APRIL 2019

The Autonomous Industrial Plant – Future of Process Engineering, Operations and Maintenance

Plenary at IFAC DYCOPS 2019 in Florianópolis, Brazil, 25 April 2019

Alf Isaksson, ABB Corporate Research, Västerås, Sweden

ABB

The world is changing at unprecedented speed

Technology influences the future of how we…

…power

>$4 tn of renewable investment

…produce

+300% industrial IoT[1] devices installed

…work

+300% robot sales

…live

+1 bn people in cities

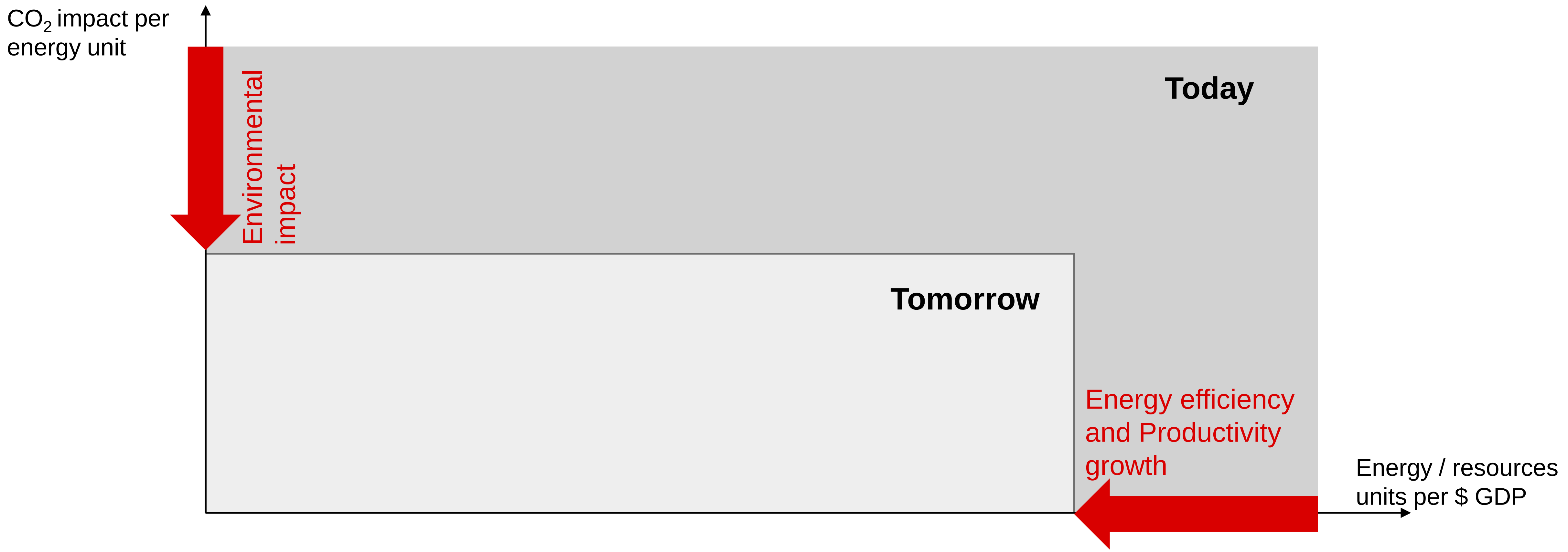
…move

~30% CAGR[2] for EV[3] sales

Source: BNEF 2018, Gartner 2018, IFR 2018, UN World Urbanization Prospects 2018, BNEF Electric Vehicle Outlook 2018
[1]Internet of Things; [2]Compound annual growth rate; [3]Electric Vehicles
Note: trends development 2018 – 2030; installed IoT devices 2018 – 2025

Key challenge: decoupling economic growth from environmental impact

Two key levers: Increasing Productivity/Efficiency and lowering carbon footprint



Outline

Facts about ABB

Future Automation

Integration of power and automation

The modelling complexity

Modular Automation

AI for Manufacturing Industries

Transition into Autonomous Systems

Conclusions

The new ABB

ABB

Pioneering technology leader in digital industries

~$410 bn market

~$29 bn revenues

34% Asia, Middle East and Africa	**31%** Americas	**35%** Europe

~110,000 employees

R&D at ABB – facts and figures

$1.5 bn
Annual investment

9,500+
Scientists and Technologists

10 countries
with major R&D Centers

5 Analytics Solutions Centers (ASCs) bring analytics-based solutions to our customers

>100
University collaborations

20 active
Startup investments

5 Venture funds

15
Strategic Partnerships

>10,000 patent families
40% of patents related to digital portfolio

Revolutions that are changing the industry

Digitalization, emobility, automation, and robotization

Energy revolution

The fourth industrial revolution

eMobility revolution

Utilities

Industry

Transport & Infrastructure

ABB Ability™: brings industry leading digital solutions to our customers

ABB Ability™

210+ ABB Ability™ solutions

Utilities solutions

Industry solutions

Transportation & Infrastructure solutions

Platform
(common technologies for device, edge, and cloud)

Microsoft | Hewlett Packard Enterprise | IBM

What — Delivers customer value (safety, uptime, speed, yield…) with AI based solutions

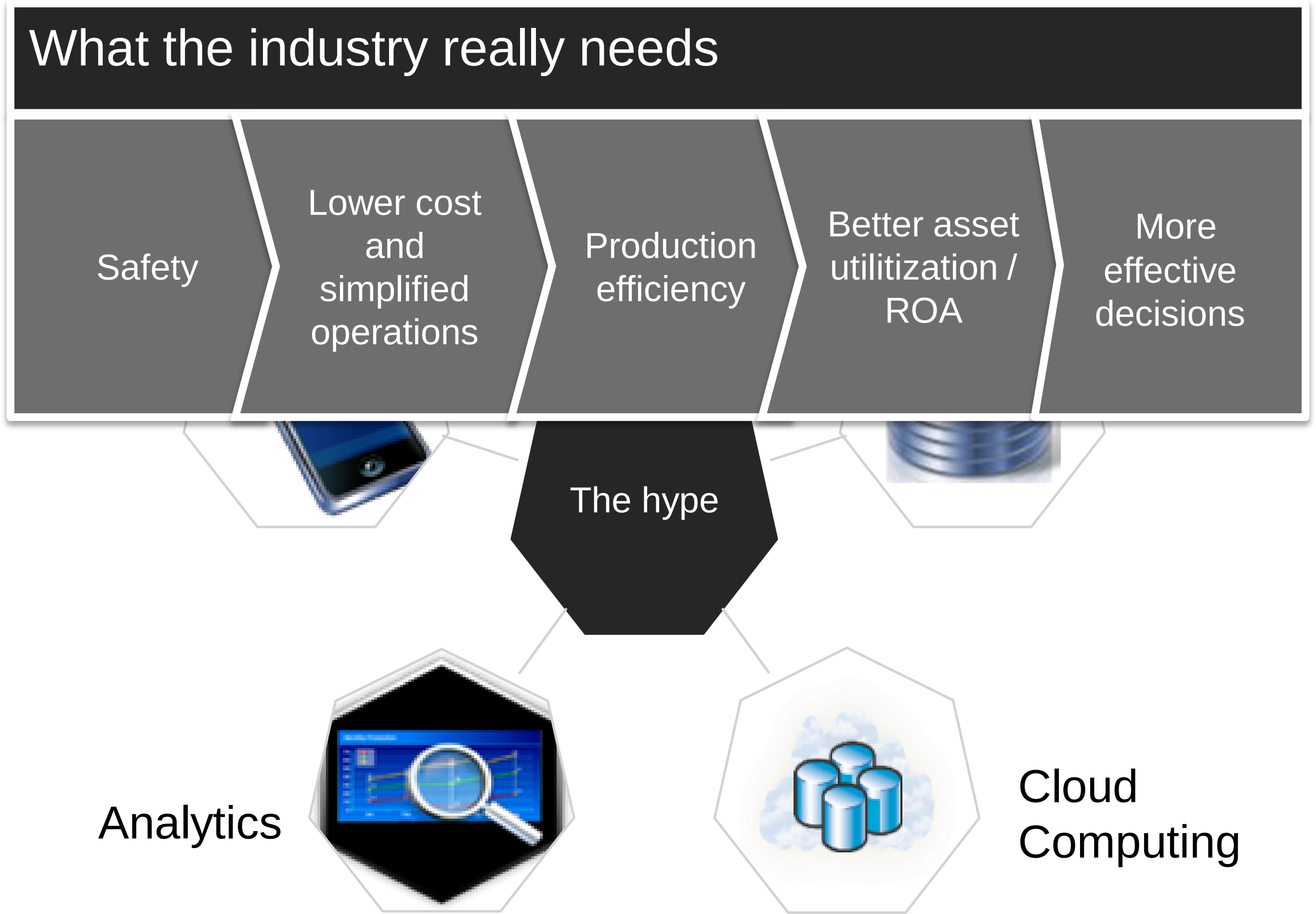
How — Provides ABB with efficiency and scale through AI

Our customers own their data and IP

Outline

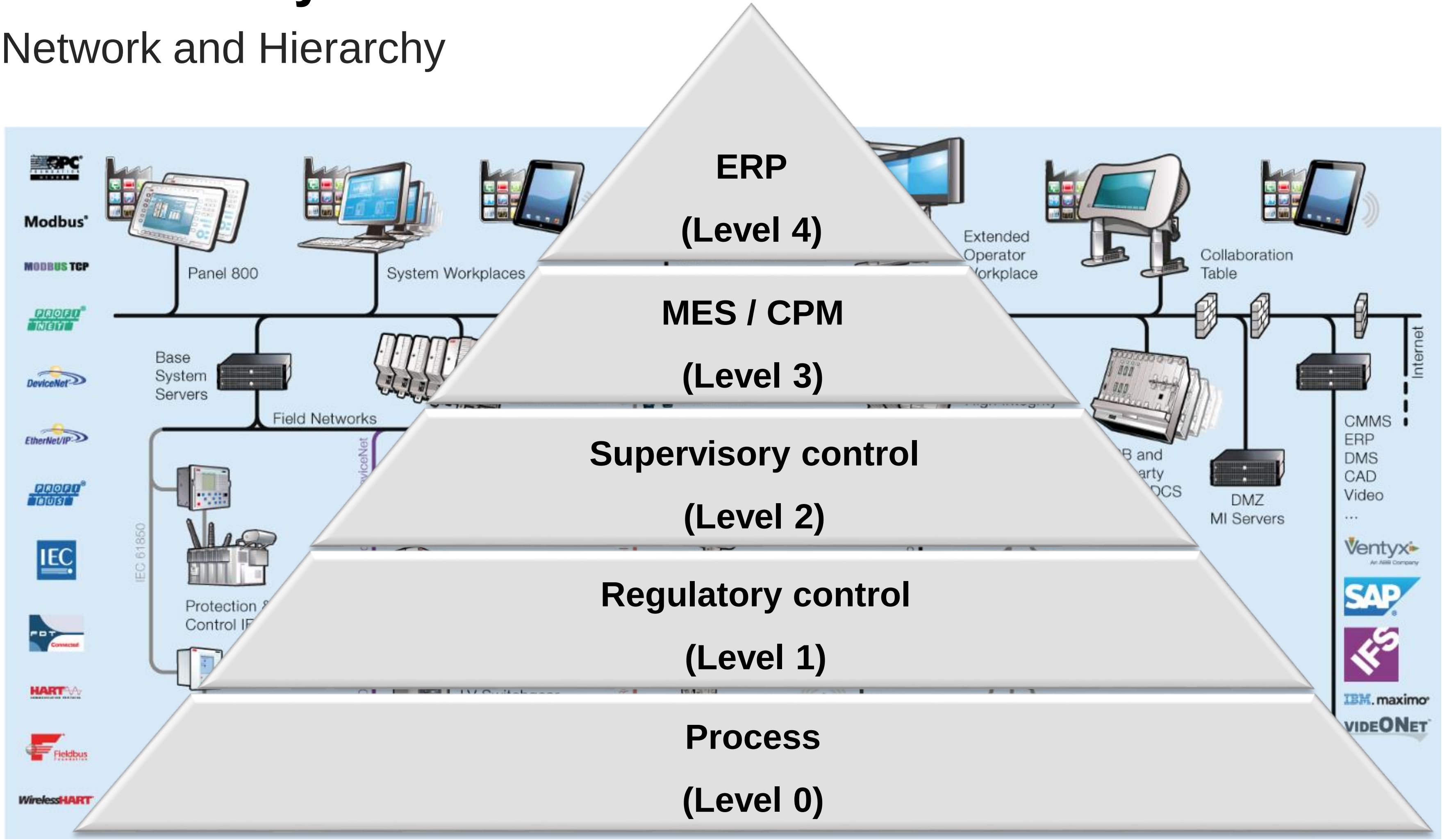
Market Trends

The Five Major Trends that Manufacturers Must Follow



Today's automation systems

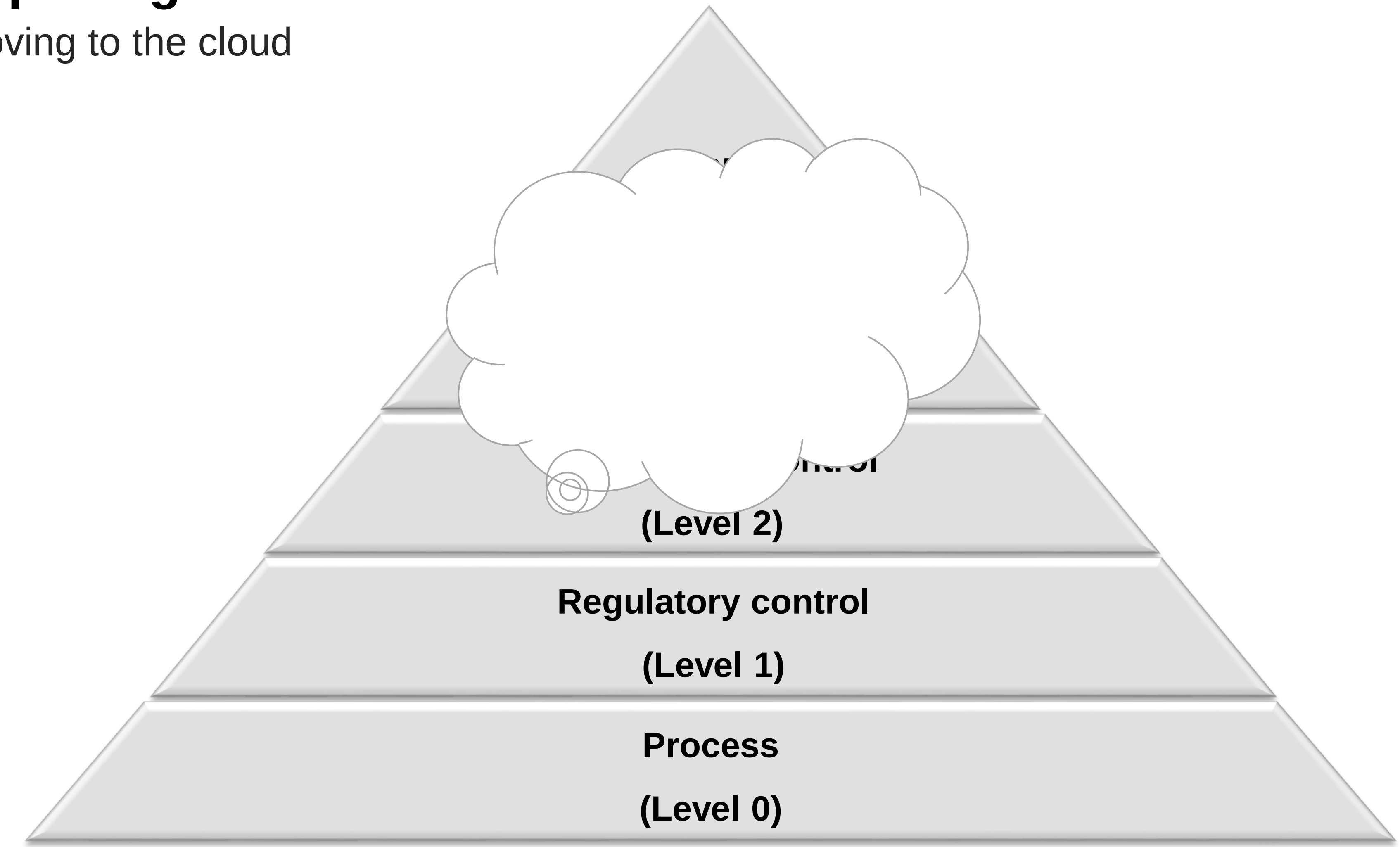
Automation Network and Hierarchy



ABB

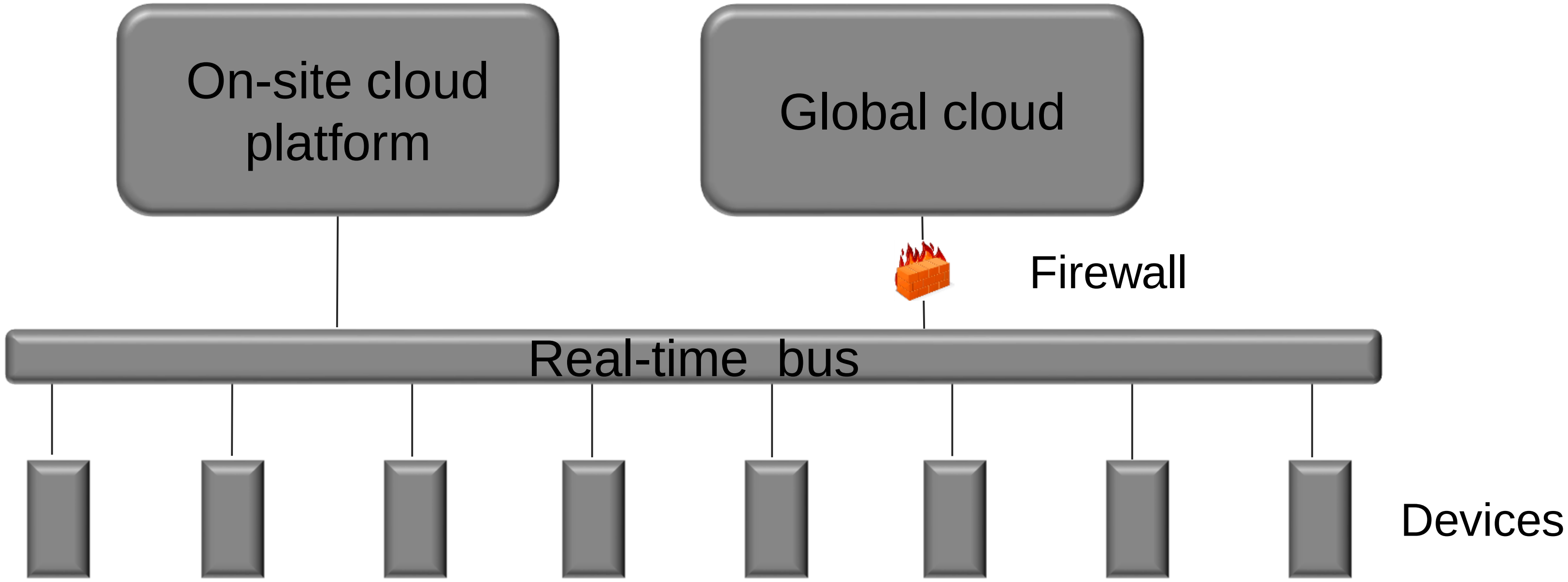
What is happening next?

Upper levels moving to the cloud



Future automation system architecture

Trade-off between edge and cloud



OPTIMAX® PowerFit

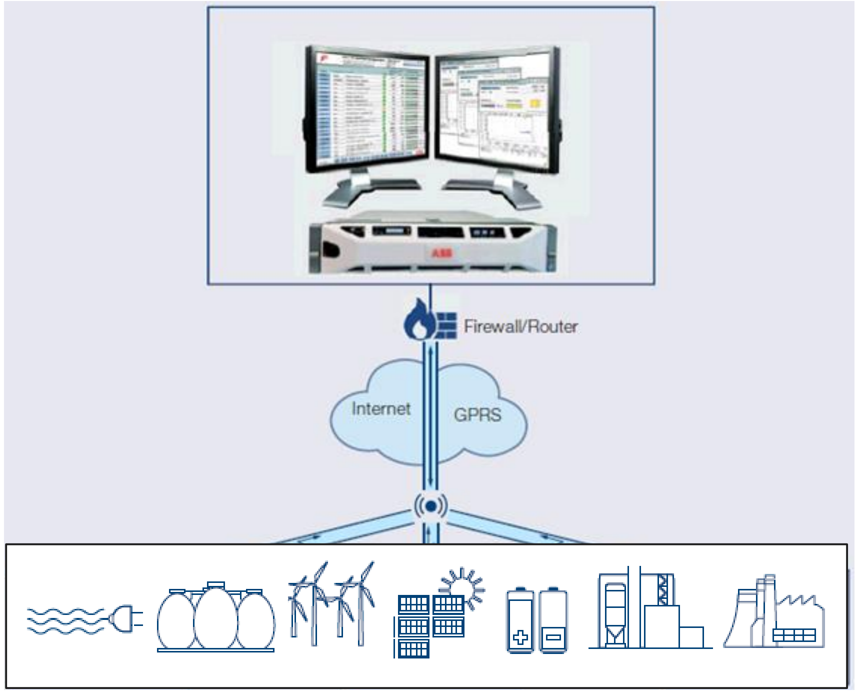
Optimizing control of Virtual Power Pools

Task

- Aggregate many small production units and treat them like one big power plant
- Exploit multiple forms of energy (e.g. el and heat) and storages

Solution

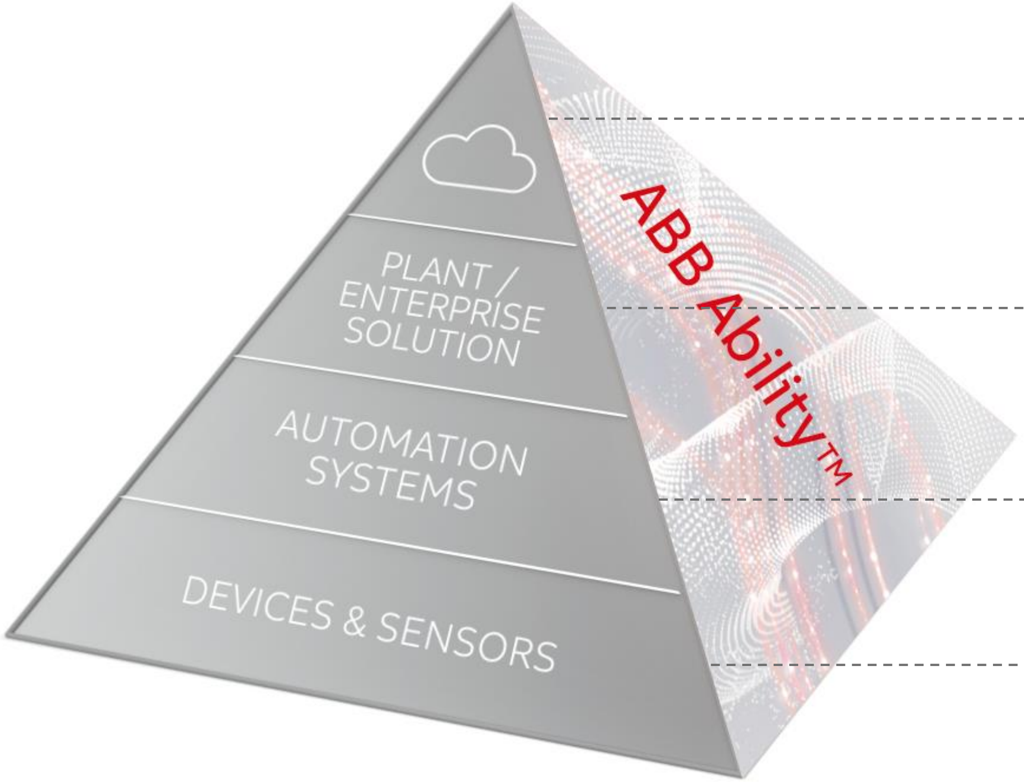
- Build overall plant model (exploiting Modelica multi-physics)
- Formulate optimizing control task as mathematical program
- Online optimization of set points and plant schedules



Digitalization enables the interconnection of power generation, consumption, storage and production

ABB Ability™

Industry-leading digital solutions built on a common set of standard technologies



- Open access, intelligent cloud
- New end-to-end digital solutions
- Systems to master process control
- Closing the loop with connected devices

Outline

Facts about ABB

Future Automation

Integration of power and automation

The modelling complexity

Modular Automation

AI for Manufacturing Industries

Transition into Autonomous Systems

Conclusions

End of Isolated Solutions

Balancing Between Control Systems

Energy availability and pricing (smart grids)

Grid control

Industrial demand-side management

Production Management (Planning & Scheduling, APC, Analytics, …)

Integration of scheduling and control

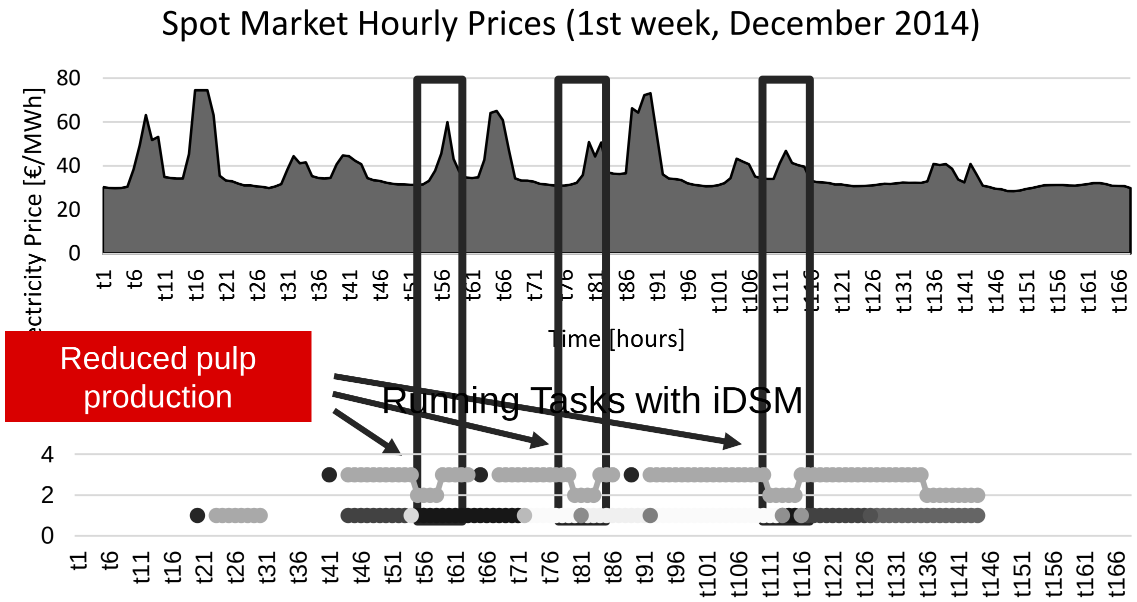
Process variations, e.g. quality, yield, disturbances (DCS)

Process control

Industrial demand side management in pulp & paper
Coordination of production planning and energy management

Mechanical pulp production

- Thermo-mechanical pulp (TMP) production is highly integrated with other parts of paper plant
- Most energy consuming production steps are moved **to low cost times**
- Paper output of plant is **not reduced**



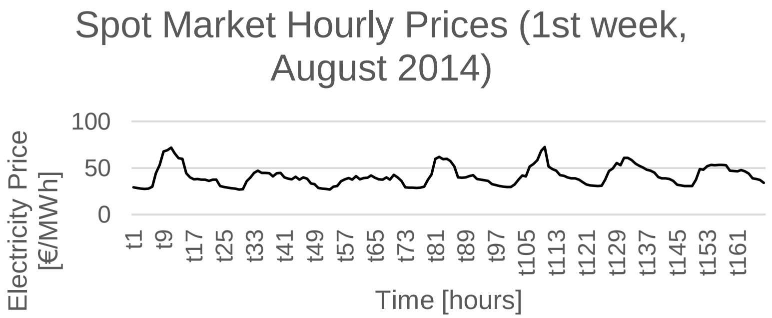
Industrial demand side management in pulp & paper

Evaluating market opportunities for thermo mechanical pulping (TMP) mills

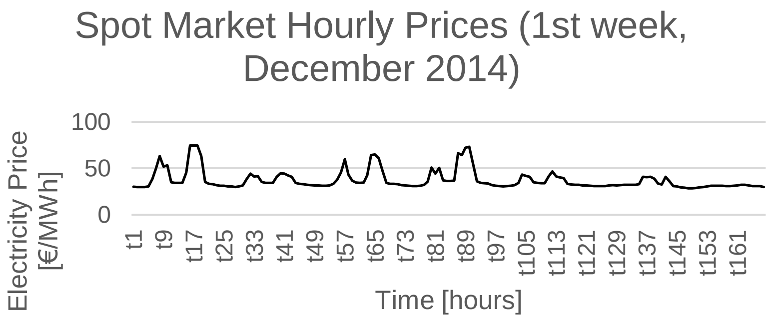
Case study with TMP mill

- Real world plant and production data of a Nordic paper mill
- Different scenarios evaluated

Scenario	Energy cost	Allowed pulp storage levels
S0	No	20%-80%
S1	Yes	20%-80%
S2	Yes	5%-95%



	No. of starts	Savings
S0	8	0%
S1	24	6%
S2	26	5%



	No. of starts	Savings
S0	7	0%
S1	34	4%
S2	33	4%

Outline

Facts about ABB

Future Automation

Integration of power and automation

The modelling complexity

Modular Automation

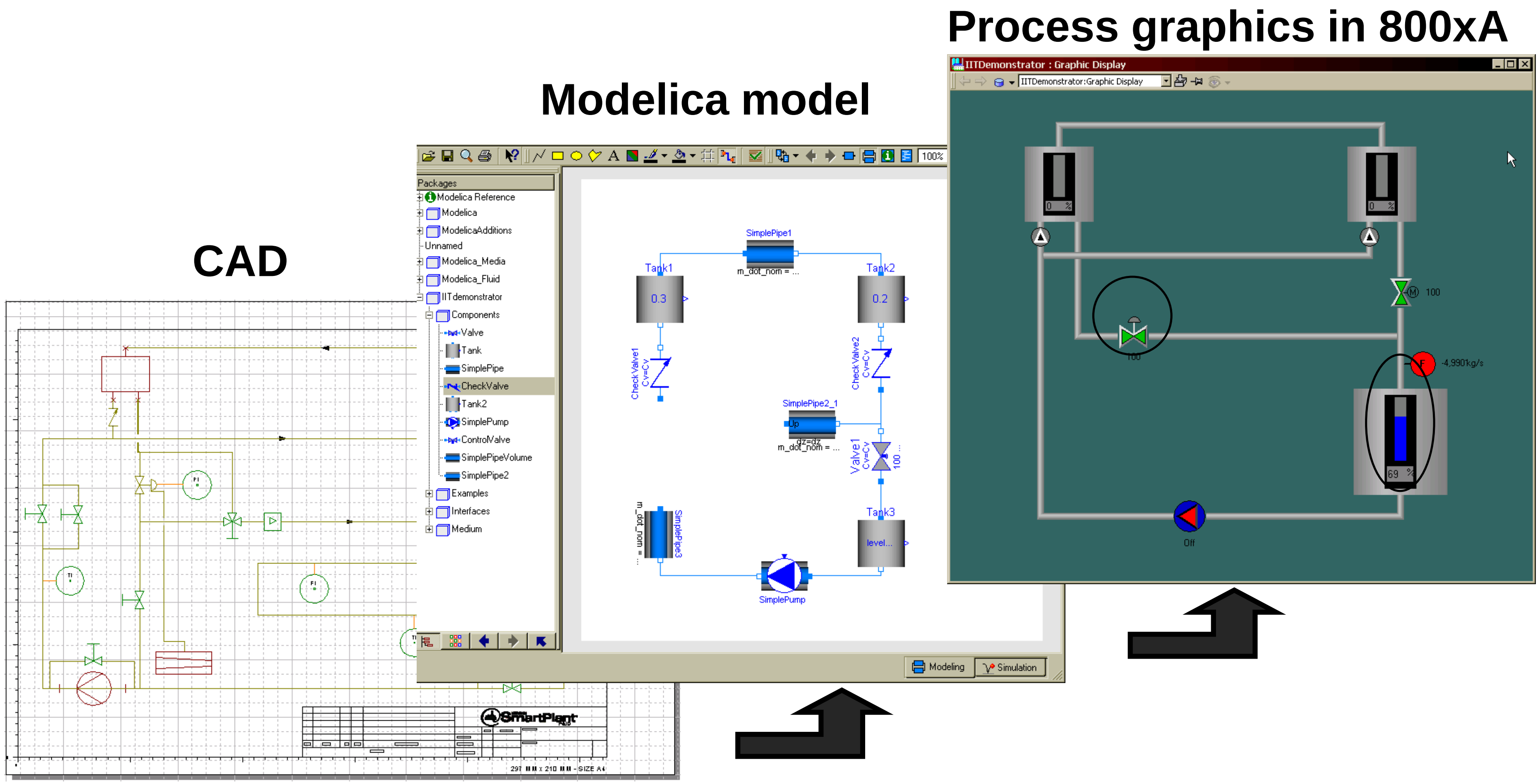
AI for Manufacturing Industries

Transition into Autonomous Systems

Conclusions

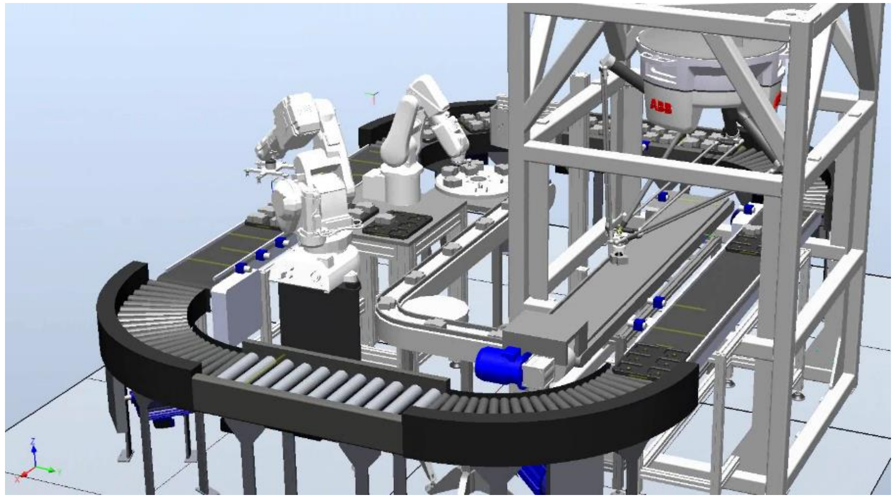
Modelling vision – Automation of automation

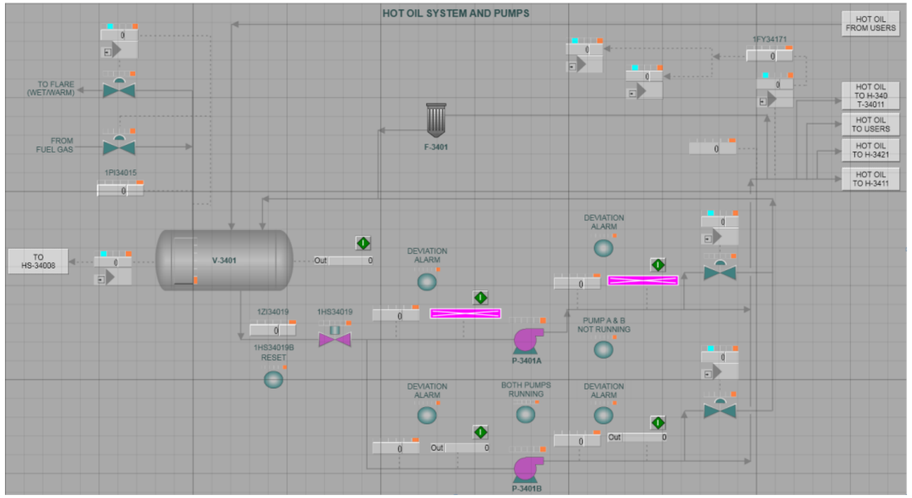
Automatically generate models for control and optimization from CAD



Virtual commissioning

Commissioning using a (simulated) virtual reality





Manufacturing: Mechanical objects up to cells, lines, incl. 2D or 3D simulation are coupled with automation systems (hardware or software in the loop)

Process automation more difficult due to lack of easily available process models. Currently piloting simulation models derived from P&I diagram to be used for FAT.

Learning models from historic data

Finding intervals that are useful for modelling

- Original method for system identification using single input – single output data
- Less than 5 % of normal operating data found useful for identification
- Implementation in ABB Ability^{TM} Manufacturing Operations Management (MOM) for MIMO process data
- Can (historic) data be used also for applications learning decision models rather than process models? For example
  - Alarm management
  - Production scheduling
  - Supply-chain optimization

Outline

Modular Automation

Background - Why Modular Plants?

Market situation and challenges

- Highly competitive
- Volatile markets
- Shorter product lifecycle required faster time-to-market.

Challenges in process industries

- Flexible, but efficient, modular plant concepts.
- Short time span between development and production.
- Numbering-up instead scale-up

ABB

Modular Automation

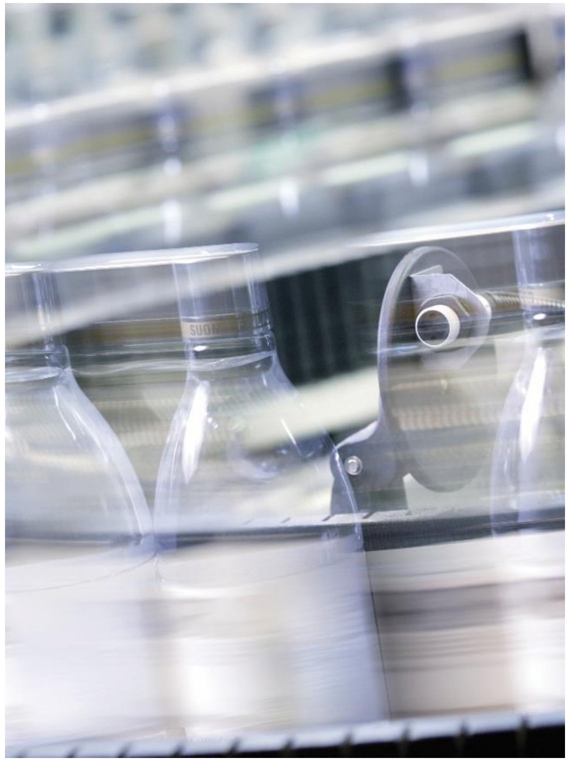
Targeted industries

Pharmaceutical industries

Biotech industries

Fine chemical industries

Food and Beverage



Pilot project since 2014

Together with Bayer, INVITE, Helmut-Schmidt University and TU Dresden

Source: Achema 2018

- Several modules engineered using our prototype „Module Designer“ and „Orchestration Designer“ with Freelance controller for modules and System 800xA as supervisory control system
- First demonstrated at ACHEMA Fair in Frankfurt June 2018

Concepts on:

- System architecture
- Module configuration
- Module integration into an orchestration system
- Automatic generation of operation and orchestration environment
- Operator workplace

Outline

Definitions of Artificial Intelligence

Many different definitions available

Working definition:

"**AI is the science of making machines do things that require intelligence if done by men**" (Minsky, 1968)

Neglected alternatives:

A: 1: A branch of computer science dealing with the simulation of intelligent behavior in computers
2: The capability of a machine to imitate intelligent human behavior (Meriam Webster)

B: "Artificial Intelligence is the study of mental faculties through the use of computational models" (Charniak, McDermott Introduction to Artificial Intelligence, 1985)

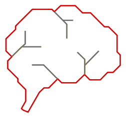
C: (In this view), the problem of AI is to describe and build agents that receive percepts from the environment and perform actions. (Russel, Norvig, Artificial Intelligence, A Modern Approach, 1995)

There is not one definition and no clear and generally agreed structuring of the field!

Branches of Artificial Intelligence

Overview of our structuring

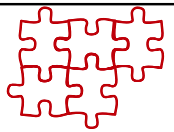
Knowledge & Inference



Emulate expert decisions and expert behavior

Pre-Requisites: Capturing expert knowledge, Contextual-knowledge

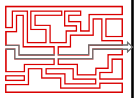
Problem Solving



Find solutions automatically for problems like packing problems or design tasks

Pre-Requisites: Precise problem definition, heavy modeling task

State & Action Planning



Find a good or optimal sequence of actions to reach a predefined goal

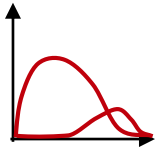
Pre-Requisites: Modelling of planning problem

Natural Language Processing

Interpret & process human natural languages for computer-human interaction

Pre-Requisites: Signal processing, semantics or lots of data

Learning Probabilities



Derive probability distributions from data for predictions & risk analysis

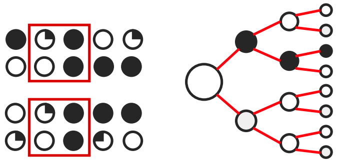
Pre-Requisites: Prior experiences, informative data

Machine Perception

Deduce real world aspects by using sensor input information

Pre-Requisites: Data models, good quality sensing, dealing with uncertainty

Machine Learning



Create the ability to perform tasks without explicitly programming a machine

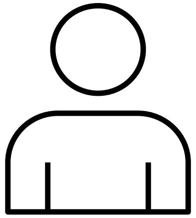
Pre-Requisites: Computation power, amount of data, good models, labeled data

The branches of AI are not independent and have many overlaps

AI – a paradigm shift in ease of installation and use of robots

From programming to teaching and learning

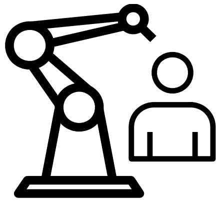
Yesterday: **programming**

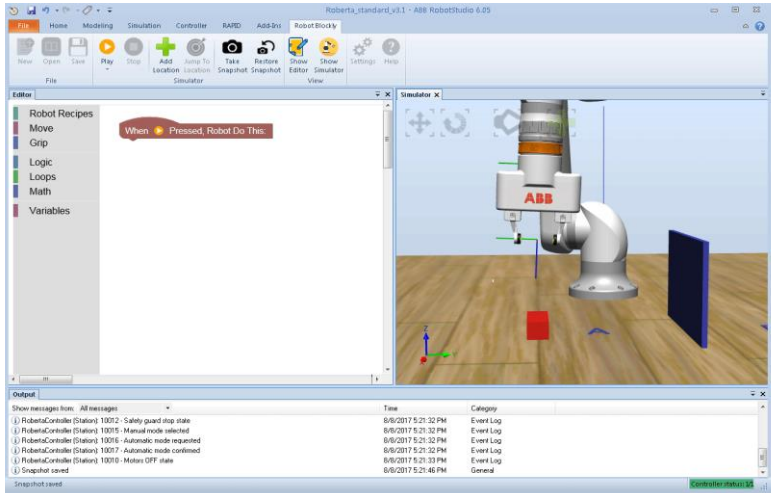


```
//Defining single location in RAPID

CONST robtarget
rb_Location1:=[[471.90028601, -
160.550088443, 259.855061587],
[0.0196845700059949, 0.999779442304461, -
0.00713127900217168, 0.00165206200050307],
[-1, -1, 1, 0], [9000000000, 9000000000,
9000000000, 9000000000, 9000000000,
9000000000]];
```

Today: **teaching**





Tomorrow: **learning**

Mainstream AI going beyond image recognition

First it was all games and fun

1997 IBM Deep Blue – Kasparov
Result: 3½-2½

State Space Complexity

10^{120}

- Thousands of **rules and heuristics**
- Handcrafted by strong **human players**
- Try to account for every eventuality

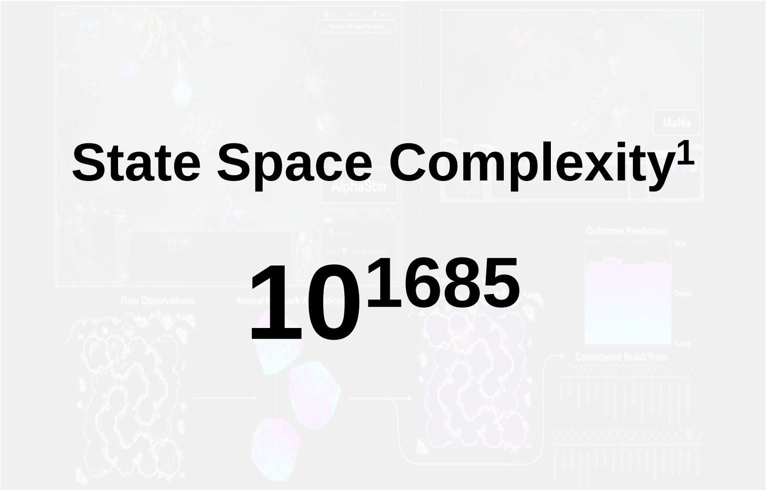
2016 Google AlphaGo – Lee Sedol
Result: 4-1

State Space Complexity

10^{174}

- Knows nothing except basic rules
- Learns by **Self-Play** against itself
- Highly dynamic, “**unconventional**” style

2019 Google AlphaStar – “MaNa”[1]
Result: 5-0



State Space Complexity[1]

10^{1685}

- Raw data fed to a deep neural network
- 1^{st} learned from footage of human games
- 2^{nd} played against a league of AI players

[1]Grzegorz "MaNa" Komincz, one of the world’s strongest professional StarCraft players
https://liquipedia.net/starcraft2/2018_StarCraft_II_World_Championship_Series_Circuit/Standings

Complexity of the industrial reality

Life isn't playing a game

Well defined rules and limited states in games

Unlimited states in reality[1]

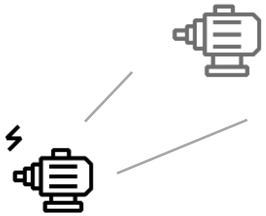
Moving from a closed world to reality requires Industrial AI

[1]Visual by William Sadler - Napoleon.org.pl, public domain, https://commons.wikimedia.org/w/index.php?curid=15176449

Industrial AI addressing the complexity in industrial reality

Combining domain knowledge with data

Know (foresight)



$$\dot{x} = Ax + Bu$$
$$y = Cx + Du$$

Domain knowledge

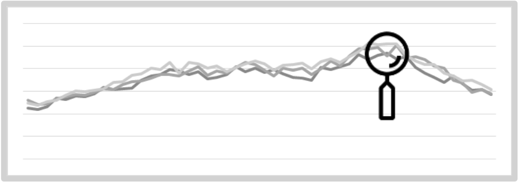
First principles models and simulation

- Described, but not yet observed

Safety, control and optimization

- Engineered well-defined solutions

Observe (hindsight)



Data science

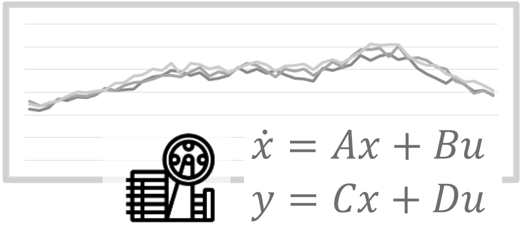
Data driven models

- Observed, but not a priori described

Industrial AI

- Complex scenarios

Combined approach



$$\dot{x} = Ax + Bu$$
$$y = Cx + Du$$

Build on what is known

Safely avoid known dangers

Explore the unknown through data analysis and simulation to increase flexibility

Industrial AI needs a combination of domain and data expertise to be successful

Example: Remaining Useful Lifetime of Azipod® Bearings

Prescriptive service solution for marine application

Can we estimate and prolong the lifetime of an asset?

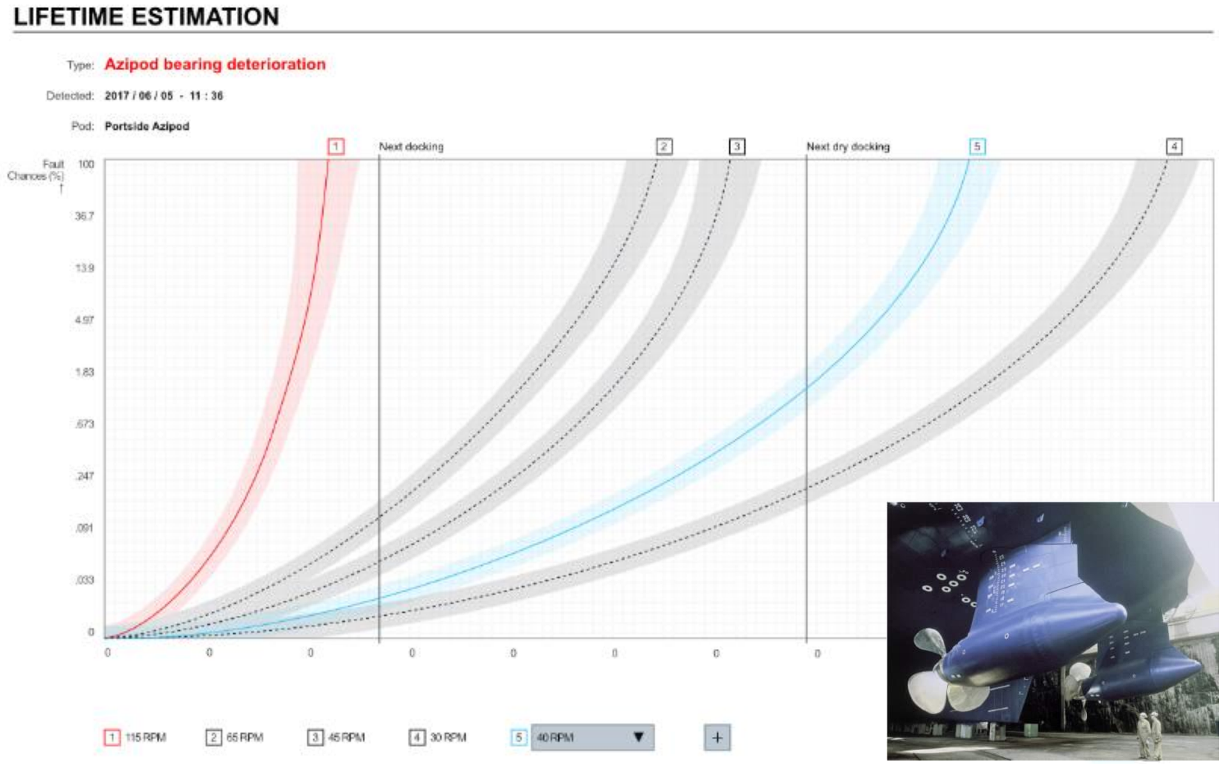
An accurate estimate of remaining useful life (RUL) for the critical component, i.e. Azipod® bearing, enables to avoid unplanned stop and maximize reliability.

– Early detection of bearing faults based on signal processing and physical models, using the resonance as well as bearing fault frequencies

– Estimation of a degradation vector based on machine learning using condition monitoring signals

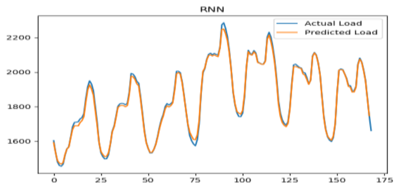
– Lifetime model predicting the RUL of the Azipod® bearing as a function of operational condition (physical model) and estimated degradation vector (data driven)

– Use of the estimated RUL for an optimal maintenance planning through adaptation of operational condition



Machine Learning / Artificial Intelligence Projects in ABB Corporate Research

Overview

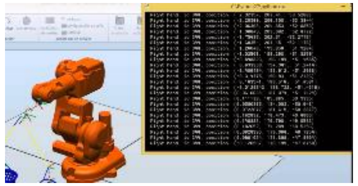


Distributed Energy Resource (DER) forecasting

Improved yield in grinding circuit operation

Cloud tracking – prediction of the power output from a solar PV park

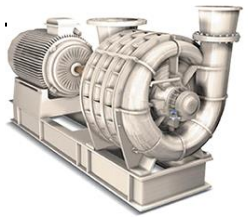
Artificial Intelligence supported building automation



Integration of machine learning frameworks into Robot Studio

Anomaly detection of robotic paint system

Motor failure prediction using data analytics and machine learning

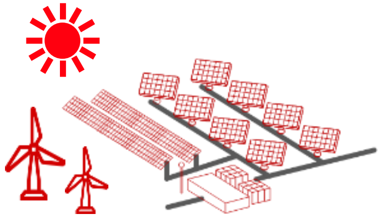


Optimized multi-compressor efficiency

Increased uptime by advanced Alarm management

Preventive maintenance of wind turbines

Foaming prediction to prevent plant shutdowns



Increased PV plant uptime

Glimpse into the future

AI Assistants as unified interface to advanced analytics

Connected with ML Services

Proactive Assistance

Graph-based Dialogs for Analytics

AI assistant connected to machine learning services

Proactively approaching user with relevant information

Unified user experience with natural-language interfaces for all algorithmic functionality

Outline

Facts about ABB

Future Automation

Integration of power and automation

The modelling complexity

Modular Automation

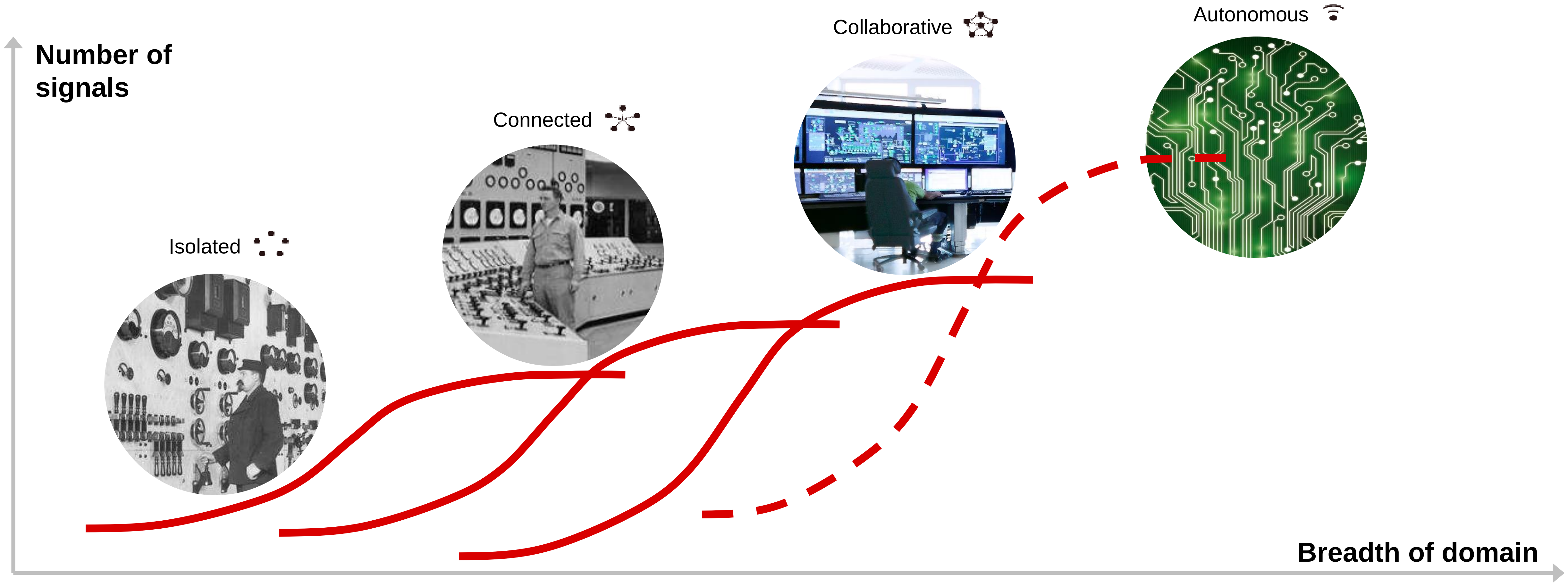
AI for Manufacturing Industries

Transition into Autonomous Systems

Conclusions

Industrial automation has progressed for more than one century

Broader application space, going beyond classical control, move towards autonomous



What do we mean by an Autonomous System?

Definition

Systems that [without manual intervention] can change their behavior in response to unanticipated events during operation are called “autonomous”

Autonomous Systems David P. Watson and David H. Scheidt at John Hopkins Applied Physics Laboratory

Remote Control and Autonomous Systems

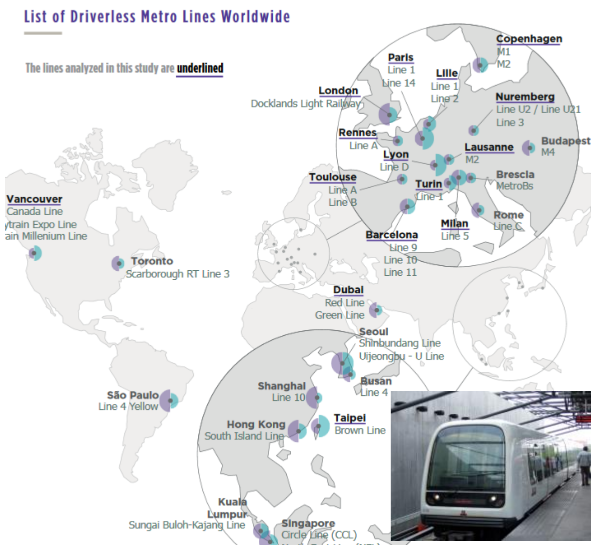
Examples from other Industries

Airplanes/Drones (Military)

General Atomics MQ-9

IAI Heron

Driverless metros



Sources: Wavestone research and analysis, UN data, UITP

Warehouse robots

Amazon Robotics
(formerly Kiva Systems)

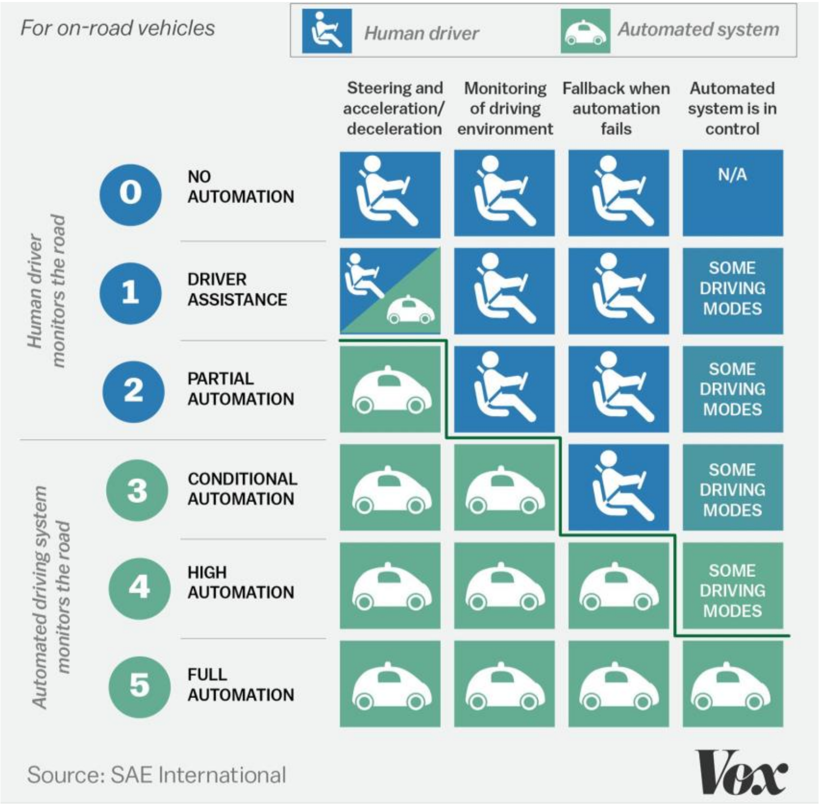
Cars

Google's self-driving car

Autonomous Systems are appearing in various industries

Levels of autonomy

Definition from the Society of Automotive Engineers (SAE)



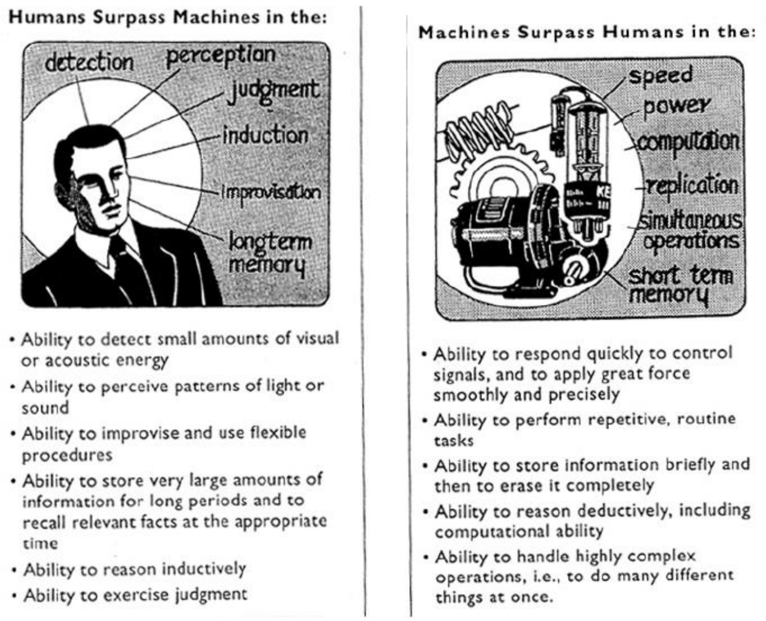
Driving in traffic with Tesla's autopilot controlling distance from the lead car and centering the vehicle in the lane**.

Tesla Autopilot system is considered to be an SAE level 2 system.

Academic origins of levels of autonomy

Decades of research leading up to the SAE 0..5 scale

Function Allocation (1951)

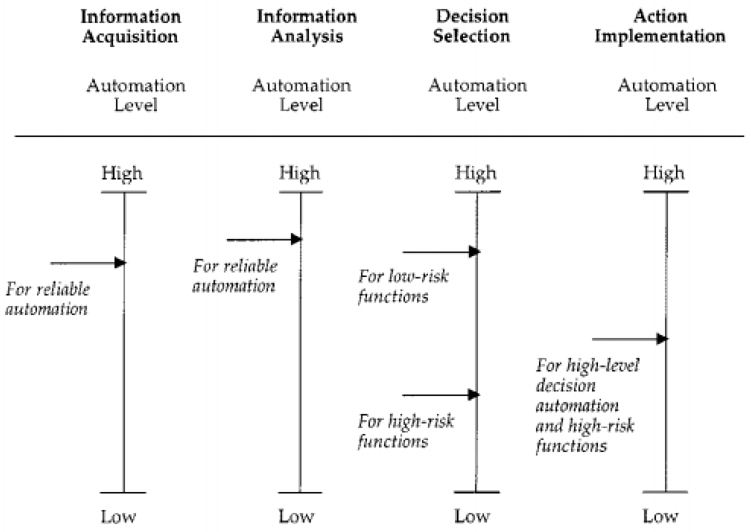


Methods for Function Allocation

Level of Automation (1978)

1. The computer offers no assistance: human must take all decision and actions.
2. The computer offers a complete set of decision/action alternatives, or
3. narrows the selection down to a few, or
4. suggests one alternative, and
5. executes that suggestion if the human approves, or
6. allows the human a restricted time to veto before automatic execution, or
7. executes automatically, then necessarily informs humans, and
8. informs the human only if asked, or
9. informs the human only if it, the computer, decides to.
10. The computer decides everything and acts autonomously, ignoring the human.

Levels & Stages of Automation (2000)



Parasuraman, Sheridan, & Wickens (2000)
(2600+ citations)

Moving towards autonomous industries

Increasing the level of autonomy

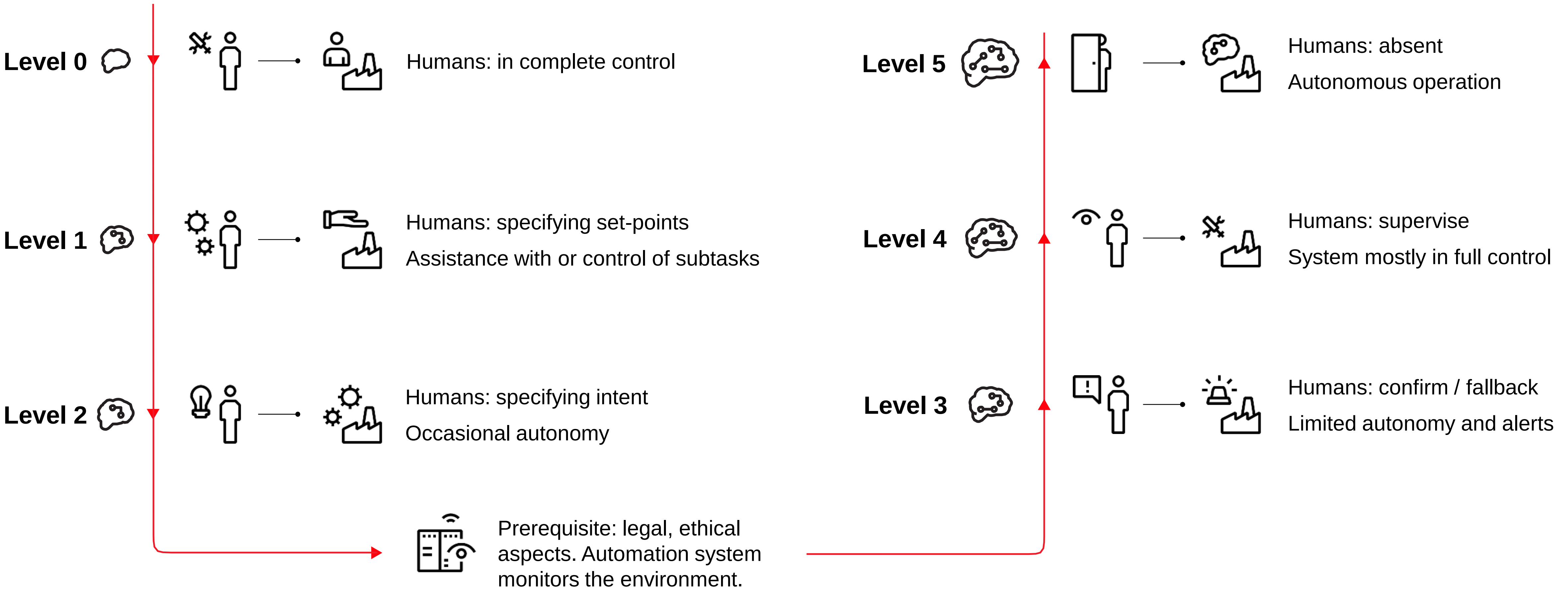
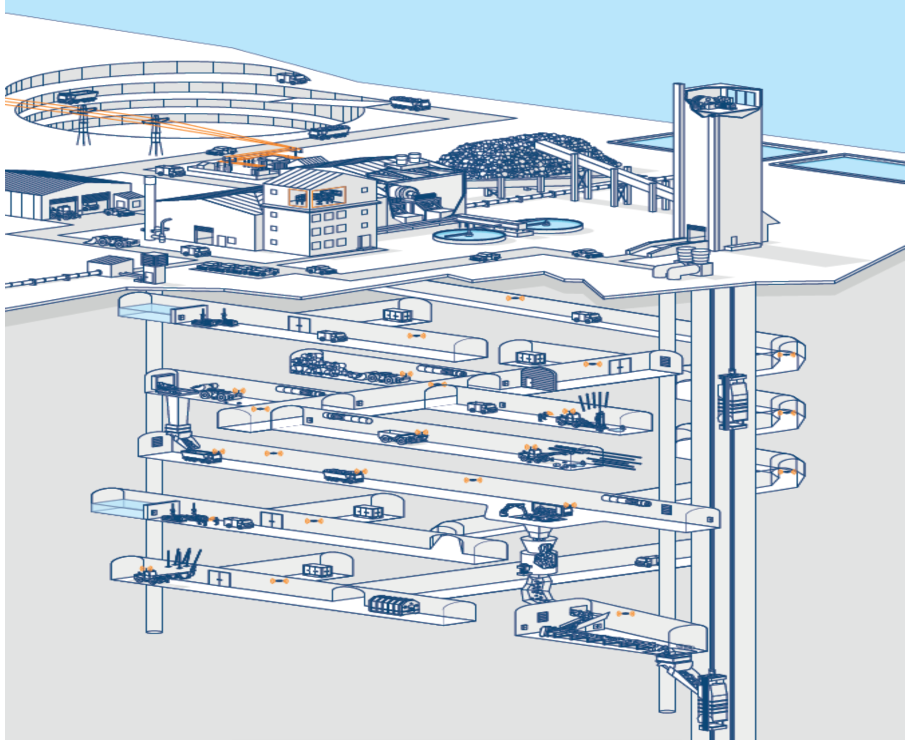


ABB Application Example – Mining

Future underground mine will possibly be fully autonomous with no people underground



SIMS
SUSTAINABLE
INTELLIGENT
MINING SYSTEMS

Swedish mining companies – Boliden and LKAB – are world leaders in automation

Comparison of “our world” with automotive

Why it is not as easy with the process domain as with automotive

Life cycle phase	Operation	Operations*, possibly others too
Autonomous key feature	Driving	Control room operation, field operation, process optimization, production scheduling
Human role(s)	Driver	Control room and field operator, process engineer, dispatcher, …
# tasks / set points	Low: speed, lane position	High: dozens to hundreds
# of artifacts	Medium: ECUs, sensors, valves, …	High: I/Os, controllers, valves, pumps, compressors,…
Homogeneity of tasks	High: each driver can drive every car	Low: Operators cannot (easily) be switched between plants

* Operations is more than control room operations (which would be similar to “driving” in automotive) and includes, e.g., maintenance, too

Autonomous plant / factory

Autonomous key features for lifecycle phase operations (work in progress)

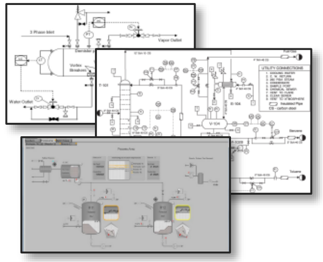
	Definition – Plant/Factory	Control Room Operation	Field Operation / Maintenance	Planning and Scheduling
0	No Autonomy: Humans carry out all necessary operations without assistance	Manual control of all assets. No support by automation system.	All field operator tasks executed by humans.	Manual development of plans and the corresponding schedule.
1	Operations Assistance: Automation system provides decision support for necessary operations by remote / digital assistance. Humans always responsible.	Automation of control loops during steady - state. Manual startup and shutdown of the plant. Manual execution of transitions. Alarm based notification.	Automation system notifies humans about field activities. Some tasks are automated , e.g. operating valves.	ERP plan creation on human request. Human decides when and how to execute the plans and adapts plans.
2	Automation system is in control in certain situations on request (humans pull support, e.g. for plant startup). Humans always responsible.	Automation system assisted plant startup, transition, steady-state, and shutdown. Manual fault correction supported by decision support system.	System guided field operation tasks. Humans get instructions what to do and when by decision support system.	Adaptations of plans to current situations by operator request.
3	Automation system is in control in certain situations. Plant actively alerts to issues and proposes solutions. Humans confirm.	Automated plant shutdown, startup and transition, on human request. Automatic correction of known deviations. Decision support for unexpected/unknown faults.	Most tasks required for standard operations are automated, like shutdown, startup and transition phases. Number of humans in the field heavily reduced.	Continuous feedback and re-planning in case of production deviations.
4	Autonomous operations in certain situations: automation system has full control in these situations, humans supervise actions.	Autonomous control in certain situations with automatic fault and deviation correction and avoidance.	Almost human free field operation. Only human field operation in exceptional situations.	Continuous autonomous planning and scheduling without user interaction. Detection of production deviations and re-planning. Manual schedule release.
5	Full autonomous operation in all situations. Humans may be completely absent.	Full autonomous control, fault correction and avoidance in all situations. No human supervision required.	Full autonomous field operation, no manual actions in the field necessary. No humans remain in the plant.	Autonomous development and execution of plans and schedules. Autonomous re-planning in case of production deviations. No human interaction.

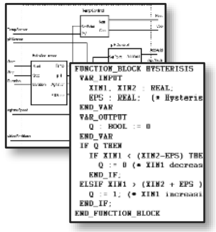
Future of Autonomous Plants

Scenario Overview

Efficient Engineering: intent-based automation

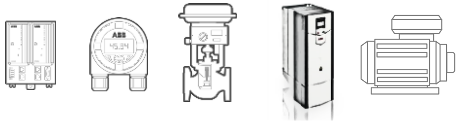
Automatically turn process to automation design and simulation

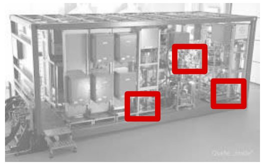


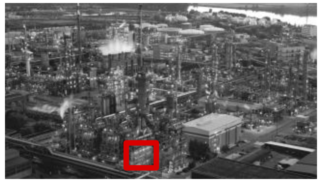


Rapid Commissioning and Reconfiguration: plug & produce for complex systems

Self-integration and -configuration of components, automated testing, emerging systems

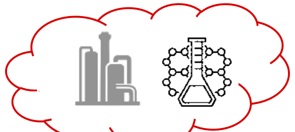






Efficient, Continuous Operation: decision-making AI

AI running operations as “world’s best operator”,
trained on high-fidelity simulations; move beyond AI assistants



Example: optimize brownfield plant

- Increase availability: 100% available plant
- Increase productivity: from 85% to 95%
- Highest quality and security desired
- Rapid upgrade free of side-effects

The transition to autonomous systems in industry

Value proposition of autonomy

Handle increasing complexity of Industrie 4.0 systems

Lot size one production

Higher productivity / yield and increased quality

Lower cost and energy consumption

Improved worker health & amplify human potential

Bring out and accelerating new innovations

Enable new business models and value propositions

Opportunities currently not imagined at all

Outline

Facts about ABB

Future Automation

Integration of power and automation

The modelling complexity

Modular Automation

AI for Manufacturing Industries

Transition into Autonomous Systems

Conclusions

Conclusions

Autonomy needed along entire lifecycle of manufacturing

- First applications of Autonomous Systems in autonomous transport/vehicles (cars, metros and for ABB e.g. mining, cranes, ships and logistics)
- Standard for autonomy levels already in place for autonomous driving and emerging for shipping
- ABB is now looking at autonomy also for industrial plants
- AI and Machine Learning are key enabling technologies for Autonomous Systems
- In ABB, we have a long tradition of Machine Learning, especially for Condition Monitoring
- Industrial AI and autonomy will need combination of modelling and data based learning

Value proposition always most important consideration

Towards autonomous operations: Let’s build a bridge into this future

See also: www.mx3d.com, using ABB robots.

Acknowledgements

The speaker is grateful to many ABB colleagues for discussions and slides.

In addition to my co-authors – Thomas Gamer, Benjamin Kloepper, Mario Hoernicke and Reinhard Bauer – I would like to thank Rüdiger Franke, Christopher Ganz, Iiro Harjunkoski, Antony Hilliard, Tomas Lagerberg, Michael Lundh, Lennart Merkert and Benedikt Schmidt.

ABB