The digital transformation of Industrial Systems – The Roadmap to Industry 4.0

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System

A set of interacting elements that seek a common goal.

Figure 1.1

Principles of Systems

1. An assembly of components
2. Components are connected in *organised* manner
3. A logical objective or purpose
4. Components work together towards the common objective

Design or Study the State of a System

- Identify the components of the system to be designed or studied
- Understand the role and relationship between the components and the inputs and outputs
- Recognise and capture the logical interrelationship between the components, inputs and output
- Infer from the inputs, outputs and the interrelationships the **State** and **Objectives**

Evolution of Systems Thinking

2025 - …

Mid 20th – 1st Quarter 21st century

19th – Mid 20th century

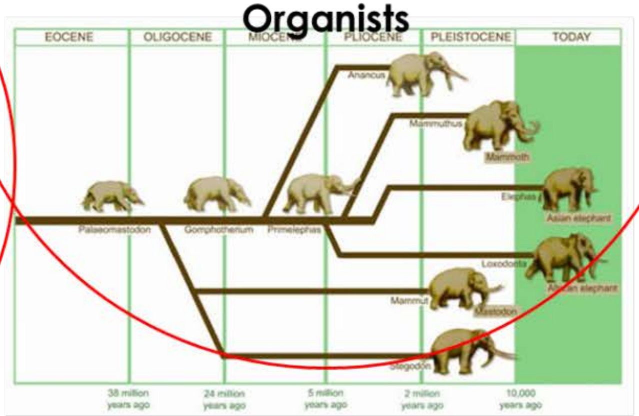
Mechanists

Repetitive
Algorithmic
Fixed Logic

Total = Sum of Parts

Adaptive

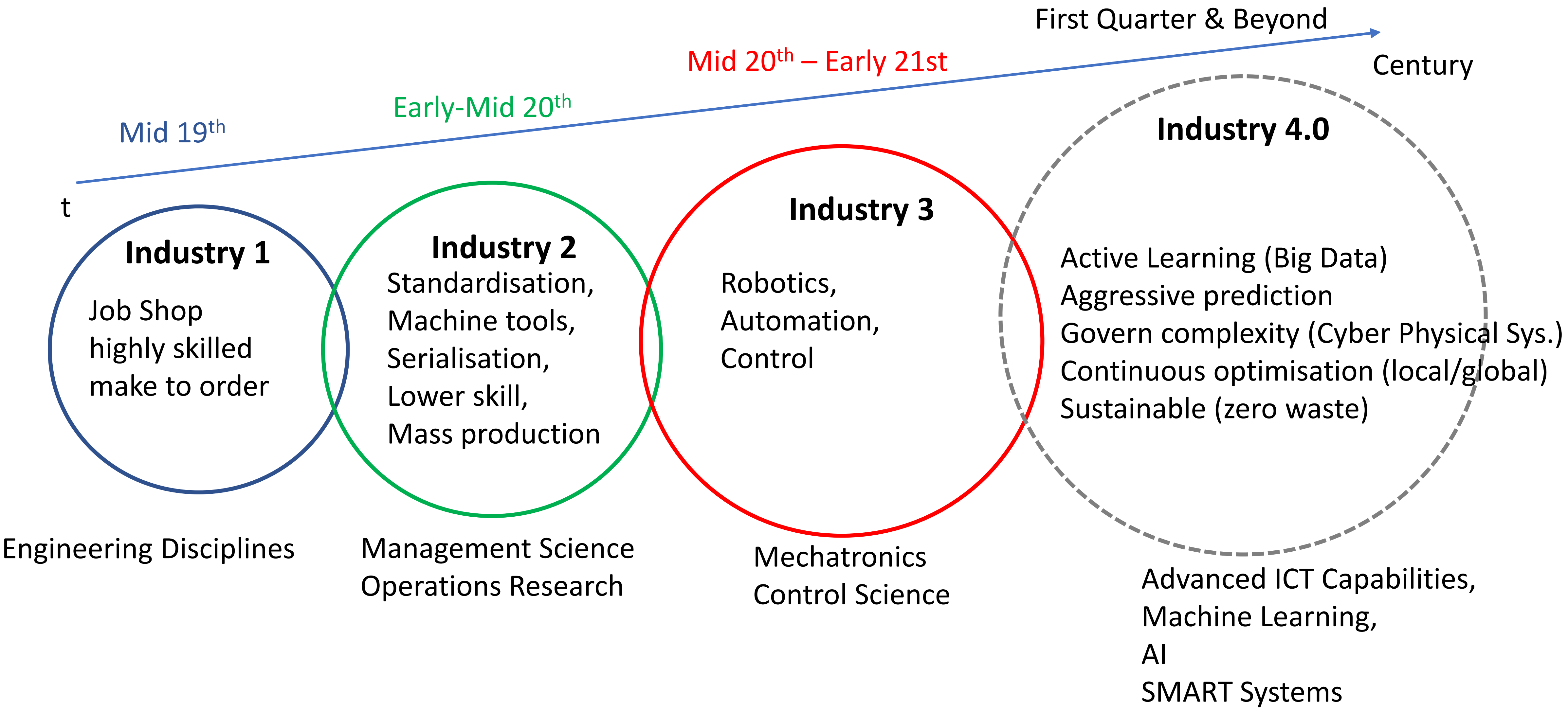
Organists



Viable/Sustainable

- ✓ Smart (intelligence)
- ✓ Agile
- ✓ Active Learner
- ✓ Aggressive Predictor
- ✓ Mastering Complexity
- ✓ Not only adapt but influence

Industrial Systems Transformation



Industry 4.0

A catalyst for manufacturing and the associated service sectors is a web of interdependencies of a range of technologies and concepts that include:

- the Internet of Things,
- Big Data, Cloud Computing,
- Cyber Security,
- Robotics,
- Digital Society and
- Artificial Intelligence.

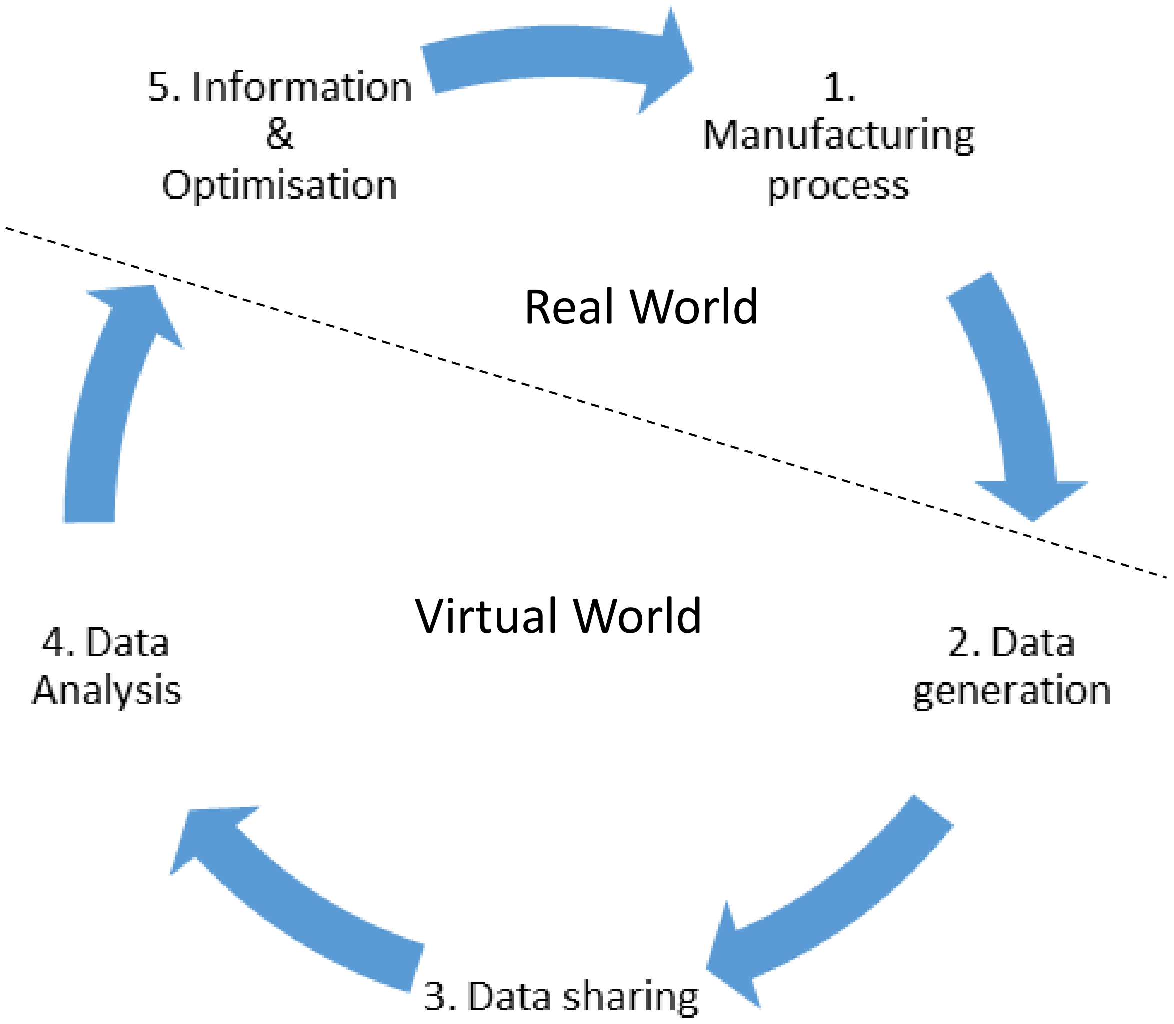
The web of interdependencies

Requires the building of an information-rich environment in which the **dynamics of the real-world demand and supply** are:

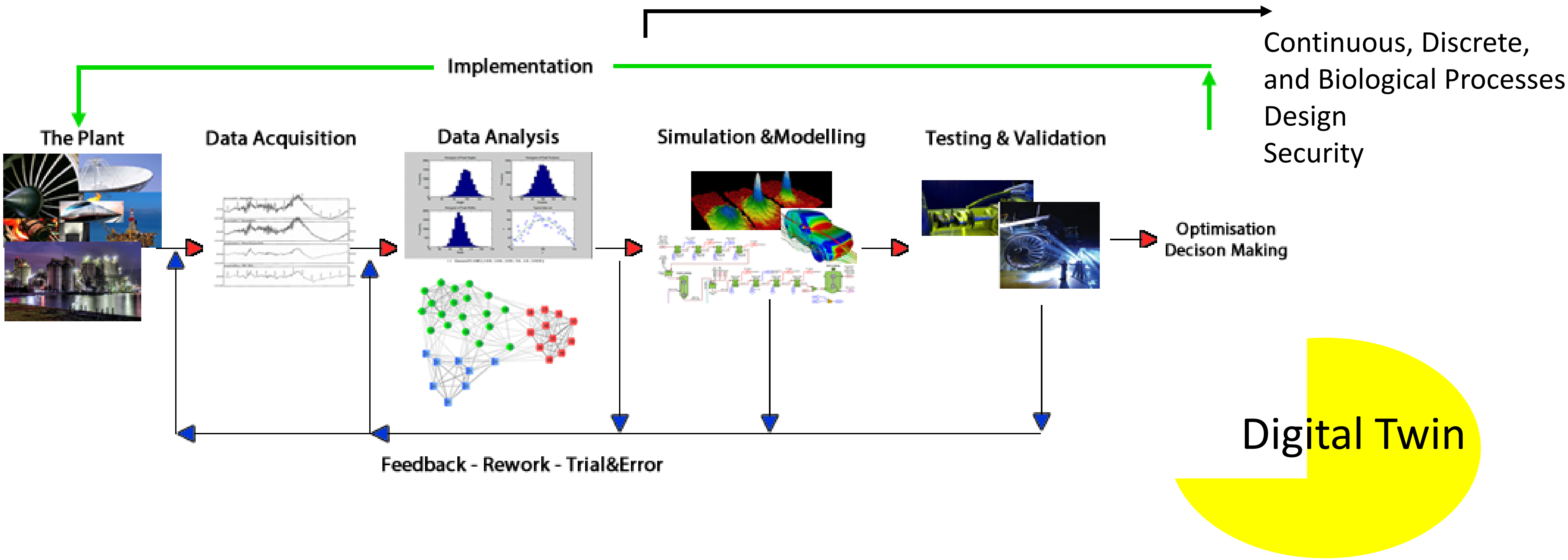
1. integrated,
2. monitored and
3. optimised. More importantly,

The enabling technologies of Industry 4.0 will allow **for real time and predictive adjustments of operations** by utilising the evolving data analytics methods.

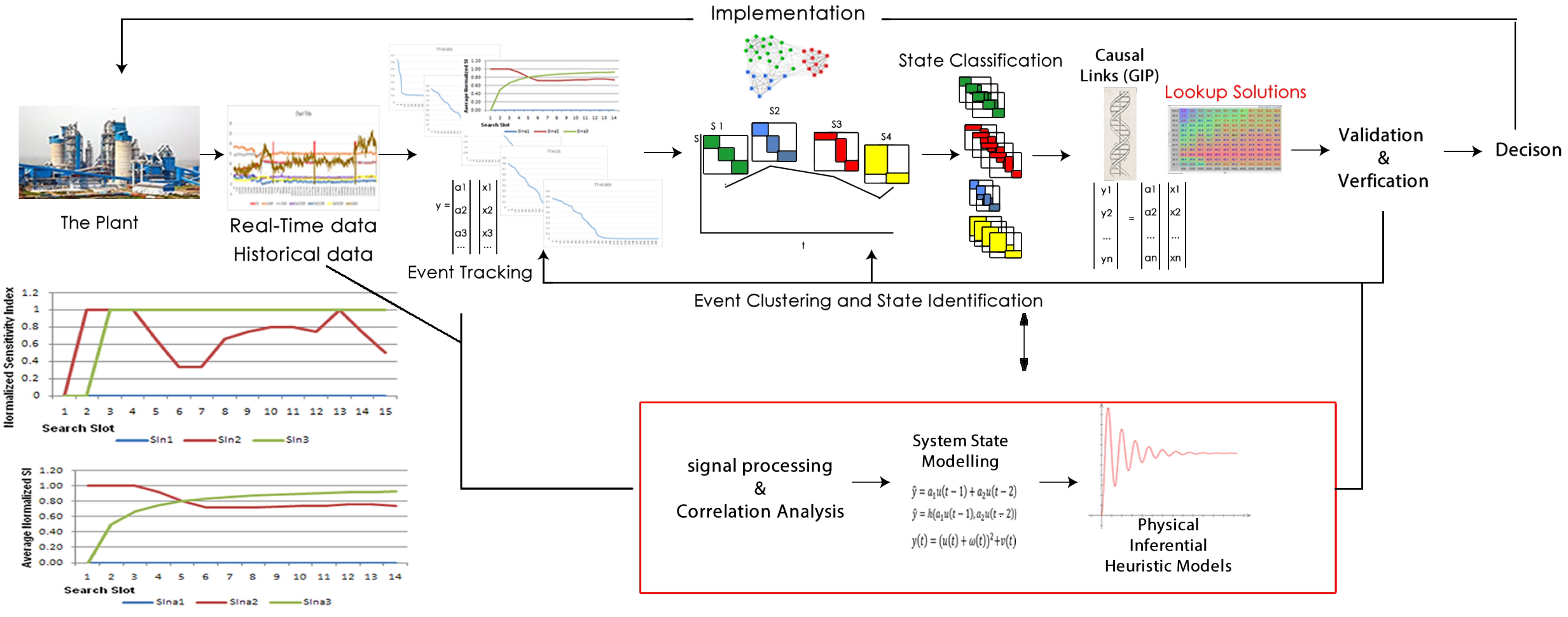
The value creation cycle of industry 4.0



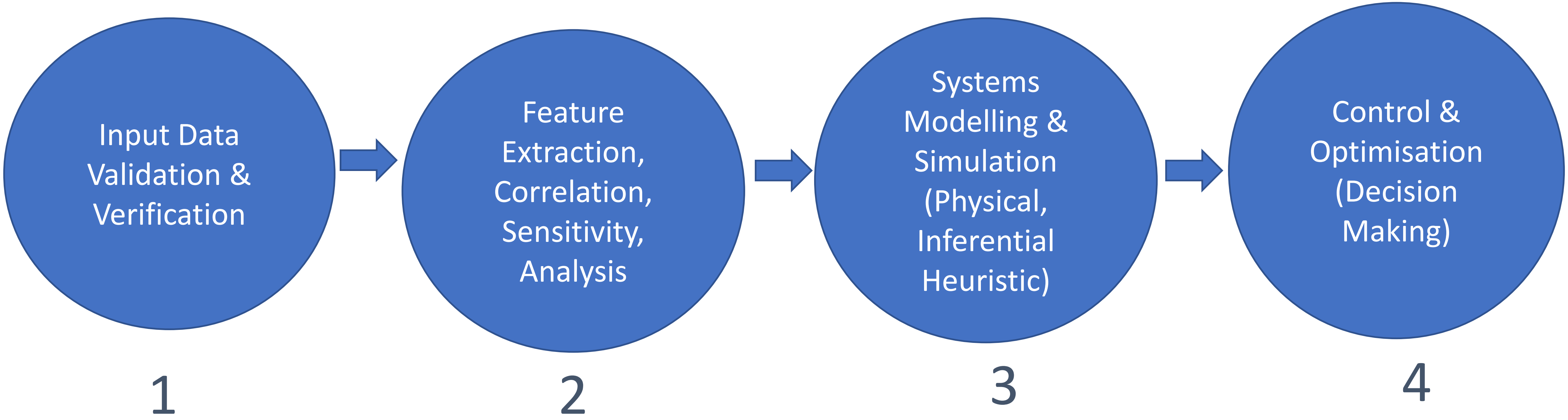
The Digital Revolution & Industrial System



The Modus Operandi



Questions to be answered in the Transformation Process



Quality of Input Data (error estimation)

Problem: Dealing with intermittency of connection or sensor failure

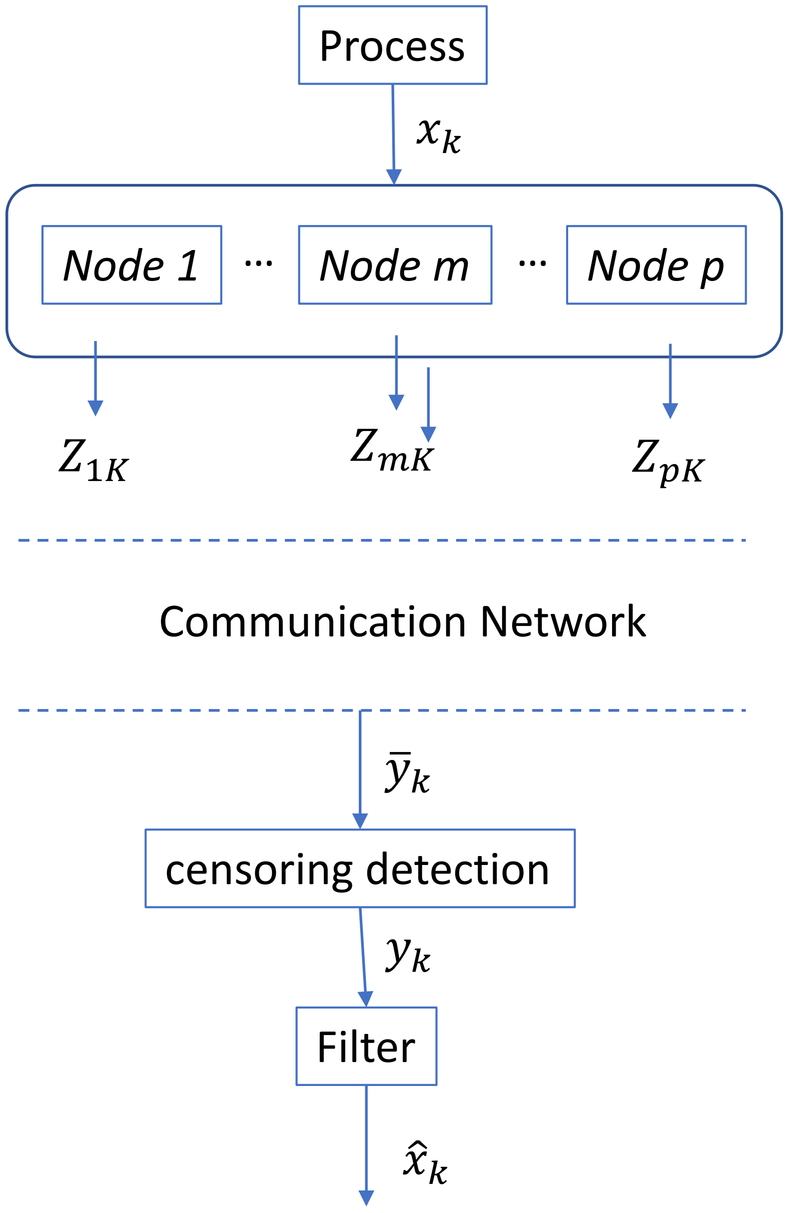
Applications: Wireless Control Area Network – Low Cost Sensors

Kalman Filters for well defined noise patterns, more complex conditions iterative KF, particle KF or Tobit KF dealing with estimating error (censured observation)

-> Introduced: Network Protocol Base TKF

Method: Examining the statistical property of the error covariance of the state estimation

Result: augmentation induction and integration

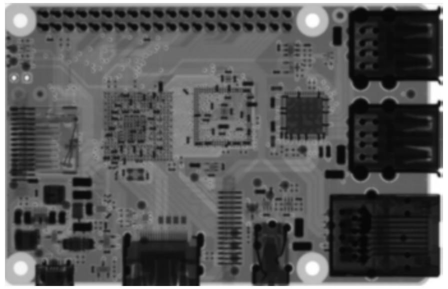


Quality of Input Data (Sensor Fusion)

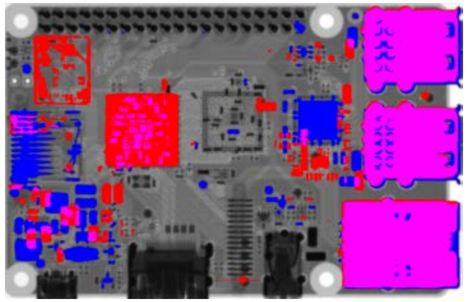
Electronics Quality & Provenance

Optical images

X-Ray images



Merging X-ray and Optical Image
Detailed detection and classification)

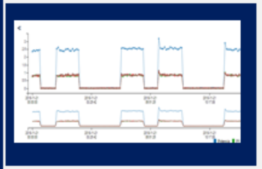


Quality of Input Data (Soft Sensors)

Development of GHG prediction models and control algorithms

SMART-Plant Systems

Energy monitoring

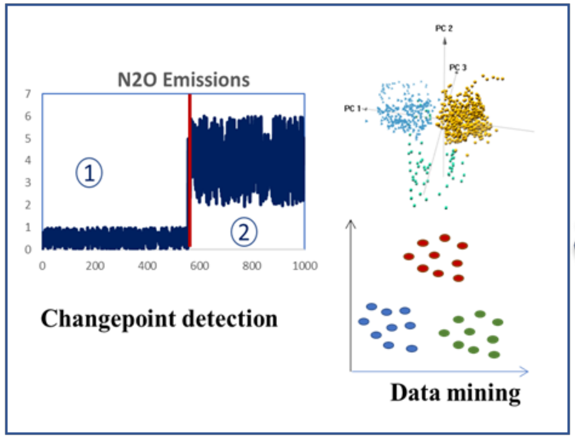


Sensor and laboratory data

GHGs monitoring

CH_4 N_2O

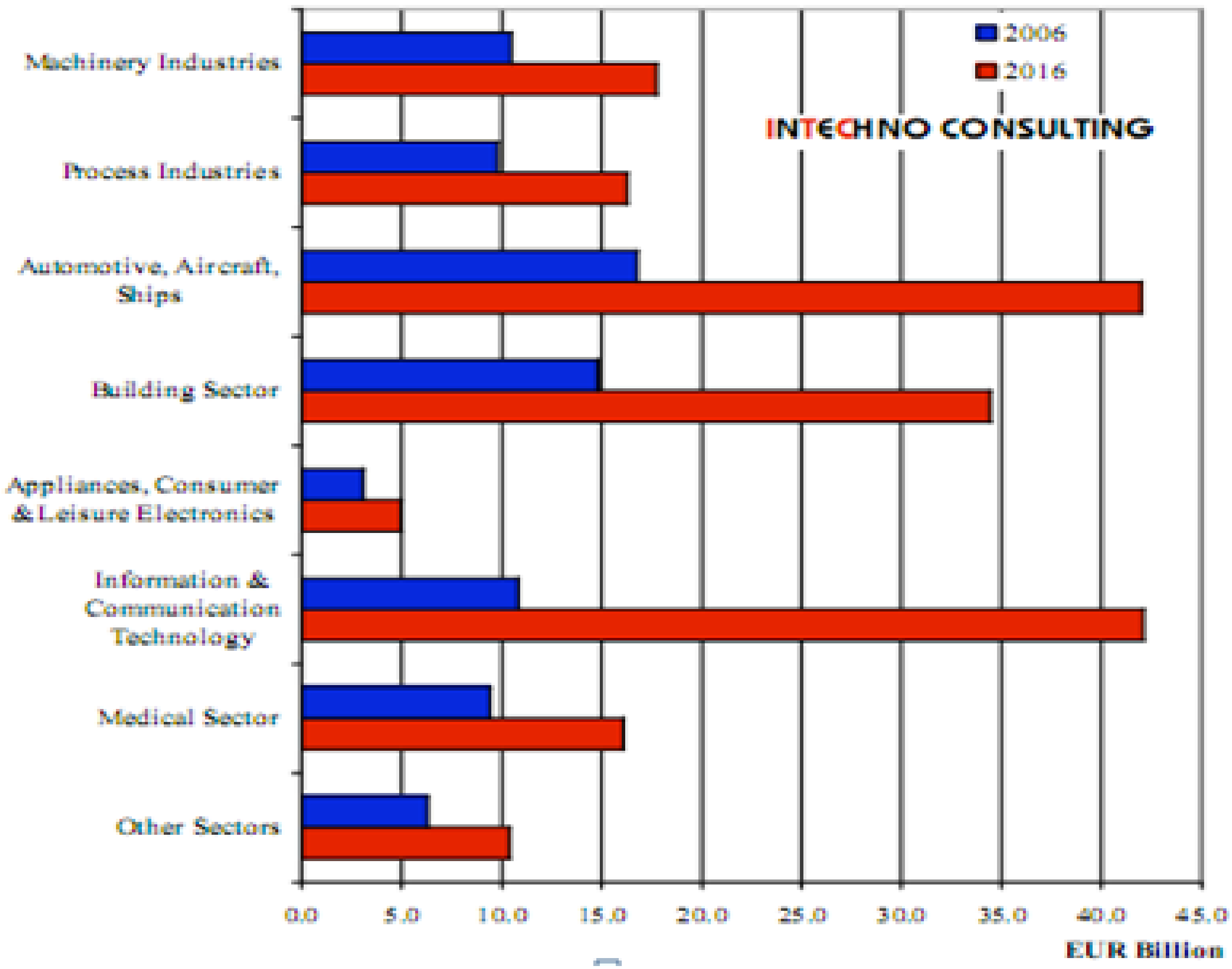
Knowledge discovery - Translation of data into actionable information



- Actionable insights 24 hours a day
- Detection of process irregularities
- Identification of operational modes to mitigate GHGs
- Integration of data to build prediction models

Support WWTP operation and facilitate the integration of sustainability metrics in the decision making.

Sensor Technology Adoption



Analysis of the non-military, Open World Market for sensors until 2016: subdivision by major industries. (source: Analysis of Industry 4.0, Definition and Future Direction, 2017, *EU-Commission*, by Mousavi et al)

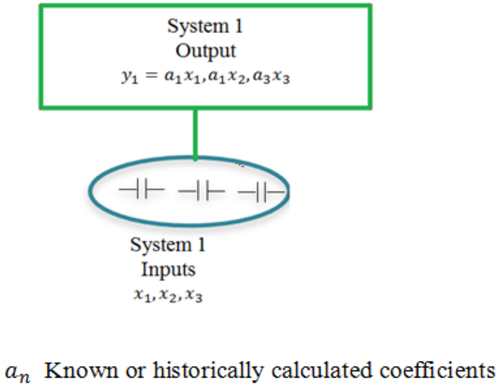
2. System Modelling and Simulation using Hybrid Learning techniques

- **Deep Learning & Neural Networks: constraints of Historical Data and Curve Fitting**
  - Image Processing: HOG+SVM vs **EGI (real-time and computational time/effort)**
  - Helps for reinforced learning
- **Event Modelling for Real-Time modelling and Decision making**
  - Digital Feature Extraction, State Space Definition Modelling, Control and Optimisation (DNA of process)
  - Improving Numerical Models for Multi-objective optimisation (e.g. scheduling problem, Estimating Remaining Useful Life, GHG emissions, Energy Efficiency, Autonomous Vehicles, Decision Making in Real-time)
  - Applied to a wide applications in Process, Security, Autonomous Vehicles, Smart Machine Tools & Robotics

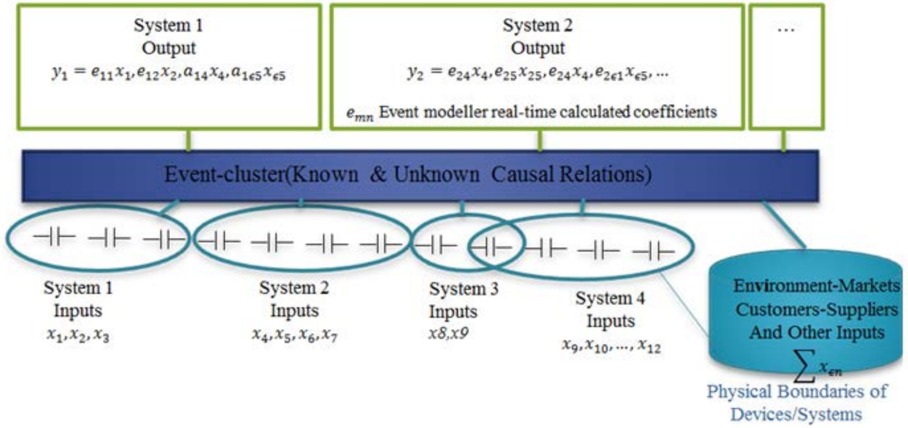
Introduction to Event Modeller: Complex system theory approach

- Current complex system model relies on the isolated system combined into predictive models

- Event Modeller is tool for detecting, classifying and analysing the impact of the previously unknown factors



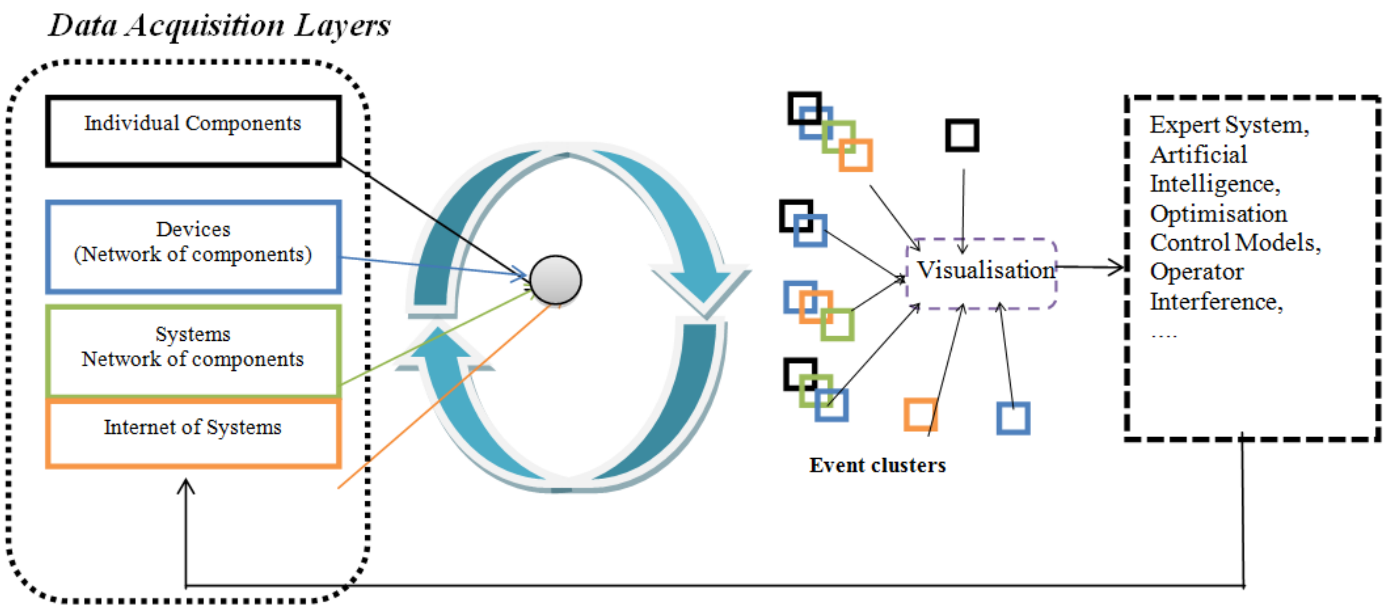
Current system model



EventCluster model

Event Modeller Concept

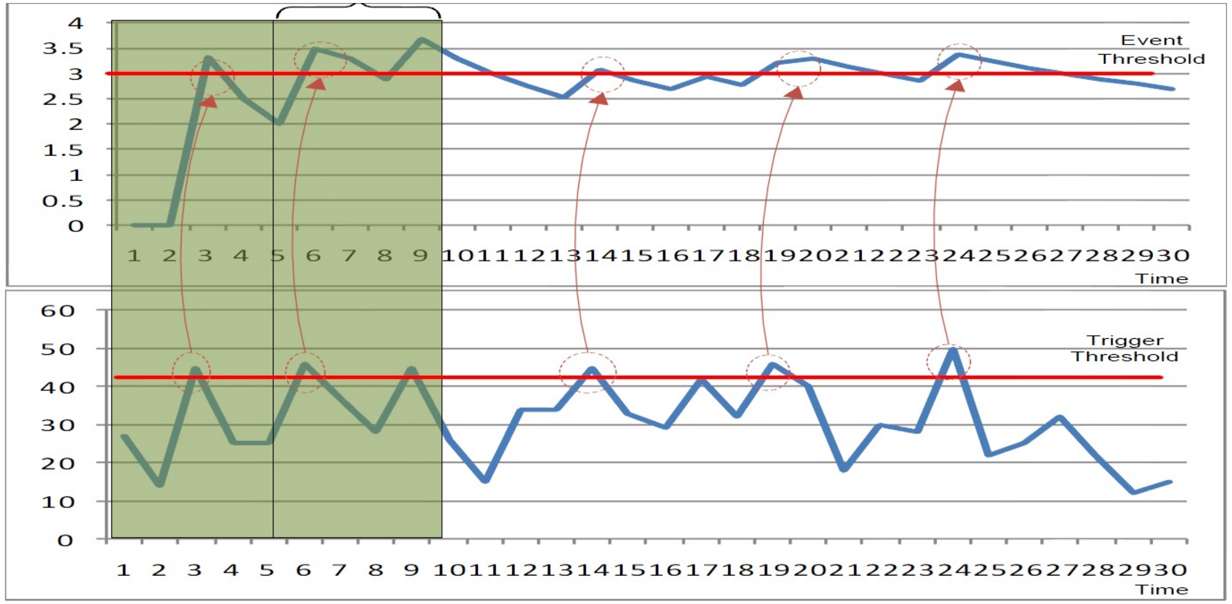
- A big picture to helps to visualise
- System's input/output correlations
- Decomposition of data which comes from divergent source and then composition of cause-effect clustering of system's input events
- middleware between plant and environmental information sources (raw data) with higher level information management systems and optimisation tools.



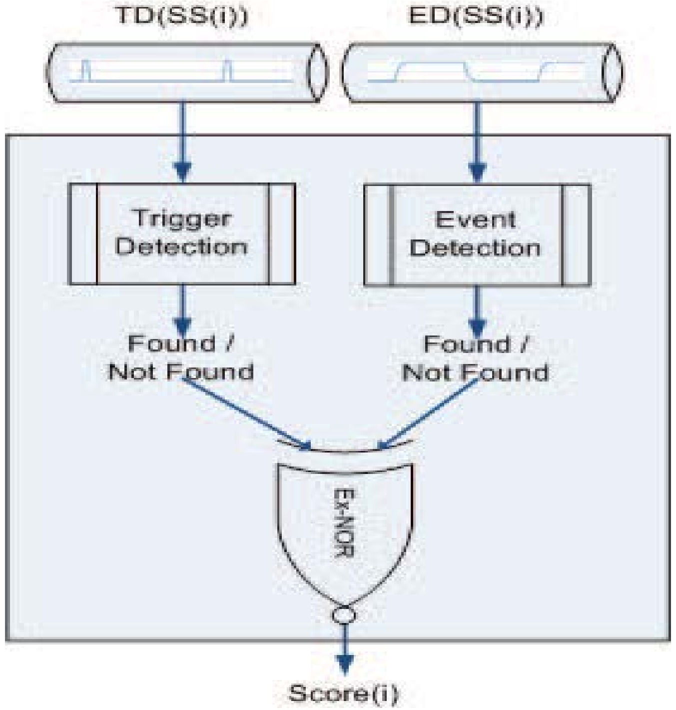
Data decomposition and composition in EventModeller

Introduction to Event Modeller: Algorithm

I. Trigger Data and Event Data detection/ Two-way Matching



Input 1	Input 2	Output
0	0	+1
0	1	0
1	0	0
1	1	+1



Introduction to Event Modeller: Algorithm

II. Build a coincidence matrix of inputs events (rows) and process outputs (column) (Many to One Relationship)

III. Implement Rank Order clustering (ROC) algorithm (Many to Many)

IV. Normalisation of ROC matrices and Classification of System State

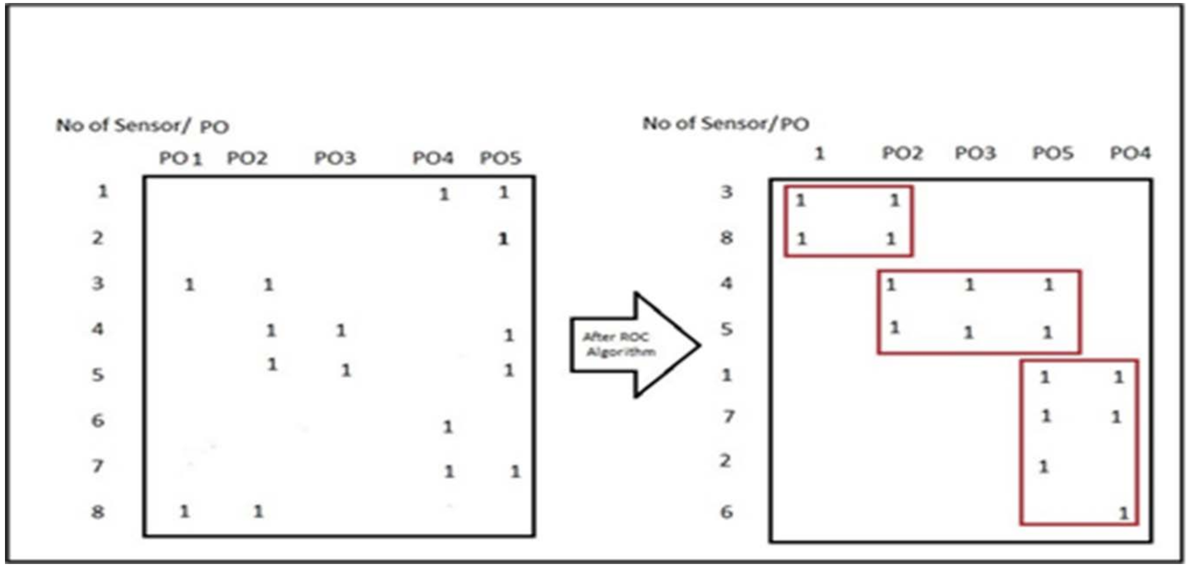
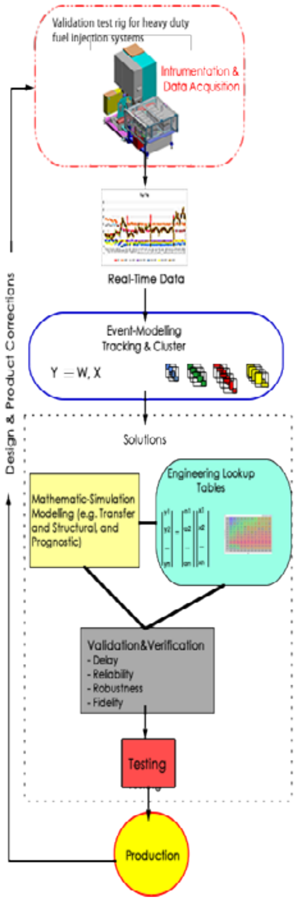
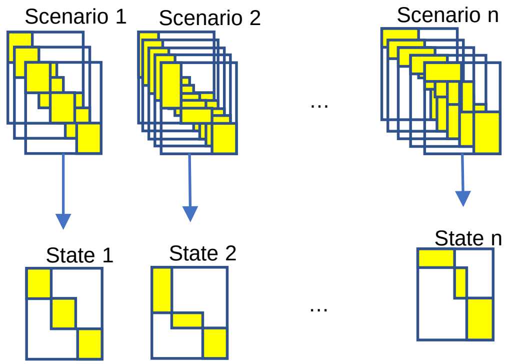
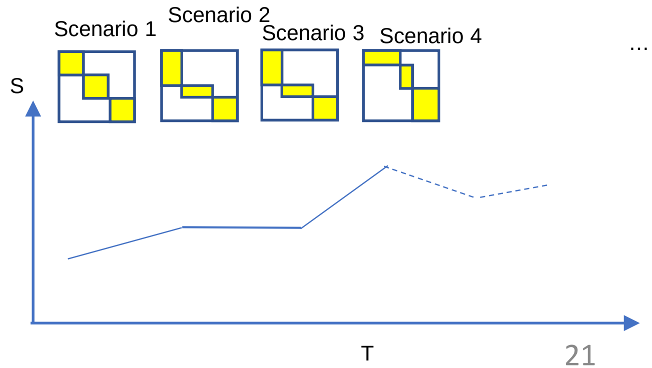


Figure 2: The proposed generic adaptive product testing and evaluation platform



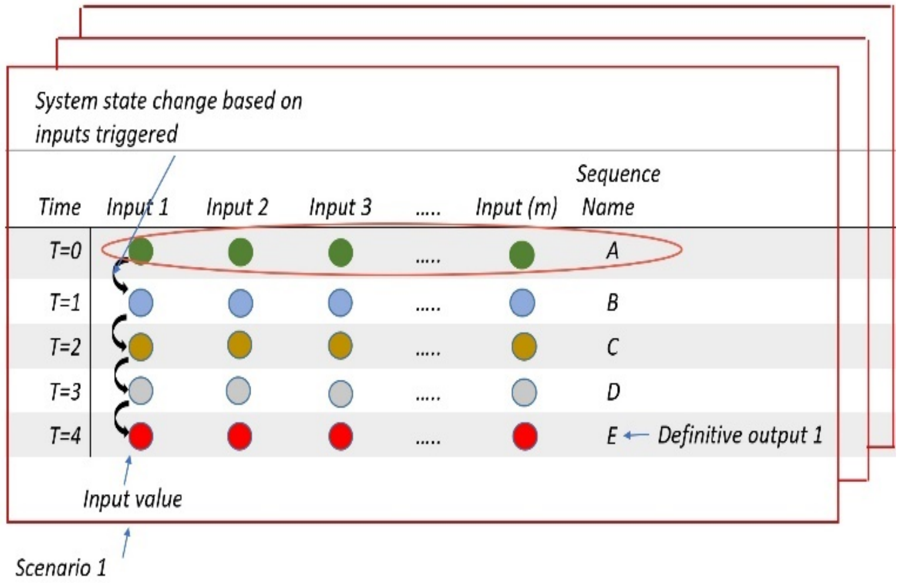
Event Modeller Look up Solution





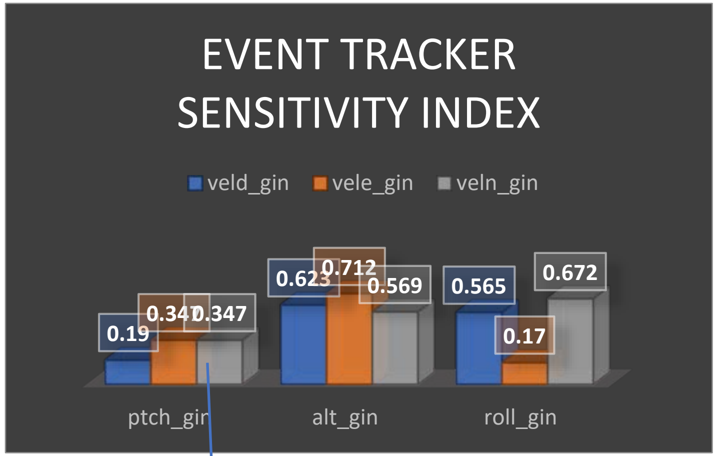
Introduction to Event Sequence Predictor (ESP)

- Based on Theory of Event-Base Genomics of Industrial Process (GIP)
- The Theory of GIP's term was borrowed from biology and genetic science to label and establish sequential event differentiation.
- Akin to a DNA chains the string of events are symbolised representing manufacturing process causal relationships and contiguous occurrences.
- These labelled genomes of the process are being used to predict the events according to their occurrence sequence.

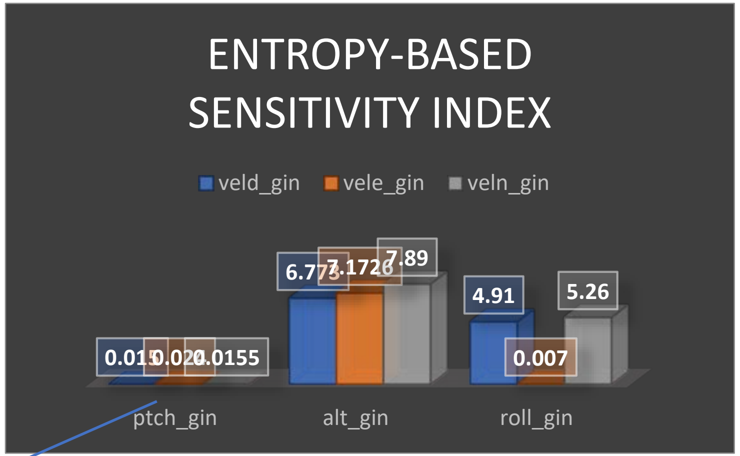


EventTracker vs Entropy-based Sensitivity Analysis

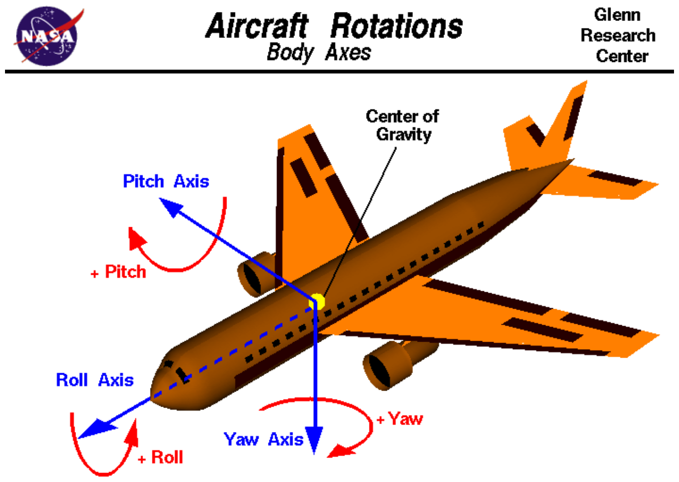
Comparison at 90msec interval



Range 0-100



Range 0-10



Tera bytes of flight data from a Bae aircraft

Input	Output
Velocity Down	Altitude
Velocity East	Pitch angle
Velocity North	Roll angle

Area of interest…

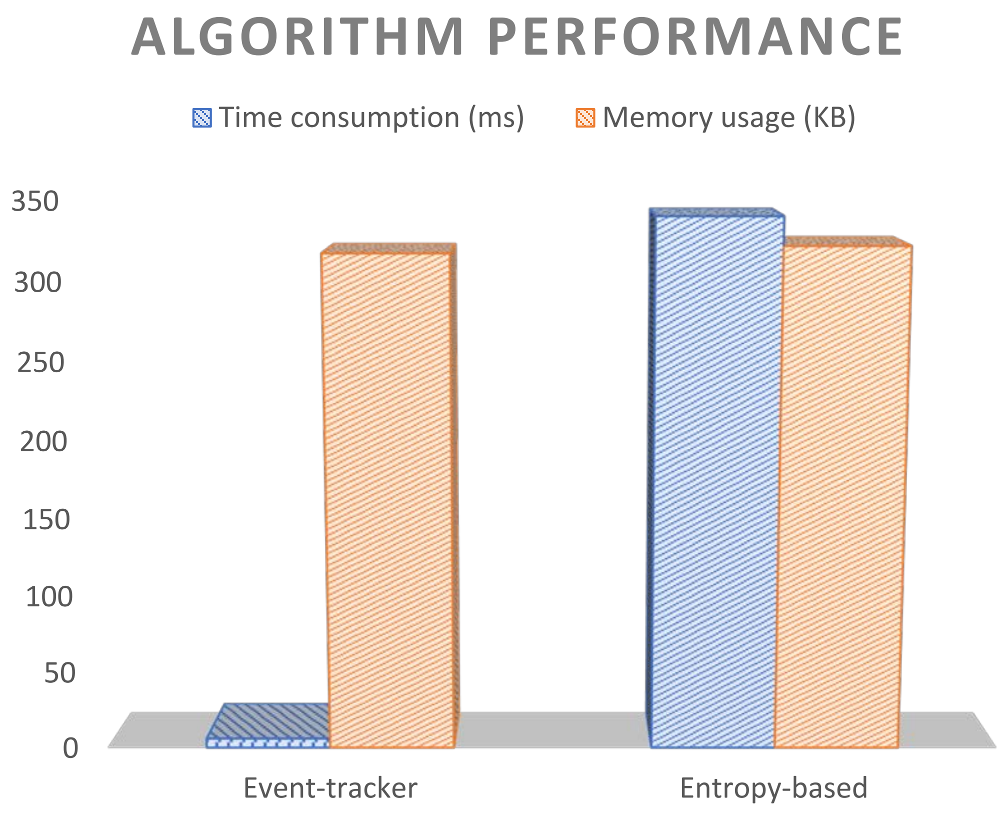
Sensitivity Analysis results are Similar

Time Critical Systems – Quick response

- Same computational effort
- 65 times faster faster
- Same results in detecting the relationship between system parameters

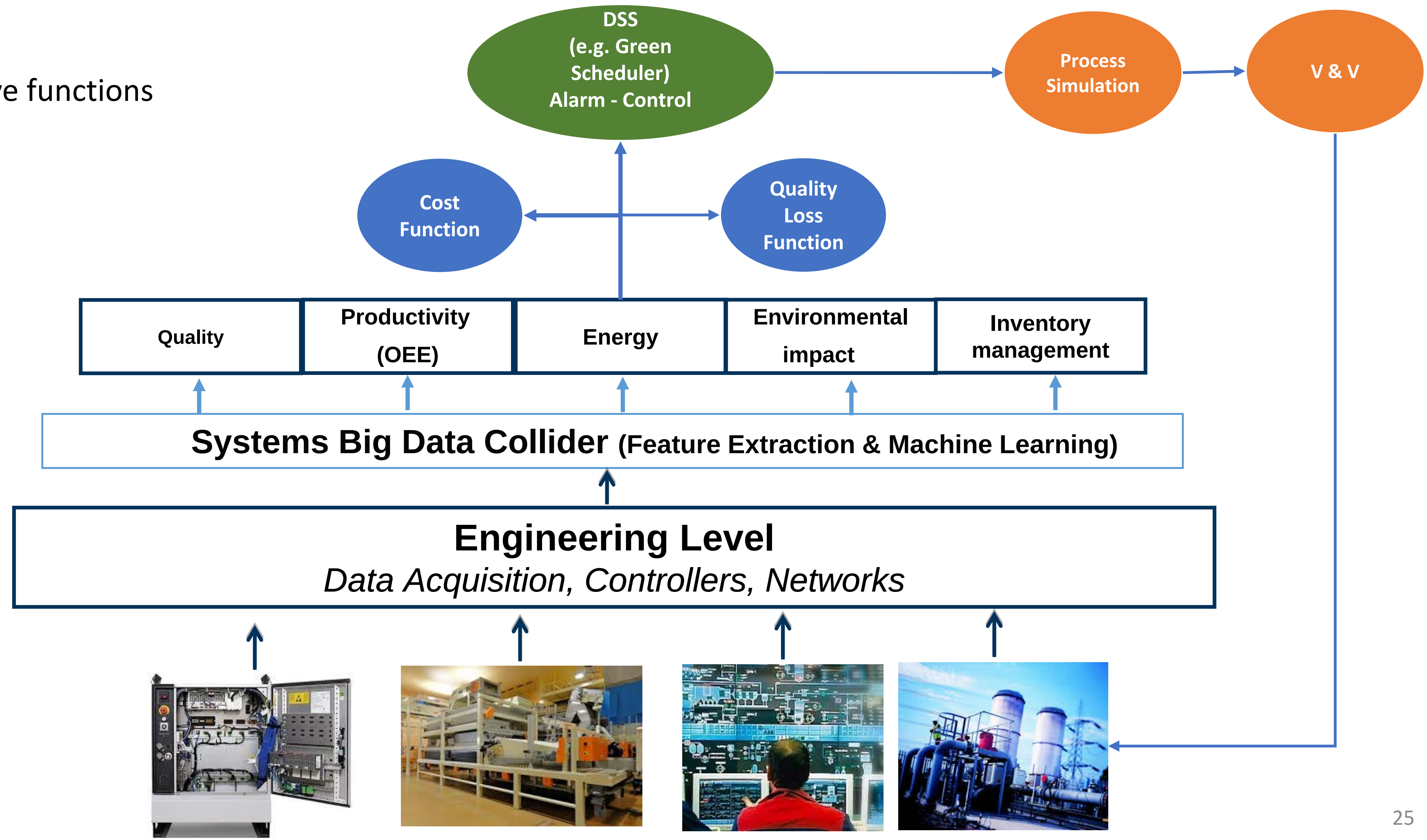
- Alternative pathways to a solution

back



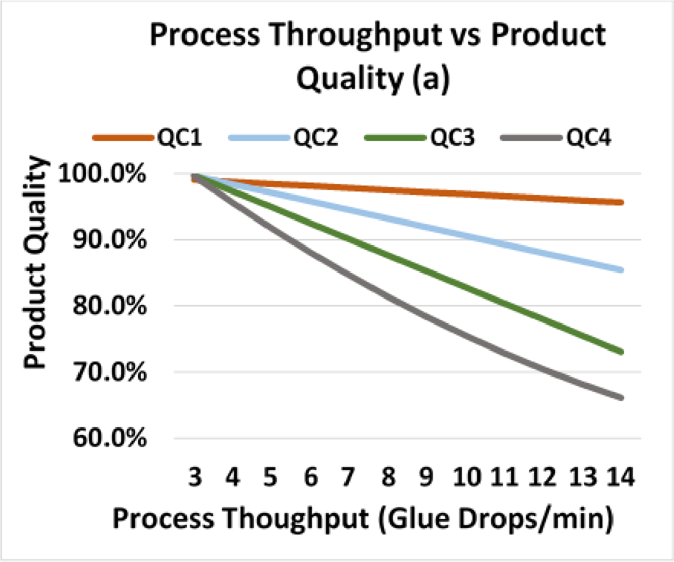
3. Systems Modelling

Multi-objective functions

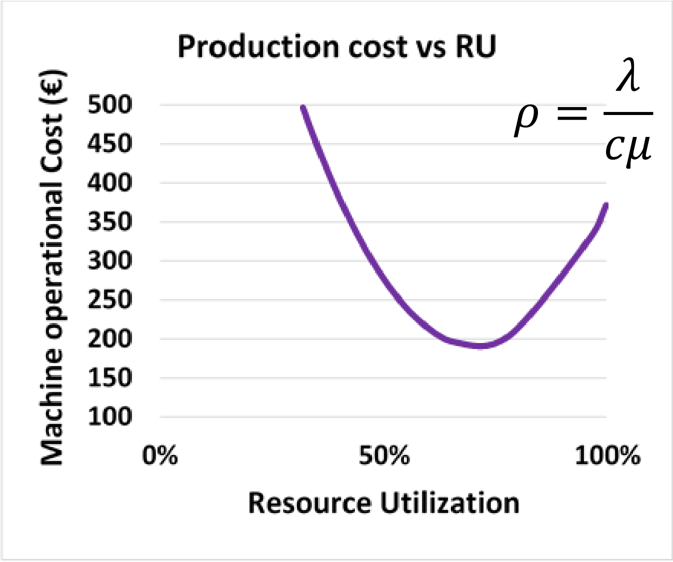


4. Integrated Cost Function for OEE

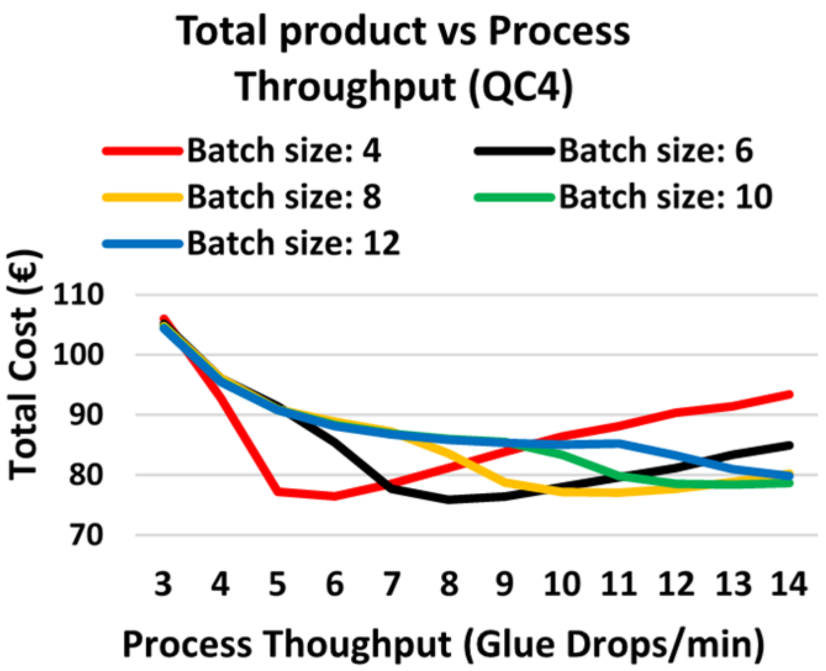
Cost Function in Semiconductor sector



a



b



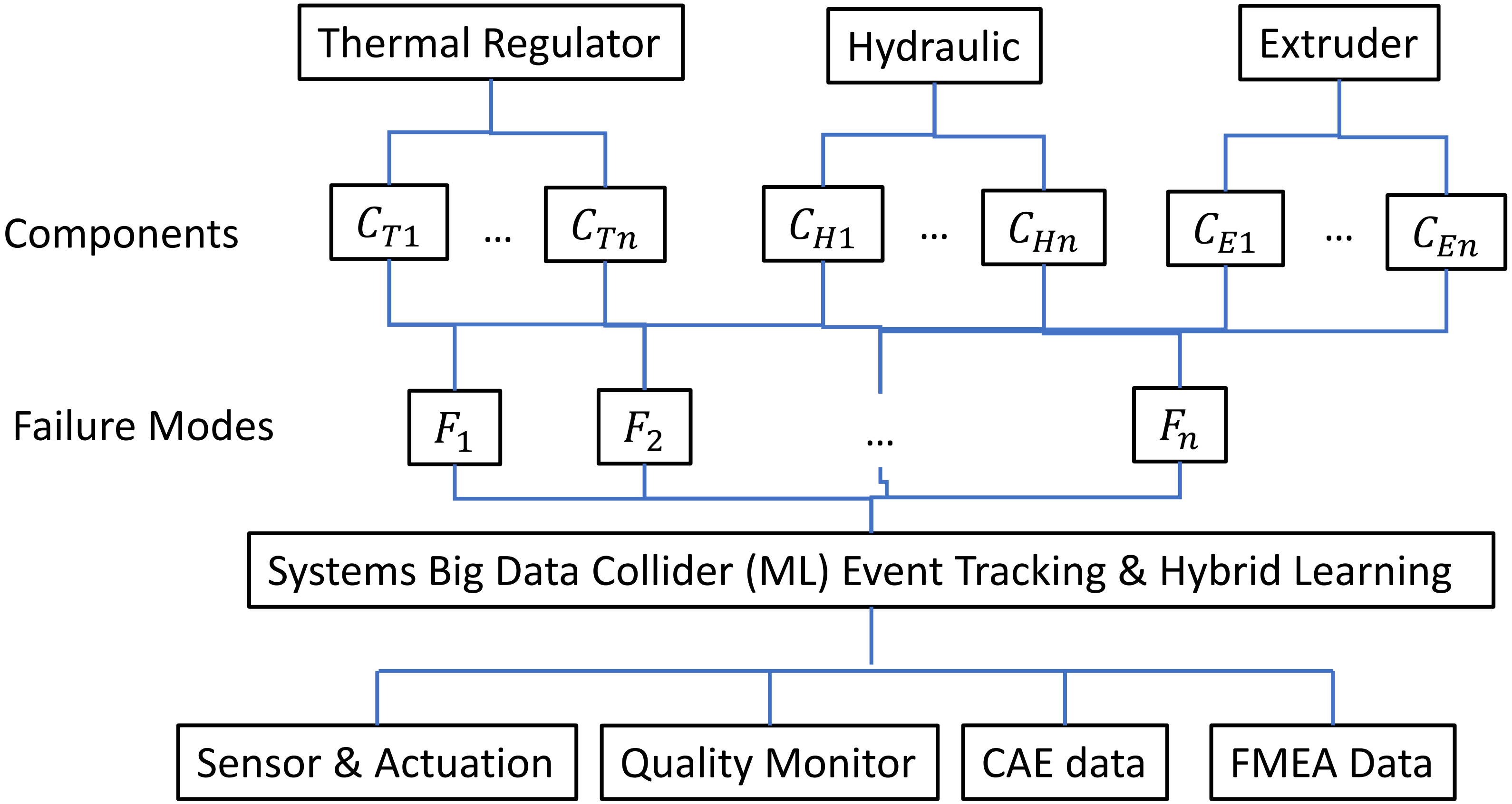
c

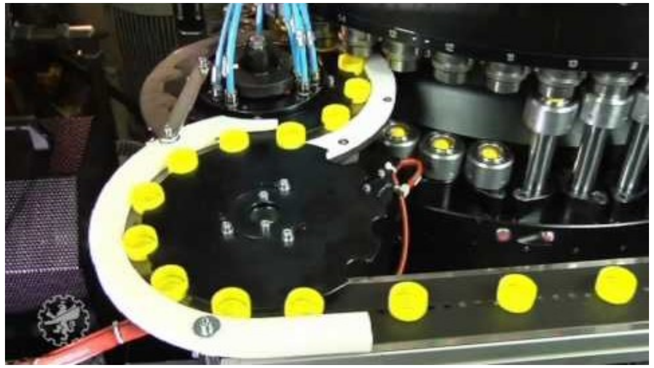
Micro… use case: Quality curves vs machine speed (left) and machine operational cost vs resource utilization (right)

Cost model vs process throughput for a real Plant use case

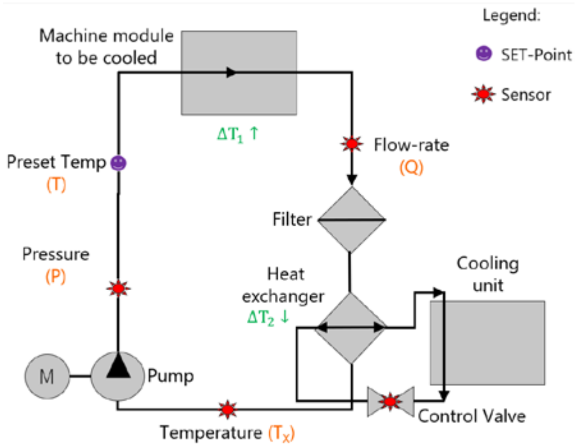
[Ref]

Predictive Maintenance of High value Machines

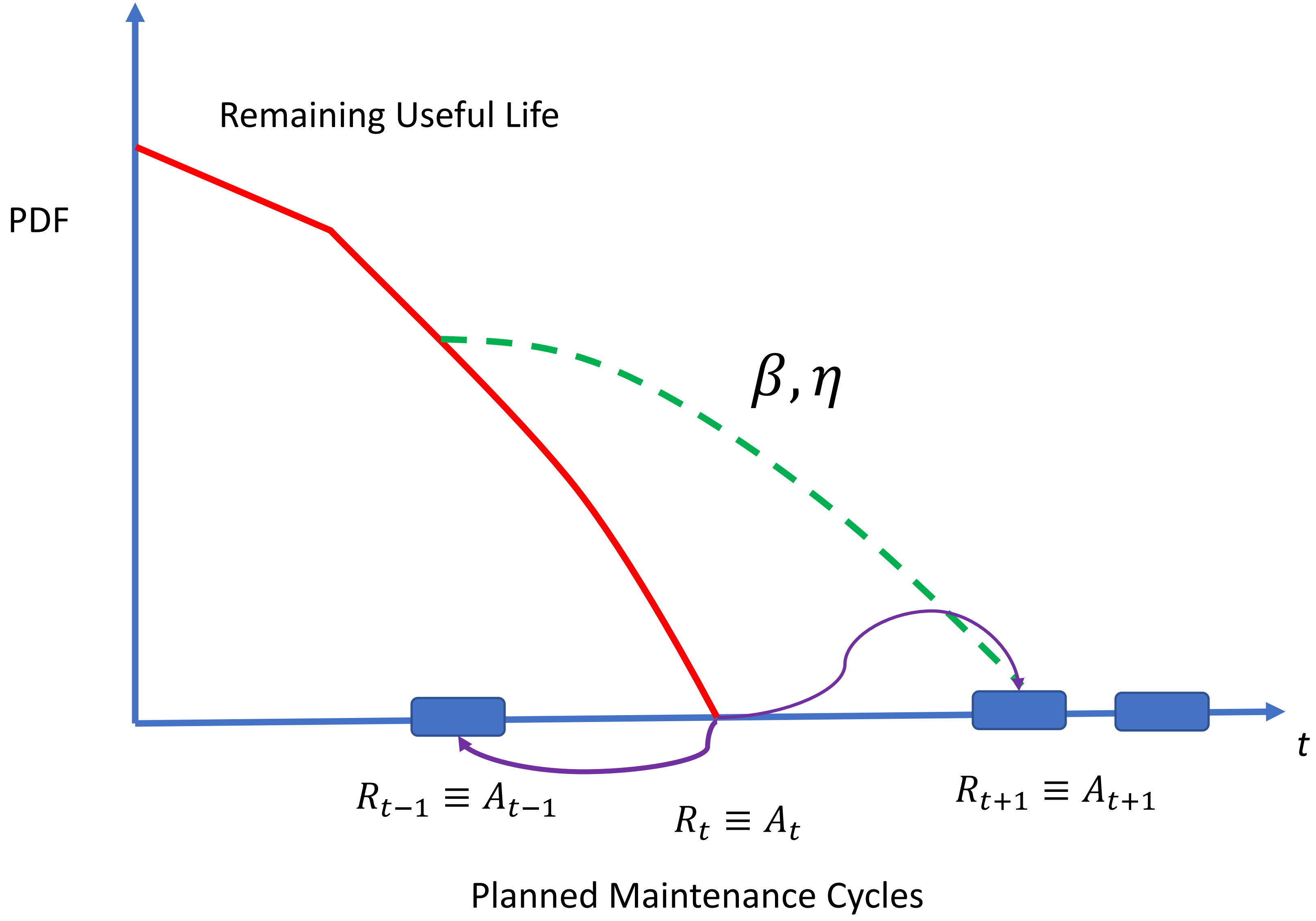




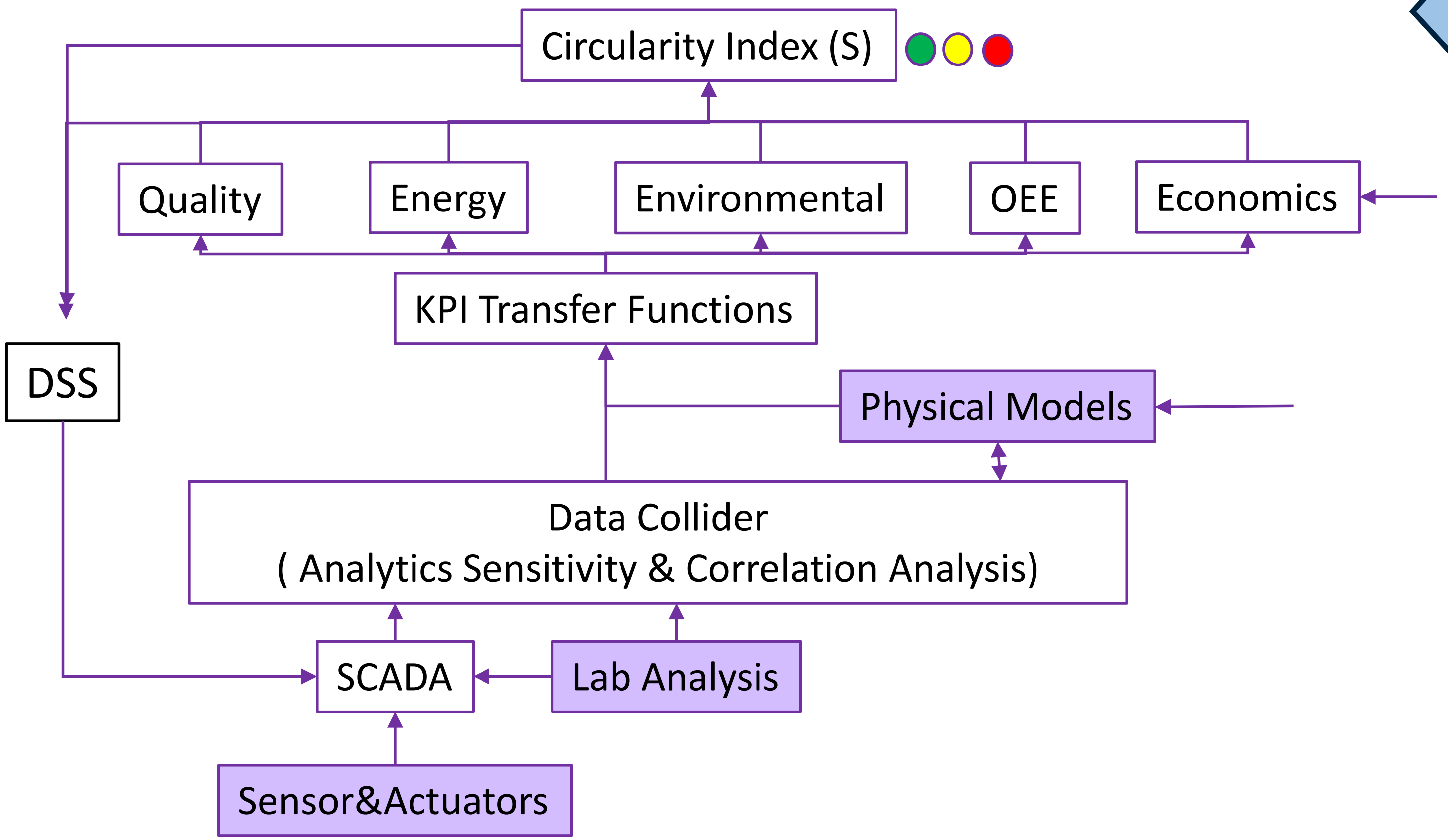
200 caps per minute
Sudden Breakdown costs $5M/hour



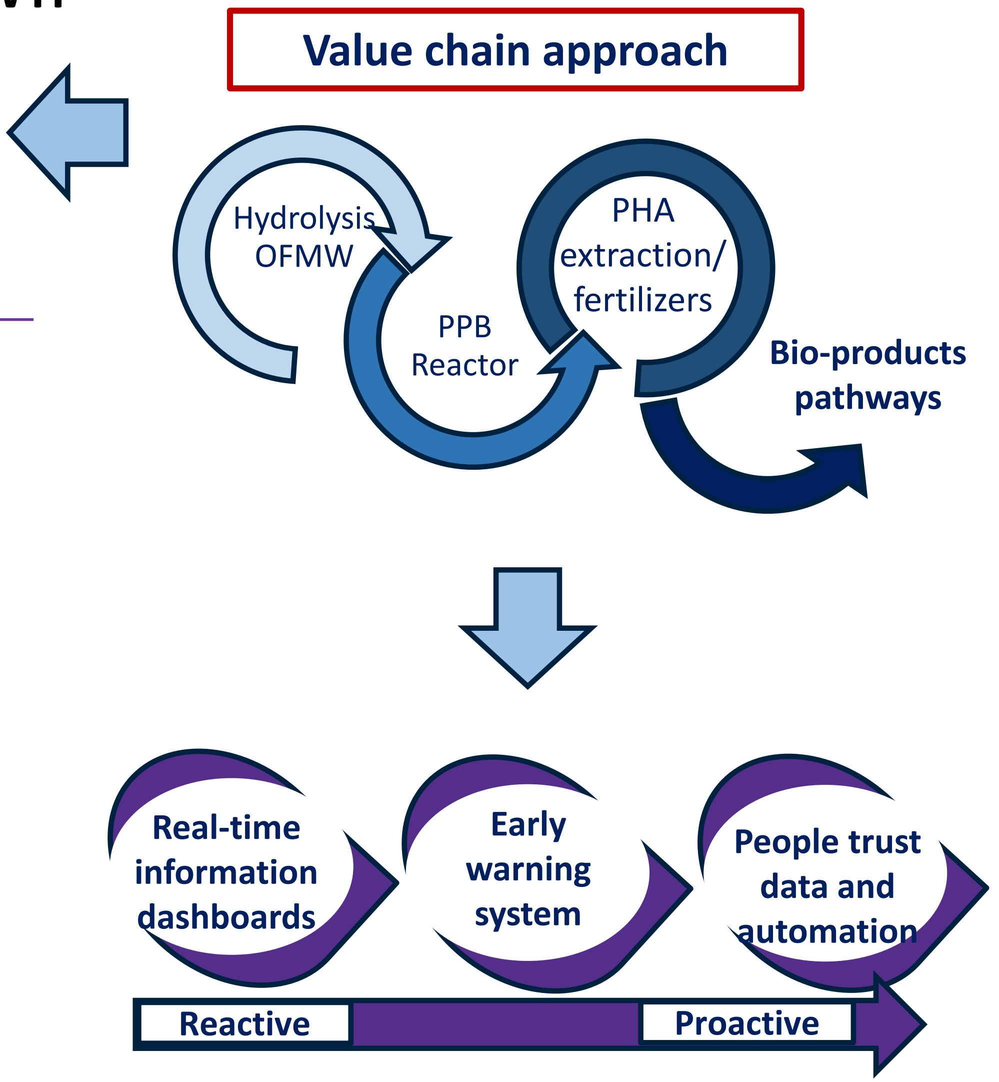
Dynamic Depreciation Curve – Maintenance DSS



Measurement and Scale Up of Digital Platform for Water & WWTP



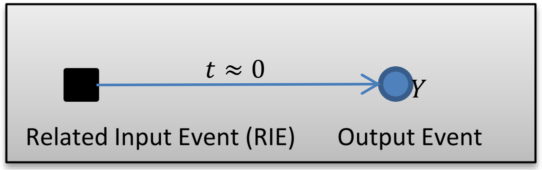
Process Map



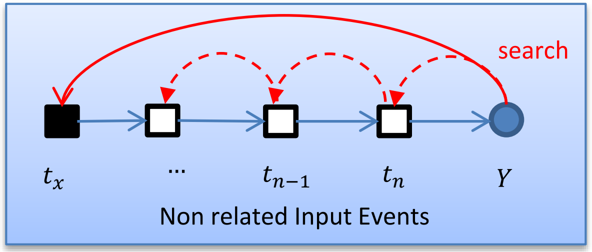
"This project has received funding from the Bio Based Industries Joint Undertaking (JU) under the European Union's Horizon 2020 research and innovation programme under grant agreement No 837998. The JU receives support from the European Union's Horizon 2020 research and innovation programme and the Bio Based Industries Consortium.".

Event Tracking & Control Challenges

t_n: time the Output Occurs

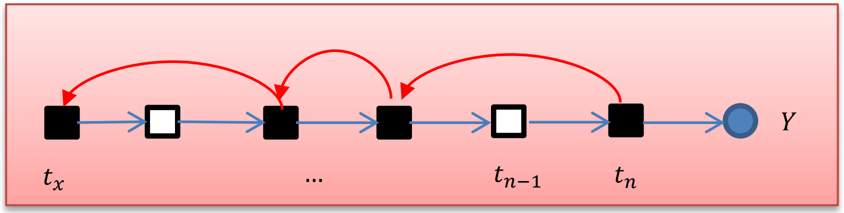


Instantaneous Deterministic Event (Current Event Tracker Model)

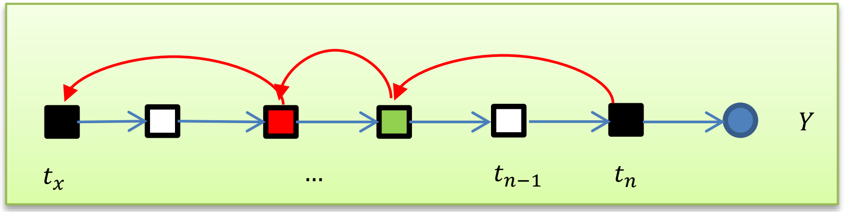


Fixed Time Delayed Deterministic Event – Output event occurs after a fixed time when The relevant input occurs. This can also help us optimise scan rates.

$$Input\ (t_x) \xrightarrow{T=t} Output(x)$$

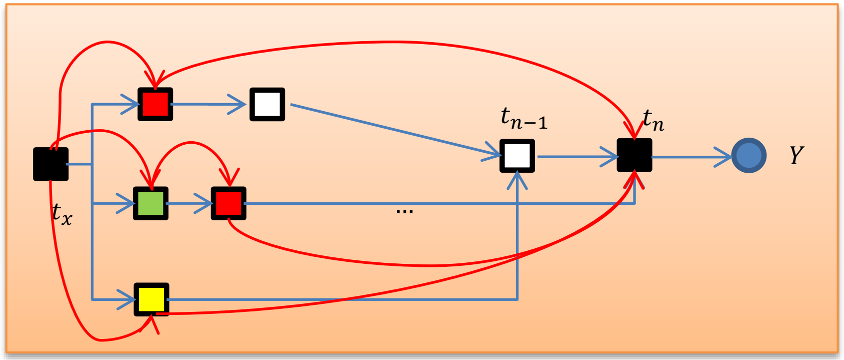


Deterministic singular input multiple occurrence delay. In this case the same input event should repeat itself a number of times until the output event occurs. $n \times Input(x) \xrightarrow{T=t} Output(x)$



Deterministic sequence of different input events causing an output event (Deterministic Process). In this case a number of specific input event series results in a specific output. Conditional Chain

$$Input\ (x) \wedge Input(y) \wedge Input(z) \wedge \ldots \xrightarrow{T=t} Output(x)$$



Search in various scenarios for common input event and find the alternative pathways, akin to a tree Petri-Net, Monte-Carlo Tree, ….
Conditional Random Events in Markov Process $P(E/F)\ \frac{P(E)\cap P(F)}{P(F)}$

30

Future Proliferation and Scale Up:

1. Sensors and Data acquisition science and technologies
2. Automation and Smartification of Continuous and Discrete Advanced Manufacturing/Production Processes
3. Embedding Intelligence in Machine Tools and Robotics
4. Zero Waste Industrial Systems through Industry 4.0


A TIME OF TRANSFORMATION.
STRATEGY NUMBER ONE NEXT
BMW Group's plan of action is to be NUMBER ONE and to inspire people on the move. We shape tomorrow's individual premium mobility.
BMW PRODUCTION NEXT
Production strategy targets:
THE LEADING PRODUCTION SYSTEM: We integrate future products and technologies that exceed customer expectations.
MINI NEXT.
MINI NEXT is our plan of how Plants Oxford and Swindon will contribute to the BMW Group's strategy.
2018 We improve our competitiveness.
THE COMPETITION IS CHANGING.
New, cash-rich, tech giants are also exploring revolutionary car technology. Artificial Intelligence and driverless cars will change our world.
CURRENT COMPETITORS.
NEW COMPETITORS.
dyson
INDUSTRY 4.0.
Industry 4.0 is the fourth phase of the industrial revolution. It is a major shift forwards in modern manufacturing.
Human-robot collaboration
Automating repetitive tasks improves ergonomics and supports associates.
3D Virtual Simulation
The virtual world allows us to test processes before they are implemented on the line.
3D printing
We can quickly and economically prototype fixtures, fittings and parts.
2019 We are the best LU plant in the BMW Production network.
New and existing partnerships
New partnerships give us access to the skills, knowledge and technology we need to be NUMBER ONE!
MINI
The first fully electric MINI will be built at Plants Oxford and Swindon and we are proud to be part of the future.
2020 We launch the electric MINI.
VALUES.

24/10/2020

Sample Publications on Real-Time Feature Extraction, Data Analytics and Systems Modelling – Control and Process Optimisation

1. Geng, H., Wang, Z., Cheng, Y., and Mousavi, A. (2020). Protocol-Based Tobit Kalman Filter under Integral Measurements and Probabilistic Sensor Failures, *under review in IEEE Transactions on Signal Processing. Minor final revision sub*mitted Oct 2020 [submitted draft available]

2. Danishvar, M., Danishvar, S. Katsou, E., Mansouri A., and Mousavi A. (2020), Implementing Multi-Objective Batch Base Job Shop Scheduling Optimisation (MOBS-NET) using Fully Connected Deep Neural Network. *International Journal of Production Research or European Journal of Operational Research.* submitted Jul 2020 [Draft available]

3. Danishvar, M., Mousavi, A., Danishvar, S. (2020). The Genomics of Industrial Process through the Qualia of Markovian Behaviour, *under review IEEE Transactions on Systems, Man and Cybernetics: Systems*. *minor revision completed and submitted* Aug. 2020 [submitted draft available]

4. Psarommatis, F., Danishvar, M., Mousavi, A., Kiritsis,D. (2020). Cost-Based Optimization of manufacturing Key Performance Indicators for Zero Defect Manufacturing, *under review International Journal of Production Research.* Submitted Apr 2020. [submitted draft available]

5. Razgon, M., Mousavi A., and Angadi, V. (2020), Relaxed Rule-based Learning for Automated Predictive Maintenance: proof of concept, *Algorithms, 13(9),* doi.org/10.3390/a13090219.

6. Vasilaki V., Danishvar S., Mousavi A., Katsou E. (2020), Data-driven versus conventional N2O EF quantification methods in wastewater; how can we quantify reliable annual EFs?, *Computers and Chemical Engineering.* doi.org/10.1016/j.compchemeng.2020.106997.

7. Huang Z, Li M, Mousavi A, Danishvar, M. and Wang, Z. (2019), EGEP: An Event Tracker Enhanced Gene Expression Programming for Data Driven System Engineering Problems, *IEEE Transactions on Emerging Topics in Computational Intelligence, 3(2), 117 – 126.*

8. Danishvar, M. Mousavi, A. and Broomhead P. (2018), Modelling the Eco-System of Causality: The Real-Time Unaware Event-Data Clustering (EventiC), *IEEE Trans Systems, Man and Cybernetics*, (99), 1-19, doi: 10.1109/TSMC.2017.2775666

9. Li, M.; Huang, Z.; Chousidis, C.; Mousavi, A. and Jiang, C. (2017), Schema Theory Based Data Engineering in Gene Expression Programming for Big Data Analytics, *IEEE Transactions on Evolutionary Computation*, Volume: PP, Issue: 99; doi: 10.1109/TEVC.2017.2771445.

10. Mousavi A., and Siervo, H.A. (2016), Automatic Translation of Plant Data into Management Performance Metrics: A Case for Real-Time and Predictive Production Control, *International Journal of Production Research*, (55) 17, 4862-4877. doi: 10.1080/00207543.2016.1265682

11. Tavakoli, S., Mousavi, A., & Broomhead, P. (2013). Event tracking for real-time unaware sensitivity analysis (EventTracker). *IEEE Transaction on Knowledge and Data Engineering*, *25*(2), 348-359. doi:10.1109/TKDE.2011.240

12. Tavakoli, S., Mousavi, A., & Poslad, S. (2013). Input variable selection in time-critical knowledge integration applications: A review, analysis, and recommendation paper. *Advanced Engineering Informatics: the science of supporting knowledge-intensive activities*, *27*(4), 519-536. doi:10.1016/j.aei.2013.06.002

13. Danishvar, M, Angadi, V C and Mousavi A, (2020), A PdM framework Through the Event-based Genomics of Machine Breakdown, *The 9th Asia-Pacific International Symposium on Advanced Reliability and Maintenance Modelling 2020, Vancouver, Canada; August* 2020 (accepted)