Multi-agent Systems to Distribute Intelligence in Industrial Cyber-Physical Systems

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INSTITUTO POLITÉCNICO DE BRAGANÇA

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Centro de Investigação em Digitalização e Robótica Inteligente

Agenda

1. Contextualization and Cyber-Physical Systems
2. Data and Artificial Intelligence as pillars
3. MAS to distribute intelligence
4. Examples of industrial MAS based solutions
5. Future challenges

Agenda

1. Contextualization and Cyber-Physical Systems

Evolution of complexity

Airbus A380

Spirit of St. Louis,
National Air and Space Museum,
Smithsonian Institution

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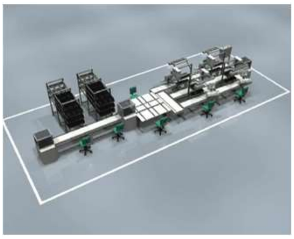
New demands in manufacturing

- Customization, quality and diversity of products, and fast response to demand

mass production → mass customization → unique products

- Reduction of **reconfiguration time**
- Plug-and-produce
- Time on market vs Time to market



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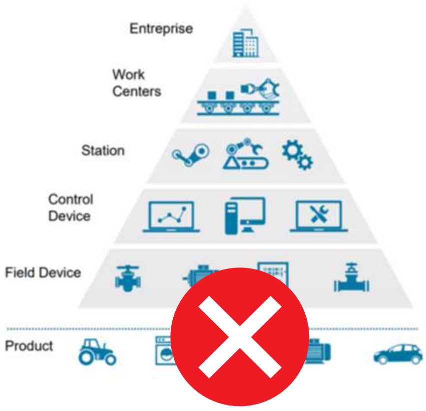
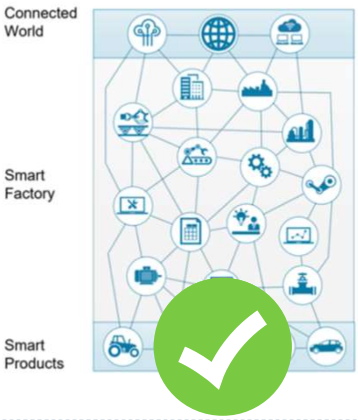
Moving to decentralized structures

Traditionally: centralized and monolithic structures

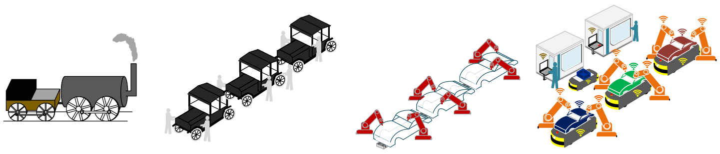


Challenge: decentralize and distribute functions



6 Source: Plattform Industrie 4.0, "Reference Architectural Model Industrie 4.0 (RAMI 4.0) - An Introduction," vol. 0, p. 21, 2016. INSTITUTO POLITÉCNICO DE BRAGANÇA CeDRI

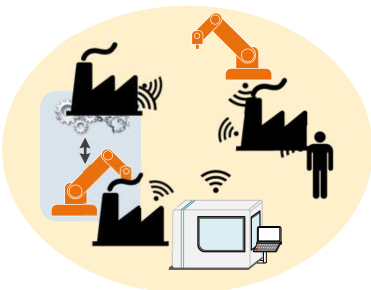
4th industrial revolution



1st	2nd	3rd	4th
mechanization of production using water and steam power	mass production using electrical machines	electronics and IT to automate the production	digitalization using CPS, IoT and IoS

Cyber-Physical Systems

- Intelligent, dynamic and adaptive systems, characterized by:
  - Integration of cyber and physical elements
  - Organized in network in a distributed manner
  - Interact to reach a common goal



- High decision capability at two levels:
  - autonomous with self-decision processes
  - collaborative with decision processes based in negotiation

Key challenges in Industrial CPS

Area	Key Challenges	Difficulty	Priority	Maturity in
CPS Capabilities	Real-time control of CPS systems	High	High	4–7 years
	Real-time CPS SoS	High	Medium	3–5 years
	Optimization in CPS and their application	High	Medium	4–7 years
	On-CPS advanced analytics	Medium	High	3–5 years
	Modularization and servification of CPS	low	High	3–5 years
	Energy efficient CPS	Medium	Medium	3–5 years
CPS Management	Lifecycle management of CPS	Medium	Medium	5–8 years
	Management of (very) large scale CPS and CPS-SoS	High	High	5–8 years
	Security and trust management for heterogeneous CPS	High	High	5–8 years
CPS Engineering	Safe programming and validation of CPS SoS	High	High	5–10+ years
	Resilient risk-mitigating CPS	High	High	5–10+ years
	Methods and tools for CPS lifecycle support	High	High	3–7 years
	New operating systems and programming languages for CPS and CPS SoS	Medium	Low	3–6 years
	Simulation of CPS and of CPS-SoS	Medium	High	3–6 years
CPS Infrastructures	Interoperable CPS services	Medium	High	2–5 years
	Migration solutions to emerging CPS infrastructures	Medium	High	3–6 years
	Integration of heterogeneous/mobile hardware and software technologies in CPS	Low	Medium	2–4 years
	Provision of ubiquitous CPS services	Medium	Medium	3–5 years
	Economic impact of CPS Infrastructure	High	High	3–6 years
CPS Ecosystems	Autonomic and self-* CPS	High	Medium	7–10+ years
	Emergent behavior of CPS	High	Medium	7–10+ years
	CPS with humans in the loop	High	High	2–5 years
	Collaborative CPS	Medium	Medium	5–8 years
CPS Information Systems	Artificial intelligence in CPS	High	High	7–10+ years
	Cross-domain large-scale information integration to CPS infrastructures	Medium	Low	6–9 years
	Transformation of CPS data and information analytics to actionable knowledge	High	High	4–8 years
	Knowledge-driven decision making/management	High	Medium	6–10+ years

Source: P. Leitão, A.W. Colombo, S. Karnouskos "Industrial automation based on cyber-physical systems technologies: Prototype implementations and challenges" Computers in Industry, 81 (2016), pp. 11–25.

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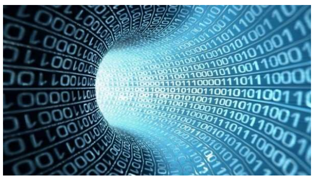
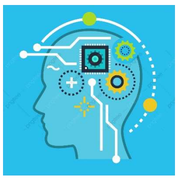
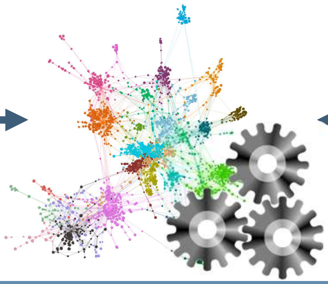
2. Data and Artificial Intelligence as pillars


Foundations

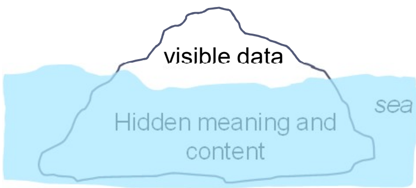
- **CPS** as the **backbone platform**

Internet of Things →  ← **Artificial Intelligence**

☞ intelligent and distributed objects that collect, store and process the relevant information along its life-cycle, and the systems composed by these objects take advantage of the generated knowledge

Data as a pillar in Industry 4.0

- **Huge volume of data is** real time collected
  - Network of sensors using **IoT**
  - **Heterogeneous** data sources



90% of data were collected in the last years, but only 0,5% is analyzed

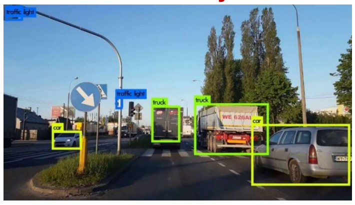
- Need to be managed in real time and not too late

AI, ML to extract value and knowledge

Chihuahua or muffin?

Créditos: Metamaven

Identification of objects



Predicting stock market

Medical diagnosis

Decision-support based on data richness

descriptive

What is happening?

diagnosis

What happened?

prediction

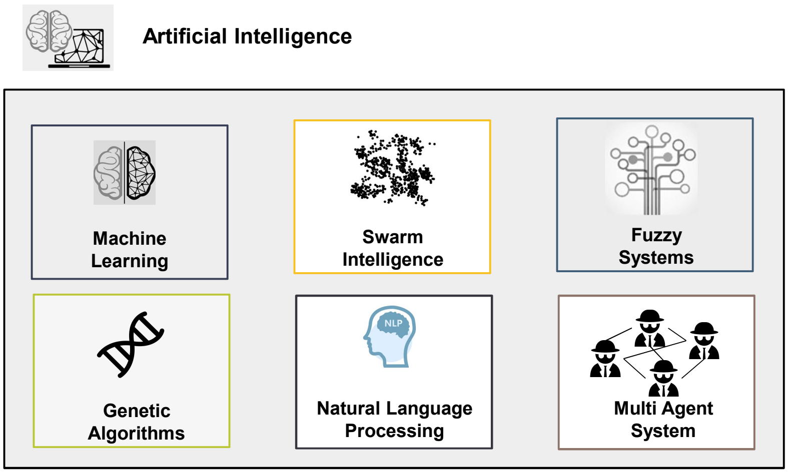
What will happen?

preventive

Which action to be performed?

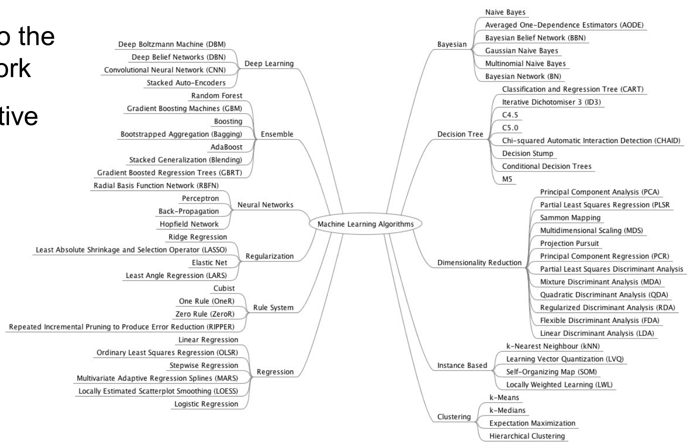
- Data analytics to, e.g.,:
  - Detect earlier possible problems (defects, disturbances)
  - Detect trends, patterns aiming prediction and optimization
- How to select the proper AI algorithms?

AI approaches



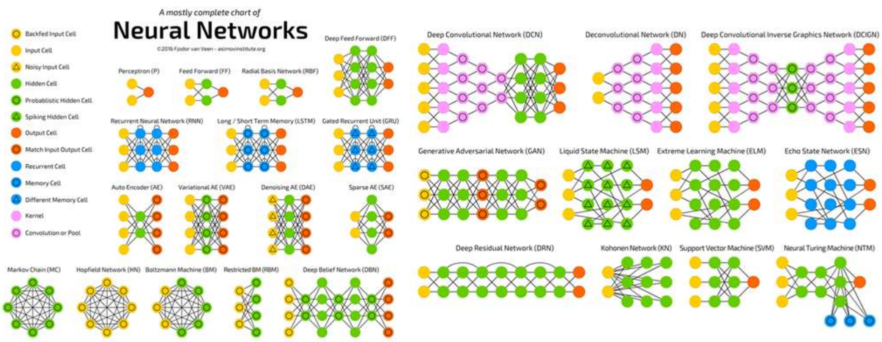
Looking into ML algorithms …

- According to the way they work
- Not exhaustive list of ML algorithms grouped by similarity



Source: https://machinelearningmastery.com/a-tour-of-machine-learning-algorithms/

Types of Neural Networks



Source: https://towardsdatascience.com/the-mostly-complete-chart-of-neural-networks-explained-3fb6f2367464

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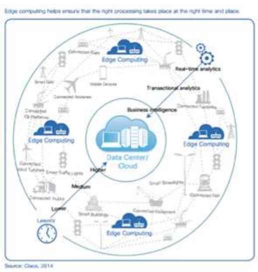
3. MAS to distribute intelligence

CREDIT: Getty Images



Intelligence and data analytics only performed in the cloud?

- Should be only performed centralized in the cloud?

https://www.quest.com/community/cfs-file/__key/communityserver-blogs-components-weblogfiles/00-00-00-00-06/1830.migrate-to-cloud-_2800_2_2900_.jpg

Sending, storing and processing data on cloud could be **expens**

Data **privacy** and **security**

…munication **latency** (…ally low bandwidth)

Some data needs to be managed in **real time**

What happen if the **connection** to cloud fails?

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Why do we need intelligence at the edge?

- Some data should be processed as close as possible to originating source and in real-time
- Performing analytics to make real-time decisions
  - Supporting real-time requirements
  - Mitigating communication failures
- Pre-processing and filtering to reduce exchanged data size
  - Optimizing the bandwidth
  - Reducing the storage costs

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Aligned with Industrial Trends

"*We should not send all collected data to be processed in the cloud but instead to make analysis in the edge*"

James Truchard, National Instruments @IFAC IMS'16

"Define data collection requirements to minimize the collection of 'big data'"

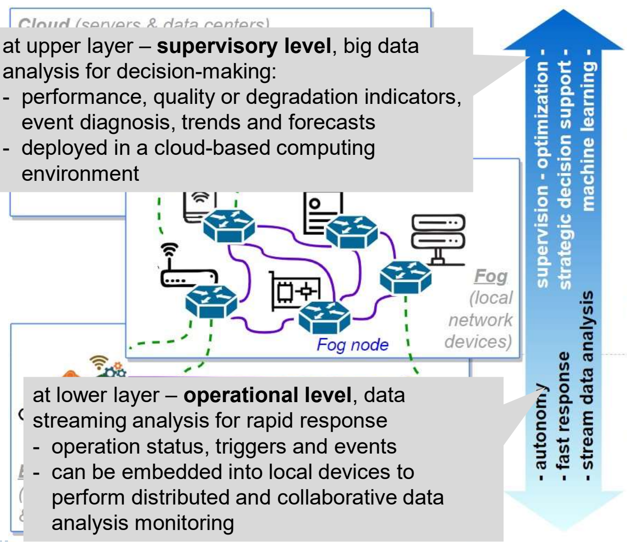
"Enable feedback of intelligence through the system to update control for optimal production"

Brian Weiss, NIST @IFAC IMS'16

"Analyzing data close to the device that collected the data can make the difference between averting disaster and a cascading system failure"

Cisco, White paper, 2015

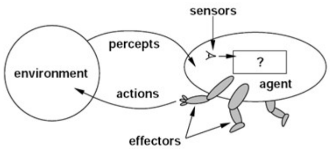
Decentralization of AI in CPS



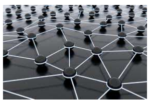
- batch, exploratory & descriptive analysis
- planning - simulation - optimization
- recommender system - diagnosis - human agent interaction
- machine learning - predictive & prescriptive analytics
- context awareness
- organization - coordination
- event & condition detection, identification & diagnosis
- streaming analysis - online learning
- self-awareness - interaction - collaboration
- dynamic adaptation
- filtering - feature extraction - aggregation
- condition monitoring - intelligent control

Multi-agent systems

- **MAS** as an **infrastructure** to distribute intelligence, implementing large-scale CPS
- **What is an agent?**

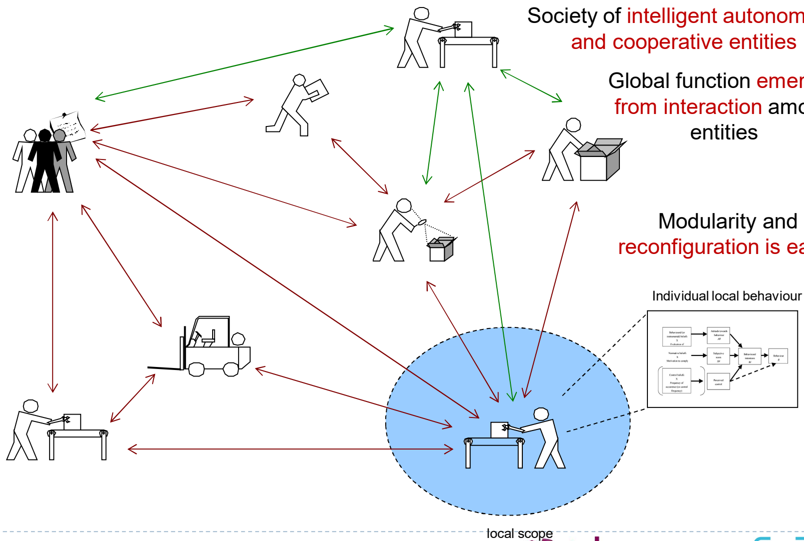


Source: Russel and Norvig 1995



Society of autonomous agents representing the system objects, capable of interacting to achieve their individual goals when they have not enough knowledge and/or skills to achieve individually their objectives

MAS working in practice



Society of intelligent autonomous and cooperative entities

Global function emerges from interaction among entities

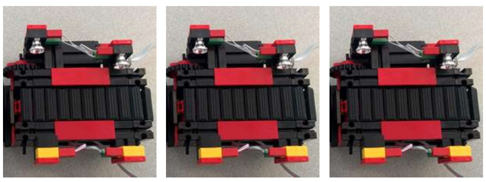
Modularity and reconfiguration is easy!

Why agent technology is a fascinating topic?

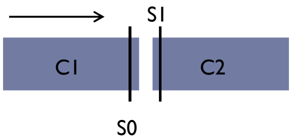
- Suitable to **build complex systems** with autonomous building blocks each incorporating the capability to take decisions **without hierarchy** but contributing for **the best of the system**
- System behavior emerges from interaction among agents
  - Allowing to reach dynamics and self-organization on-the-fly
- **MAS as potential enabler** for Industry 4.0
  - to distribute intelligence and data analysis capabilities
  - to reach reconfigurability by managing long-term alliances and short-term coalitions

Need of MAS in practice

- System comprising a sequence of modular conveyors



- Individual conveyor comprises:
  - 1 motor
  - 2 light sensors
- Transfer a part from an input to an output location



- C1 only stops when the part arrives to S1
- C2 starts when the part arrives to S0

How to implement the control system?

Using the traditional solution

- Use a centralized logical control approach
- Programmed using IEC 61131-3 running in a PLC

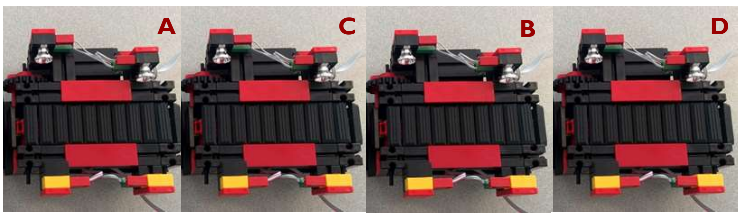
Fonte: Schneider Electric

- Simple to program
- Industrial adopted

- Lack in supporting scalability and re-configuration of the conveyor system
- Interdependencies between conveyors increases development effort and time!

Particularly, what happen if we need to …

- Switch the order of the conveyors?
- Add a new conveyor?



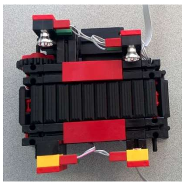
We need an alternative design approach to support the easy reconfiguration on-the-fly!!!

Using the MAS solution

Create cyber-physical components


agent


single-board computer


physical platform


cyber-physical component

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Intelligent MAS solution

agent

FIPA-ACL messages

plugability and reconfigurability on-the-fly!

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Important notes

- MAS technology is used to implement an industrial CPS
- MAS introduces **self-organization to the system**, and particularly on-the-fly reconfiguration
- **No intelligent algorithm is used**!

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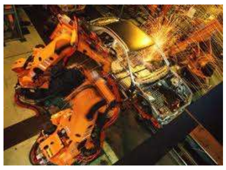
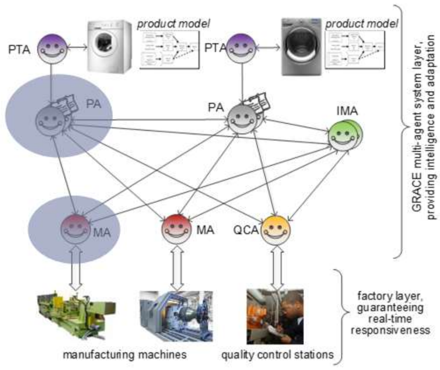
4. Examples of Industrial MAS based solutions



Objectives and architecture

Grace
InteGration of pRocess and quAlity Control using multi-agEnt technology

- Integration of quality and process control in real-time
- Improve efficiency, quality and customization
- Washing machines factory plant
- Preserving existing low-level control
- MAS for:
  - Data collection
  - Real-time data analysis
  - Correlation of operating variables



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Examples of intelligence

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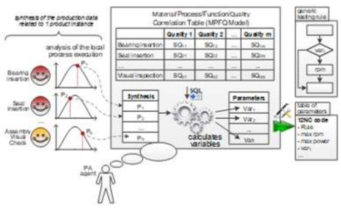
InteGration of pRocess and quAlity Control using multi-agEnt technology

- Customization of functional tests according to the on-line gathered production data
- Customization of parameters of the machine controller
- Early detection of products that never reach desired quality
- Dynamic adaptation of process parameters



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ZDM at multi-stage production

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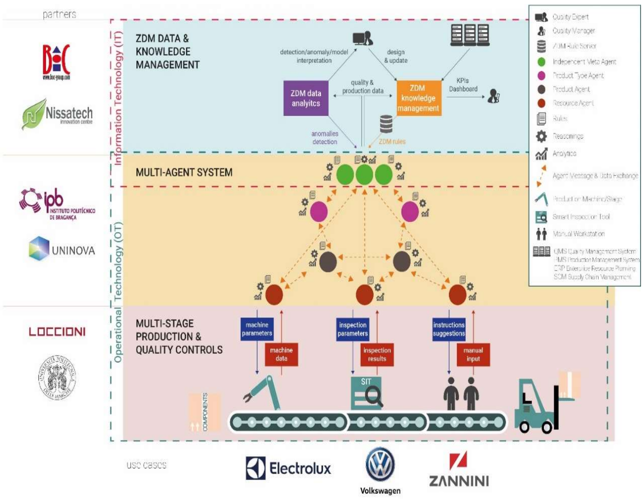
AGENT ORIENTED ZERO DEFECT MULTI-STAGE MANUFACTURING

- Integration of quality & process control in real-time
- **MAS** for:
  - Data collection
  - Real-time data analysis
  - Correlation of operating variables



Use cases

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	Electrolux Professional	Volkswagen Autoeuropa	Zannini
Industrial Sector	**Professional** food, beverage & laundry **appliances**	**Automotive** (OEM) **car** manufacturing	**Automotive** (Tier 2) machined metal **components**
Production Process	**Customized production** Highly flexible multi stage manual and semi-automatic assembly	**Serial production** Multi stage manual and semi-automatic assembly	**Batch production** High precision multi stage machining operations
Expected Results	**Time reduction and optimization of the final testing area,** to increase the productivity and reduce the Not Right First Time.	**Reduction of the final inspection and rework time** and consequent increase of productivity without compromising quality.	**Reduction of production costs,** as a consequence of the increase of the overall OEE: reduction of scraps, downtime and rework time.

Implementation

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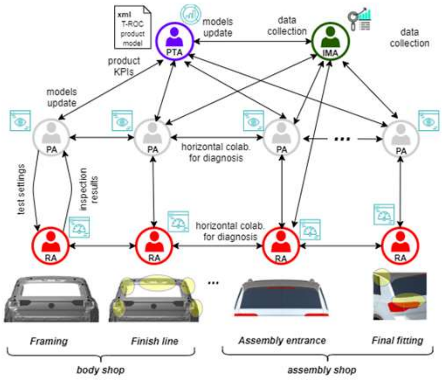
AGENT ORIENTED ZERO DEFECT MULTI-STAGE MANUFACTURING

Volkswagen

Jade OPC UA



- 1 PTA representing the T-ROC car model
- 4 RAs representing inspection stations, deployed at edge
- > 200k PAs, each one associated to a T-ROC car

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Data Analysis Deployed in RAs

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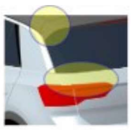
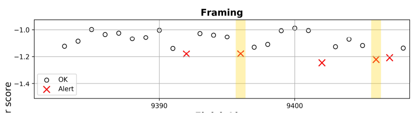
- **Objective:** monitoring deviations in the rear part of the vehicle (alignment and gaps between the frame and tailgate)

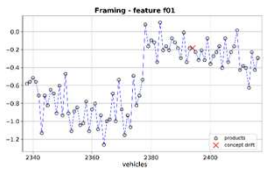


  - Anomaly detection in inspection stations



- Algorithms:
  - Nelson rules
  - Local Outlier Factor (LOF)

  - Detection of changes in the process



- Concept Drift Page-Hinkley algorithm

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Data Analysis Deployed in PAs

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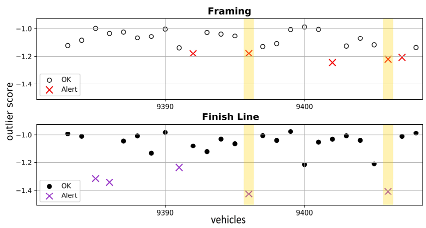
- **Objective:** correlate product data along the different stations
  - Anomaly detection in inspection stations



- Composed condition rules
  IF x1>σ1 AND x2>σ2 THEN warning1
- Control limits updated by IMA

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Data Analysis Deployed in PTAs

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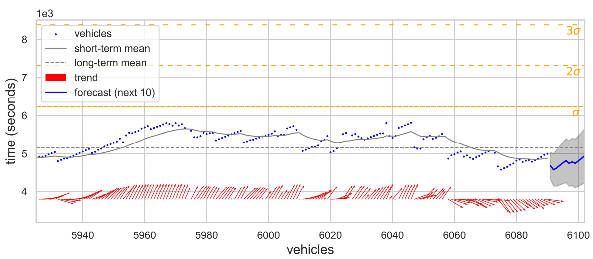
- **Objective:** long-term monitoring and supervision tasks
  - Trend monitoring and forecast of the assembling times



- ARIMA (Auto Regressive Integrated Moving Average)

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Data Analysis Deployed in IMA

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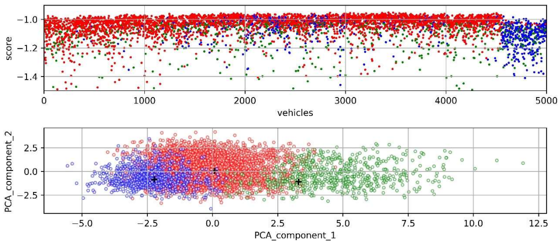
- **Objective:** keeping up-to-date the monitoring and control settings of the lower level agents
  - Anomaly detection in inspection stations



- BIRCH (Balanced Iterative Reducing and Clustering using Hierarchies) algorithm

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Benefits

GOØDMAN AGENT ORIENTED ZERO DEFECT MULTI-STAGE MANUFACTURING

- Technological perspective
  - Effectiveness, robustness and scalability
    - In operation > 1 year, > 200 k agents
    - No breakdown or need for maintenance intervention
- Operational perspective
  - Reduction of cars needing to be aligned (± 10%)
  - Reduction of production costs, due to unnecessary alignment operations (± 15%)
  - Reduction of the inspection time (± 50%)

Source: J. Queiroz, P. Leitão, J. Barbosa, E. Oliveira, G. Garcia, "Agent-based Distributed Data Analysis in Industrial Cyber-Physical Systems", submitted to IEEE Journal of Emerging and Selected Topics in Industrial Electronics (JESTIE), 2021

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Innovation Radar

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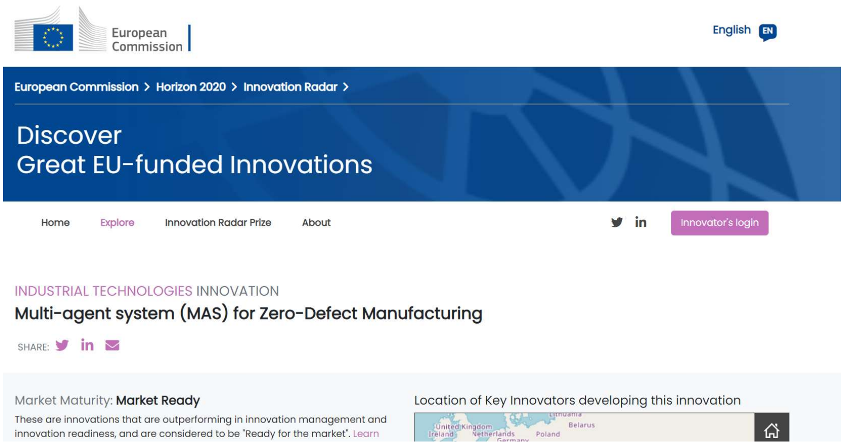


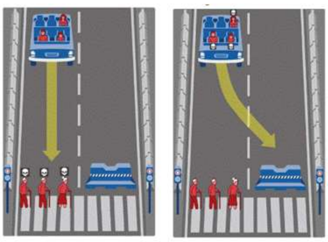
Source: https://www.innoradar.eu/innovation/34921

Agenda

5. Future challenges

Organizational, social, ethical perspectives

- Need to **look beyond technology**
  - draw important ethical, human and philosophical considerations
- Which social-organizational, legal and ethical frameworks are needed to support AI?
- Consider **legal issues**,
  - e.g., General Data Protection Regulation (GDPR)
- **Ethics** assumes important role in AI



Source: Moral machine - what should the self-driving car do?

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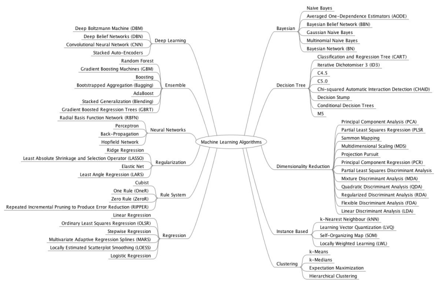
Which algorithms to select?

- None algorithm is adequate for all problems



- **Select the most appropriate ML algorithm**, depending:
  - Available volume, type of data
  - Computational resources
  - Response time

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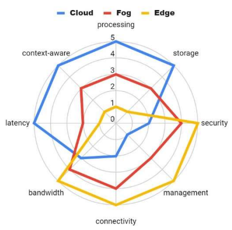
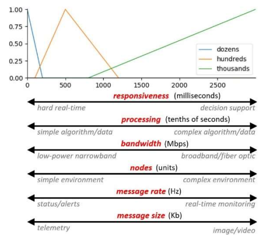
How to balance intelligence by computational layers?

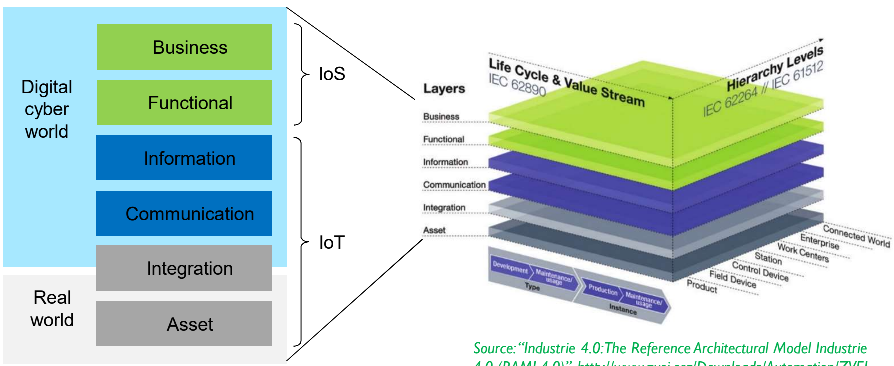
- Need to determine **the most appropriate computational layer** to implement a given data analysis task
- Consider application scenario **requirements and constraints**
- Fuzzy logic decision-making approach:





RAMI 4.0 – digitization layer

- **Why digitalizing?**
- **What digitalizing?**

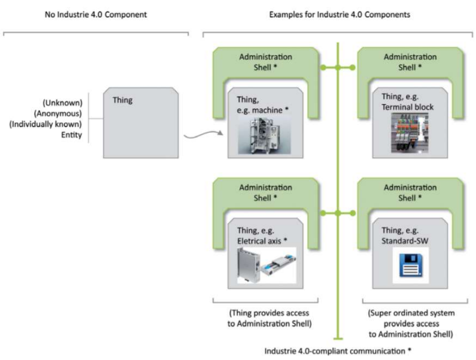


Source: "Industrie 4.0: The Reference Architectural Model Industrie 4.0 (RAMI 4.0)", http://www.zvei.org/Downloads/Automation/ZVEI-Industrie-40-RAMI-40-English.pdf

- **How digitalizing?**

How MAS matches the digitalization dimension?

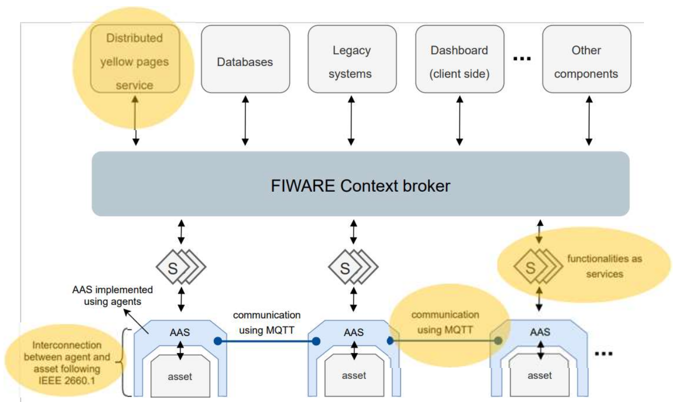
- ***Asset Administration Shell (AAS)*** has a crucial role in transforming an asset in an I4.0 component
- Industrial agents can implement AAS
  - ability to represent and interact with physical assets
  - communicate, access and exchange information with other agents or AASs
  - implement ML algorithms for monitoring, adaptation and optimization



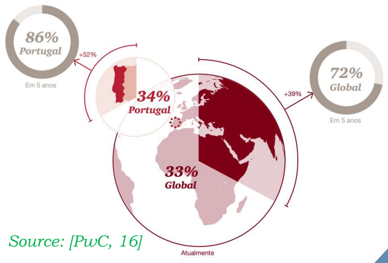
Source: "Industrie 4.0: The Industrie 4.0 Component", http://www.zvei.org/Downloads/Automation/ZVEI-Industrie-40-Component-English.pdf

Industrial Oriented Framework

- Light and industrial oriented MAS framework
- Compliance with industrial standards



New skills and training programs



Source: [PwC, 16]

- Vision dependent of:
  - Skills in emergent technologies
  - Multidisciplinary knowledge
  - Training of active professionals

- Reorganization of **training and learning programs**:
  - Bachelor and MSc focusing the multidisciplinary component
  - Short-term learning focusing specialization and re-qualification
- **Capacitation** of industry workforce

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Conclusions

- AI plays a **crucial and central role** in Industry 4.0
- **Plethora of available** algorithms
- Intelligence should be distributed by cloud, fog and edge layers
  - Think globally, act locally
- **MAS** suitable to distribute intelligence in industrial CPS
- Several important challenges, and also the need to **face industrial requirements**

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Thank you!

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