Digital Twin

Bi-Weekly 4 (18/11/2022)

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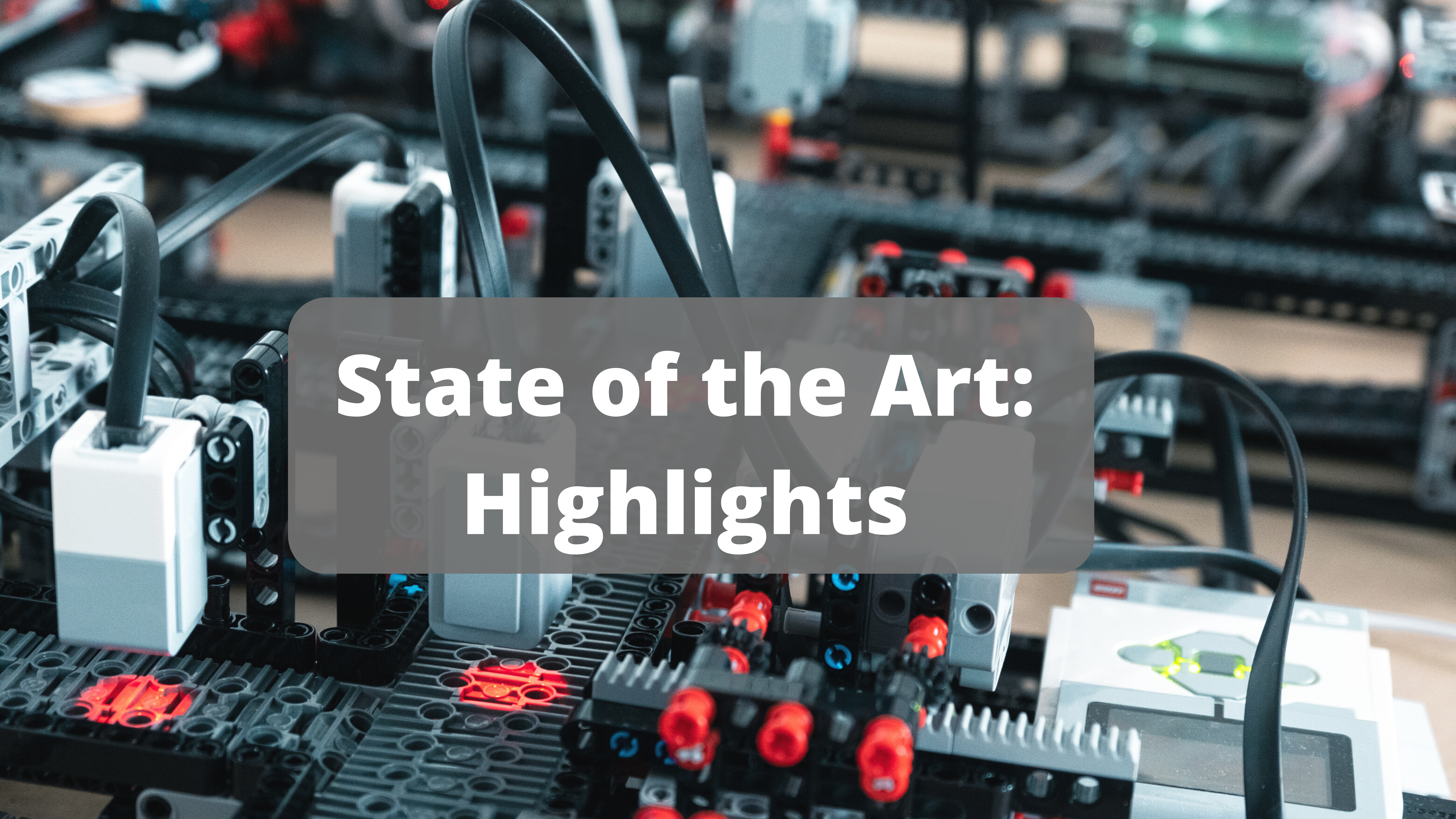
Agenda

- State of the Art overview
- Deep Dive into Papers
- Conclusions & Reflections
- Timeline and Next steps



State of the Art: Highlights

An Overview

- 10+ academic articles analyzed.
- 5+ architectures for Digital twin configuration and implementation in industrial scenarios.
- Focus on open architectures in the field of manufacturing and assembly lines.
- Review on automated model generation and its verification on 2 case studies.

Highlights 1

Hyre, A. et al. (2022) 'Digital twins: Representation, Replication, Reality, and Relational (4Rs)', Manufacturing Letters, 31, pp. 20–23. doi: 10.1016/j.mfglet.2021.12.004.

Representation

- Create digital representation of a physical object
- Data flows from the physical device to the virtual device
- Data used for visualization, validation & control of the virtual model, and analysis
- Used to capture and verify data against generated data from the original system

Replication

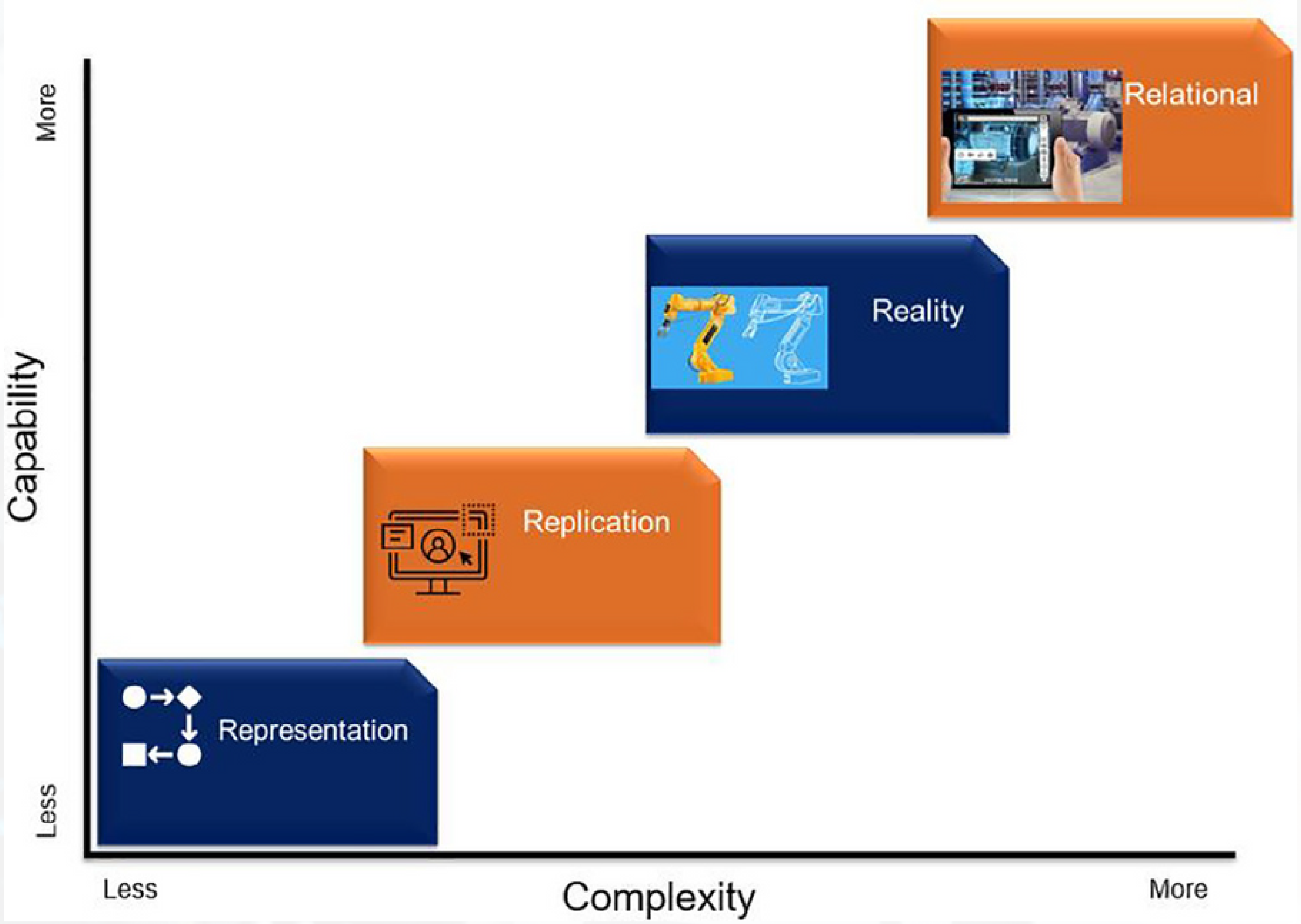
- Use data to create a digital system in a virtual environment
- The digital system is replicating the chosen components/variables from the Representation level of the cyber-physical system
- The DT is capable of reproducing outputs of the physical system given the same inputs

Reality

- Has the capability of independently providing outcomes given a set of inputs that are validated by the system
- The virtual device can work independent of the physical device
- The DT can predict the outcome if how the physical system will operate and produce with a given set of inputs

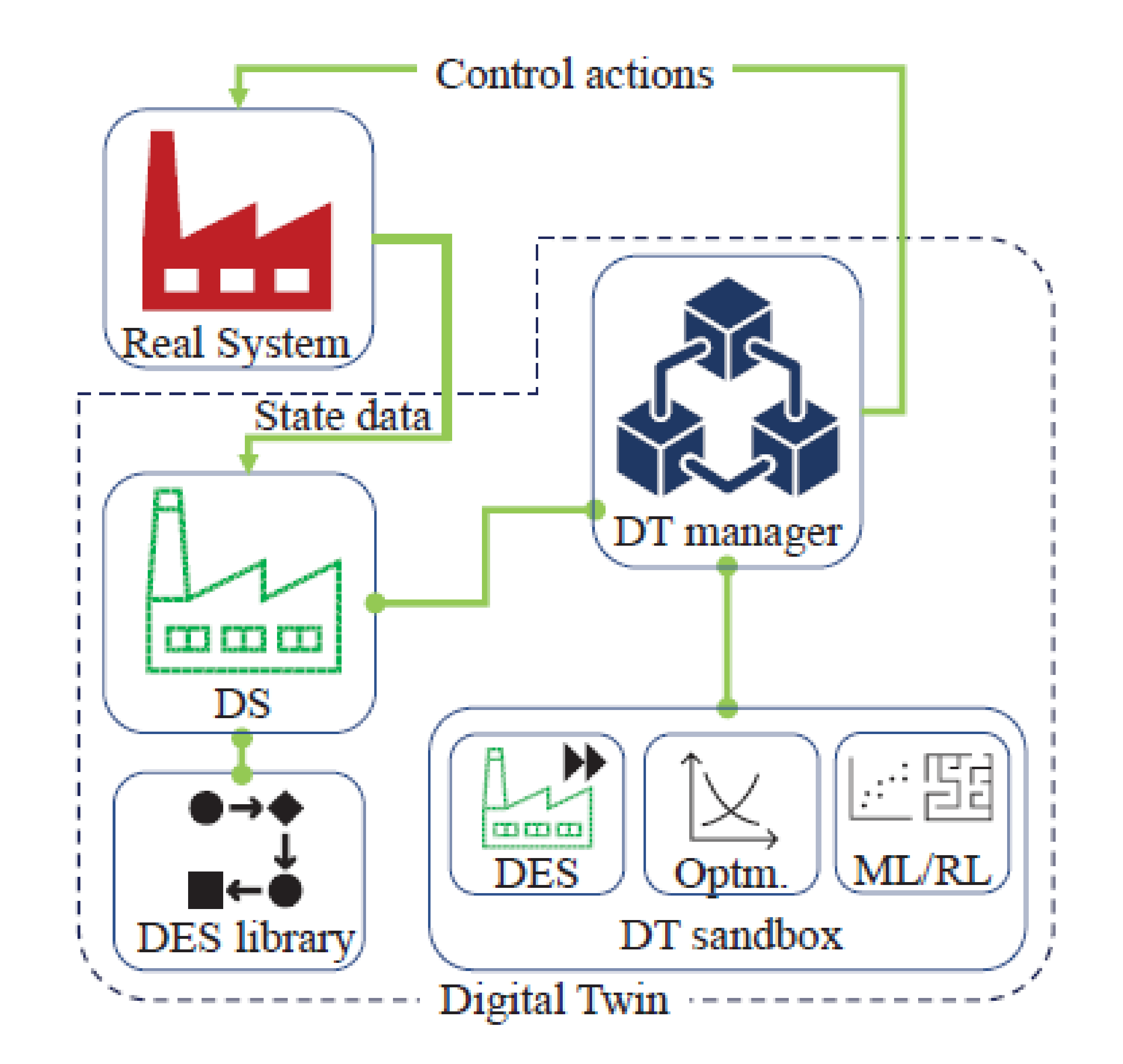
Relational

- The DT is applying technology such as machine learning and AI to perform decision making
- The DT has a level of autonomy not found in previous levels
- The DT can self-adjust, identify an optimal strategy depending on sensor data and calibrate itself

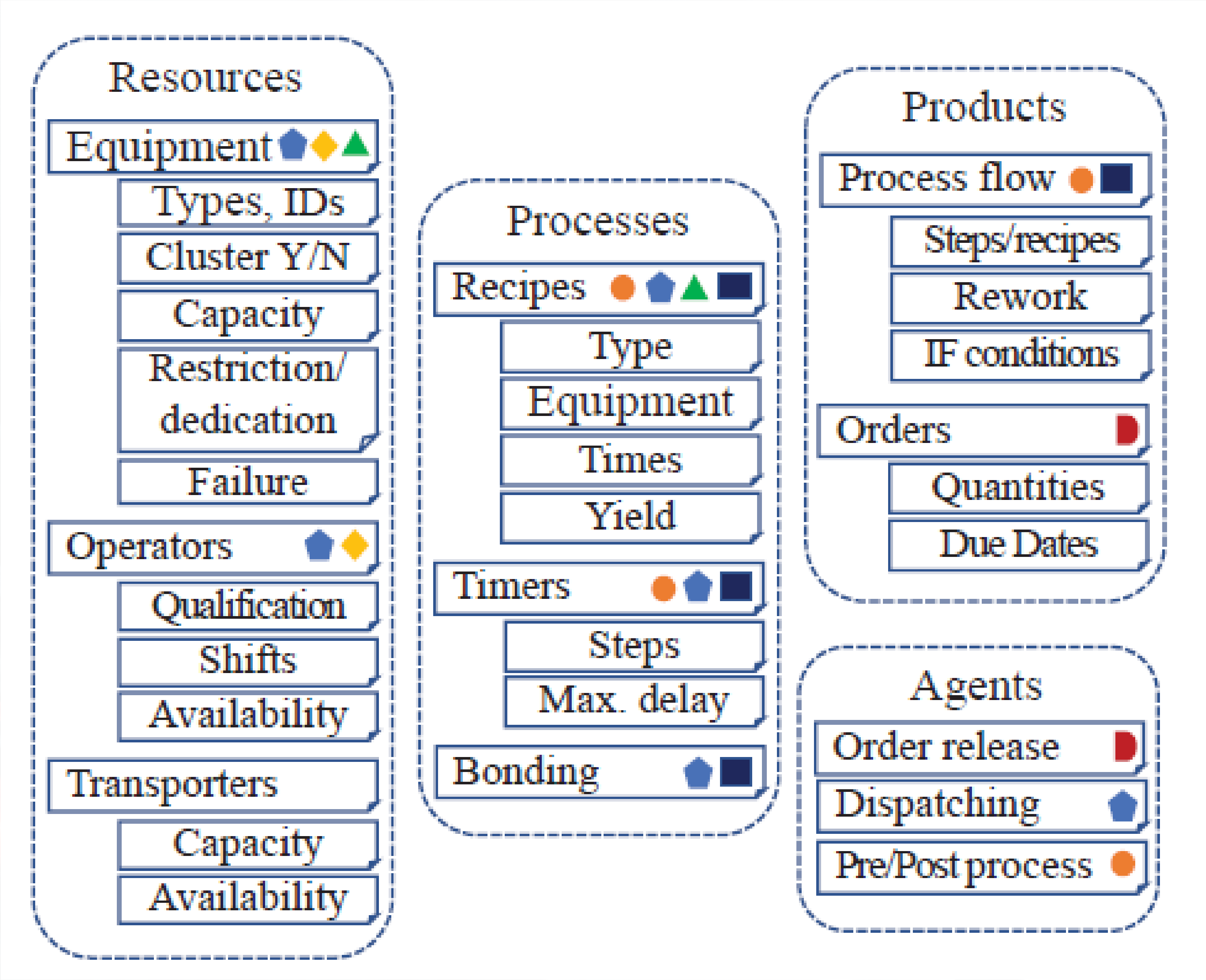


Highlights 2

Sakr, A. H. et al. (2021) 'Building Discrete-Event Simulation for Digital Twin Applications in Production Systems', IEEE International Conference on Emerging Technologies and Factory Automation, ETFA, 2021-Septe. doi: 10.1109/ETFA45728.2021.9613425.



Digital Twin Framework



Database Structure

Highlights 3

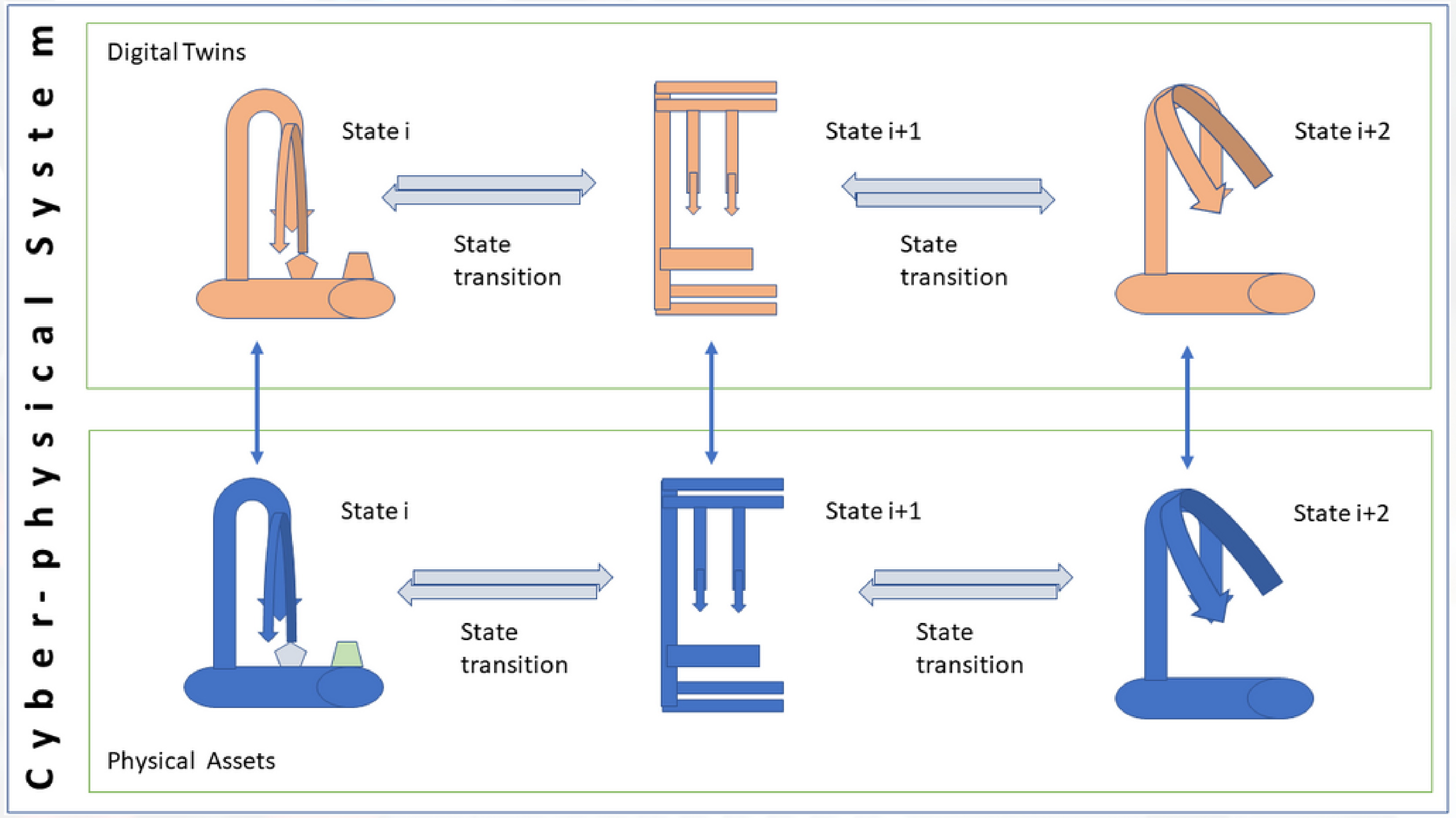
Heindl, W. and Stary, C. (2022) ‘Structured Development of Digital Twins—A Cross-Domain Analysis towards a Unified Approach’, Processes, 10(8). doi: 10.3390/pr10081490.

"The aim of this study was to investigate procedures for the development of DTs based on empirical in-depth studies and to put it into the context of existing DT concepts"

- Research Question 1: What empirically valid knowledge (in form of in-depth studies)

exists (in different application domains) about the process for developing DTs?

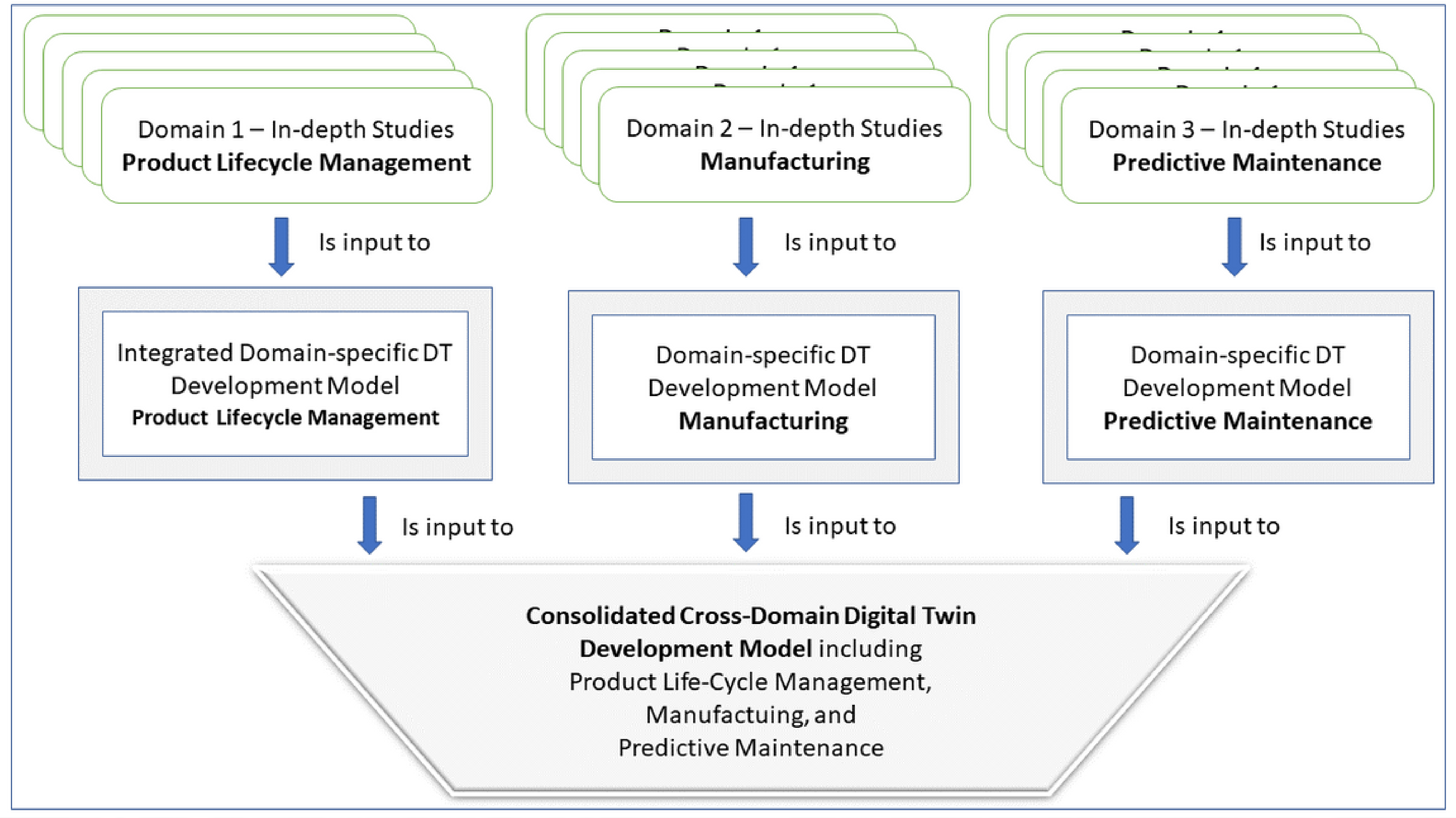
- Research Question 2: In how far can a generally applicable model be defined for the construction and further development of DTs?



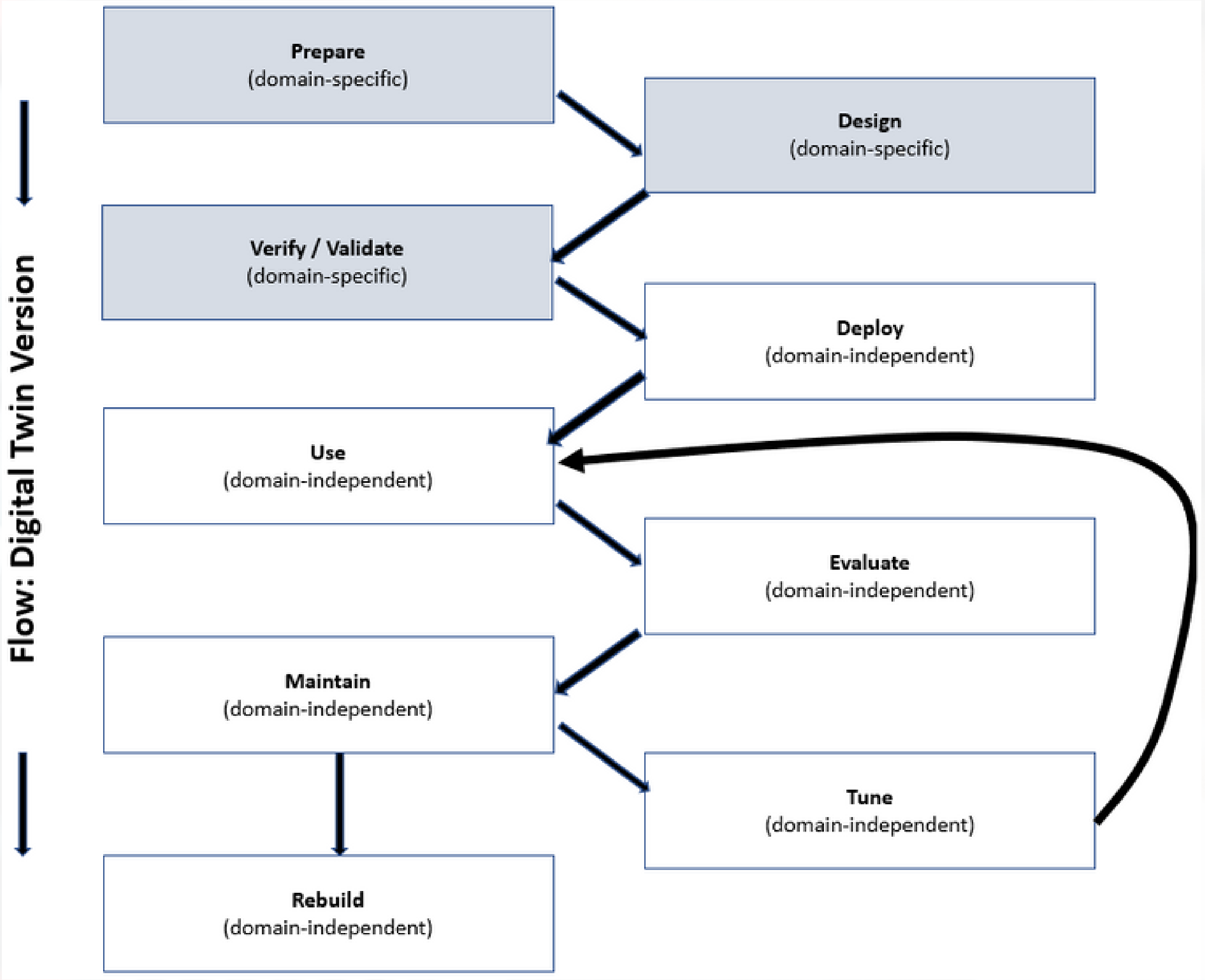
Highlights 3

Heindl, W. and Stary, C. (2022) ‘Structured Development of Digital Twins—A Cross-Domain Analysis towards a Unified Approach’, Processes, 10(8). doi: 10.3390/pr10081490.

Research Framework



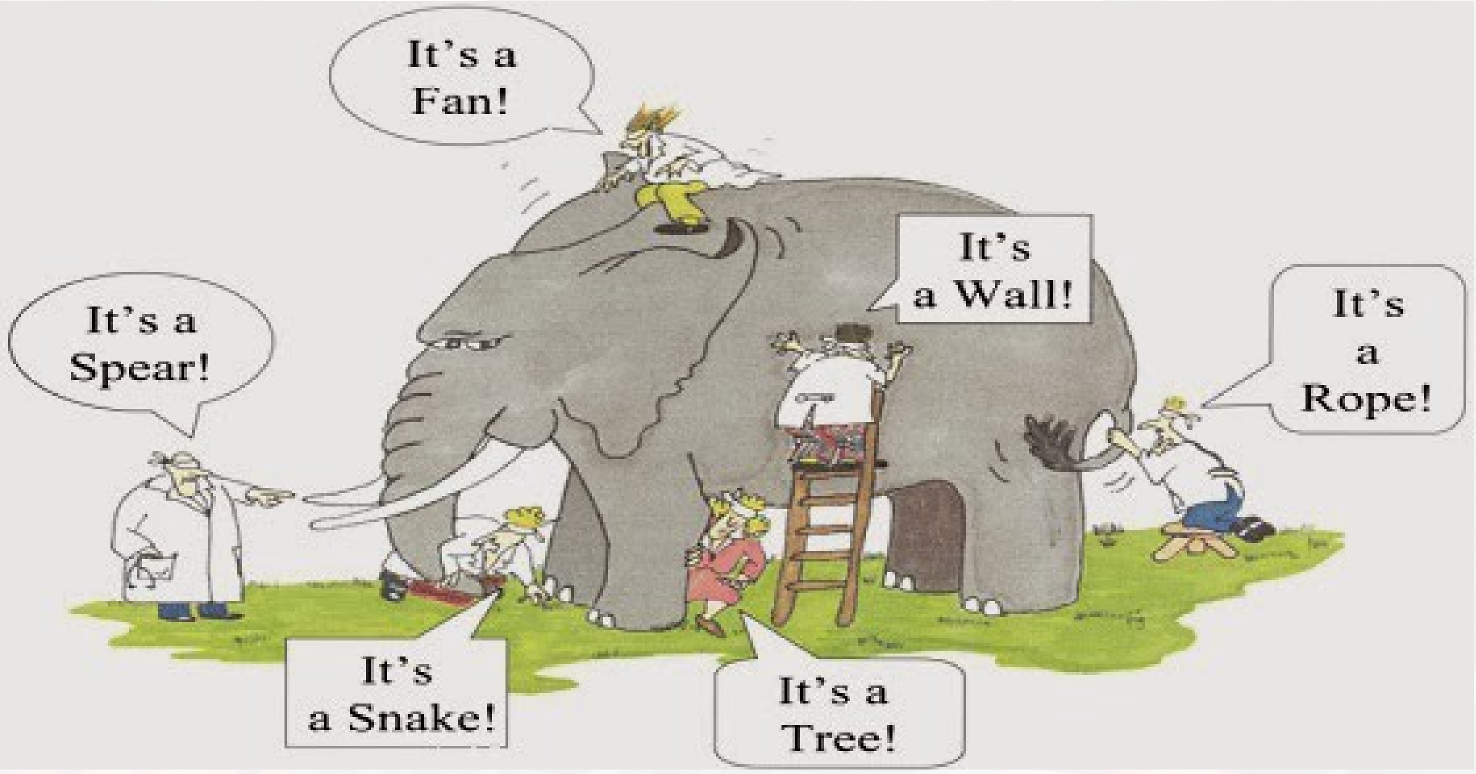
Digital Twin Framework



Highlights 4

Traoré, M. K. (2021) ‘Unifying digital twin framework: Simulation-based proof-of-concept’, IFAC-PapersOnLine, 54(1), pp. 886–893. doi: 10.1016/j.ifacol.2021.08.105.

"This paper introduces a unifying reference framework, [...] wich reconciles existing understandings of Digital Twins under a common umbrella."



Blind group of people defining an elephant

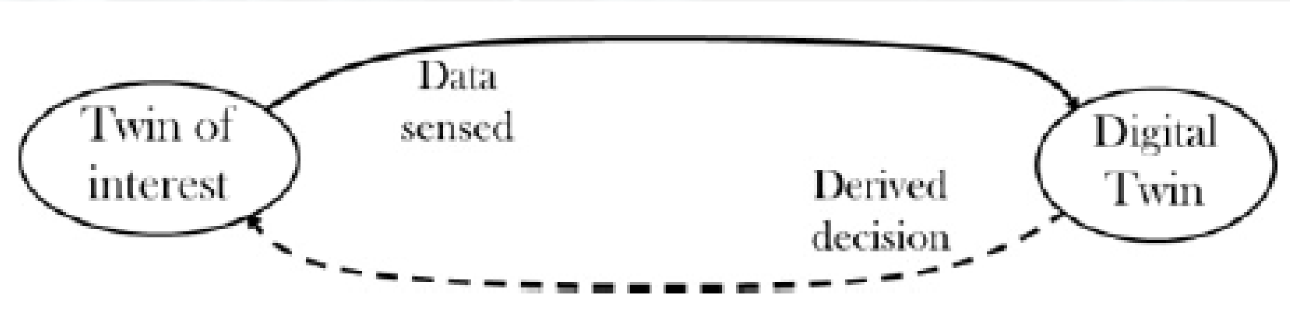
"Our work proposes a framework that unifies existing Digital Twins **viewpoints**, as each of theses viewpoints can be seen as a particular interpretation of the proposed framework"

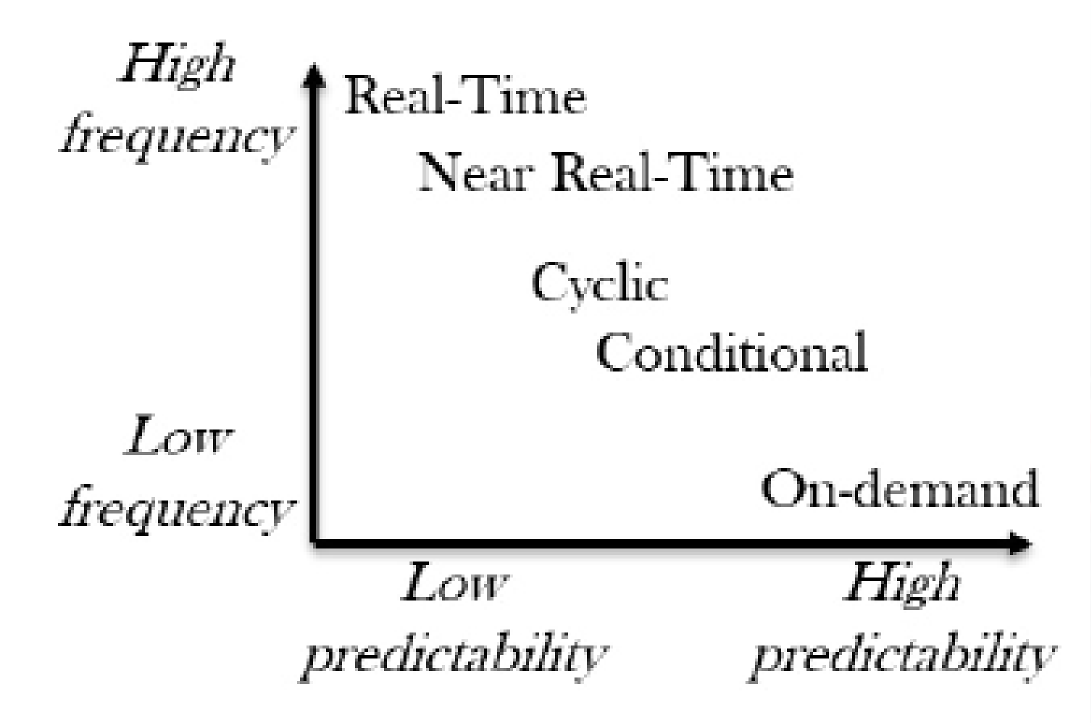
Highlights 4

Traoré, M. K. (2021) 'Unifying digital twin framework: Simulation-based proof-of-concept', IFAC-PapersOnLine, 54(1), pp. 886–893. doi: 10.1016/j.ifacol.2021.08.105.

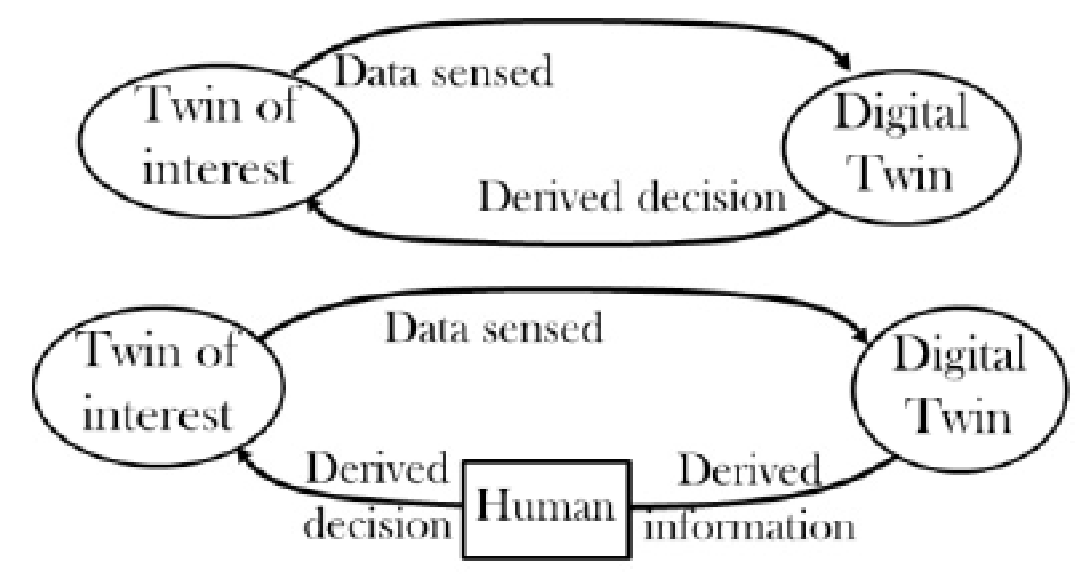
Unifying Digital Twin Framework

1. Invariant Characteristics: Synchronization





2. Closed and open twinning loops



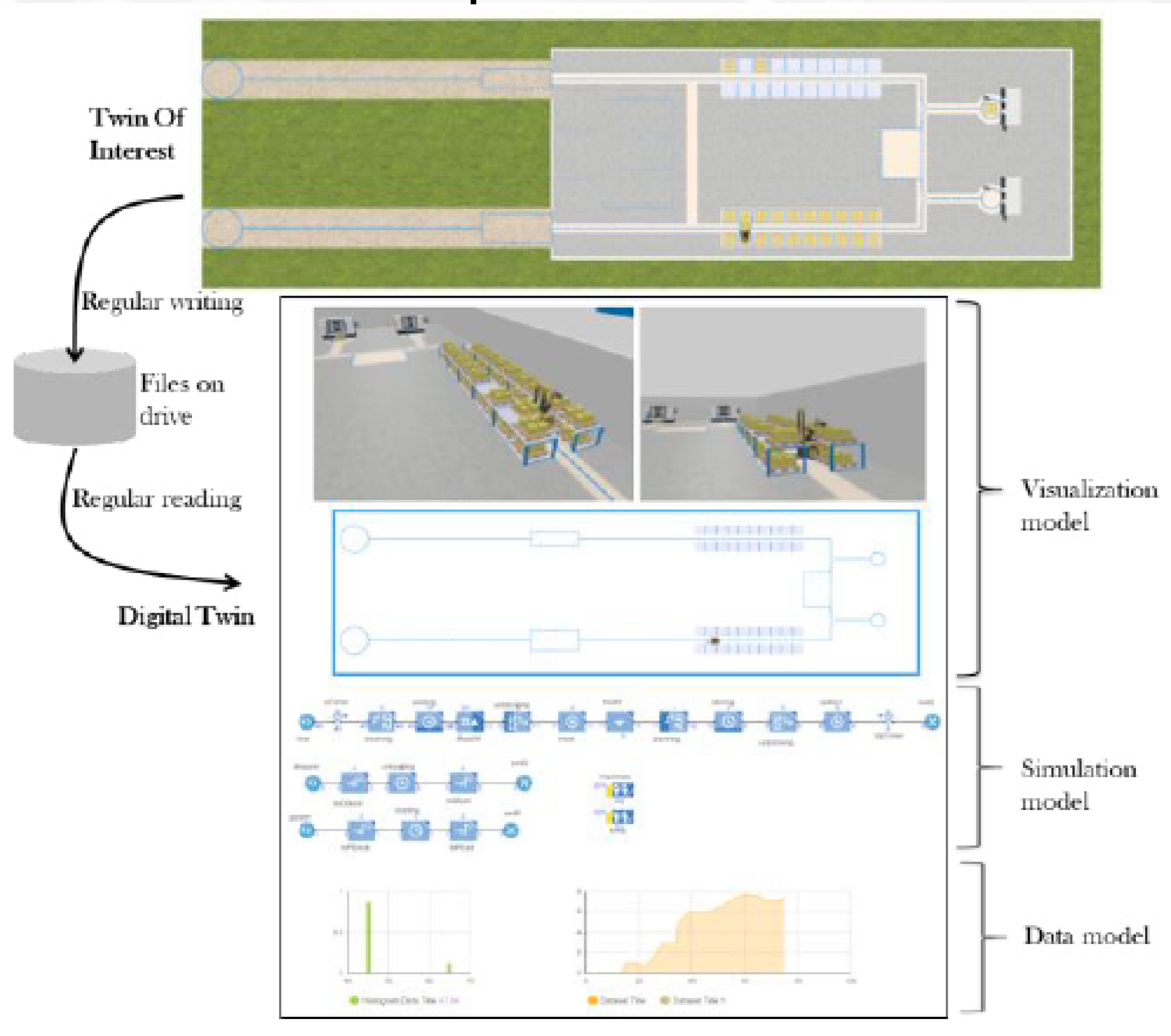
3. Role-based viewpoints

Role	*Open loop functionality*	*Closed loop functionality*
Visual interface	Visual monitoring	Visual control
Diagnosis interface	Data-based monitoring	Automated control
Prognostic interface	Simulation-based forecasting	Real-Time Simulation-based decision making
Optimization interface	Exploration-based design	Exploration-based decision making
Documentation interface	Data laking	Information mining

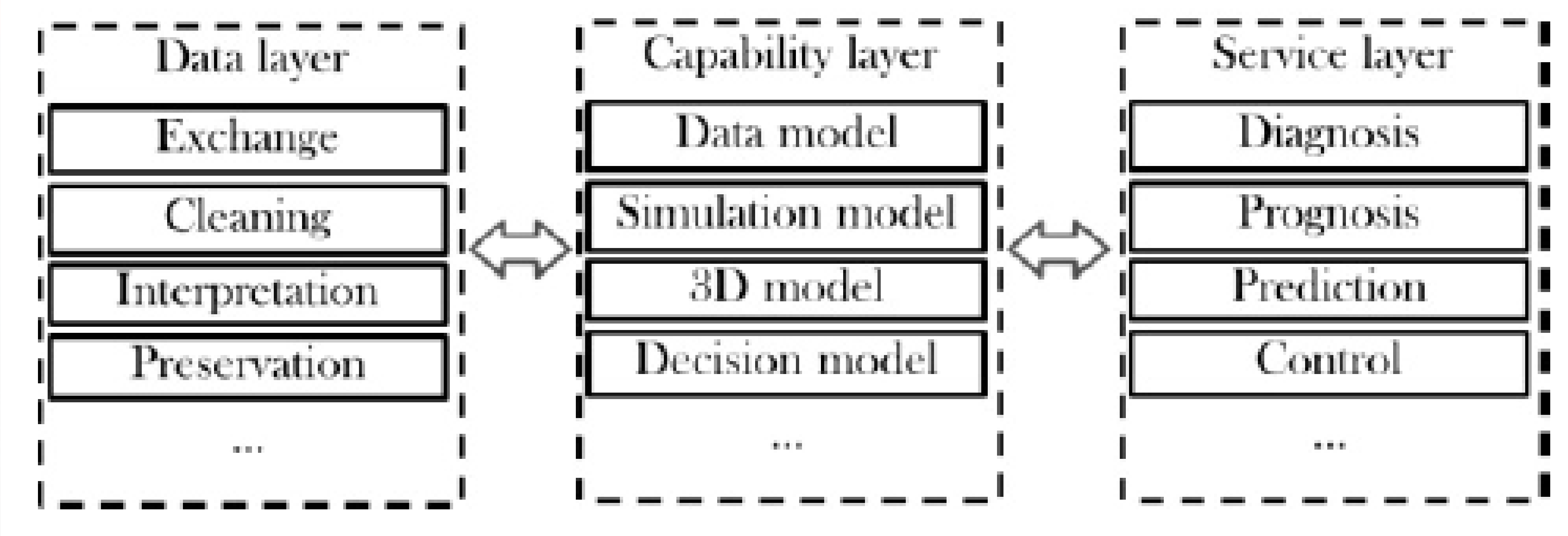
Highlights 4

Traoré, M. K. (2021) ‘Unifying digital twin framework: Simulation-based proof-of-concept’, IFAC-PapersOnLine, 54(1), pp. 886–893. doi: 10.1016/j.ifacol.2021.08.105.

Proof of concept



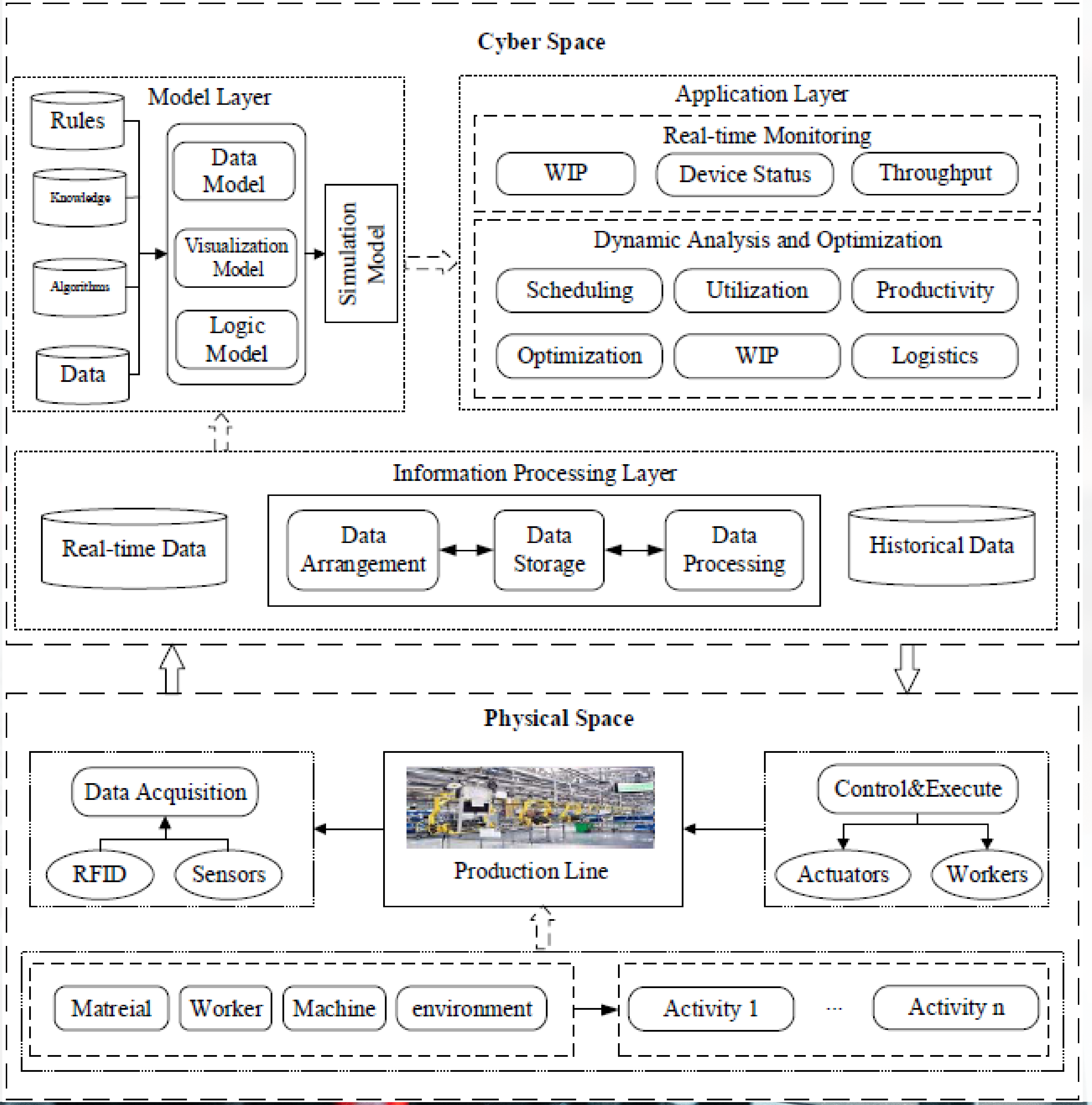
Unifying Framework



Highlights 5

"formalize the construction workflow of the production performance digital twin from data, logic and visualization aspects"

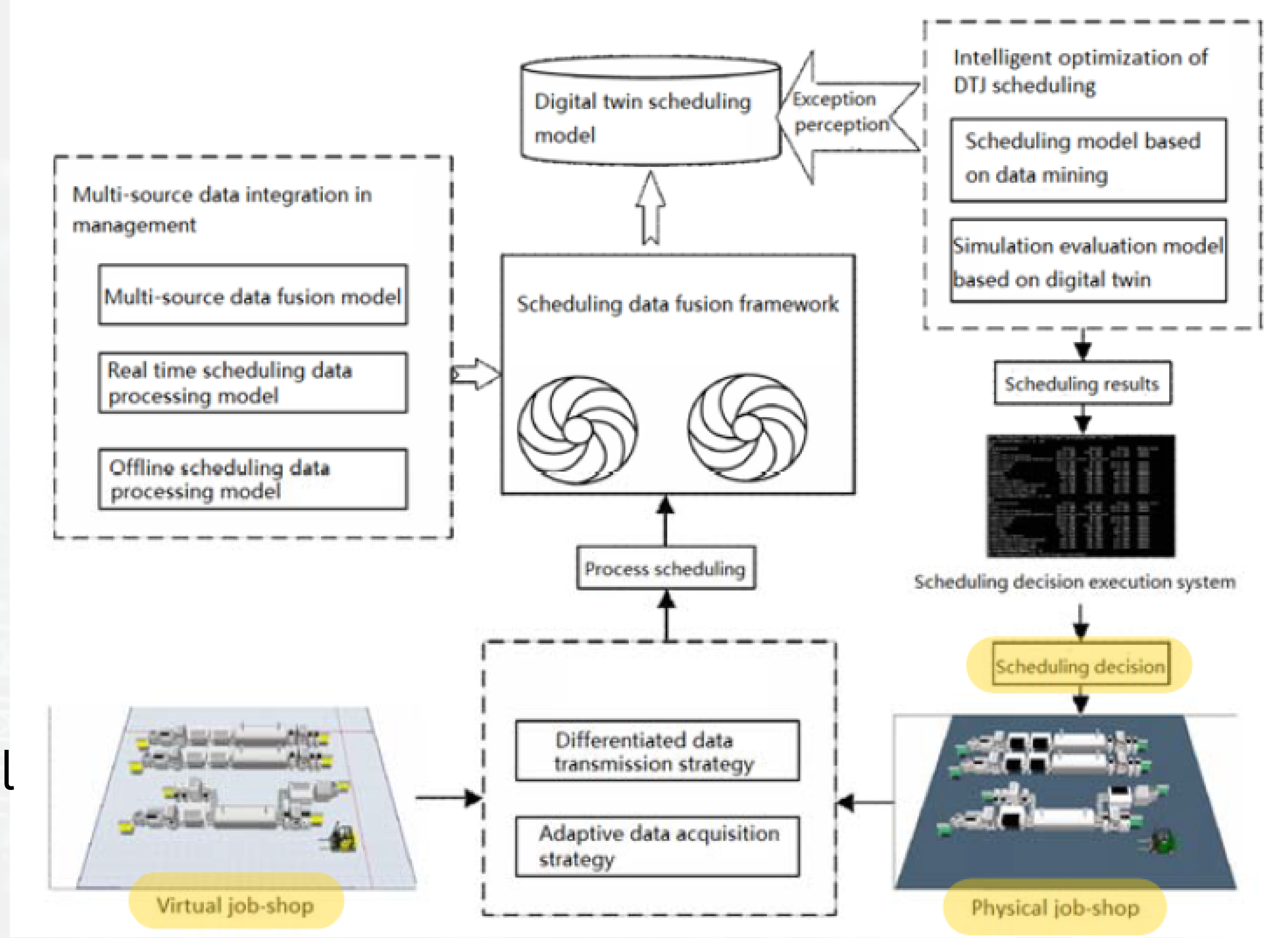
Zhang, Y. F. et al. (2020) ‘Digital twin-based production simulation of discrete manufacturing shop-floor for onsite performance analysis’, IEEE International Conference on Industrial Engineering and Engineering Management, 2020-Decem, pp. 1107–1111. doi: 10.1109/IEEM45057.2020.9309928.



Highlights 6

Xu, L. Z. and Xie, Q. S. (2021) 'Dynamic production scheduling of digital twin job-shop based on edge computing', Journal of Information Science and Engineering, 37(1), pp. 93–105. doi: 10.6688/JISE.202101_37(1).0007.

Digital twin for dynamic scheduling with edge and cloud based computing



Composition of Digital twin

- Simulation analytical model
- Job shop information model
- data exchange interface

Highlights 6

Xu, L. Z. and Xie, Q. S. (2021) ‘Dynamic production scheduling of digital twin job-shop based on edge computing’, Journal of Information Science and Engineering, 37(1), pp. 93–105. doi: 10.6688/JISE.202101_37(1).0007.

Levels in Manufacturing Enterprises

According to the ANSI/ISA-95 standard,

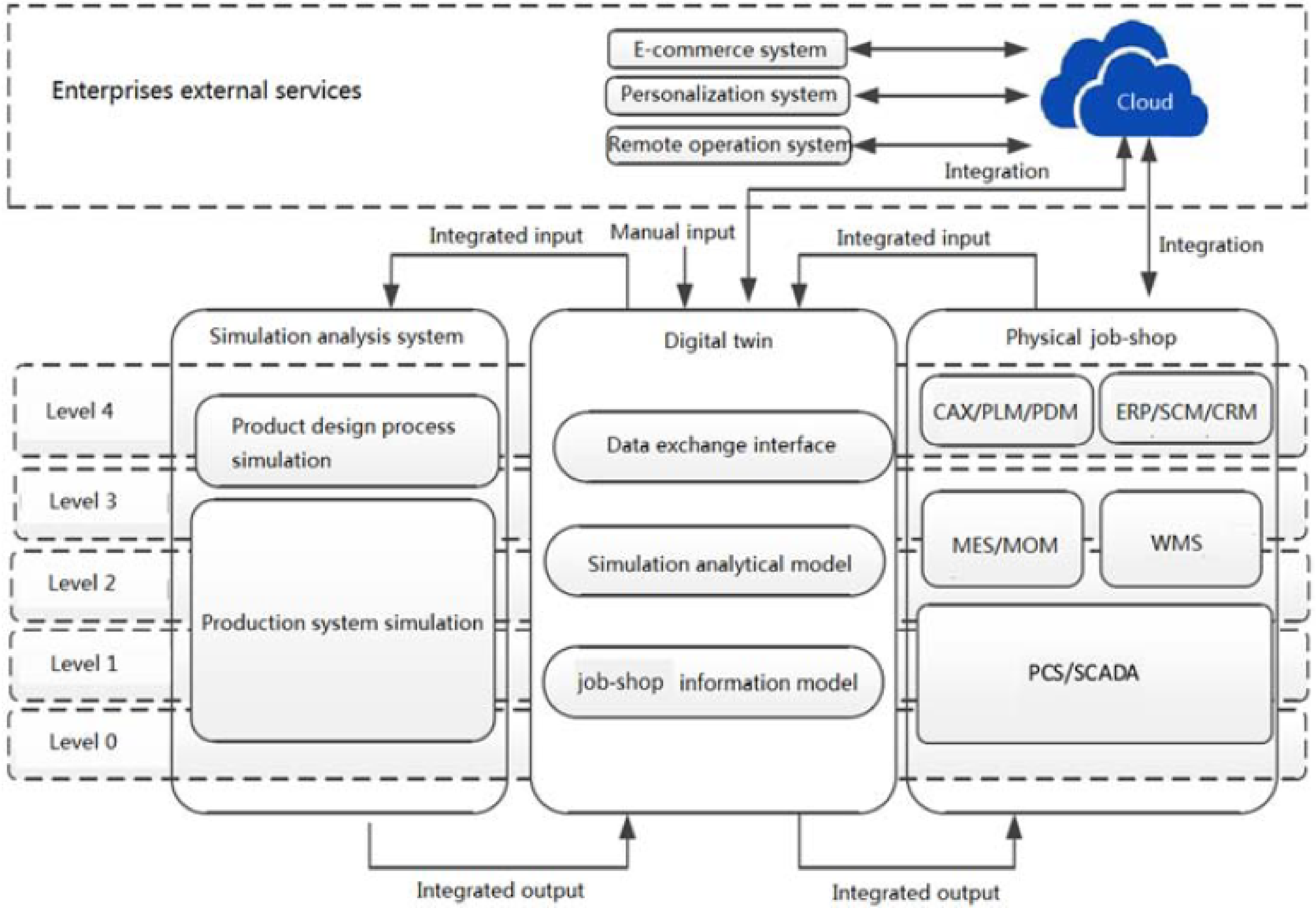
Level 4: prepares the plans for production, material demand, product delivery and shipment.

Level 3: controls the workflow and process of production

Level 2: detects, monitors and automatically controls the manufacturing process

Level 1: measures and controls the manufacturing process

Level 0: executes the production operations



Note: SCADA: Supervisory control and data acquisition; WMS: Warehouse management system; CAX: Computer-aided X; MOM: Material on machine; PCS: Process control system

Fig. 3. Information integration architecture.

Highlights 7

Lugaresi, G. and Matta, A. (2021) 'Automated manufacturing system discovery and digital twin generation', Journal of Manufacturing Systems, 59(February), pp. 51–66. doi: 10.1016/j.jmsy.2021.01.005.

Automated model generation without underlying structure & Model tuning

Event log:

- activity identifier
- workplace identifier
- time stamps

Digital Model

- directed graph
- tuple (N,A)

Nodes $n \in \mathbb{N}$	$\mathbb{P}_n$	Predecessor nodes set
	$\mathbb{S}_n$	Successor nodes set
	κ_n	Buffer capacity of a node
	ϕ_n	Frequency of a node
	ξ_n	Number of close events on a node
	π_n	Node branching policy tuples set
	$T_n = \{\tau_{k,n}\}$	Nodes flow times matrix
Arcs $a \in \mathbb{A}$	$\eta_a = (n, m)$	Nodes connected by an arc
	c_a	Buffer capacity of an arc
	f_a	Number of events on an arc
	e_a	Number of close events on an arc
	$T_a = \{t_{k,a}\}$	Arc flow times matrix

Highlights 7

Lugaresi, G. and Matta, A. (2021) 'Automated manufacturing system discovery and digital twin generation', Journal of Manufacturing Systems, 59(February), pp. 51–66. doi: 10.1016/j.jmsy.2021.01.005.

Model generation steps:

1. identify traces
2. retrieve precedence relationships among activities
3. Model tuning
4. Parameter estimation
5. Control policies identification

Numerical testcases:

1. Model calibration
2. Verification by comparing performance estimated
3. Aggregation of unrelated additional data
4. Apply to realistic event log

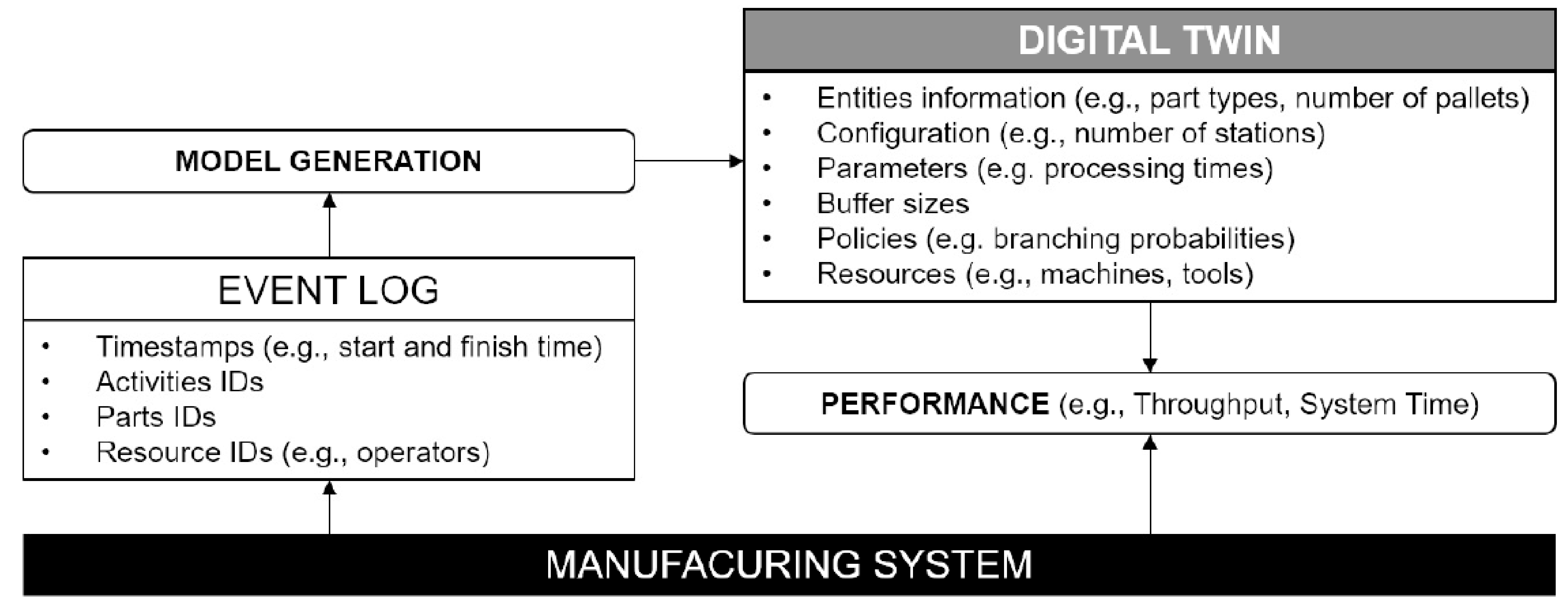
"The proposed automated generation and tuning method can positively contribute to Real-time Simulation applications, since it guarantees that an updated and reasonably detailed model of the physical system can be obtained at any time within one minute and with minimal manual intervention."

Highlights 8

Lugaresi, G. and Matta, A. (2021) 'Automated digital twins generation for manufacturing systems: A case study', IFAC-PapersOnLine, 54(1), pp. 749–754. doi: 10.1016/j.ifacol.2021.08.087.

Online Model Generation Steps

1. Create activities (Nodes)
2. Identification of traces (Arcs)
3. populate graph with properties of arcs and nodes
4. Graph model is converted in to Petri Nets or ERG



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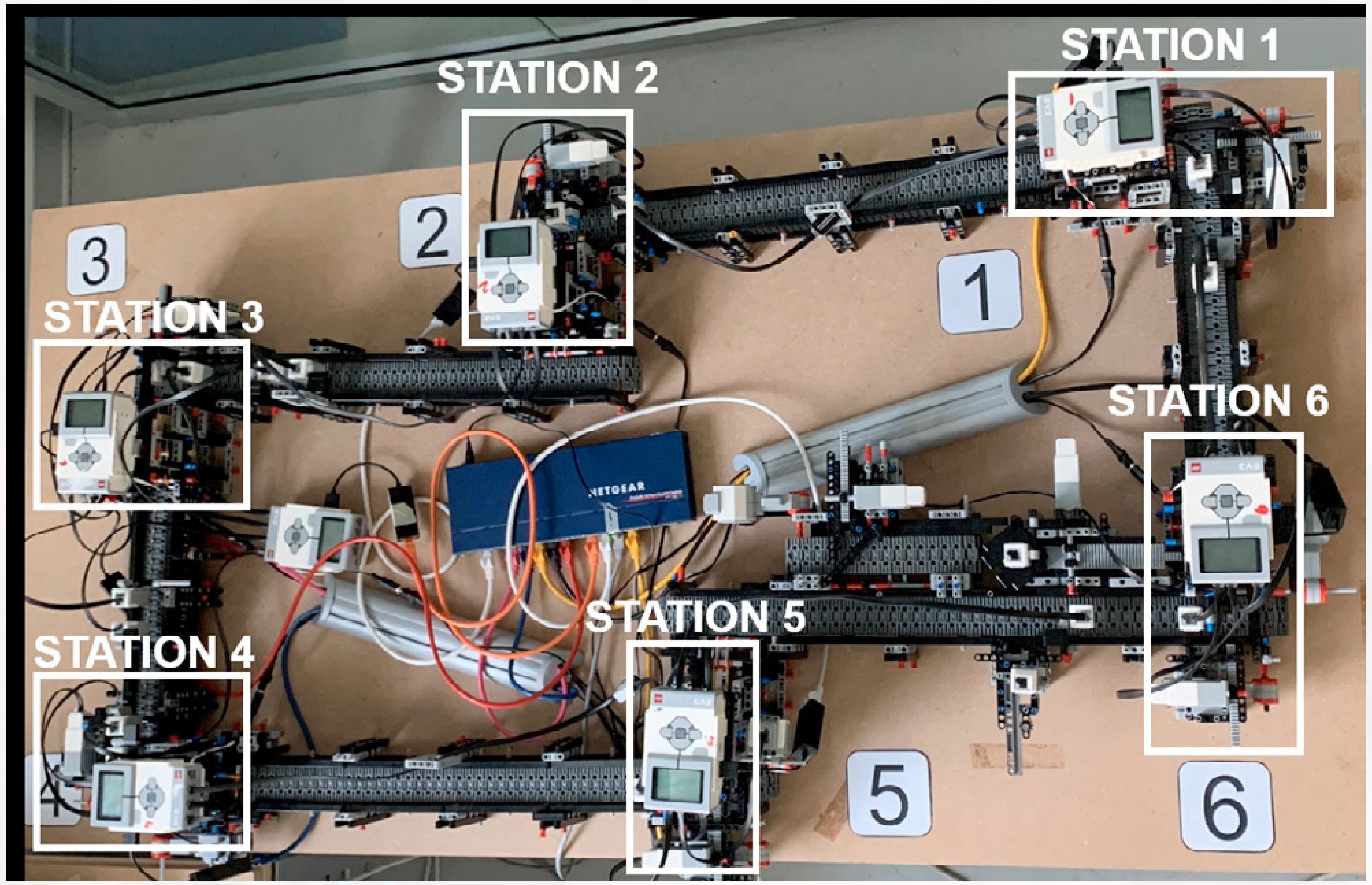
Testcase Parameters:

- Station layout
- Upstream Buffer Capacity
- Processing Time
- Failure Probability
- Repair Time

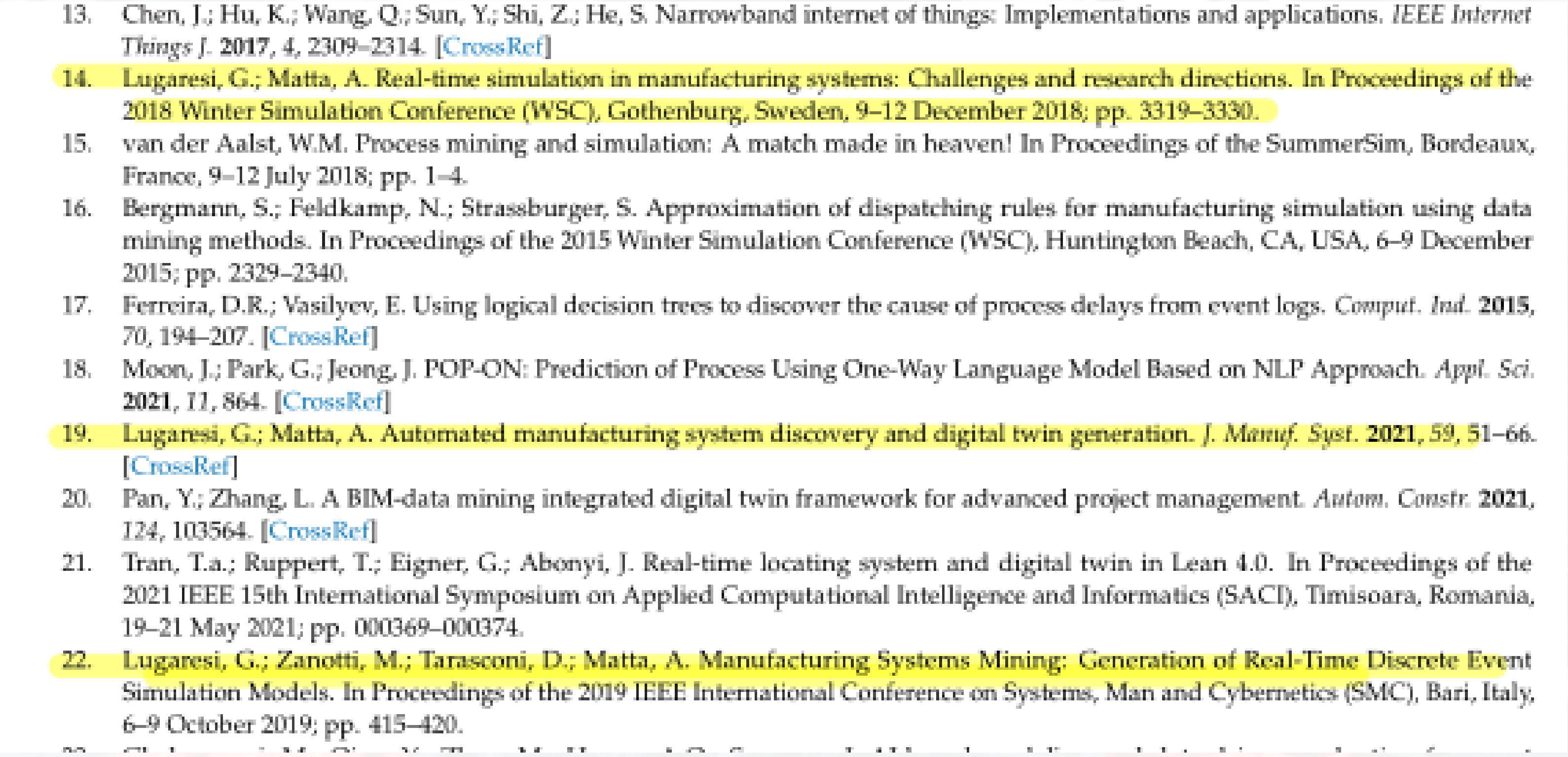


- initial transient determines the capability of discovering the correct model.
- Longer simulation time requirement for more model accuracy.
- Kernel Density Estimation and Empirical Cumulative Distribution Function produce comparable results to find distribution of operation time

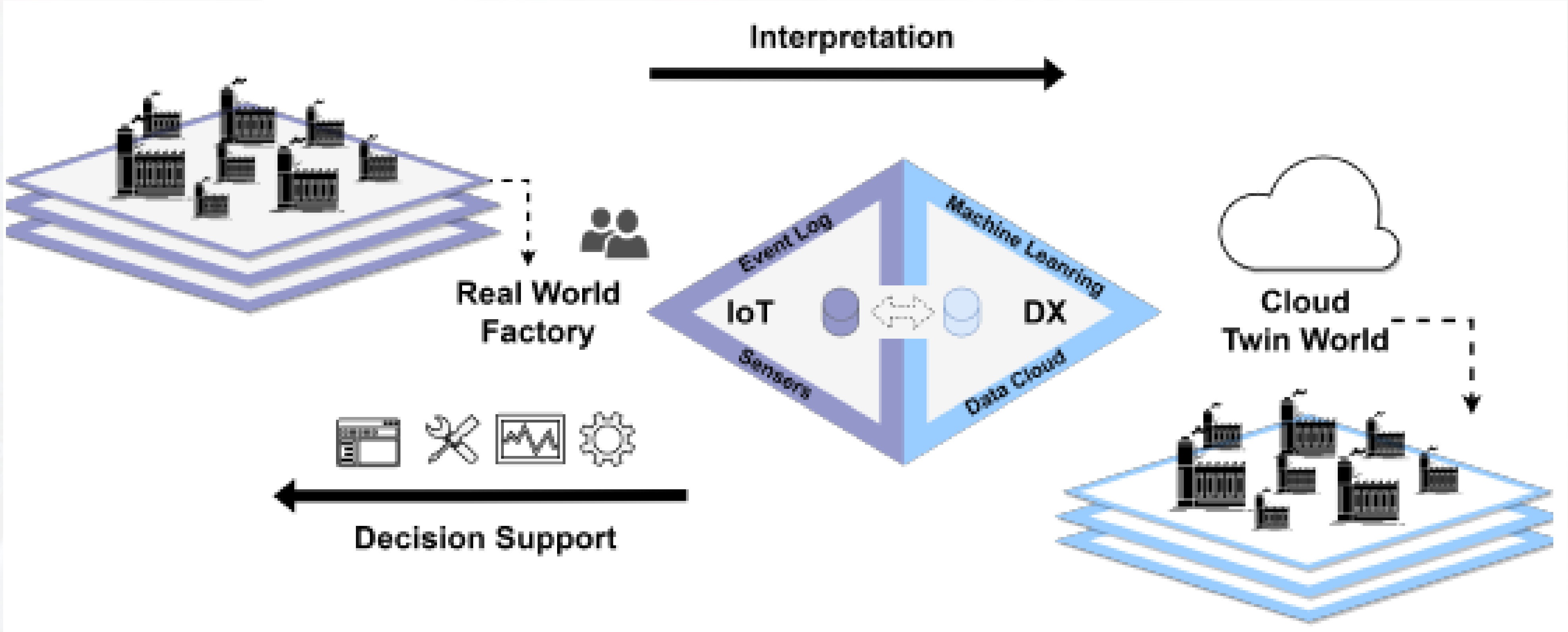
Highlights 9

Yang, M. et al. (2022) ‘A Novel Embedding Model Based on a Transition System for Building Industry-Collaborative Digital Twin’, Applied Sciences (Switzerland), 12(2). doi: 10.3390/app12020553.

"In this paper, we devised a digital twin model that predicts the remaining cycle time of a manufacturing system using event log data"



13. Chen, J.; Hu, K.; Wang, Q.; Sun, Y.; Shi, Z.; He, S. Narrowband internet of things: Implementations and applications. *IEEE Internet Things J.* **2017**, *4*, 2309–2314. [CrossRef]
14. Lugaresi, G.; Matta, A. Real-time simulation in manufacturing systems: Challenges and research directions. In Proceedings of the 2018 Winter Simulation Conference (WSC), Gothenburg, Sweden, 9–12 December 2018; pp. 3319–3330.
15. van der Aalst, W.M. Process mining and simulation: A match made in heaven! In Proceedings of the SummerSim, Bordeaux, France, 9–12 July 2018; pp. 1–4.
16. Bergmann, S.; Feldkamp, N.; Strassburger, S. Approximation of dispatching rules for manufacturing simulation using data mining methods. In Proceedings of the 2015 Winter Simulation Conference (WSC), Huntington Beach, CA, USA, 6–9 December 2015; pp. 2329–2340.
17. Ferreira, D.R.; Vasilyev, E. Using logical decision trees to discover the cause of process delays from event logs. *Comput. Ind.* **2015**, *70*, 194–207. [CrossRef]
18. Moon, J.; Park, G.; Jeong, J. POP-ON: Prediction of Process Using One-Way Language Model Based on NLP Approach. *Appl. Sci.* **2021**, *11*, 864. [CrossRef]
19. Lugaresi, G.; Matta, A. Automated manufacturing system discovery and digital twin generation. *J. Manuf. Syst.* **2021**, *59*, 51–66. [CrossRef]
20. Pan, Y.; Zhang, L. A BIM-data mining integrated digital twin framework for advanced project management. *Autom. Constr.* **2021**, *124*, 103564. [CrossRef]
21. Tran, T.a.; Ruppert, T.; Eigner, G.; Abonyi, J. Real-time locating system and digital twin in Lean 4.0. In Proceedings of the 2021 IEEE 15th International Symposium on Applied Computational Intelligence and Informatics (SACI), Timisoara, Romania, 19–21 May 2021; pp. 000369–000374.
22. Lugaresi, G.; Zanotti, M.; Tarasconi, D.; Matta, A. Manufacturing Systems Mining: Generation of Real-Time Discrete Event Simulation Models. In Proceedings of the 2019 IEEE International Conference on Systems, Man and Cybernetics (SMC), Bari, Italy, 6–9 October 2019; pp. 415–420.



Digital Twin Definition

Highlights 9

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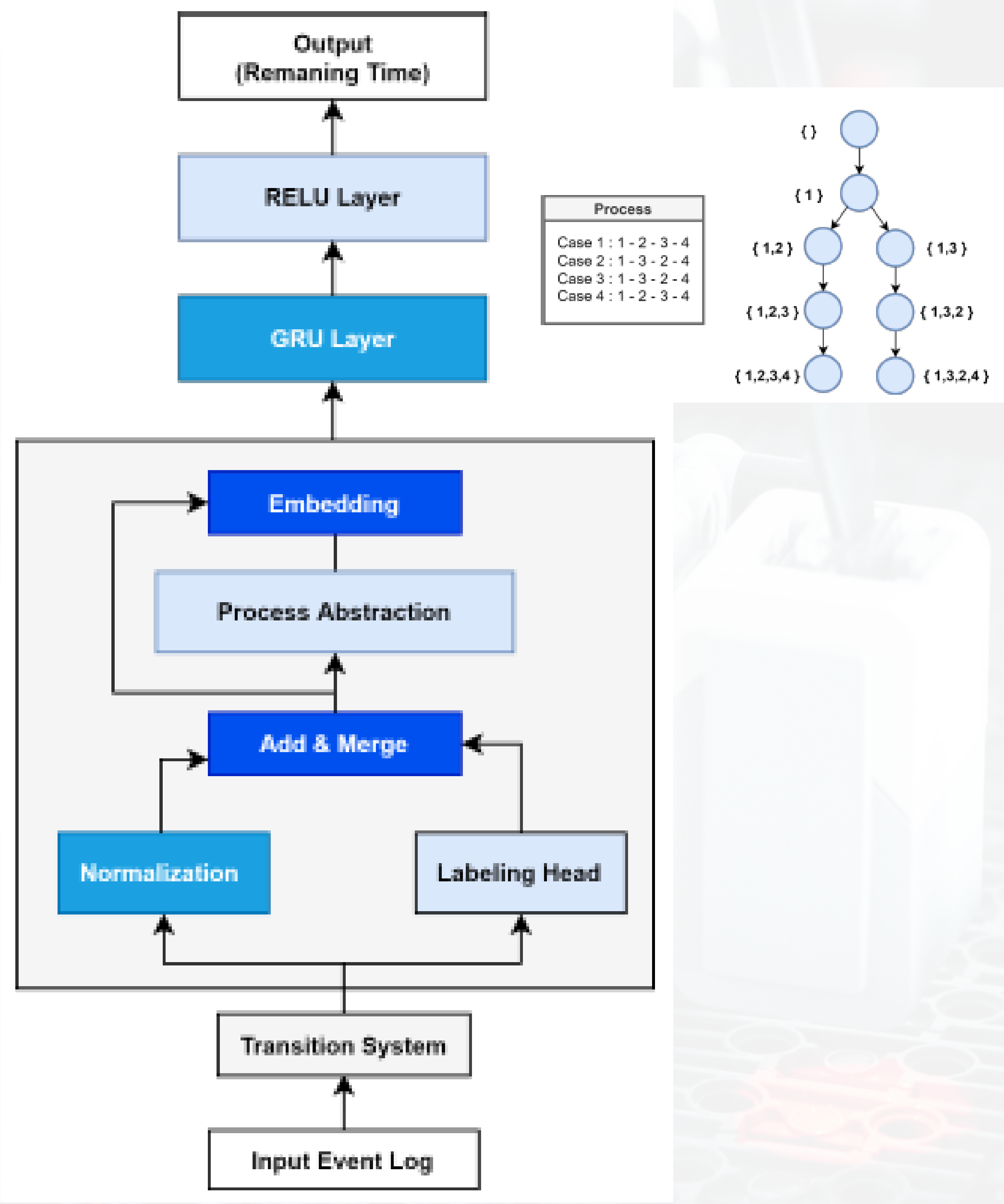
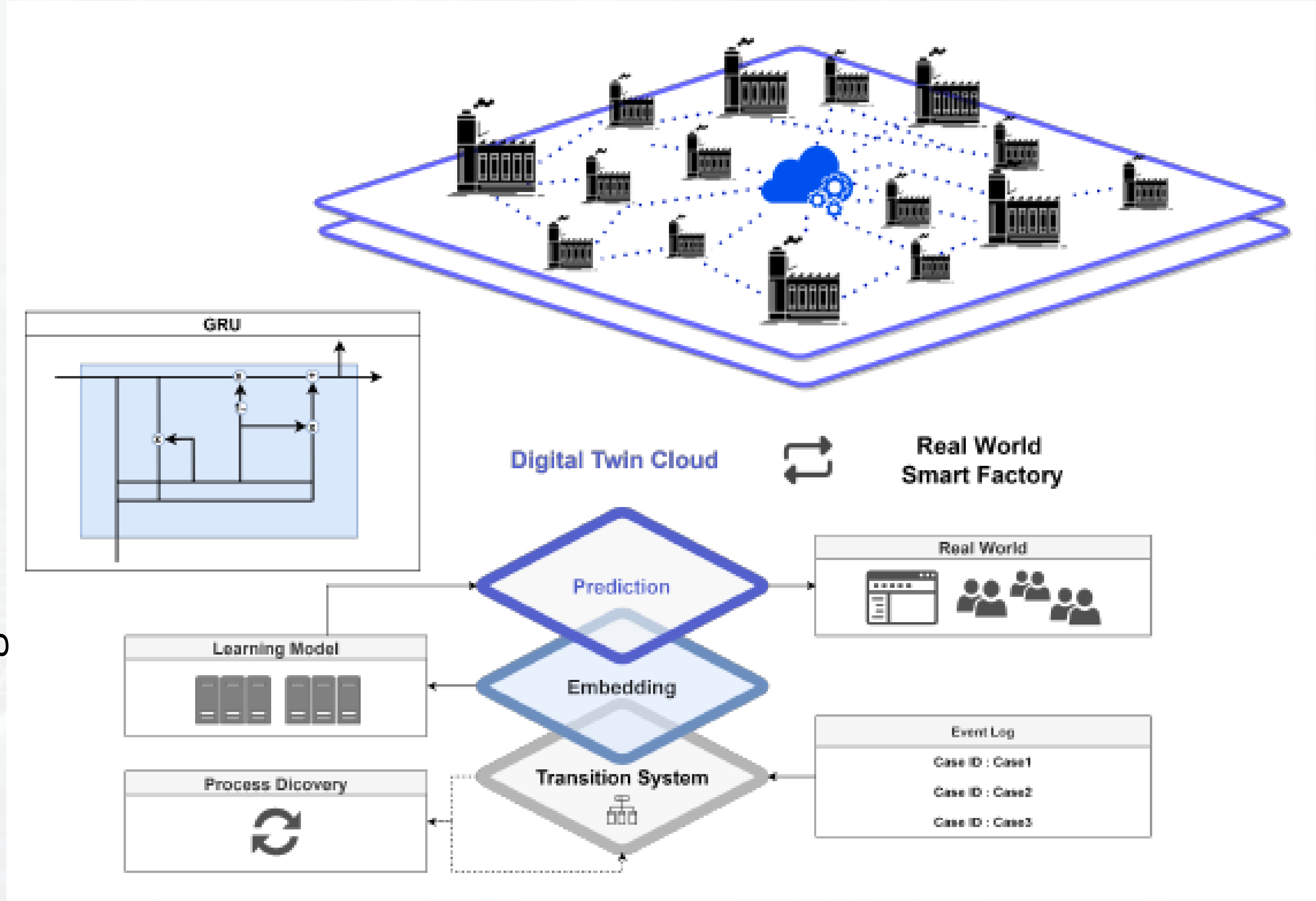


Transition system-based embedding

Digital Twin Archtecture



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Log-events files

Case ID	Start Time	End Time	Product	Machine	Qtty
Case 01	3 July 2021: 13:00	3 July 2021: 13:10	A	1	10
Case 01	3 July 2021: 13:20	3 July 2021: 13:40	A	2	10
Case 01	3 July 2021: 13:55	3 July 2021: 14:10	A	3	10
Case 01	3 July 2021: 14:20	3 July 2021: 14:30	A	4	10
Case 02	3 July 2021: 15:00	3 July 2021: 15:30	B	1	20
Case 02	3 July 2021: 15:40	3 July 2021: 16:20	B	3	20
Case 02	3 July 2021: 16:30	3 July 2021: 17:10	B	2	20

Normalization of the event log

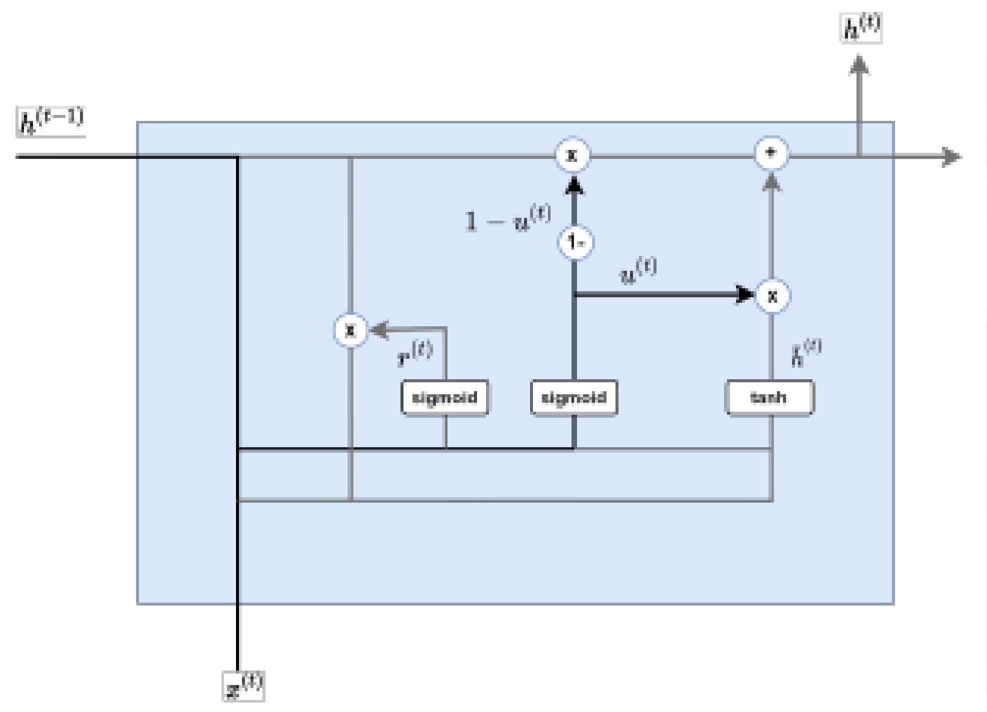
Case Id	Trace	Product	Qtty	End Time
Case 01	$< 1^0, 2^{20}, 3^{55}, 4^{80} >$	A	10	90
Case 02	$< 1^0, 3^{40}, 2^{90}, 4^{140} >$	B	20	180
Case 03	$< 1^0, 3^{32}, 2^{55}, 4^{90} >$	A	5	115
Case 04	$< 1^0, 2^{42}, 3^{65}, 4^{210} >$	B	10	190
Case05	$< 1^0, 2^{35}, ??, ?? >$	B	10	??

Data Vectorization

Product	1	2	3	4	5	Remaining Time
A	0	0	0	0	0	9.00
A	1	0	0	0	0	7.00
A	1	1	0	0	0	3.50
A	1	1	1	0	0	1.00

$$\text{Remaining Time}\left(S, P_{\text{product}}\right) = \frac{S_{\text{End time}} - S_{\text{Machine start time}}}{P_{\text{product}}}$$

GRU machine learning



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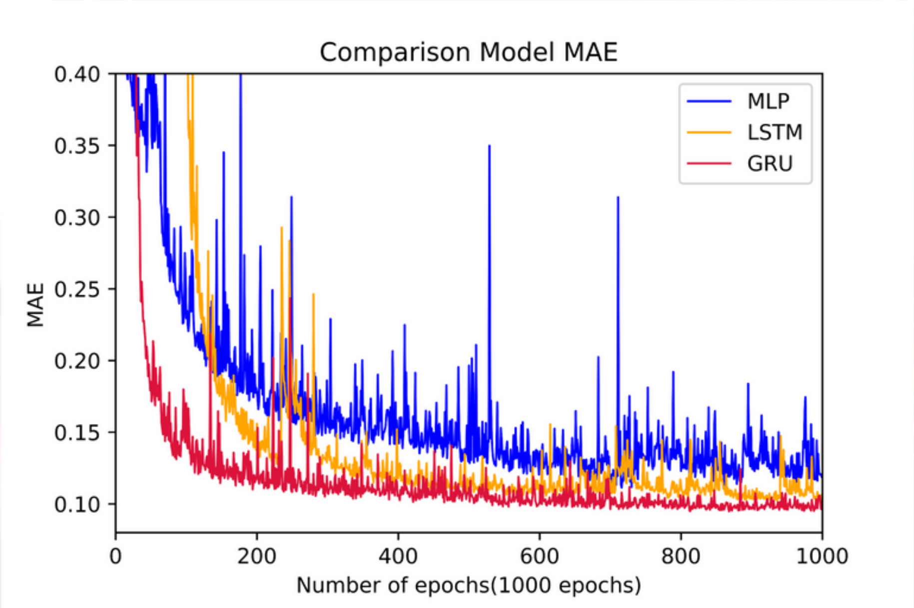
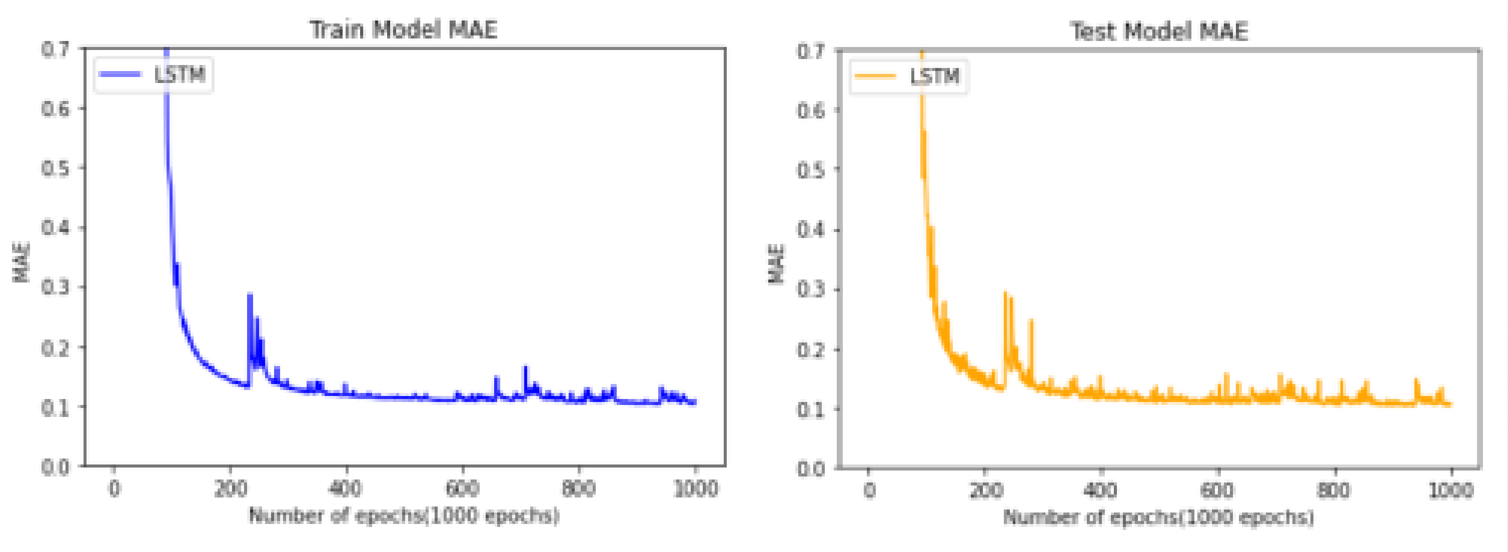
Main contribuitions

1. "Transition system-based embedding" to extract process characteristics from event log
2. Implement artificial intelligence learning for the model generation of the Digital Twin
3. Cloud computing style digital twin architecture.



Could be better...

1. Explanation of the machine learning part, its applications, and benefits
2. Even using real event logs, the experimental approach could be exploited better
3. Not even mentioning important parts of DTs, such as synchronization, validation, ...

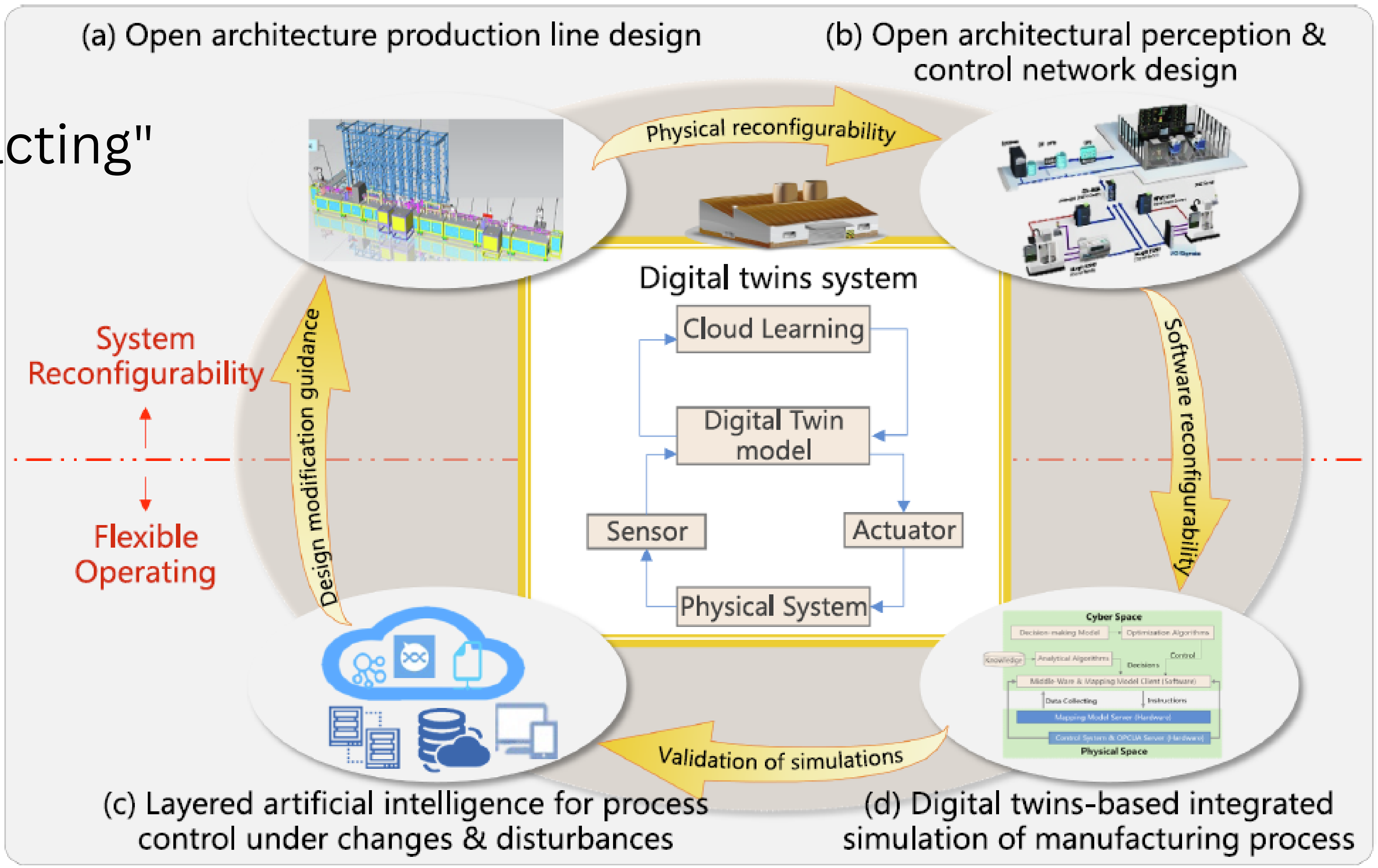


Highlights 10

Leng, J. et al. (2022) ‘Digital twins-based flexible operating of open architecture production line for individualized manufacturing’, Advanced Engineering Informatics, 53(January), p. 101676. doi: 10.1016/j.aei.2022.101676.

"Learning-Optimization-Reacting" Approach

Edge side for localized proactive decisions and cloud side for DES and parameter updating.



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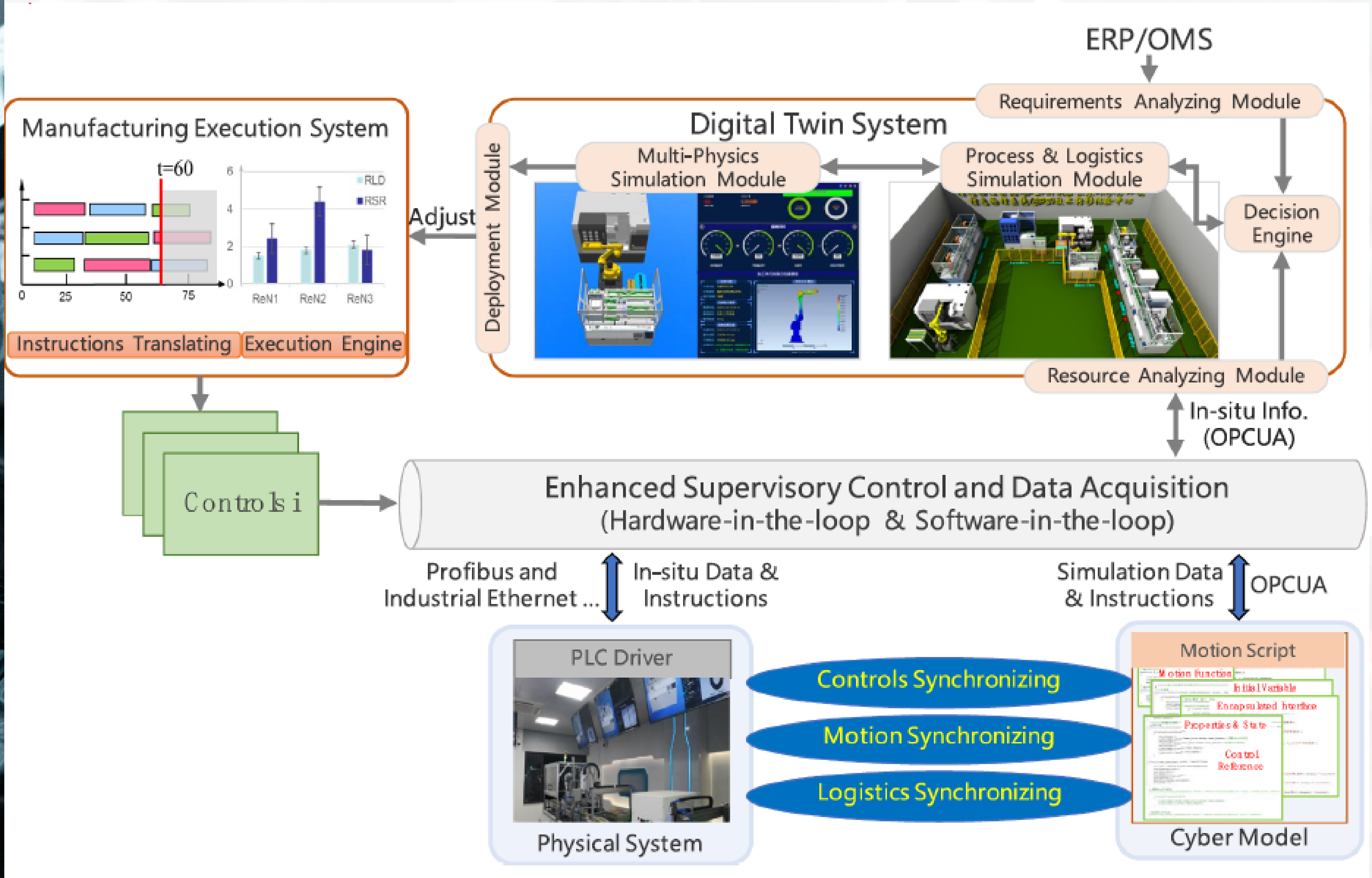


Key components to increase flexibility of production line

- Reconfigurability
- Dynamic Scheduling

DT validation is did by contextual computing (context-aware computing)

Highlights 10

Leng, J. et al. (2022) ‘Digital twins-based flexible operating of open architecture production line for individualized manufacturing’, Advanced Engineering Informatics, 53(January), p. 101676. doi: 10.1016/j.aei.2022.101676.

Case study: stepping motor assembly line

Performance Indices: Total WIP | Throughput rate | OEE | Cycle time | Lead time

Evaluation of the DTS method compared with the original method.

Methods	Manufacturing Execution Performance			System Reliability		
	Set-up Time (h)	Balance Ratio	UPH (pcs/h)	*DCT*	*MTBF*	*MTTF*
Before implementation	8	70%	7	68	~8760	~8752
After implementation	0.4	87.5%	10	14,324	2812	2811.6

Major reasons for improvement:

- Efficient bottle neck management
- Better handle of product mix especially in terms of routing and reconfigurability
- strategic parameter updating for dynamic load balancing and buffer reconfiguation and job dispatching


Conclusions
& Reflections

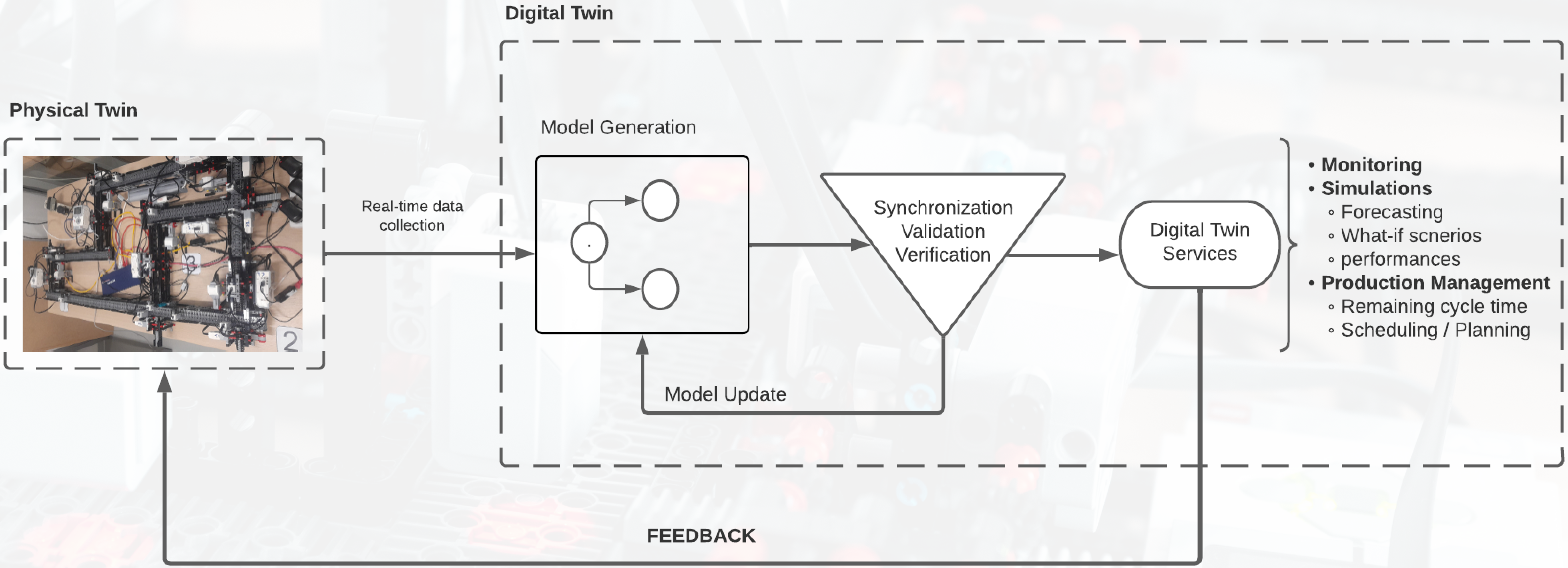
Conclusions & Reflections

- Presence of **multiple** digital twin **definitions** which are not entirely aligned with our concept of a digital twin.
- Presence of **multiple** digital twin **architecture**. Some are verified by implementing on testcase scenarios like assembly lines.
- **Process mining** approach has been verified as comparable way to generate physical twin configuration and estimate parameters.

Conclusions & Reflections

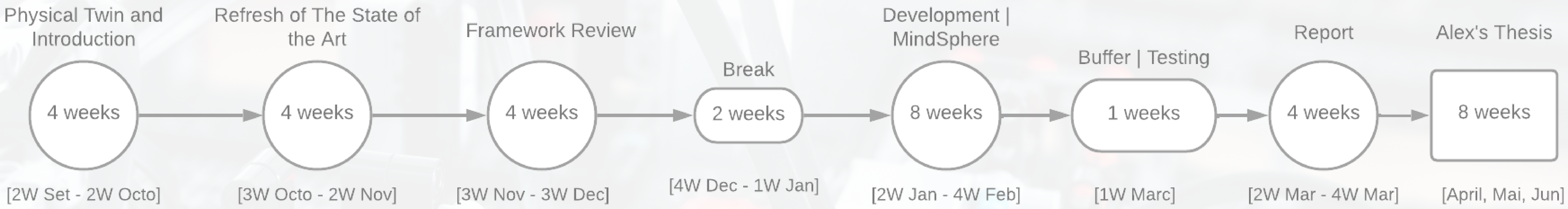
- Various **digital twin use case scenarios** are already available, such as dynamic scheduling, predictive maintanenence, reconfiguration of flexible machine production lines.
- A wide set of authors agree that further study has to be done on **increasing the efficiency** of the digital model and its **reliability**.
- Further study to be done from the **safety** and **sustainability** point of view.

Conclusions & Reflections

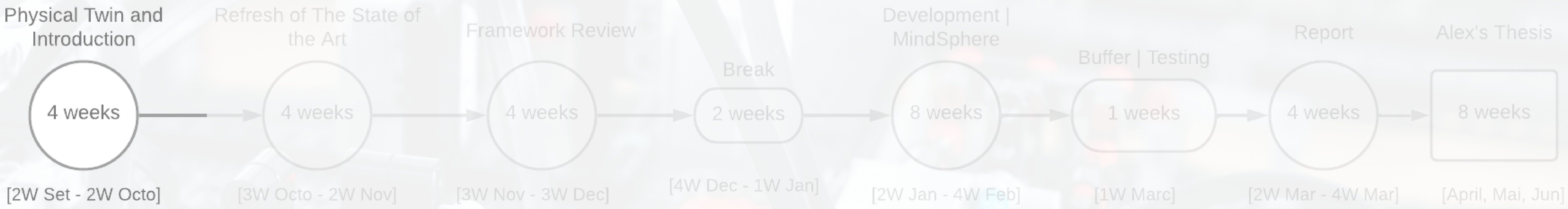


Timeline and Next Steps

Timeline and Next Steps



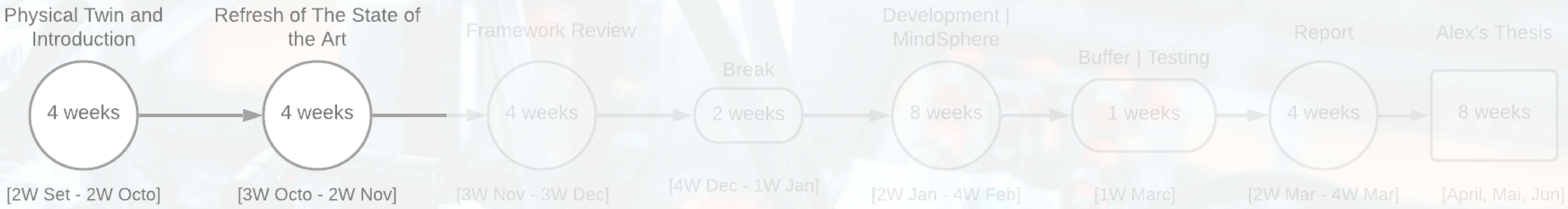
Timeline and Next Steps



1. Physical Twin and Introduction

- Learn how to use the Lego System (EV3 components)
- MQTT communication
- Influxdb database
- Proof of Concept ("Supervisor")

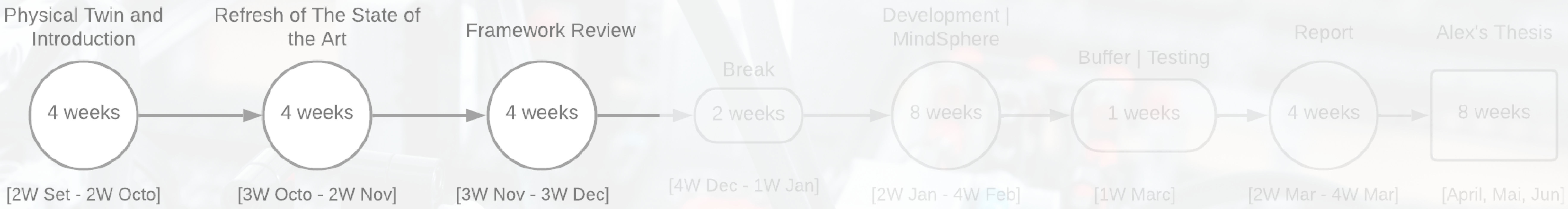
Timeline and Next Steps



2. Refresh of The State of the Art

- Research Framework
- Query Search
- Paper Selection (algorithmic, manually score, and skimming)
- Reading selected papers
- Highlights (we are here!)

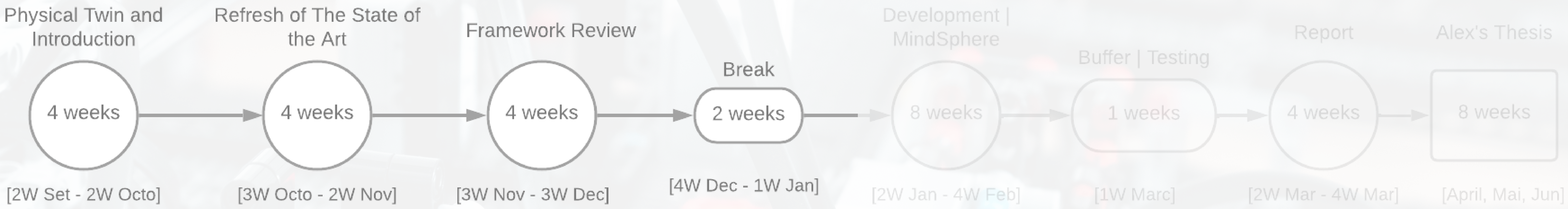
Timeline and Next Steps



3. Framework Review

- Review of existing Framework (1 week) - See the DT
- implementation and scientific work review (2 weeks)
- Alignment analysis and update framework (1 week)

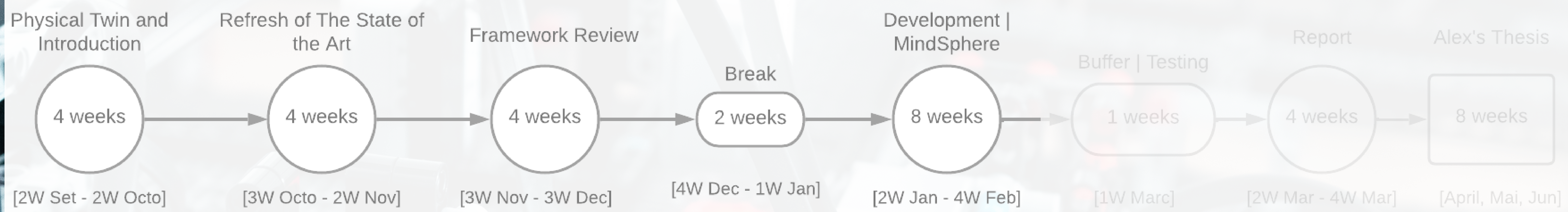
Timeline and Next Steps



4. Break

- Christmas and New Year break
- From 19/12/2022 to 05/01/2022

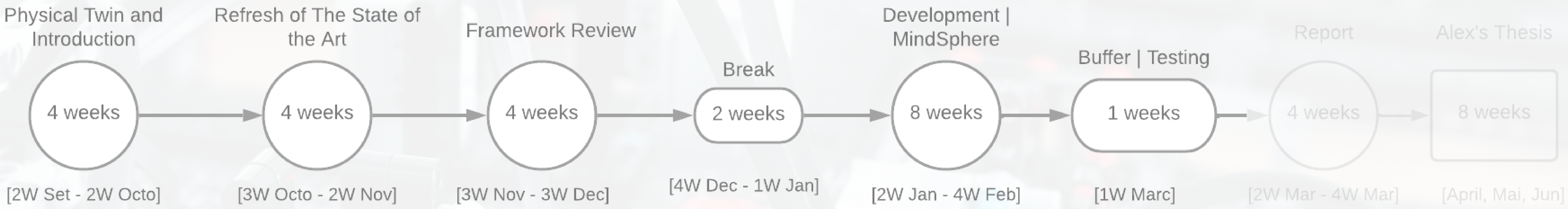
Timeline and Next Steps



5. Development | MindSphere

- Data collection (check compatibility)
- Model generation (check compatibility)
- Synchronization and Validation (check compatibility)
- Digital Twin's Services **(Need to be done)**
- Feedback implementation **(Need to be done)**
- Alignment with MindSphere

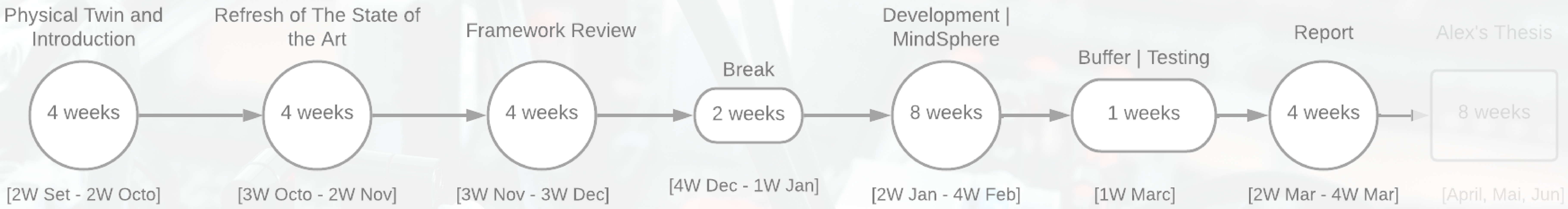
Timeline and Next Steps



6. Buffer | Testing

- Buffer in case of delay
- Testing bench for validation of the development

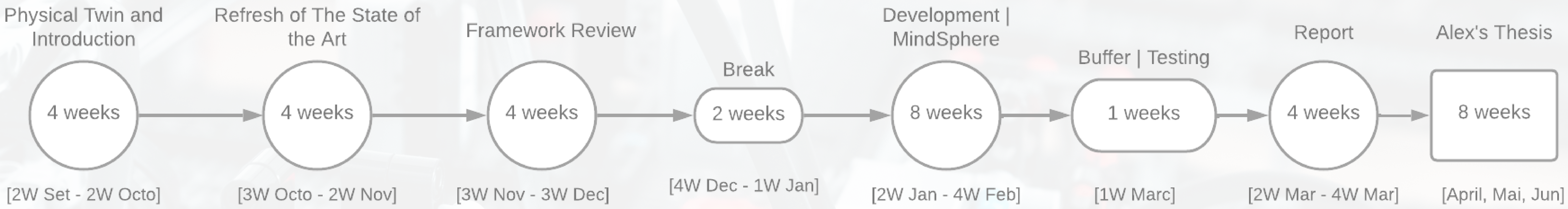
Timeline and Next Steps



7. Report

- Report (middle-term)
- Report submission for Pedro's university
- *Paper submission?*

Timeline and Next Steps



8. Alex's Thesis

- Alex keeps going with the Thesis
- Pedro keep helping Alex
- Improvements in previous steps and academic refining the work


Thank You