Cognitive Digital Twins for the Process Industry

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Arne works with Digital Platforms and Systems Interoperability, focusing on Big Data and processing support for Analytics/AI/Machine Learning with Industry 4.0 and Digital Twin applications in various Domains – in particular in Process industry, Energy, Manufacturing, Ocean, Agriculure, Fishery, Aquaculture and Building and Construction. He is involved in a number of ongoing Norwegian and European Horizon 2020 projects including being the Technical Coordinator of CogniTwin and DataBench and participation to others, such as VesselAI, DEMETER, ACROSS and DataCloud.
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Background for the COGNITWIN EU Horizon 2020 project

- **Work program topics addressed:**
  DT-SPIRE-06-2019 Digital technologies for
  improved performance in cognitive production plants (IA)

- **Type of action**: Innovation Action

- **Budget**: EUR 7 MEuro

- **Partners**: 14

- **Timeline**: September 2019 – September 2022

- https://cognitwin.eu

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Partners

- 14 Partners from 7 Countries
  6 Industries, 4 Technology Providers, 4 R&D Partners

SINTEF (Norway),
Elkem (Norway),
Hydro (Germany),
Sumitomo (Finland),
Sidenor (Spain),
Saarstahl (Germany),
DFKI (Germany),

Cybernetica (Norway),
Nissatech (Serbia),
Fraunhofer (Germany),
University of Oulu (Finalnd),
Teknopar (Turkey),
Noksel (Turkey),
Scortex (France)

Coordinator

Partners

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Challenges Process Industry

- ❑ Sensors
  - process (hostile) conditions – robust, quality <u>and</u> cheap
- ❑ Data – managing streams of variations
  - Volume, Velocity, Varity, Veracity, Value
- ❑ Hybrid Modelling and Analytics
  - Extreme complexity (e.g. raw material variations)
  - Intermediate transformations "hidden"
- ❑ Cognitive Control
  - Full States of the systems often not known
  - Self-adaptive control models usually not present
- ❑ Plant Optimization
  - Mostly relaying on process engineer's experience & knowledge
  - Full digitalisation and use of data and analytics still rare

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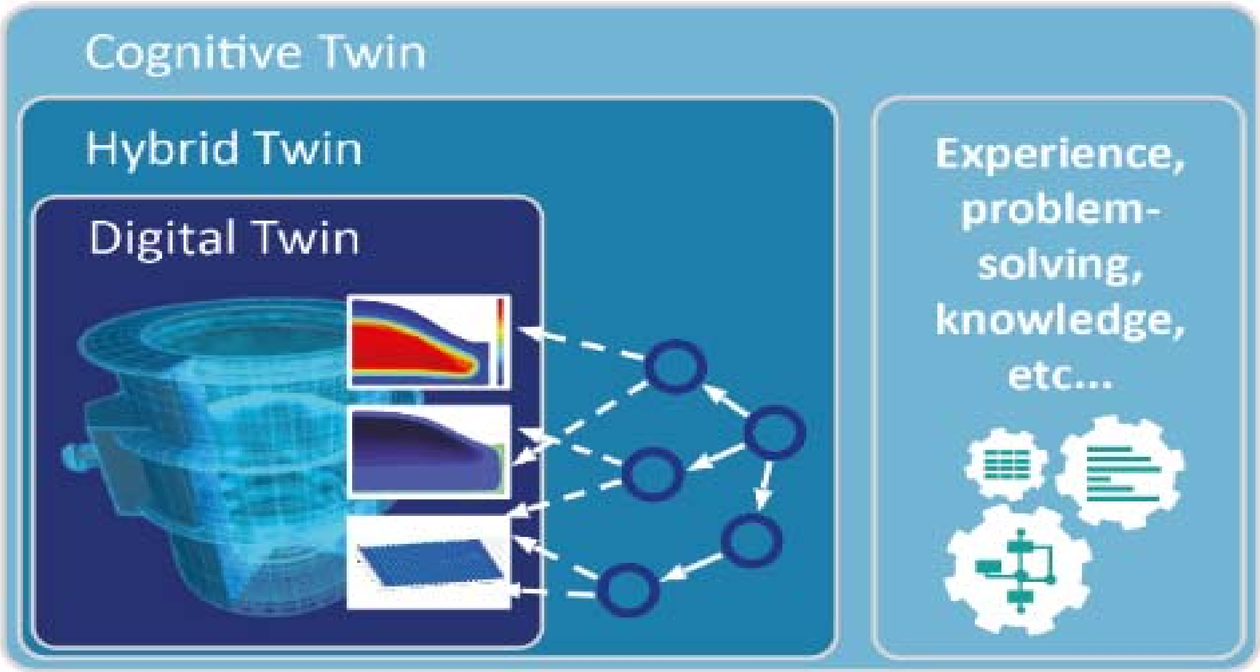
3-layered approach to define “twins”



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Digital Twin

Digital Twin (DT) A digital replica of a physical system that captures attributes and behaviours of that system. The purpose of a DT is to enable measurements, simulations, and experimentations with the digital replica in order to gain understanding about its physical counterpart. A DT is typically materialized as a set of multiple isolated models that are either empirical or first-principles based.

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Hybrid Digital Twin

Hybrid Digital Twin (HT) An extension of DT in which the isolated DT models are intertwined to recognize, forecast and communicate less optimal (but predictable) behaviour of the physical counterpart well before such behaviour occurs. A HT integrates data from various sources (e.g., sensors, databases, simulations, etc.) with the DT models, and applies AI analytics techniques to achieve higher predictive capabilities, while at the same time optimizing, monitoring and controlling the behaviour of the physical system. A HT is typically materialized as a set of interconnected models, achieving symbiosis among the DT models.

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Cognitive Digital Twin definitions (1/4)

CT (COGNITWIN) : “an extension of Hybrid Digital Twins incorporating cognitive features that enable sensing complex and unpredicted behaviour and reason about dynamic strategies for process optimization, leading to a system that continuously evolve its own digital structure as well as its behaviour”. [2]

***Common agreement - CT is a DT extended with some forms of cognitive capabilities, however there is no widespread consensus on what kind of cognitive capabilities a CT should encompass*.**

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Cognitive Digital Twin definitions (2/4)

CT: "digital representation, augmentation, and intelligent companion of its physical twin as a whole, including its subsystems and across all of its life cycles and evolution phases" [5].

CT: "virtual representation of a physical object or system across its lifecycle (design, build, operate) using real time data from IoT sensors and other sources to enable learning, reasoning and automatically adjusting for improved decision making" [14].

CT: the virtual, state-full representation of a physical object or system across its life-cycle (design, build, operate) using operational real-time data and other sources to enable understanding, learning, reasoning, and dynamically recalibrating for improved decision making" [7].

CT: "using cognitive (natural language processing (NLP), ML, object/visual recognition, acoustic analytics, and signal processing) to improve testing a digital twin can determine which product tests should be run more frequently and which should be retired. Or cognitive sensing can improve what/when data from sensors is relevant for deeper analysis. Cognitive digital twins can take us beyond human intuition to design and refine future machines" [12].

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Cognitive Digital Twin definitions (3/4)

CT: “by having the ability to execute cognitive tasks, a digital twin of a service fulfillment or product manufacturing process will be able to examine the current structure of a system or a process and give recommendations regarding what can be improved at the current moment” [13].

CT : “artificially intelligent Digital Twin that has the potential to serve as an 'autonomous maintenance engineer'” [1].

CT : “digital expert or copilot, which can learn and evolve, and that integrates different sources of information for the considered purpose. The structure of a CT partially emulates the structure of the corresponding human mental models” and define an architecture for “Associative Cognitive Digital Twin”. [6]

CT: “Digital Twins (DT) with augmented semantic capabilities for identifying the dynamics of virtual model evolution, promoting the understanding of interrelationships between virtual models and enhancing the decision-making based on DT”. [11]

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Cognitive Digital Twin definitions (4/4)

ECT - “Enhanced Cognitive Twin” (ECT) “introduce advanced cognitive capabilities to the DT artefact that enable supporting decisions, with the end goal to enable DTs to react to inner or outer stimuli. The ECT can be deployed at different hierarchical levels of the production process, i.e., at sensor-, machine-, process-, employee- or even factory-level, aggregated to allow both horizontal and vertical interplay” [4].

CT: “digital reflection of the user, intended to make decisions and carry out tasks on the user's behalf”, to “highlight the key role that cognitive mechanisms play in modeling human decision making in the IoT digital space” [16].

Cog-DT : “digital replica of a person’s cognitive process in relation to information processing”, including a VR platform that collects information preference data during training, contains the modelling and optimization algorithm of DT modelling of human cognitions, and an adaptive UI design based on real-time cognitive load measures and Cog-DT models. [3]

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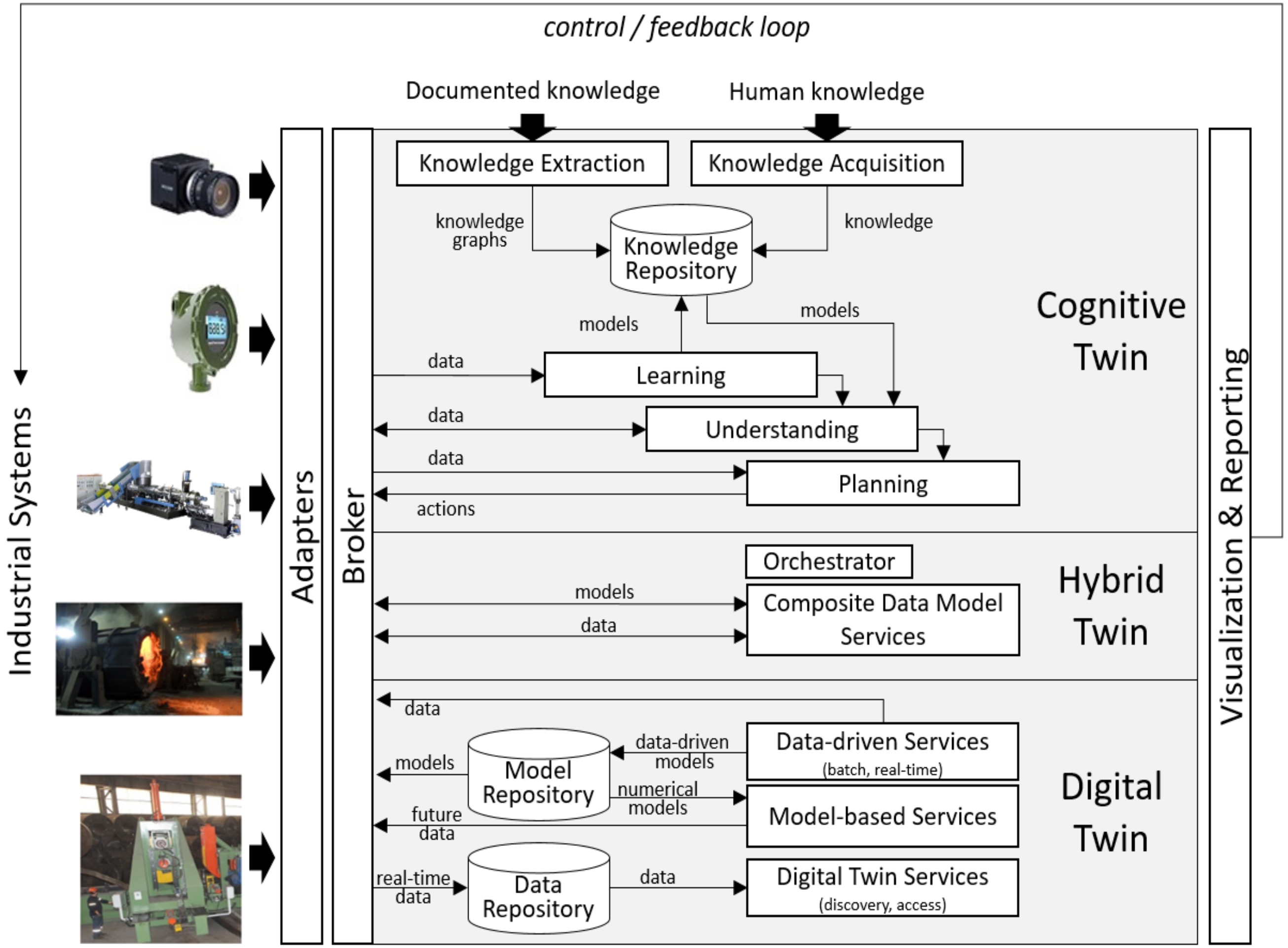
Cognitive Twin - Conceptual Architecture



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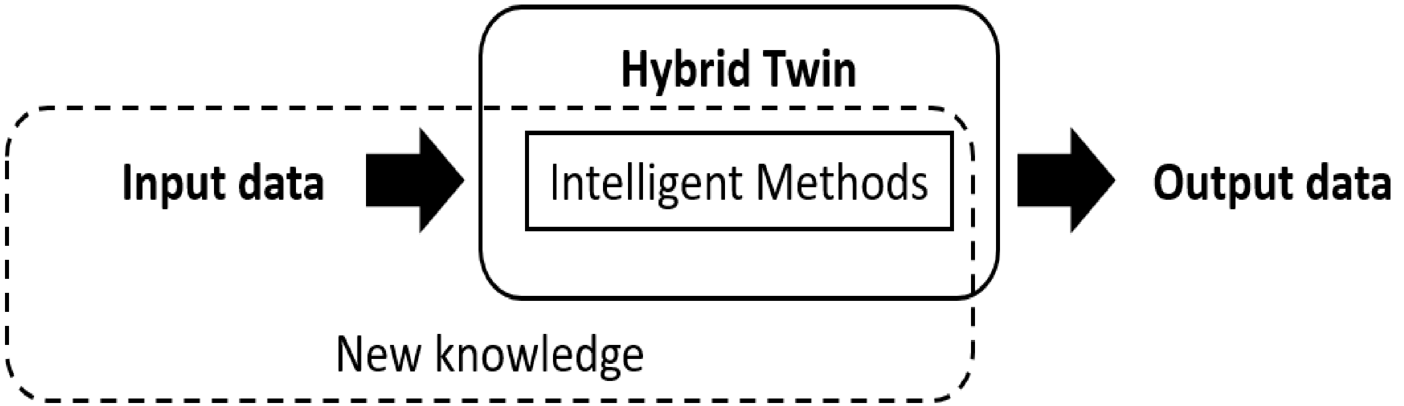
Cognition extending Hybrid Digital Twins



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Cognitive Twin Layer

Cognition services is to enable understanding of the behaviour of the monitored system under various types of uncertainties/unknowns, to support reliable decision making (by human experts) or control (in autonomous systems).

Uncertainties can be of different types, but we focus on two most important types from the DT point of view: lack of data and unavailability of models regarding the current system behavior.

Processing steps in cognition services.

1. Inserting new knowledge (relevant for the problem).
2. Learning models that are more accurate by applying new knowledge.
3. Better situational understanding (e.g., lower interpretation uncertainty), by applying new models.
4. Planning actions for resolving the problem, based on improved situational understanding. We describe these steps as follows:
    a. Knowledge extraction and knowledge acquisition,
    b. Learning, which encompasses applying new knowledge on the existing data, models, and methods, with the goal of learning more accurate models (from existing datasets). T
    c. Understanding, which is related to applying new models on real-time data for getting a better interpretation of the situations of interests (e.g., problem/anomaly detection).
    d. Planning, for defining optimal actions based on system behaviour understanding.

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Challenges for Cognition – Knowledge representation (1/2)

How knowledge can be formally represented to enable the fact that a DT learns from experience and behaves intelligently, like a human. Two parts: ontologies for representing the domain knowledge and rules for representing the problem-solving knowledge.

- Represent the domain knowledge which includes the vocabulary domain-experts apply (e.g., brick wall, types of bricks like red shale or clay bricks, the features of bricks like thermal shock resistance or mechanical strength, etc.) as well as the constraints (e.g., temperature threshold at which the stone is unusable).
- Take into account existing standards for the domain (e.g., standards from the steel process industry for the use case described in Section IV).
- Support collaboration between DTs, e.g., for cooperative execution of complex tasks.

Although simple constraints (e.g., temperature of a ladle must not exceed a certain threshold) can be modelled by using ontologies, there are many scenarios where complex (functional or behavioural) constraints should be considered (e.g., calculations that include results of different physics-based/AI/statistic-based models).

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Challenges for Cognition – Knowledge representation (2/2)

To mimic the reasoning of human expert in solving knowledge intensive problems, there is a need to use rules (e.g., event condition action rules).

Rules should be used even in the present of incomplete and/or uncertain information to (i) focus the attention to the most important aspects and (ii) collect additional, goal-oriented information relevant for a given context. This can be done by mapping of raw sensor data and/or outputs of different DT models to actions (such as control decisions or recommendations for human operators).

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Challenges for Cognition – Knowledge acquisition

To make the tacit knowledge explicit and machine-understandable and machine-processable, different cognitive technologies could be used such as NLP, speech recognition, etc.

Possibility: Apply a speech-to-knowledge approach, as speech is relevant for the shop floor workers for short information interchange allowing hands-free conversations. Ontologies can help achieving higher accuracy of resulting rules, as synonyms, multilingual aspects, context, etc., can be taken into account. In this way, the domain and problem-solving knowledge will be connected.

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Challenges for Cognition – Knowledge update

In addition to collecting knowledge, the ability to learn, to unlearn and continuously update knowledge is crucial for CTs to create competitive advantage.

Knowledge update is however a complex process, which includes knowledge extension (e.g., adding a new entity in the ontology for new types of bricks), knowledge forgetting (removing an ontology entity representing material not used anymore for bricks) and knowledge evolution (e.g., changing a max temperature of a ladle).

The similar strategies can be applied on the problem-solving rules. The challenge lies not only in ensuring the consistency after applying a change, but also more importantly in discovering the need for a change. This can be done by applying usage-driven strategies (e.g., by monitoring whether the proposed decisions were accepted by domain experts) or by using structure-driven methods (e.g., by using ontology-based reasoning to discover conflicting rules or generalized/specialized rules).

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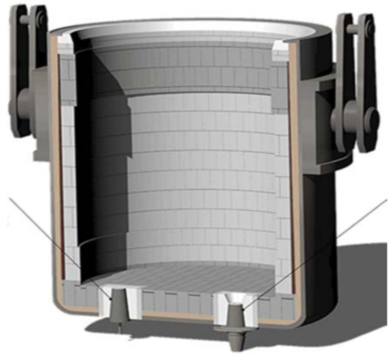
Use case from the Process Industry – Steel production



- DT: The DT in this case is a mathematical representation of the ladle during each steel refining process that focuses on the refractory brick behaviour. Physics-based models account for refractory wear due to thermal and mechanical stresses on the walls whereas ML models are developed using process parameters to estimate the conditions of the refractory bricks.
- HT: Combining these two approaches gives us the HT, which can possibly provide reliable estimates of brick's conditions.
- CT: A CT in this specific case helps the engineers and technicians to make better judgements about the brick health based on the historical data and the brick demolition/repair routines followed.

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Use case from the Process Industry – Steel production

If one were to address this problem using DTs, a mathematical model that simulates the behaviour and degradation mechanism of the bricks in the ladle would be an obvious starting point. By developing advanced ML algorithms, it may be possible to develop programs that can predict when the bricks need to be replaced. In addition, it is possible to develop physics-based models that simulate the brick wall conditions when subjected to severe mechanical and thermal stresses, which can further improve the ML-based models to create a HT of the process.

The CTs on the other hand will include the human intelligence factor in the models to deal with the uncertainty inherent in the process. One of the main challenges for resolving this problem is the lack of sufficient data, given that the process is rather complex. Ideally, it would help to detect false negatives; meaning decisions to replace the brick lining were taken even if it was not required. This however is not always available due to practical reasons. The models in the CTs would include instances that were exceptional and rare scenarios and decisions taken by the manual intervention to best suggest whether the bricks in the ladle will need be replaced or repaired.

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Further use cases

- Operational optimization of gas treatment centre (GTC) in aluminium production, where CT of the GTC recommends optimal operating parameters for adsorption based on real-time data gathered about conditions such as the pressure, temperature, humidity, etc., from sensors.

- Minimize health & safety risks and maximize the metallic yield in Silicon (Si) production to provide best estimates of when the furnace can be emptied to the ladle for further operations.

- Real-time monitoring of finished steel products for operational efficiency with an ability to react on its own to situations requiring an intervention, thus stabilizing the production process further.

- Improving heat exchanger efficiency by predicting the deposition of unburnt fuel mixtures, ash and other particles on the heat-exchanger tubes based on both historical practices and real-time process.

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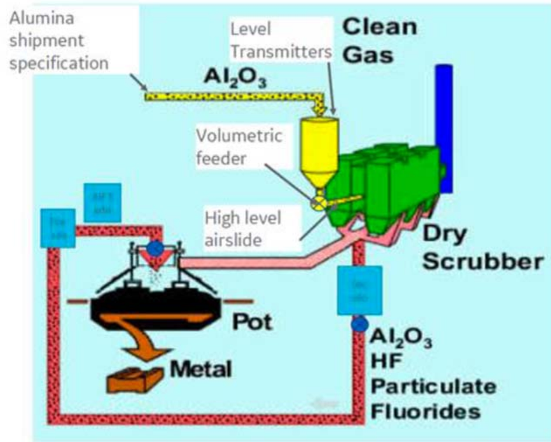
A. Operational optimization of gas treatment centre (GTC) in aluminium production



DT: A digital twin of the GTC will simulate the gas adsorption phenomenon either using physics based or empirical models.

HT: The first principles models will consist of complex differential equations such as kinetic, mass, and energy balance of the adsorption process. The data-based models will be developed using various ML (machine learning) and AI (artificial intelligence) algorithms where the dependent variable would be the HF gas concentration in the raw gas, to be adsorbed by alumina in the GTC. Thus, both DT & HT will provide solutions for optimal quantity of fresh alumina to be used to even the out the HF adsorbed to alumina.

CT: The CT of the GTC will suggest optimal operating parameters for adsorption based on real-time data gathered about conditions such as the pressure, temperature, humidity etc., from the sensors. All of these process variables are highly dependent on the external factors that cannot always be controlled such as the surface area of the alumina and ambient conditions (weather). Thus, the HT & CT provide plant operators best suggestions that adapt and evolve continuously.

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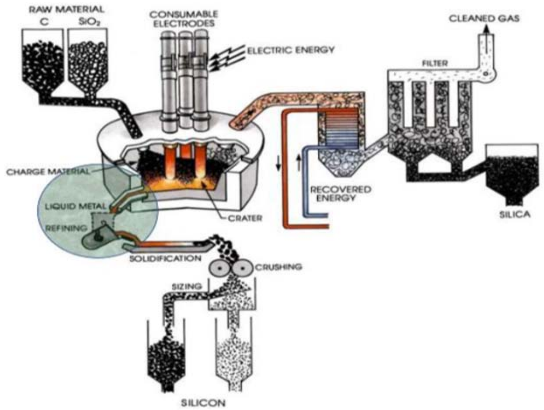
B. Minimise health & safety risks and maximise the metallic yield in Silicon (Si) production



- DT: A DT that represents the refining/alloying process during post tap-hole operations is generally described by the usual mass, energy, and momentum conservation equations from computational fluid dynamics (CFD).
- HT: A HT simulates the ladle characteristics by combining the previously mentioned mathematical equations along with empirical models that are developed using various ML algorithms applied to images generated by thermal cameras.
- CT: A CT of the ladle would include the same models in HT, however, the equations are parameterised CFD equations typically using optimisation routines such as genetic algorithms or particle swarm optimisations for improved accuracy. Combining these representations of the ladle can provide best estimates of when the furnace can be emptied to the ladle for further operations

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C. Real-time monitoring of finished products for operational efficiency

- DT: Based on the DT of the production process section provided by the steel bar tracking system with sensor data
- HT to combine the tracking model with sensor data collected in the production process for example to predict error-prone situations before they occur and allow an operator or operational system to react accordingly, but also to allow for a real-time adaption of process parameters to enable advanced quality management based on predictive model outputs or the linked data from the entire production process directly.
- CT: A CT of such a system would feature all attributes of a HT together with an innate ability to react on its own to situations requiring an intervention, thus stabilizing the production process further.

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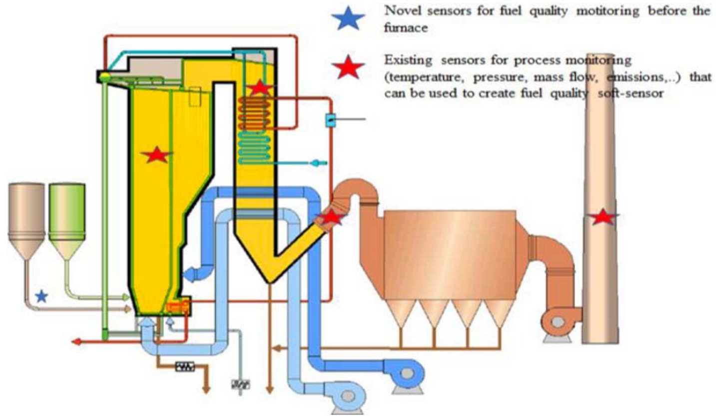
D. Improving heat exchanger efficiency



- DT: Heat exchange sensor data
- HT: A HT for this use case is represented by mathematical and ML models to take actions to remove the deposits from the heat-exchanger tubes before the operators may have to stop their process and take the equipment out for servicing.
- CT: The CT of the heat exchanger will predict the deposition of unburnt fuel mixtures, ash and other particles on the heat-exchanger tubes based on both historical practices and real-time process data to suggest clean-up of the tubes in the heat exchanger before the deposits build up more strongly.

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General Progress on Cognitive architectures

- Progress on cognitive architectures is seen through the development of hybrid representations that combine symbolic and numeric content, mechanisms for learning procedural and control knowledge, incorporation of large-scale knowledge structures, construction of embodied and interactive agents, and support for both declarative and episodic memories [9].
- Less progress has been made in areas such as abductive understanding, dynamic memories that acquire new conceptual structures, creative aspects of problem solving, emotional processing, and agent personality, along with the plausibly related topics of metacognition and goal reasoning [9].

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COGNITWIN activities

- Conceptual approach to enhance functionalities of Digital Twins by introducing the notions of Hybrid and Cognitive Twins and by describing a toolbox-based solution to realize this vision.
- Future work will focus on the realization of twins as well as on the management of different levels of twins (DTs, HTs, CTs).
- Develop methods and tools that support the whole lifecycle of a twin, starting from modelling, over to generation, connection, operation, reuse, and sharing to continuous improvement

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Conclusion and future work

- We introduced the concept of CTs in the context of the process industry and proposed a CT architecture a baseline for building CTs
- Despite recent attempts in defining CTs, the concept is still emerging; with various aspects and perspectives presented in the literature and no shared agreement on the scope of CT, other than extension of DTs with cognition elements
- We reviewed the relevant definitions in the literature
- We provided our architectural perspective on the type of cognitive services needed for CTs in the context of process industry, identified the challenges for realizing the proposed cognitive services, and discussed their role in the context of a concrete use case in the process industry
- We plan to apply the CT approach in a total of six different Process Industry use cases

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