XXVII Congresso delle Materie Plastiche
Villa Torretta, Sesto San Giovanni (MI)
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UNIVERSITÀ DEGLI STUDI DI PADOVA

La digitalizzazione dei processi nell’industria delle materie plastiche: benefici e strategie di implementazione

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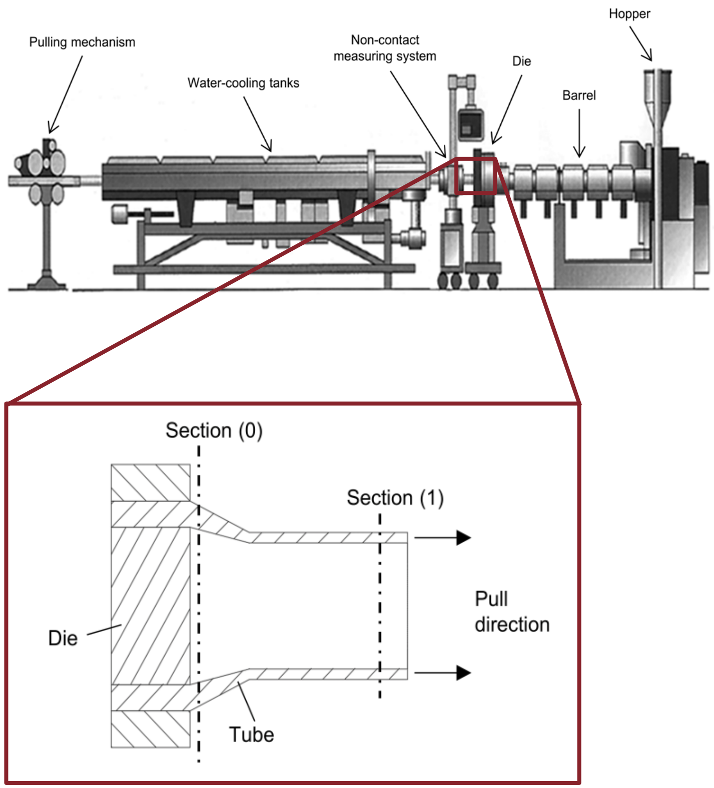
Overview

- Case study
- Benefits of manufacturing digitalization
- Enabling factors
- Implementation

Case study: problem statement

Customer requirements

- **Weight per unit length** (*g/m*)
- **Thickness** (*mm*)



Issue

Process settings tuning based on time consuming trial & error procedures

- high process inefficiencies in scrap rates
- lengthy setup phases

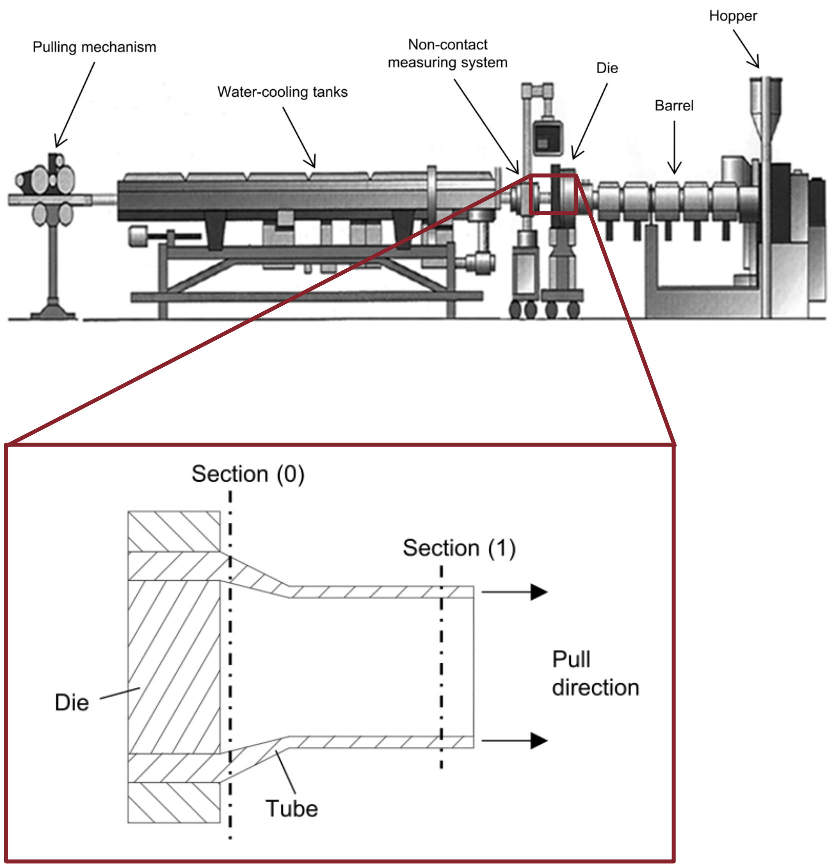
Proposed solution

Development of a soft sensor for the **flow rate monitoring *Qv*** of the extruder

Advantages

- **real-time monitoring** of the throughput of the extruder (cm^3/min) and **detecting deviations** from target product specifications
- no need for expensive equipment (X-ray systems, gravimetric dosers)
- providing the machine operator with **suggestions to adjust operating parameters** thus achieving target product specifications

Weight and thickness estimation



Soft-sensor (predictive models)

Volumetric flow rate **Qv(0)**(cm^3/min)

density ρ(g/cm^3)

Mass flow rate **Qm(0)**(g/min)

Continuity equation

Section(1)(cm^2)

Pulling speed(m/min)

Tube thickness (mm)

Weight(g/m)

Experimental

Materials

Three flexible PVCs with different viscosities

Material	Hardness, ShA	density, $\frac{g}{cm^3}$	S-PVC K70, %	$CaCO_3$, %
PVC A	80	1.44	43	28.8
PVC B	78	1.52	34.2	39.3
PVC C	80	1.35	52.9	15.3

Design of experiment

Factors	Levels
Material	PVC A, PVC B, PVC C
Die diameter, mm	17, 18, 20, 22
Screw speed N, rpm	10,15,20,25,30,35,40,45,50,55
Temperatures set, °C	L: [145,150,155,155,145,150,150,150] H: [155,160,160,165,155,155,155,155]

216 runs

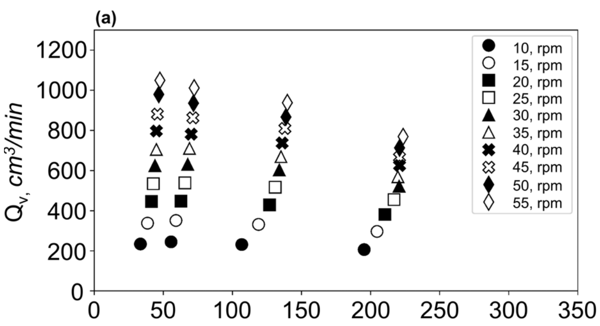
Recorded parameters

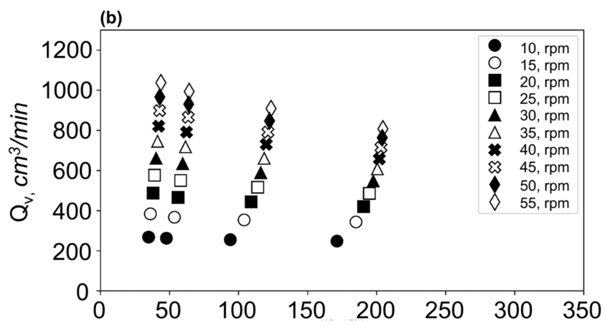
Single Screw Extruder: barrier screw, 60 mm

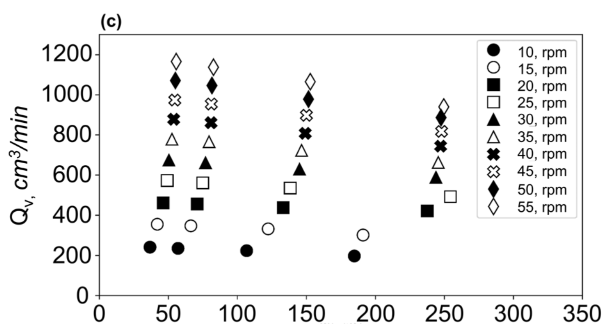
Process parameters	Screw speed N, rpm Barrel and die zone temperature (zone no. 1, 2, 3, 4) T_{barrel}, °C Pulling speed v_{line}, $\frac{m}{min}$
System parameters	Die pressure drop ΔP, bar Melt temperature T_{melt}, °C
Output parameters	Volumetric flow rate Q_v, $\frac{cm^3}{min}$ Outer diameter D, mm Inner diameter d, mm

Experimental results

Experimental results: extruder throughput







Volumetric flow rate prediction models

- Tadmor & Klein model for non-Newtonian fluids

Analytical

- Adjusted Tadmor & Klein model for materials exhibiting wall-slip

- Machine Learning Regression models

Data driven

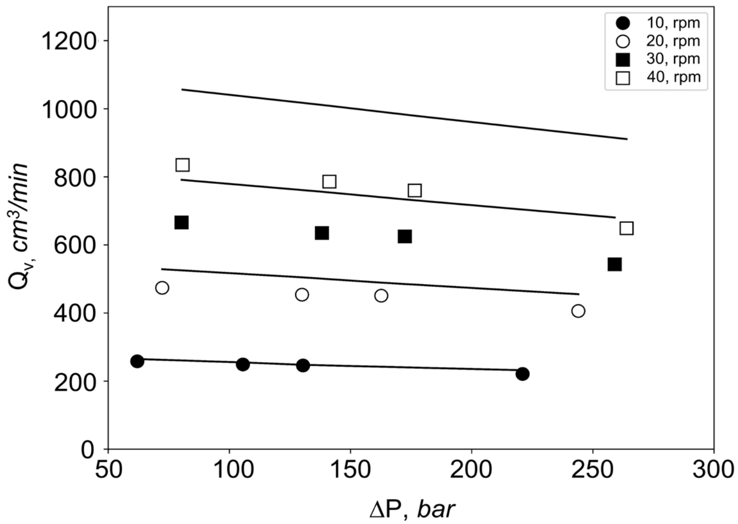
Prediction performance metric

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(Q_{v_i} - \widehat{Q_{v_i}}\right)^2}$$

Flow rate prediction: analytical models

Tadmor & Klein model

$$Q_v = \left(\frac{4+n}{10}\right)\alpha N - \left(\frac{1}{1+2n}\right)\beta\frac{\Delta P}{\mu}$$



$$\text{RMSE} = \pm 45\ \frac{\text{cm}^3}{\text{min}}$$

Issues

- the volumetric flow rate is not proportional to the screw speed at low pressure drops
  PVC exhibits wall - slip
- at constant screw speed, the model cannot describe the decrease of the flow rate when the pressure drop increases, especially at high pressure drops

Wall slip model

$$Q_v = \alpha \boldsymbol{N'} - \beta\frac{\Delta P}{m(T)\boldsymbol{N'}^{n-1}}$$

analogy with **Navier slip law**

$u_s = -\beta\tau^b$

$$N' = N - N_{slip} = N - kN^{\delta}$$

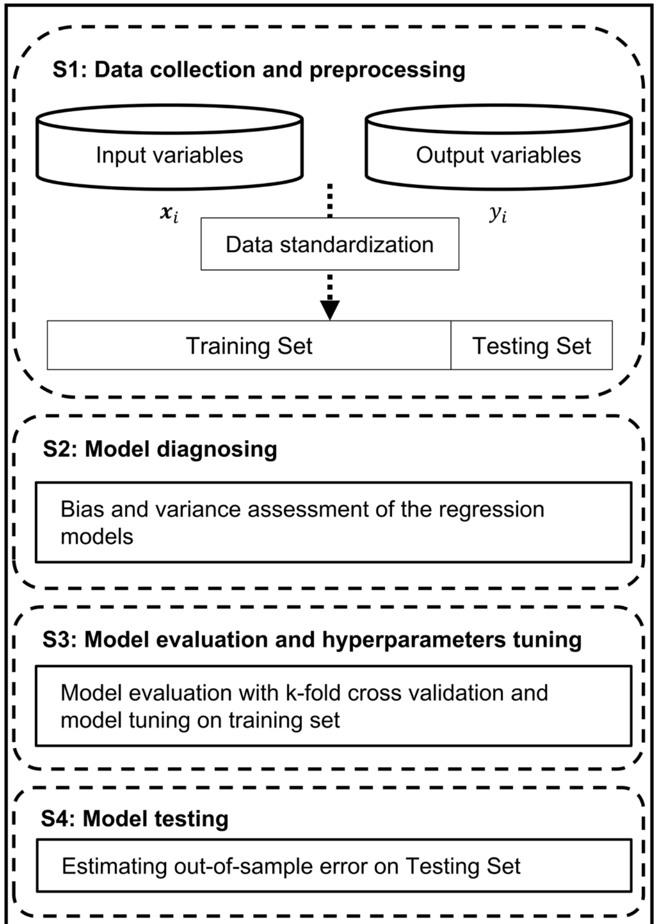
$$\text{RMSE} = \pm 29\ \frac{\text{cm}^3}{\text{min}}$$

Issues

Quality production standards require even higher prediction performance

Machine learning models

Machine Learning Regression model: Flow Rate prediction



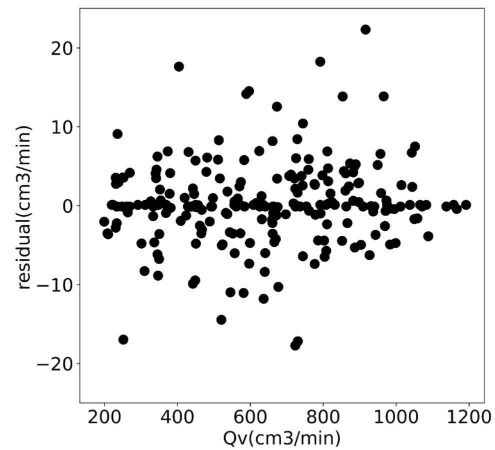
	Variable	Unit
Input Variables x_i	Screw speed, N	*rpm*
	Die pressure drop, $\Delta\mathbf{p}$	*bar*
	Melt viscosity, μ	*Pas*
	Slip	\
Output variable y_i	Flow rate, Q_v	$\frac{cm^3}{min}$

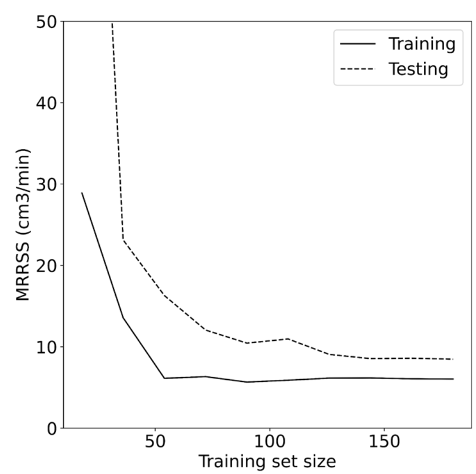
Regression results

Model evaluation

Regression method	10-folds CV test error RMSE, $\frac{cm^3}{min}$
Analytical (Tadmor-Klein)	45.00
Analytical (Slip Model)	29.26
Data-driven	
Polynomial Regression	10.35
SVR	8.61
MLP Neural Network	9.24

Model diagnostic SVR



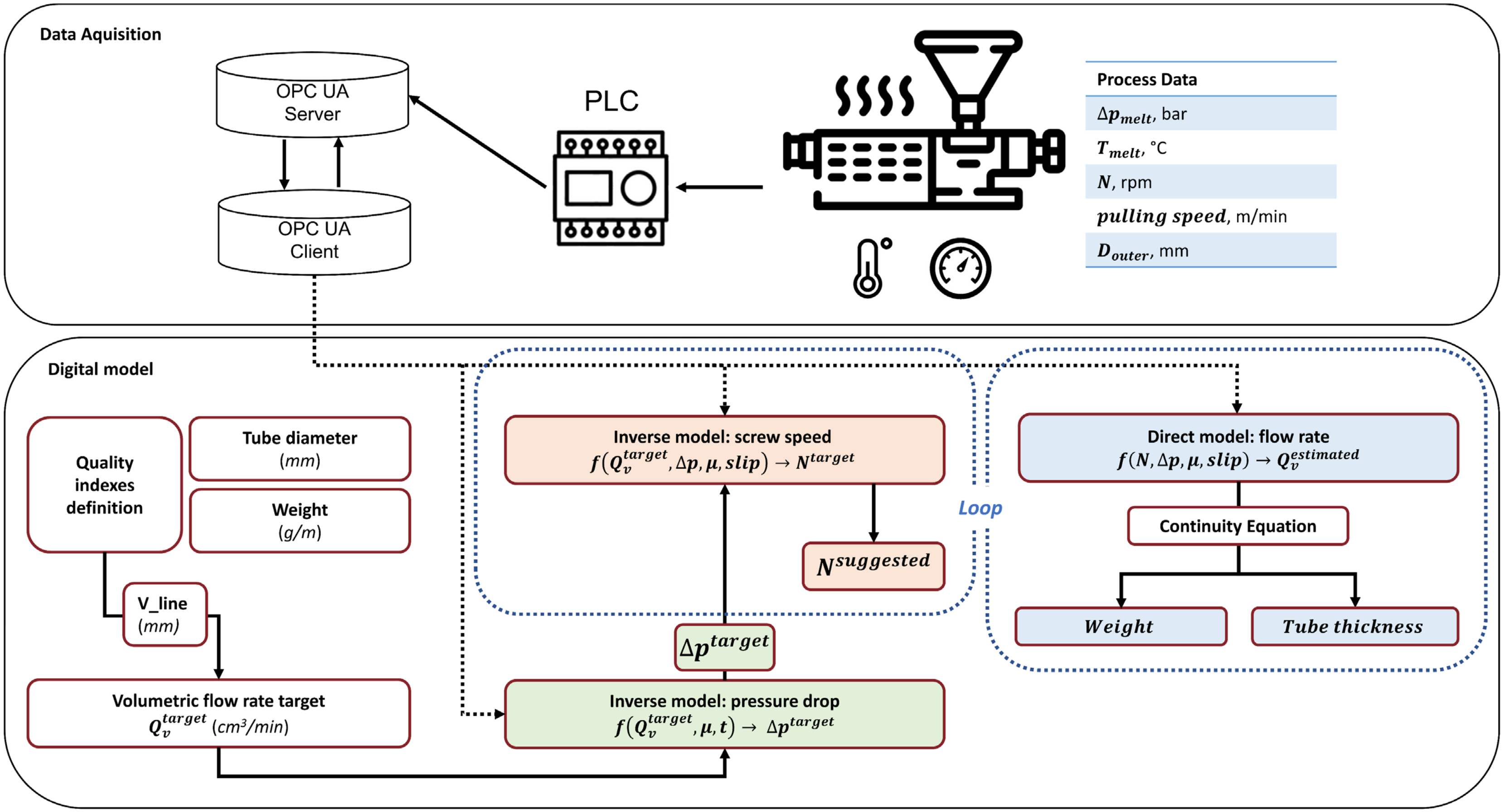


Model performance

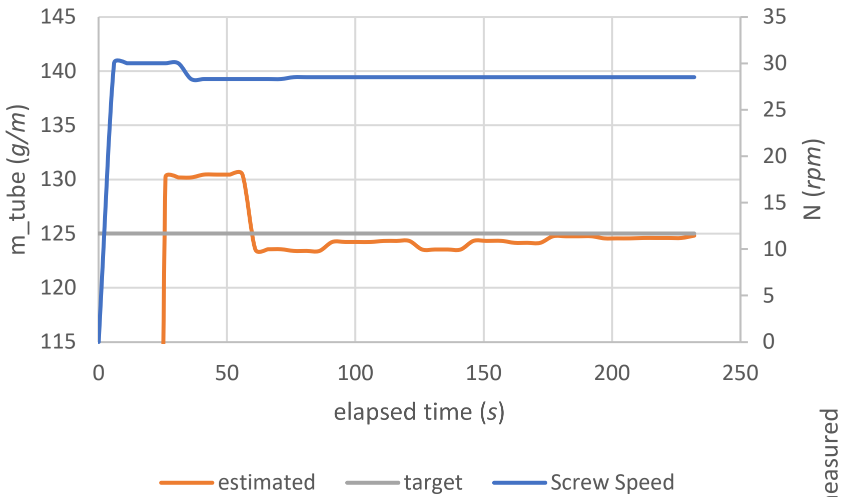
Metric		
RMSE $\frac{cm^3}{min}$	In-sample error	6.09
	Out-of-sample	7.73
MAPE %	In-sample error	0.78
	Out-of-sample error	0.89

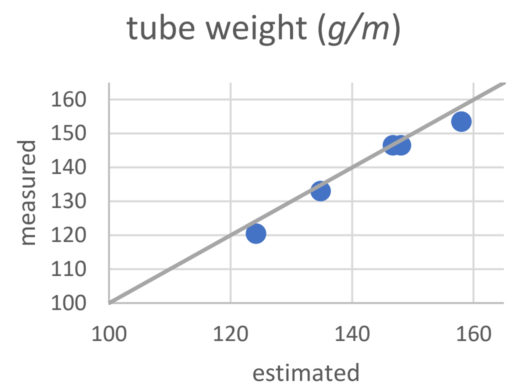
This regression model is thus suitable for predicting the extruder flow rate with the required accuracy

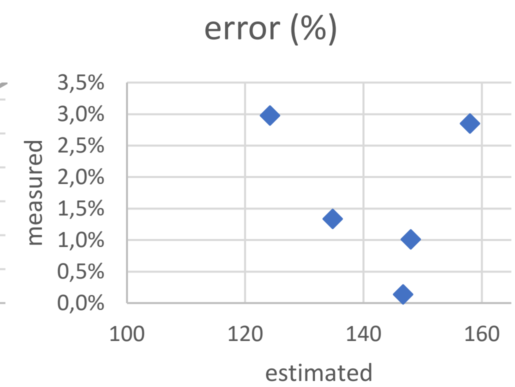
Algorithm schematic

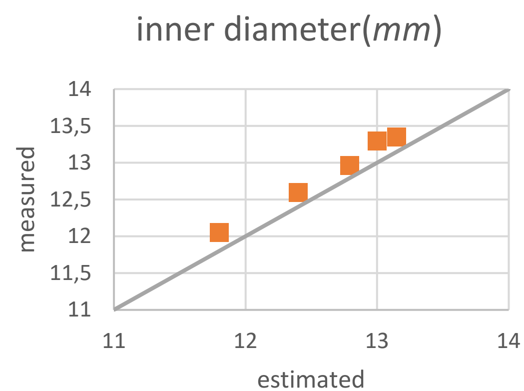


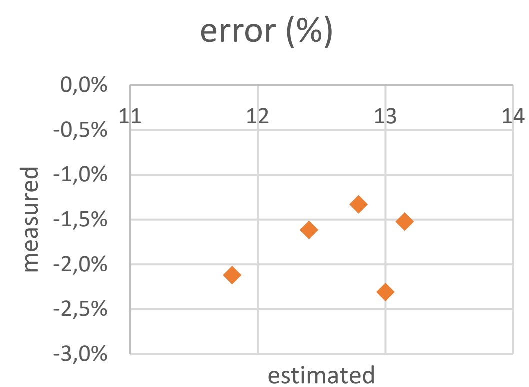
Setup simulation results











Benefits of manufacturing digitalization

1. scalability and exponential growth of the business
2. automate production
3. enable new business models
4. acquire large amounts of data
5. improve efficiency
6. manage processes through software
7. pursue mass customization

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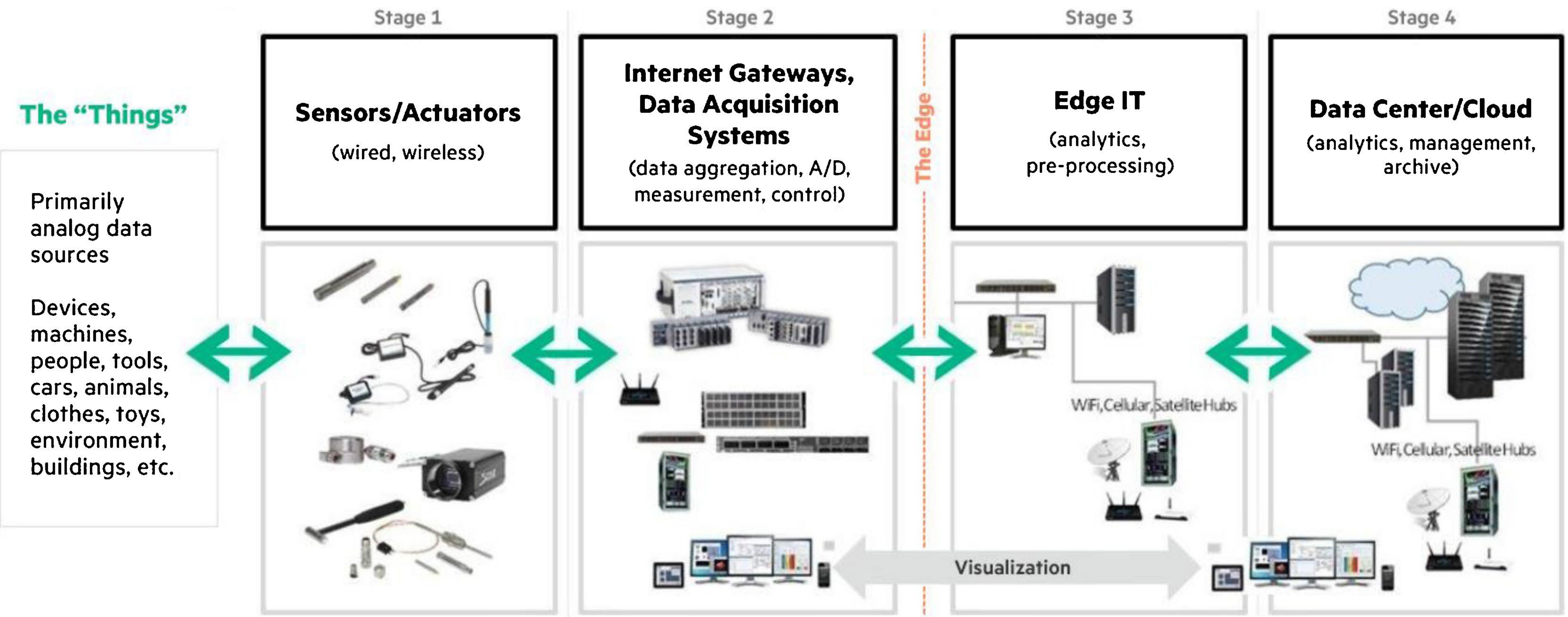
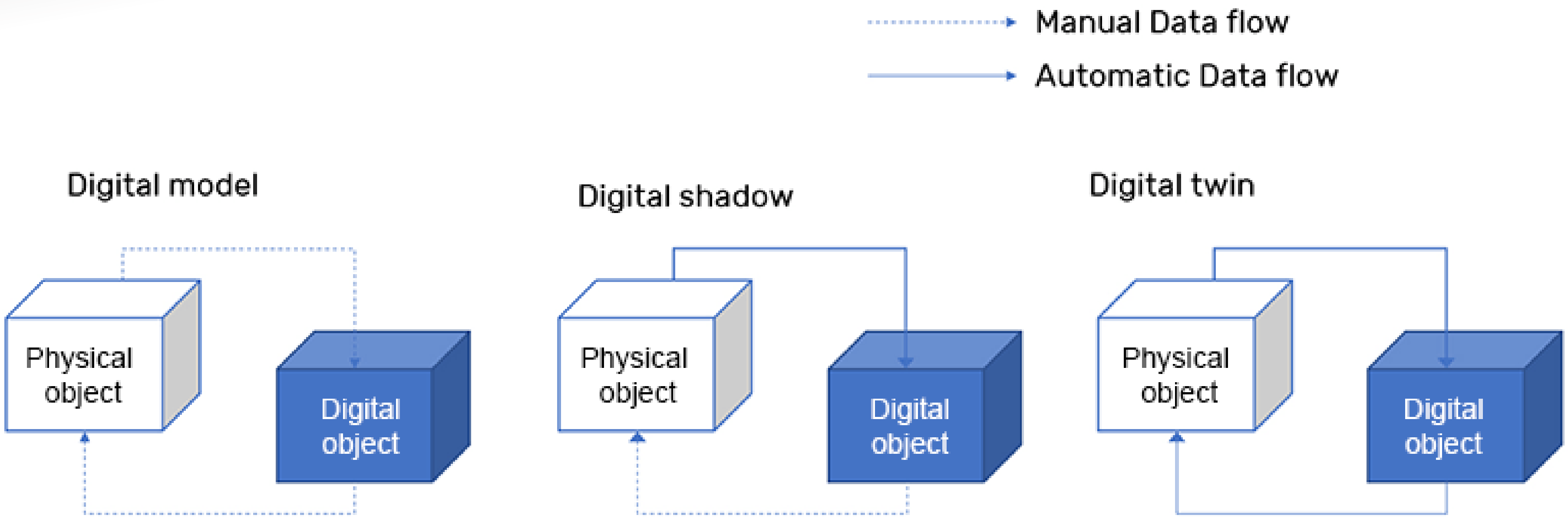
Enabling factors

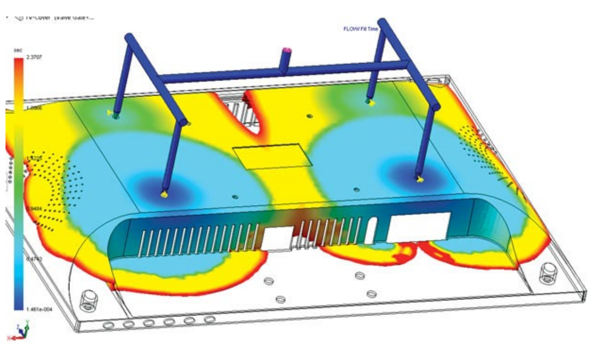
- Increased ease of use of technologies
- Cost reduction of technologies (sensors, microcontrollers, etc.)
- Machine-to-machine communication (IIoT)
- Last-generation communication networks (4G, 5G)
- Increase in computing power (cloud computing)
- Better performing network security systems
- Development of artificial intelligence (deep learning, machine learning)

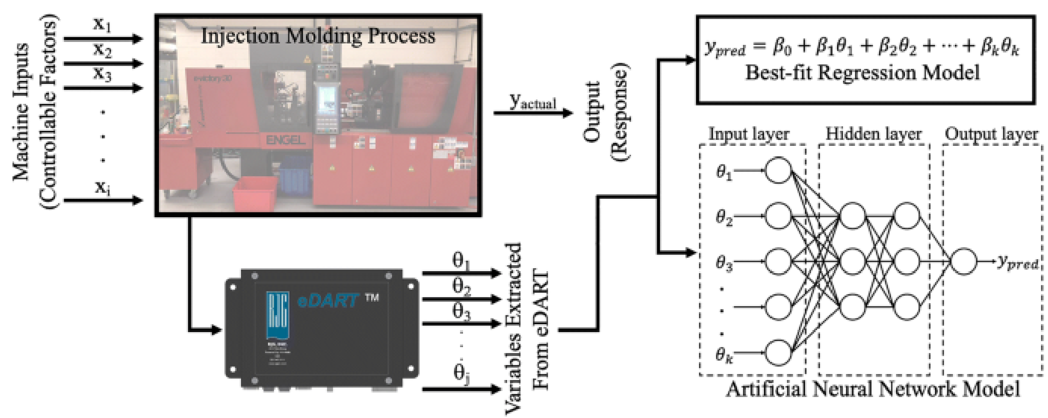
Industrial Internet of Things (IIoT)



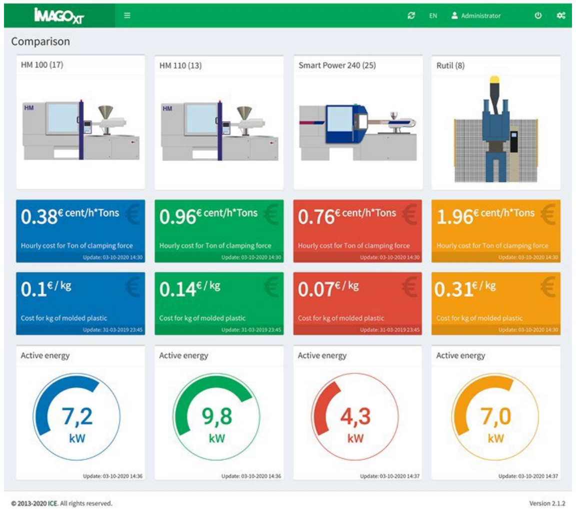
Digital Twin vs. Model







Types of Digital Twins (Shadows)

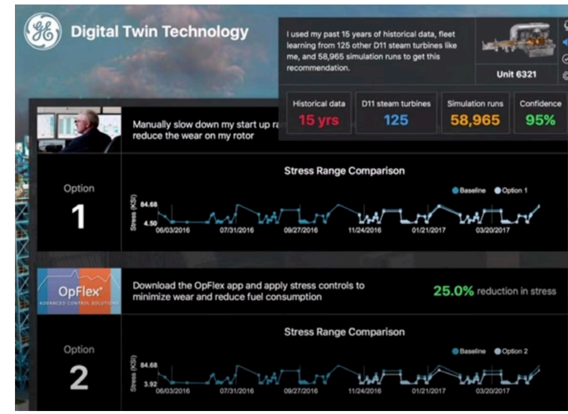


Status Twin

Typically used for basic condition monitoring applications such as dashboards and simple alerting systems. It indicates operating parameters and is generally created with visualization tools.

Operational Twin

It is linked to a set of actions or workflows where users can interact with the twin and change operating parameters where control capability is allowed.



Simulation Twin

Leverages different types of simulation or artificial intelligence capabilities to predict, forecast, or provide insight into future operational states.

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