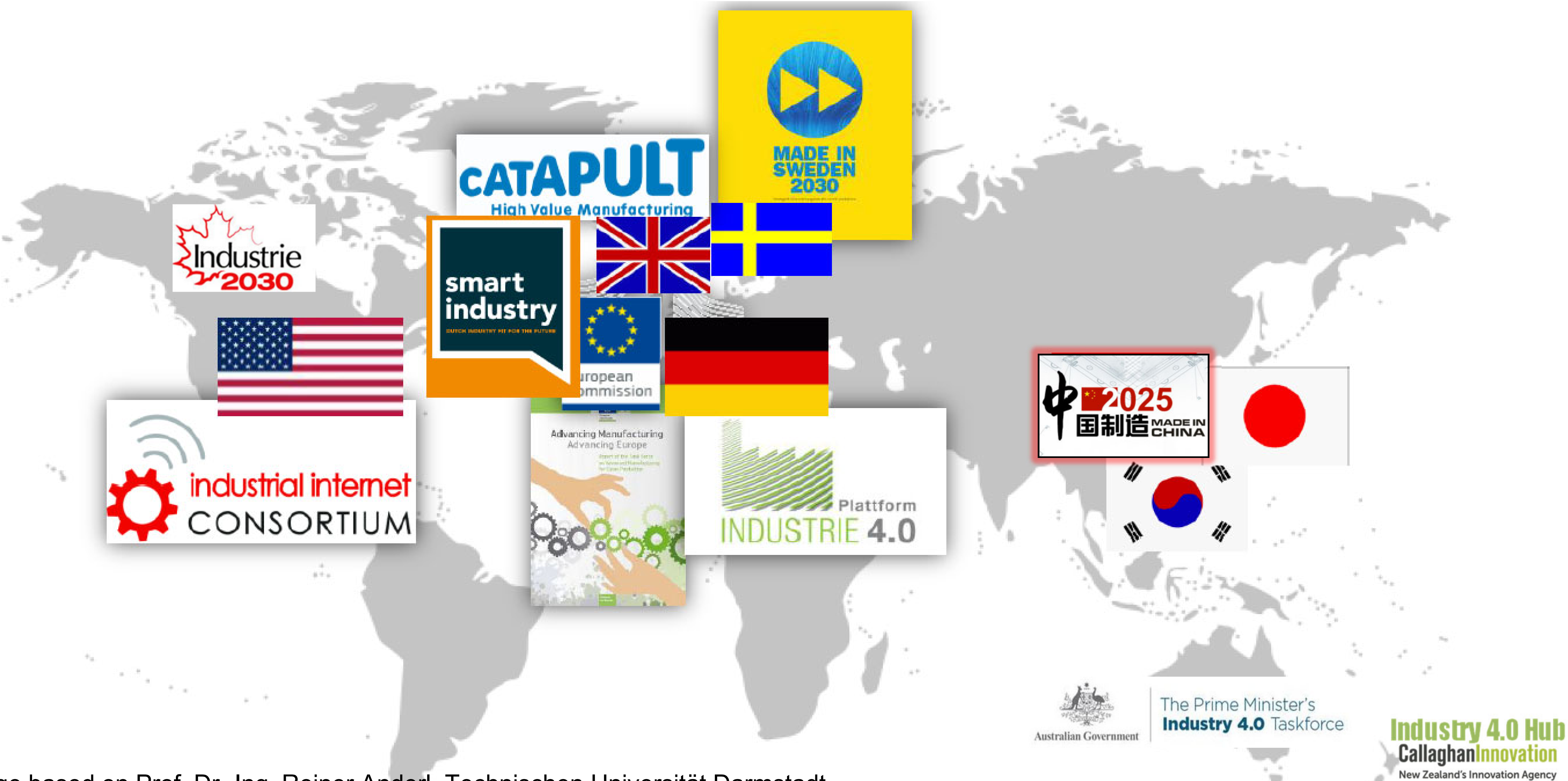


Figure based on Gartner Research 2012. VDMA

Industry 4.0 is not alone



- Image based on Prof. Dr.-Ing. Reiner Anderl, Technischen Universität Darmstadt
- To read more: Stephen Ezall. "Why Manufacturing Digitalization Matters and How Countries Are Supporting It", April 2018. Information Technology & Innovation Foundation. USA

i4.0 Laboratory for Industry 4.0 Smart Manufacturing Systems

Some Keywords

- Internet of Things - Connectedness
- Data – Data Analytics – Intelligence/Autonomy
- Services

- Smart Manufacturing - Autonomics of Production
- Cyber-Physical Production Systems (CPPS)

Digitalization of

economic and social processes

physical systems

<u>First wave: since the 1980s</u>

Digitalization of immaterial information-based processes, e.g. financing, consultancy, publishing, music-industries, communication

<u>Second wave: since the 2000s</u>

Integration of Internet/virtual world with physical systems – Internet of Things, Cyber-physical Systems, Industrie 4.0, Cloud Manufacturing

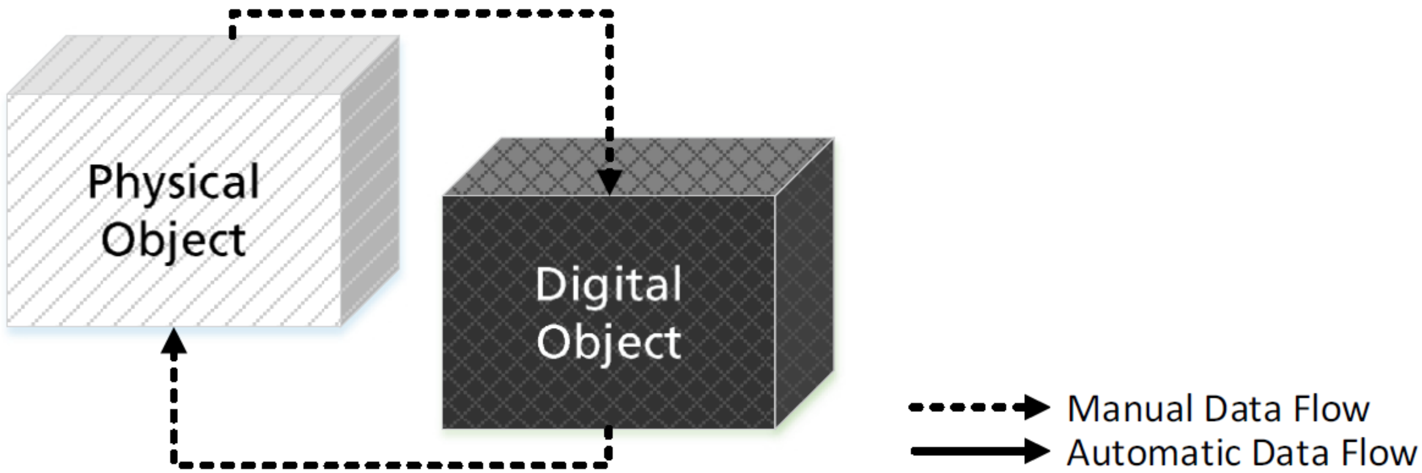
Digitalization and Integration

Depending on the level of data integration between the physical and digital counterpart, we can have

- Digital Model
- Digital Shadow
- Digital Twin

Digital Model of a physical object

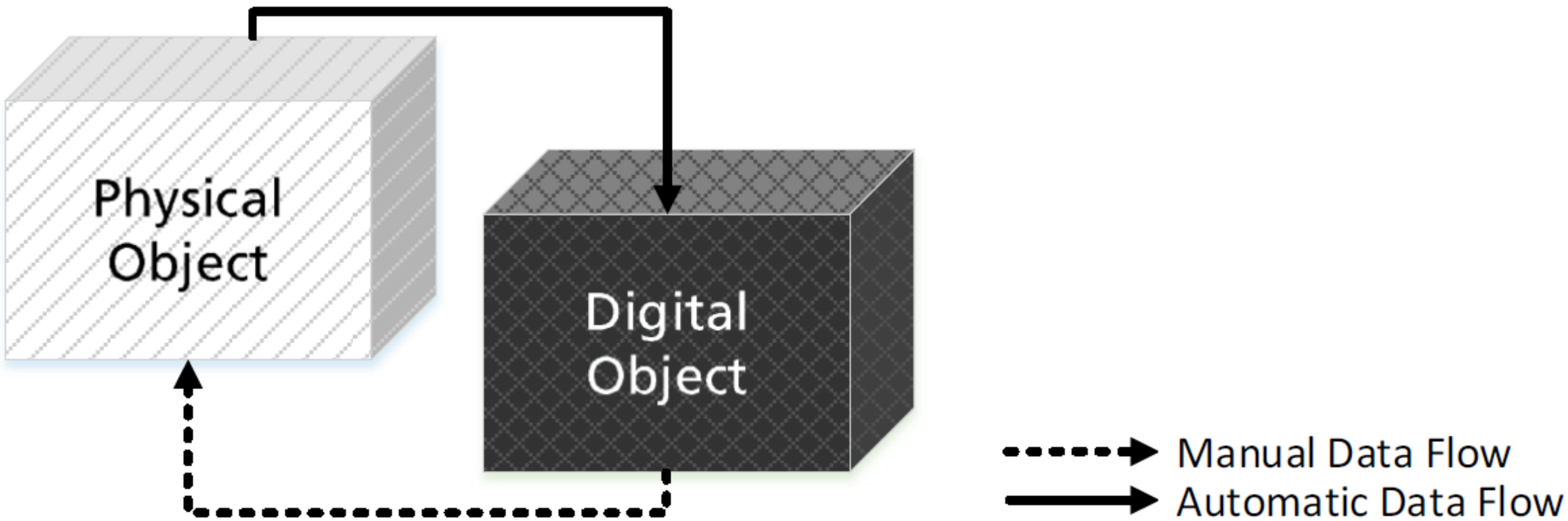
Digital Model is a digital representation of an existing or planned physical object that does not use any form of automated data exchange between the physical object and its digital counterpart.



Kritzinger, W, et al. “Digital Twin in manufacturing: A categorical literature review and classification”, IFAC Papers On Line 51-11 (2018) 1016–1022

Digital Shadow of a physical object

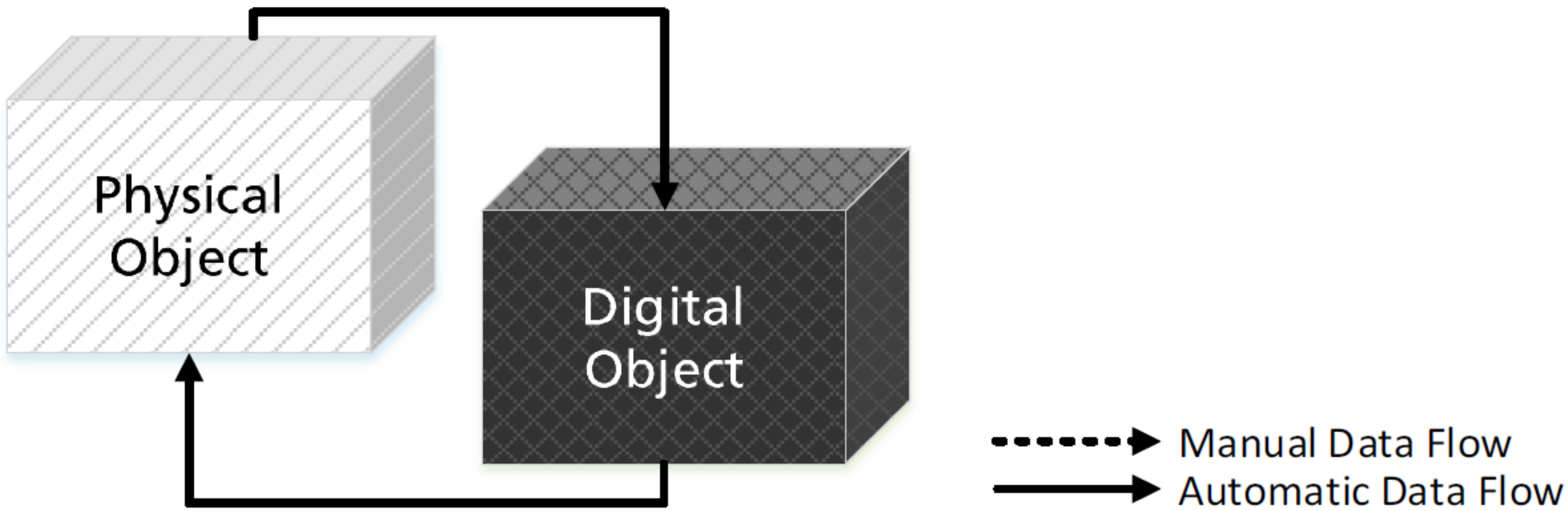
There is an automated one-way data flow between the state of an existing physical object and its digital counterpart.



Kritzinger, W, et al. “Digital Twin in manufacturing: A categorical literature review and classification”, IFAC Papers On Line 51-11 (2018) 1016–1022

Digital Twin of a physical object

- The data flows between an existing physical object and its digital counterpart are fully integrated in both directions.
- A change in the state of the physical object directly leads to a change in the state of its digital counterpart and vice versa.

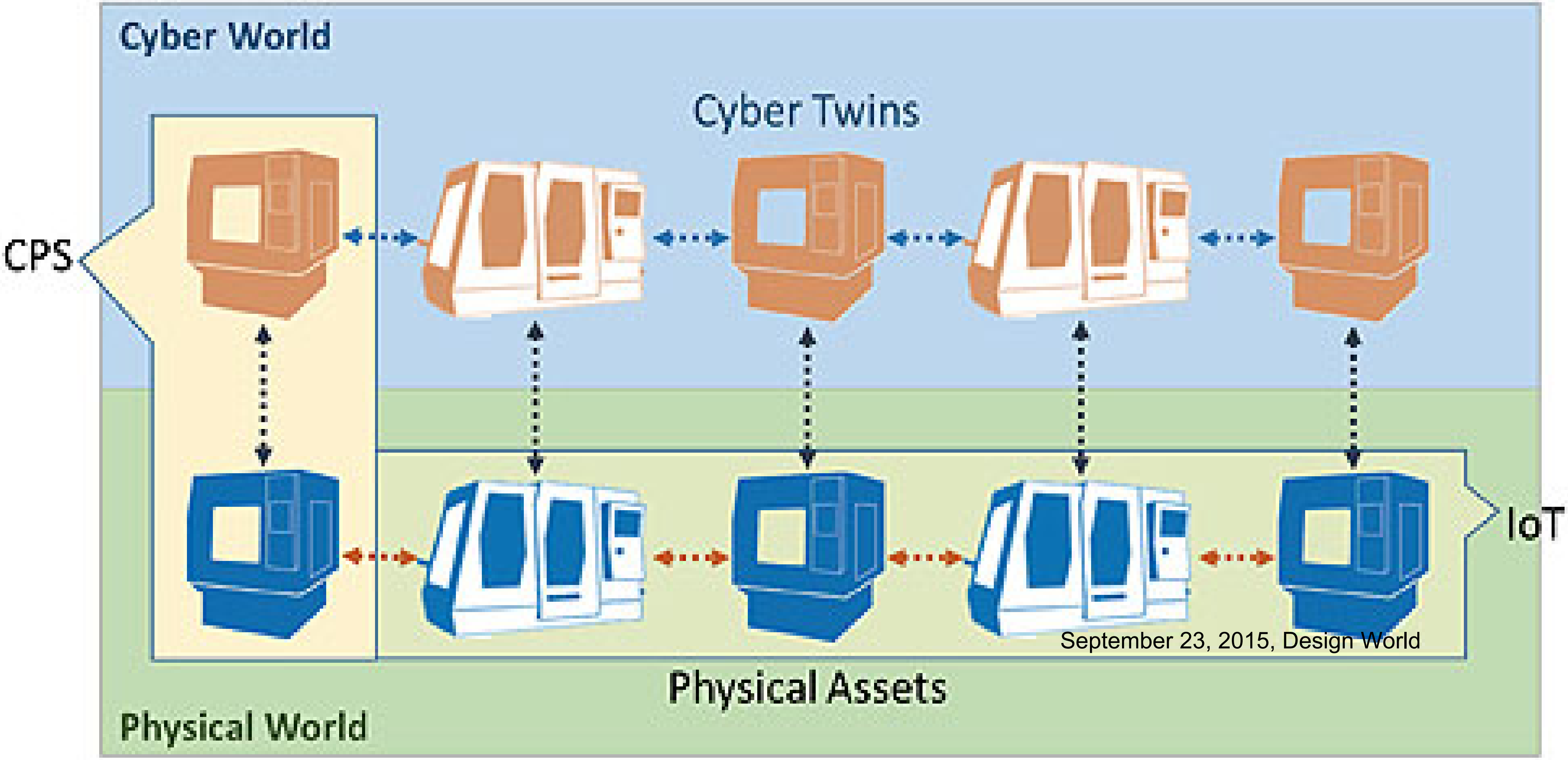


Kritzinger, W, et al. “Digital Twin in manufacturing: A categorical literature review and classification”, IFAC Papers On Line 51-11 (2018) 1016–1022

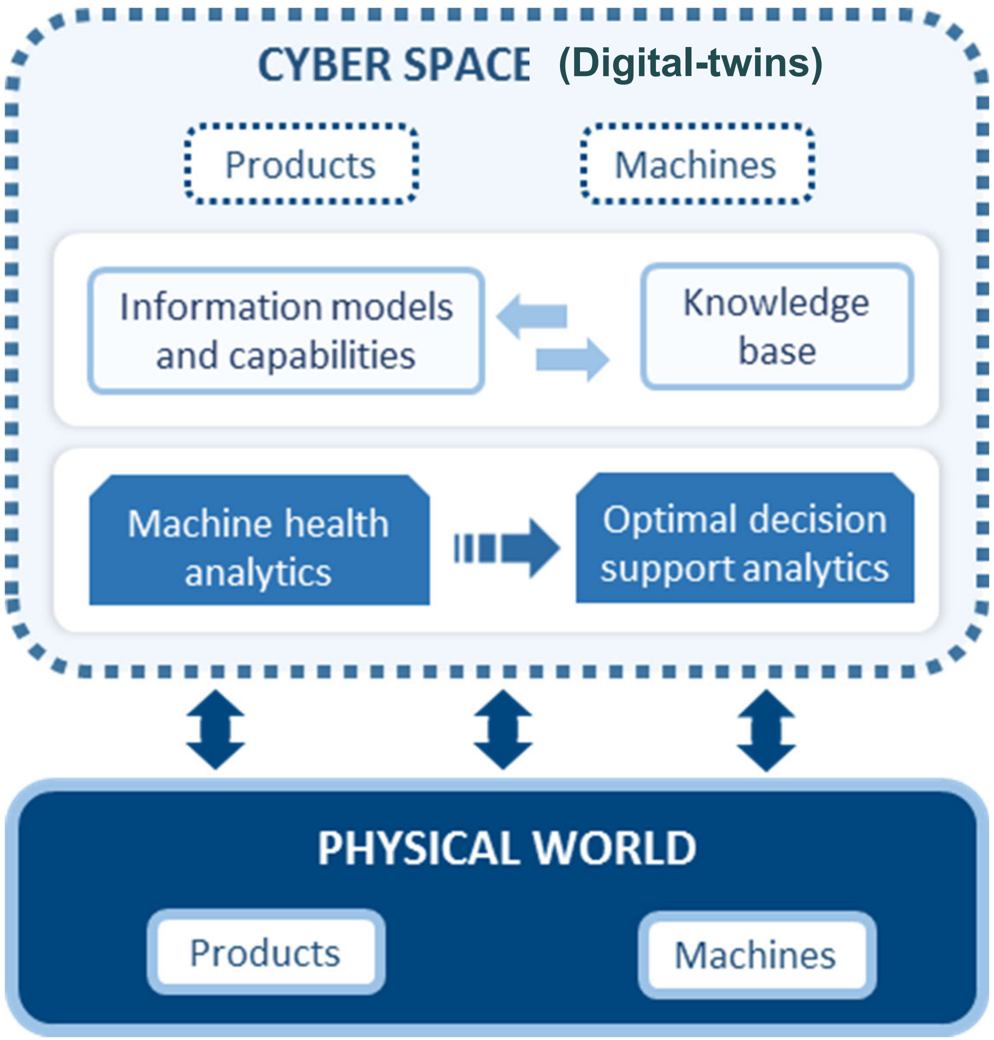
Cyber Physical System (CPS) -- What is it?

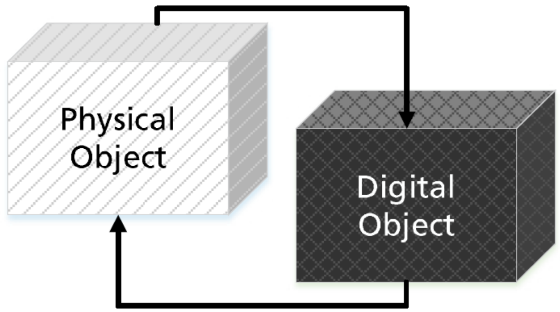
- Marry the *virtual digital (cyber-twin)* world with the *real physical* world
- Total connectedness with intelligence
- Semantic machine-to-machine (M2M) communication
  - closed embedded systems
  - self-monitoring, self-healing, proactive communications with other machines and/or operators
- Cyber-physical production systems (CPPS)

Cyber Physical System and Internet of Things (IoT)



Cyber-physical System Architecture





Definitions of “Digital Twin”

- “An integrated multi-physics, multi-scale, probabilistic *simulation* of a vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to *mirror* the life of its flying twin” - *first definition of DT by NASA* (1)
- “Virtual substitutes of real world objects consisting of *virtual representations* and *communication capabilities* making up *smart objects* acting as intelligent nodes inside the Internet of Things and Services” (2)
- “An integrated multi-physics, multi-scale, probabilistic *simulation* of an as-built system, enabled by *Digital Threads*, that uses the best available models, sensor information, and input data to *mirror* and *predict* activities/performance over the life of its corresponding physical twin” (3)

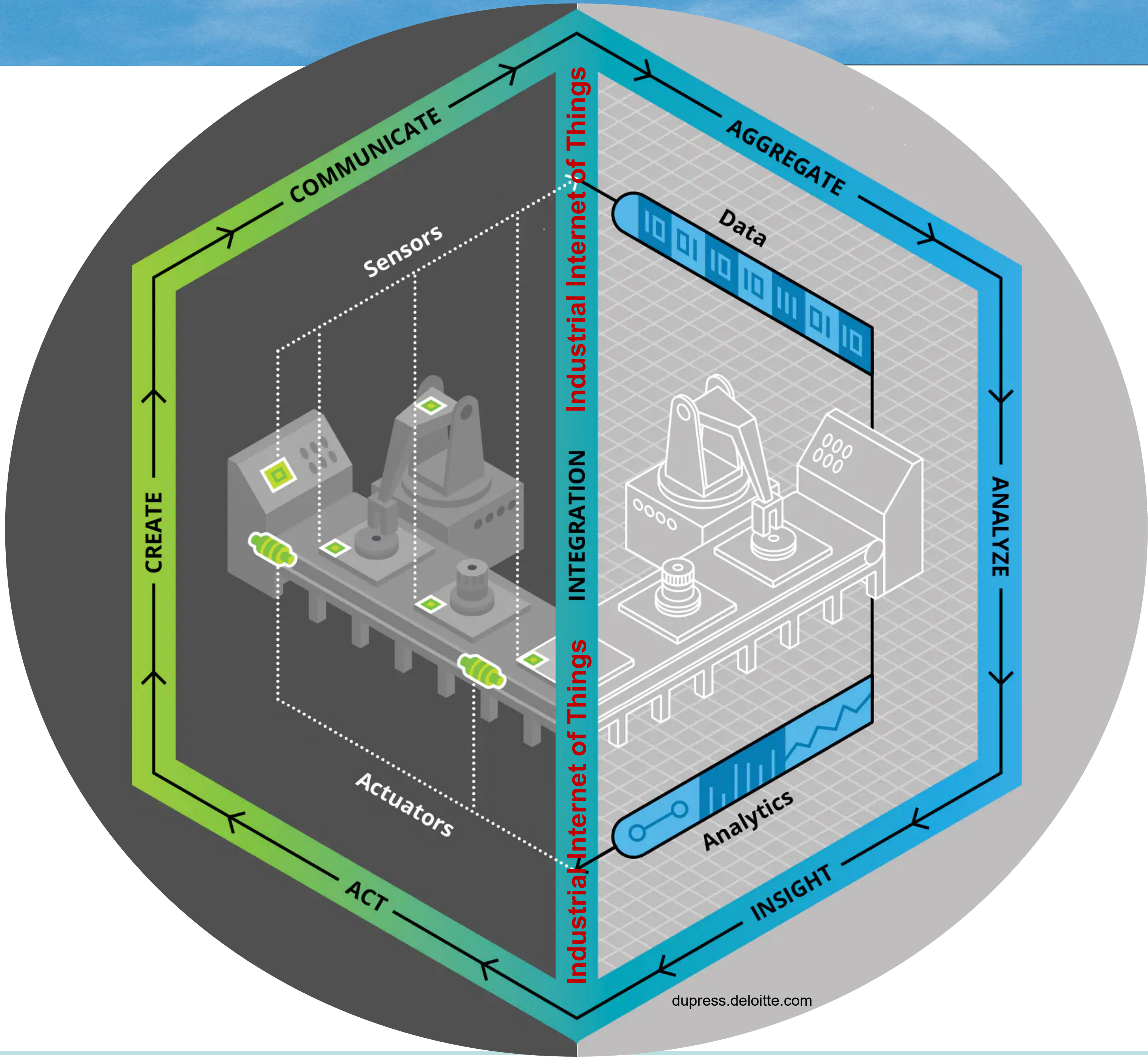
1) M. Shafto, et al, DRAFT Modeling, Simulation, Information Technology & Processing Roadmap. Technology Area 11, 2010.
2) M. Schluse, J. Rossmann, From Simulation to Experimentable Digital Twins, in: Syst. Eng. (ISSE), 2016 IEEE Int. Symp., 2016: pp. 1–6.
3) E.M. Kraft, The US Air Force Digital Thread / Digital Twin – Life Cycle Integration and Use of Computational and Experimental Knowledge II . The Evolution of Integrated Computational / Experimental Fluid Dynamics, in: 54th AIAA Aerosp. Sci. Meet., 2016: pp. 1–22

Applications of Digital Twins

- Initial intended use to support system health analyses through improved maintenance and planning:
  - Monitor anomalies, fatigue, crack paths in the physical twin;
  - Monitor geometric and plastic deformation on the material of the physical twin;
  - Model reliability of the physical system.
- Digitally mirror the life of a physical entity:
  - Provide information continuity along the different phases of the lifecycle;
  - Virtual Commissioning of a system.
- Support decision-making through engineering and statistical analyses:
  - Optimization of system behaviour during design phase;
  - Study the long-term behaviour of the system, and predict and optimize its performances.

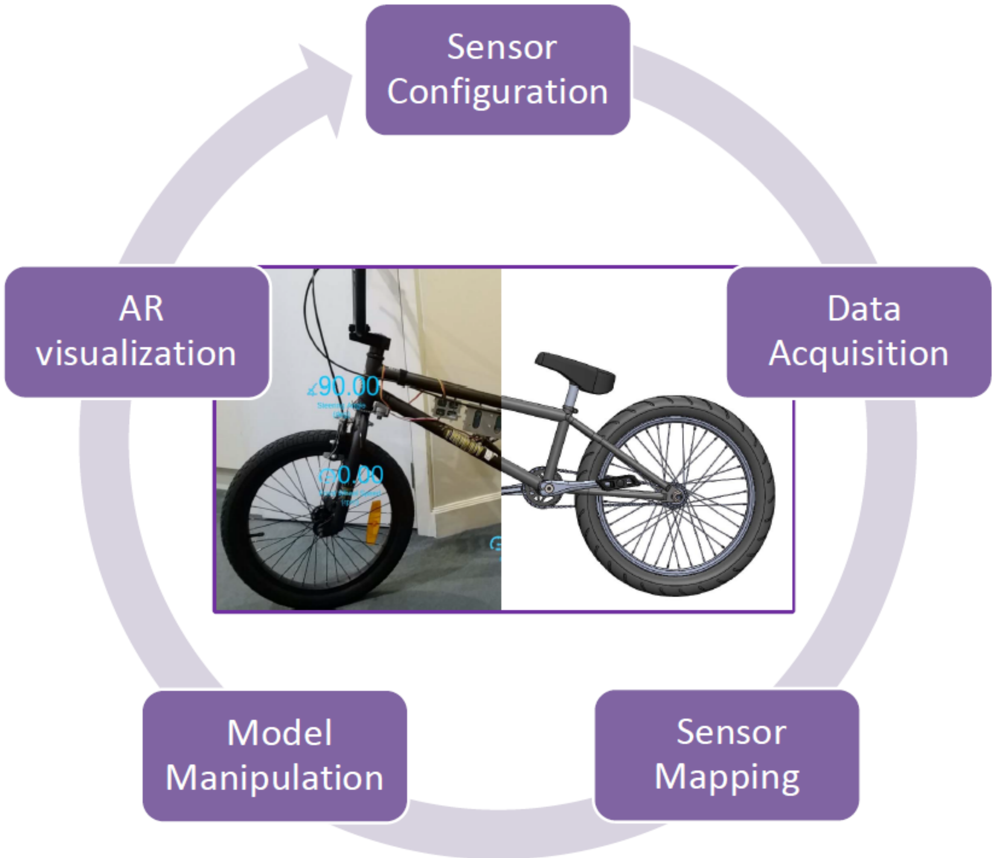
Development of a Digital Twin

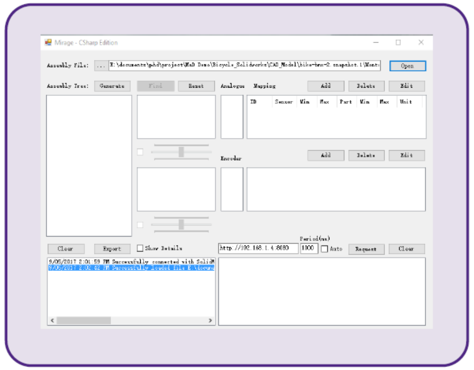
- Building a high-fidelity digital mirror to describe the equipment
- Establishing the interaction between the equipment and its digital mirror
- Consolidating/converging the data from the physical space and virtual space to generate information in support of various applications


COMMUNICATE
AGGREGATE
Sensors
Data
CREATE
ANALYZE
INTEGRATION
Industrial Internet of Things
Industrial Internet of Things
Actuators
Analytics
ACT
INSIGHT
dupress.deloitte.com

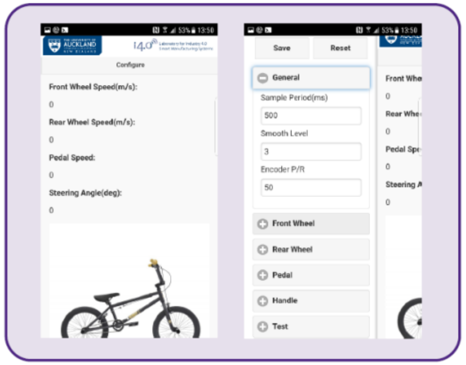
Give me some examples

Digital Twinning of a Bicycle





Physical and virtual components coupling



HMI

AR applications

Contact details: Professor Xun Xu, Department of Mechanical Engineering, University of Auckland, Auckland 1142, New Zealand
Tel: +64(9)3737599 ext.84527, Fax: +64(9)3737479, Email: xun.xu@auckland.ac.nz
https://www.mech.auckland.ac.nz/uoa/xun-xu http://www.manuclouds.org
http://www.mech.auckland.ac.nz/en/about/ourresearch/researchareas/manufacturingsystems/IIMS.html

THE UNIVERSITY OF AUCKLAND Te Whare Wānanga o Tāmaki Makaurau NEW ZEALAND

Laboratory for Industry 4.0 Smart Manufacturing Systems

Retrofitting a Legacy System for its Digital Twin

Background

In the wake of the Industrie 4.0 movement new and exciting technologies and devices arrive to the market almost daily. Successful implementation of Industrie 4.0 often becomes associated with extensive investments. However possible steps towards it are smaller than we think. Existing machines and devices can be retro-fitted to feed data in a standardised manner to a remote cloud-based system.

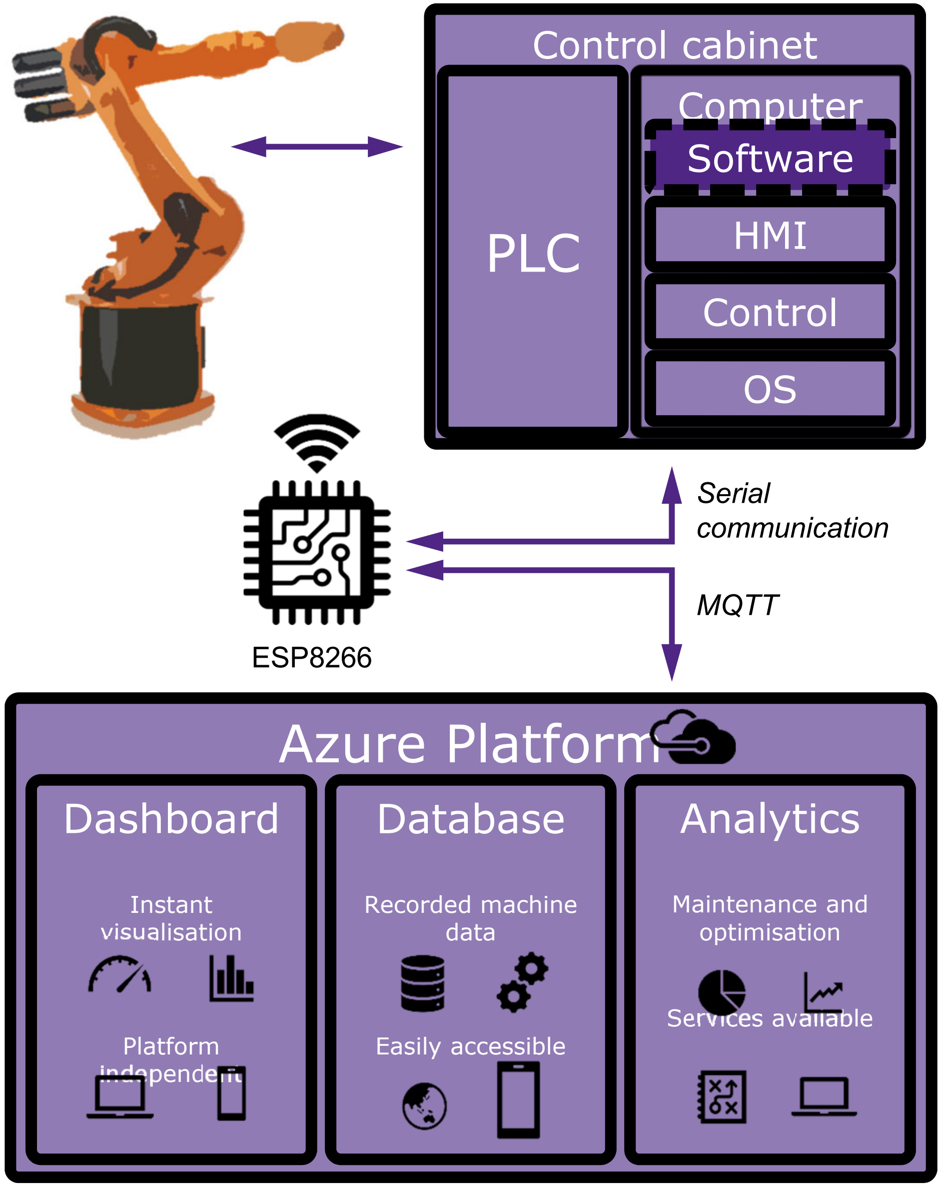
This project demonstrates the retro-fit of a KUKA KR16 industrial robot and its KR C2 control system with a 2$ WiFi-enabled chip to upload machine data into Microsoft's Azure Platform. It provides the following functions:

●**Background monitoring:** Custom software on the control computer runs in the background and sends machine data via serial port to the connected chip. The chip connects to the wireless network and forwards the data via internet using an IoT messaging protocol (MQTT). This method deals with hardware and software limitations and does not interfere with existing setup or usage.

●**Mobile visualisation:** The data can be accessed and visualised with near real-time capability through a custom website. It is not limited to a local machine, application or specific platform.

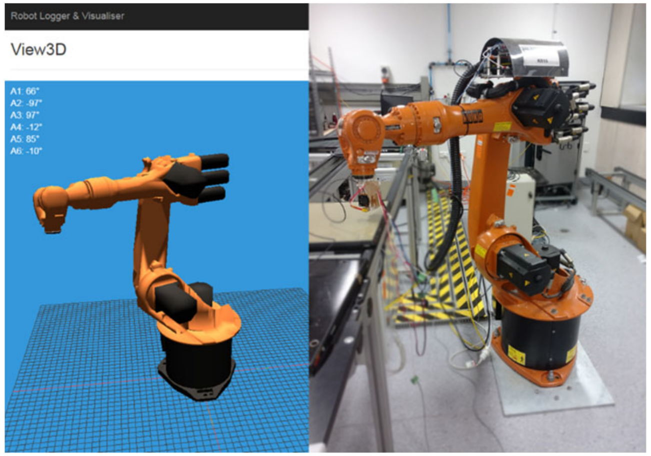
●**Storage and analytics.** A database stores the received data. Historical data can be used to analyse the uptime or reconstruct the robots movements if necessary (e.g. QA). Custom tools can be developed or available services used to connect to the database and performer further sophisticated analyses.

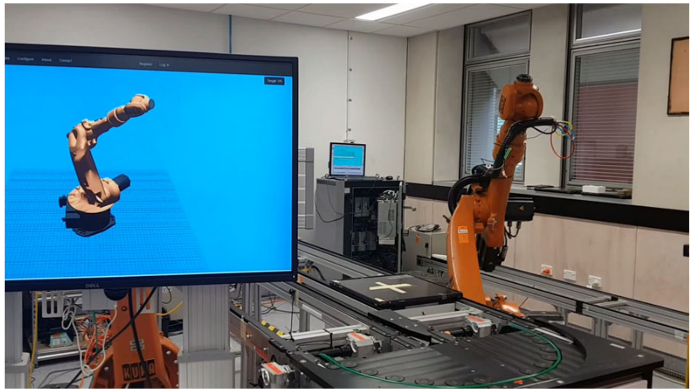
In the near future we can expect more devices with increasing computational power that can easily connect to existing devices and infrastructure. On the software-side we see a growing amount of industrial software and applications that are sold a service thus minimising investment costs for its users.

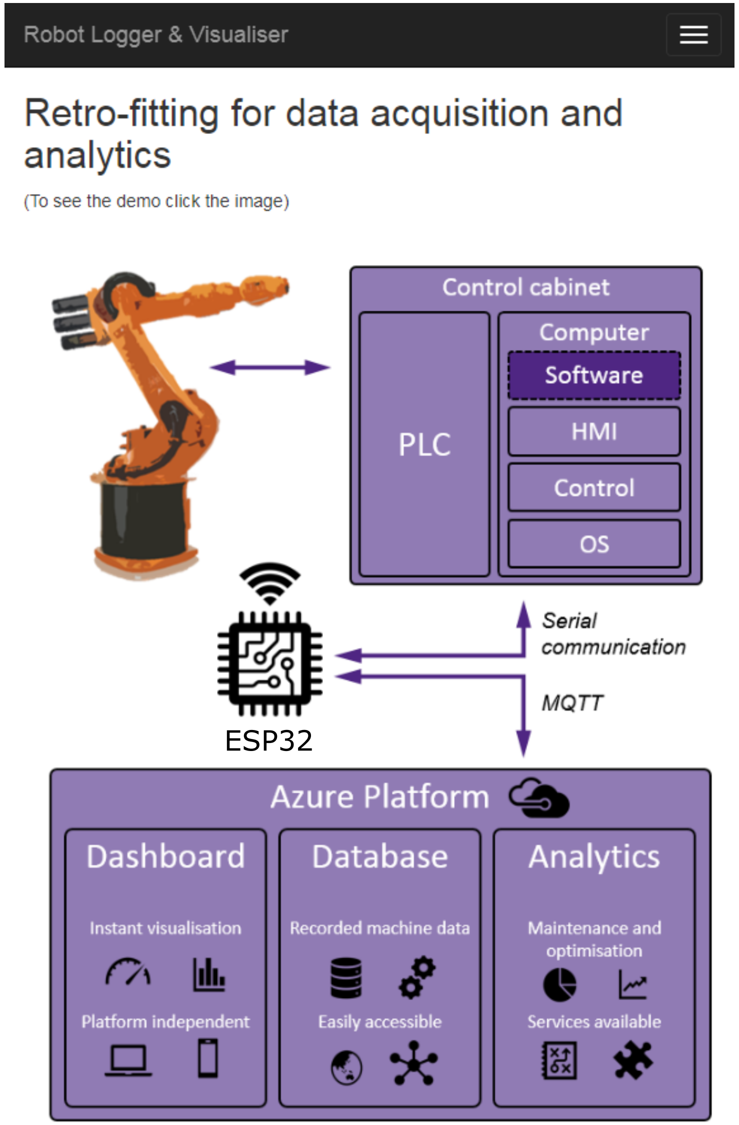


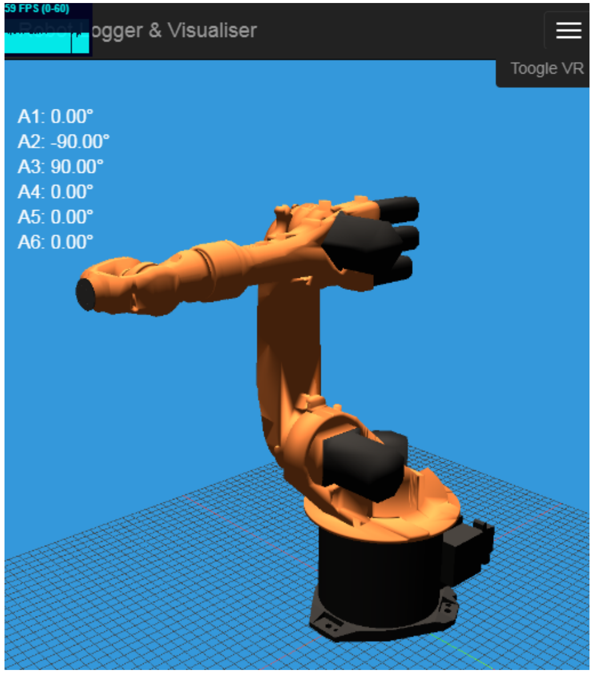
Prospective industrial applications

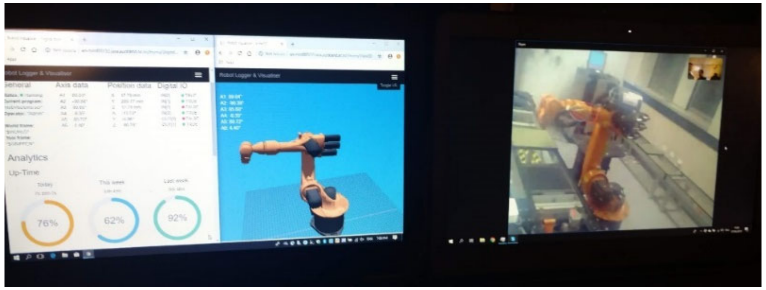
- Extension of asset's lifetime
- Mobile and worldwide asset monitoring
- Optimisation of machine uptime
- Assessment of historical data for reconstruction and QA

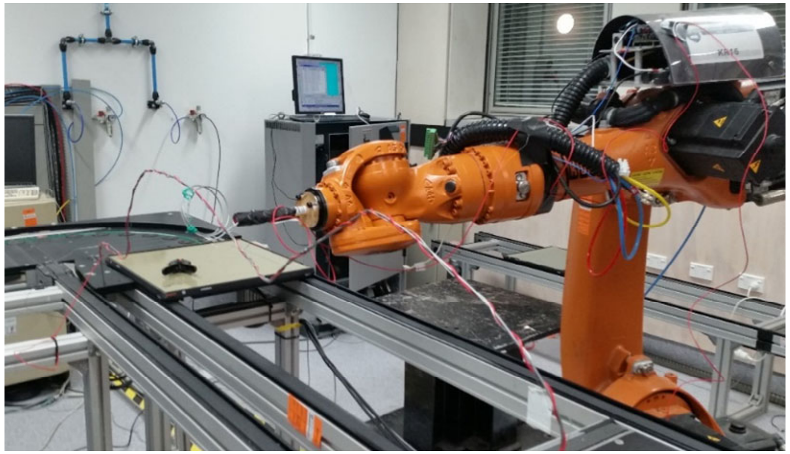

Robot Logger & Visualiser
View3D
A1: 66°
A2: -97°
A3: 97°
A4: -12°
A5: 85°
A6: -10°




Robot Logger & Visualiser
Retro-fitting for data acquisition and analytics
(To see the demo click the image)
Control cabinet
Computer
Software
HMI
Control
OS
PLC
ESP32
Serial communication
MQTT
Azure Platform
Dashboard
Instant visualisation
Platform independent
Database
Recorded machine data
Easily accessible
Analytics
Maintenance and optimisation
Services available


59 FPS (0-60)
ogger & Visualiser
Toogle VR
A1: 0.00°
A2: -90.00°
A3: 90.00°
A4: 0.00°
A5: 0.00°
A6: 0.00°





A Part 4 Research Project (2022)

Framework for a digital twin of a crane for RNZN ships

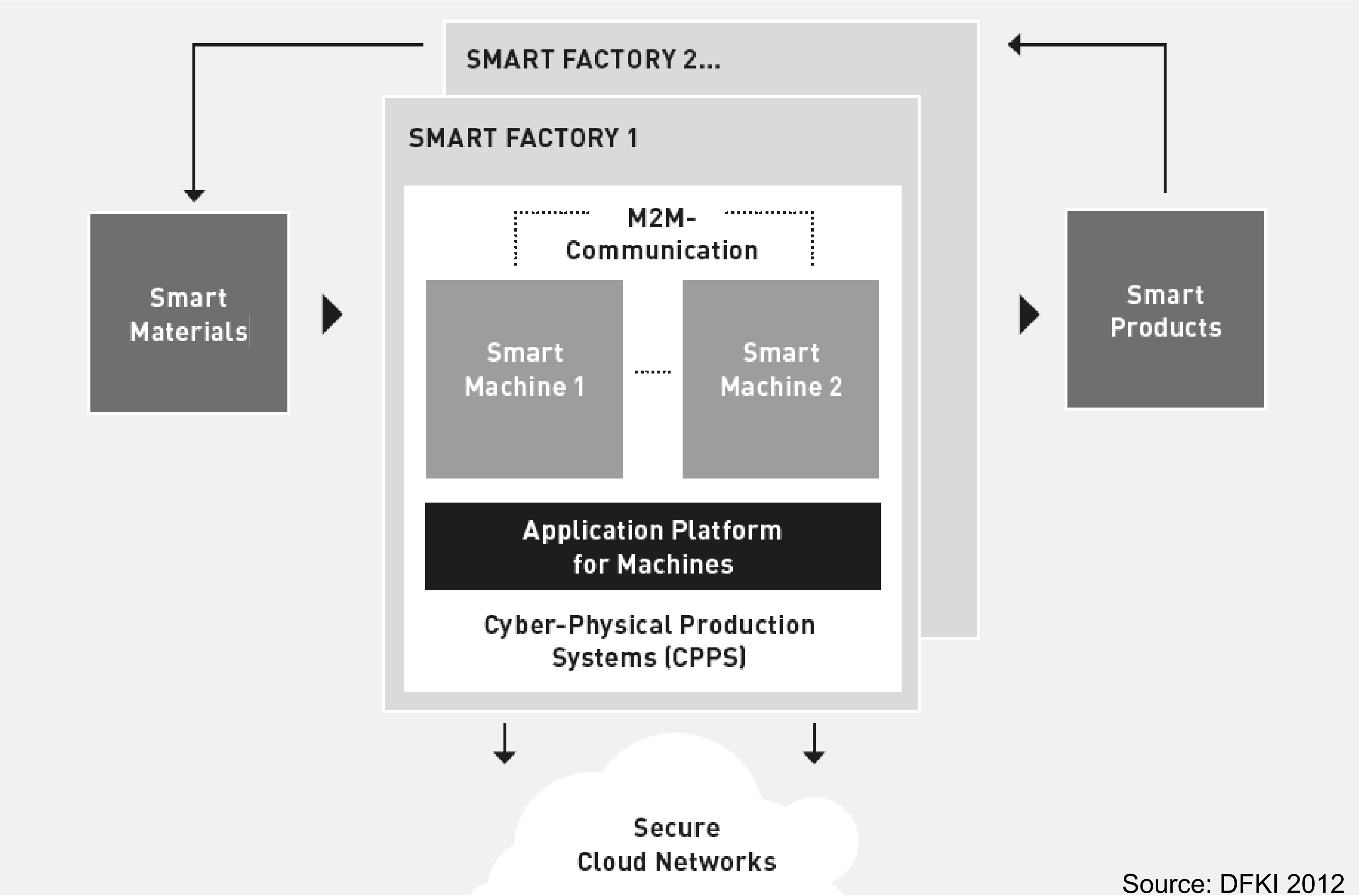
- RNZN engineers are required to conduct a broad range of engineering support and are not specialists. As such detailed understanding of the breadth of crane maintenance is limited to routine maintenance and simple fault finding.
- RNZN is moving its fleet from a time-based maintenance philosophy to a more Reliability centred maintenance (RCM) approach.
- Digital twin is to provide insight and support in the following areas:
  - Safety
  - Training
  - Emergency Response
  - Incident Investigation
  - Predictive maintenance

Smart Factory

Smart Factory

- Transition from ICT-based control mechanisms to *autonomously acting* components, machines, service robots and other systems, giving adaptability, flexibility, and self-learning characteristics
- Transition from "*automation*" to "*autonomics*"
- Connected with and optimized to a global network of adaptive and self-organizing production units – *cloud-based manufacturing*
- *Resource-efficient* production

Smart Factory Pipeline
Empowered by Cloud-based Secure Networks



Source: DFKI 2012

The soap production plant
– a demonstration Smart Factory

Source: Industrie 4.0: Smart Manufacturing for the Future, Germany Trade & Invest

The soap production plant

- Function:
  - Production of highly customized products (batch size one)
- Configuration:
  - Functional electrical components (i.e. controllers, sensors, actuators) from different vendors are flexibly networked
  - Wireless communication systems

Mobile production plant demonstrates key aspects of Industrie 4.0: collaborative machine and augmented operator

Source: Industrie 4.0: Smart Manufacturing for the Future, Germany Trade & Invest

The mobile production line

- Production (machining and assembly) of an exemplary product (incl. case cover, base, printed circuit board)
- Product controls its own production process (e.g. the digital product memory stored on an RFID tag)
- Not controlled by a standard programmable logic controller (PLC), but by a service-oriented, decentralized control system consisting of distributed microcontrollers communicating using internet standards
- Reconfigurable and flexible
- Workers supported by innovative mobile devices and augmented reality-based assistance systems

Smart factories for smart manufacturing

Smart Manufacturing

- Production process and product monitoring
  - Enhancing supervision, prompt improvement, and increasing productivity
- Full visibility of manufacturing assets
  - Asset usage and intra-factory logistics optimized to maximum capacity
- Data collection and analysis
  - Machine-machine communication and collaboration
  - Unleashing the potential hidden in the equipment, resources and people
  - preventive maintenance mechanism

Smart Manufacturing (cont.)

- Employee and asset safety
  - more controlled and predictable production environment
  - workers can be tracked by the system and warned against any possible dangers
- Production agility
  - Reconfigurable and robust manufacturing
  - Enabling low-volume, high-mix manufacturing

An example close by …

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54th CIRP Conference on Manufacturing Systems

A Smart Manufacturing Cell with Distributed Intelligence

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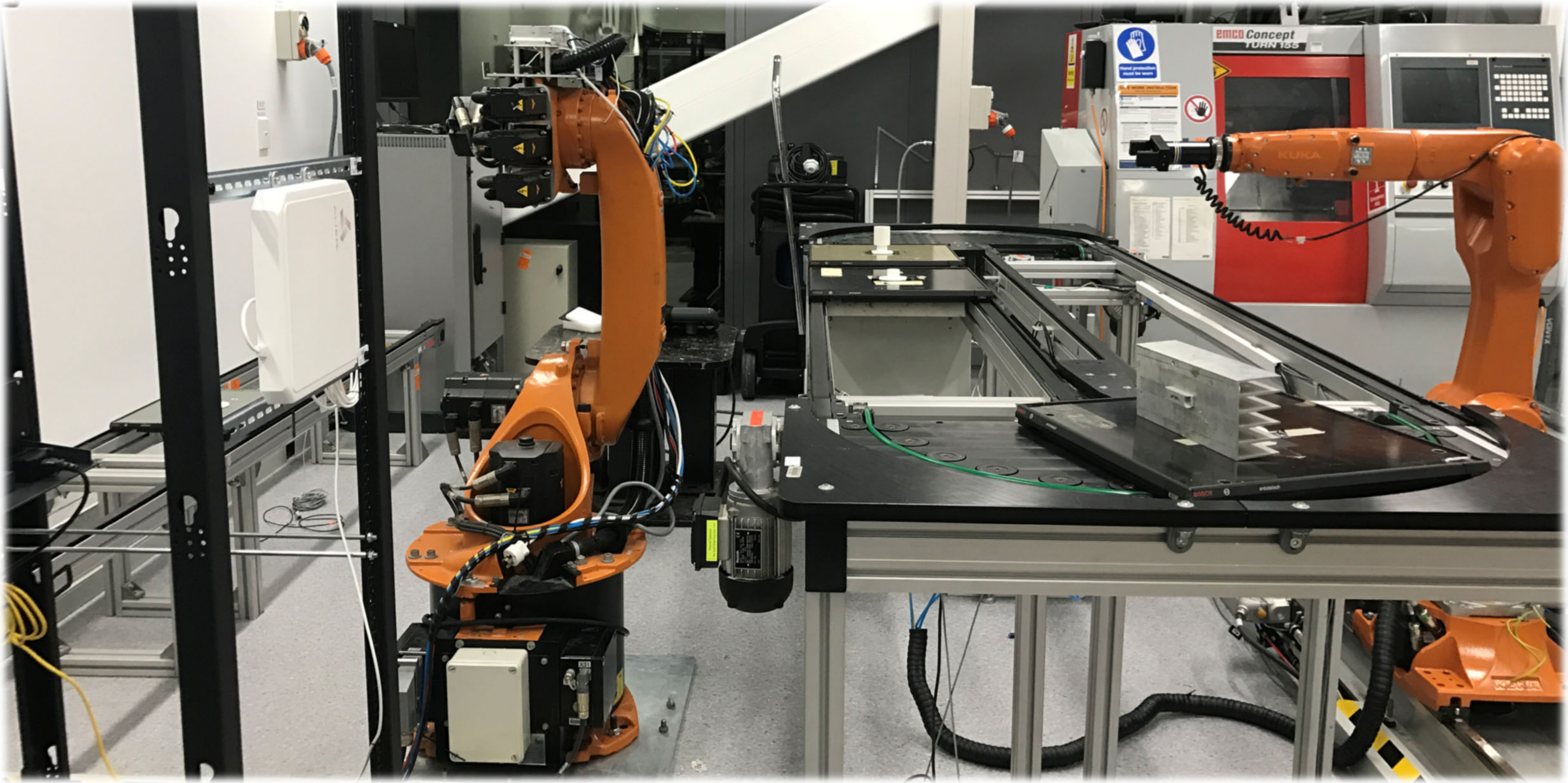
Abstract

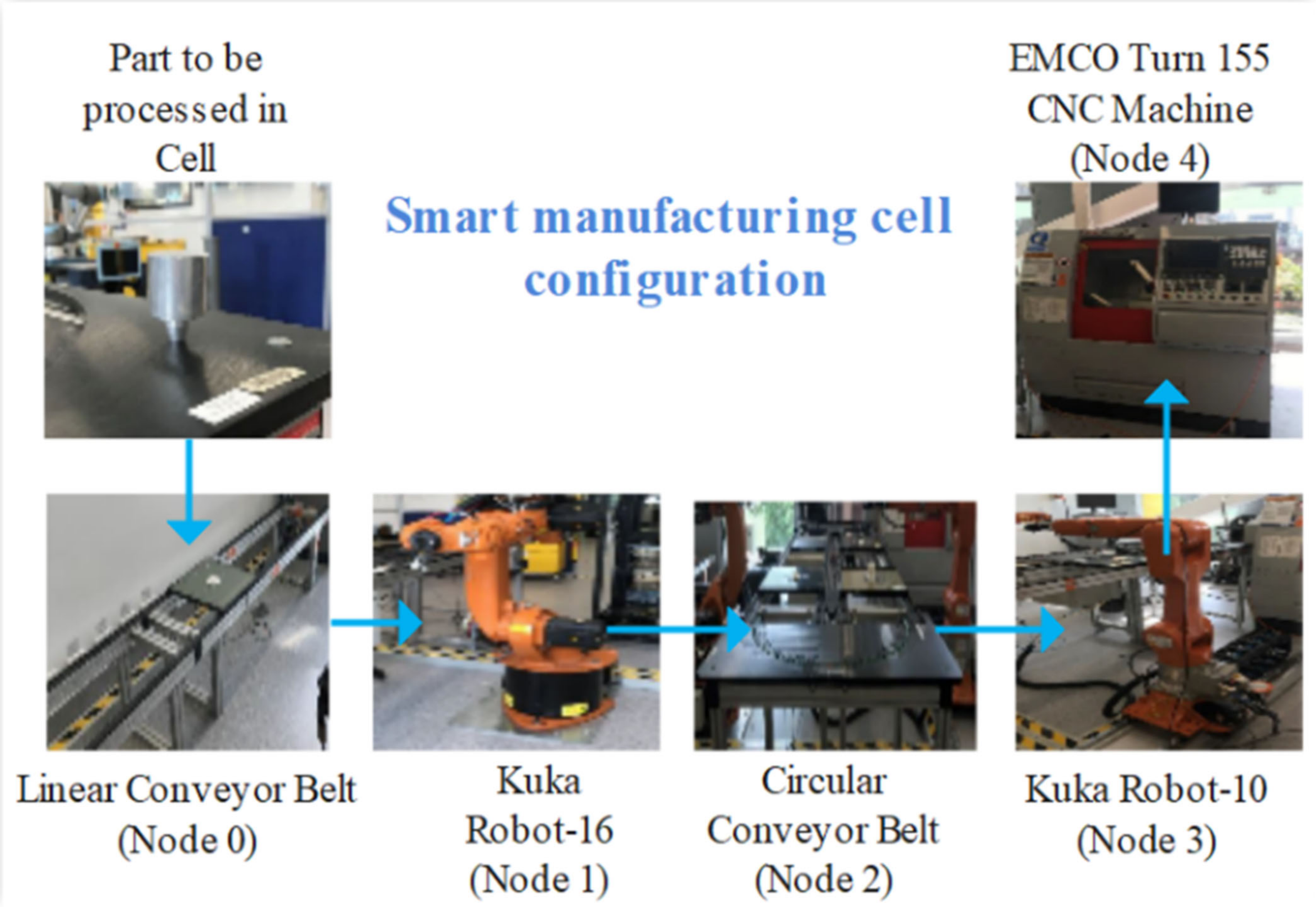
This paper presents a novel approach to implementing a smart manufacturing cell with distributed intelligence in the context of Industry 4.0. The system uses holons to model digital twins for a manufacturing cell and a Graph Node Network for production routing. The Graph Node Network allows dynamic generation of production routes for different parts. For prototyping, Robotic Operating System (ROS 2) is used, which provides a convenient way of representing individual digital twins (in the form of "nodes") for different equipment in the system. It also enabled us to create a decentralised and distributed architecture. The nodes are connected via Data Distribution Service, which utilises a publish/subscribe method for communications. The paper demonstrated a flexible, extensible, and fault-tolerant manufacturing cell that is geared toward a high-mix and low-volume production scenario.

Peer-review under responsibility of the scientific committee of the 54th CIRP Conference on Manufacturing System

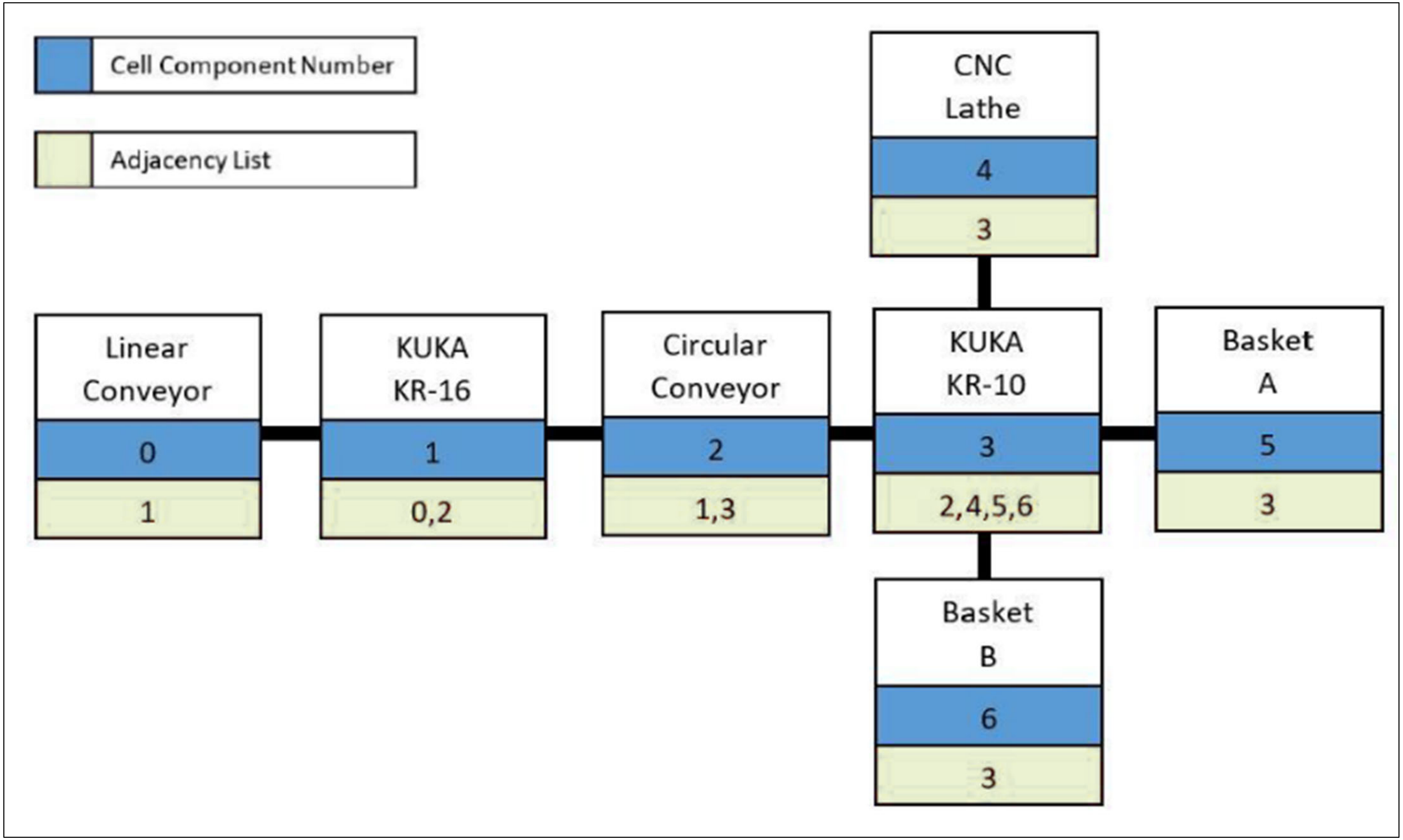
Keywords: Smart Manufacturing; Digital Twin; ROS2; Distributed Intelligence; Holons, Production routing.

Smart manufacturing cell in LISMS




Part to be processed in Cell
Smart manufacturing cell configuration
EMCO Turn 155 CNC Machine (Node 4)
Linear Conveyor Belt (Node 0)
Kuka Robot-16 (Node 1)
Circular Conveyor Belt (Node 2)
Kuka Robot-10 (Node 3)

Graph Node Network (GNN) method for production routings



Decentralized Factory Control based on Multi-Agent Technologies

J. Bidmead, S. Bhatiani, and X. Xu *Member, IEEE*

***Abstract*— In recent years, economic changes driven by an increase in consumer and small business demand for highly customised and small-batch products have necessitated a paradigm shift away from traditionally rigid manufacturing towards a more agile and decentralised approach to factory control. Such an approach, by eliminating centralised control, gives rise to factories whose production capabilities can be reconfigured at a moment's notice in order to respond to high-frequency shifts in production demand. This paper proposes a novel architecture for decentralised factory control based on multi-agent technologies. Unlike the previous research work in this field, this research differs in its being designed from the ground up using open-source software, instead of relying on existing solutions for agent-to-agent communications. The presented architecture allows for real-time production flexibility in response to changes in the factory layout, e.g. machines going offline, or new machines being added. It achieves this with a ping-response system. A piece of software has been developed to simulate the functions of the proposed architecture.**

I. Introduction

Conventional factories produce hundreds or thousands of identical products per day. This model of production has been – and continues to be – the most economical way to supply commodities on a global scale. However, modern economies are demanding a paradigm shift towards small-batch

built around MQTT, a protocol for many-to-many communication. Additionally, the research also focuses on robust scheduling algorithms to guarantee near-optimal production in response to external pressures. This research integrates priority-based scheduling as well as real-time reconfigurability into a single architecture that is built from the ground up with open-source tools and a mindset towards continuous improvement in the future.

II. Supporting Technologies

The research work builds upon some relevant technologies, e.g. agent technology and dynamic scheduling.

A. *Distributed Intelligence*

Distributed manufacturing control systems are expected to fill the gaps present in centralized control systems by having global control decisions be determined by multiple autonomous control units [3]. Two well-known examples of decentralized control systems are multi-agent systems and Holonic manufacturing systems [4,5]. The architecture herein presented uses a multi agent-based approach.

Multi-agent systems rely on the concept of agents. Agents can be defined as "an autonomous component that represents physical or logical objects in the system, capable of acting in