Digital twinning for ports: from characterization to operations' modelling

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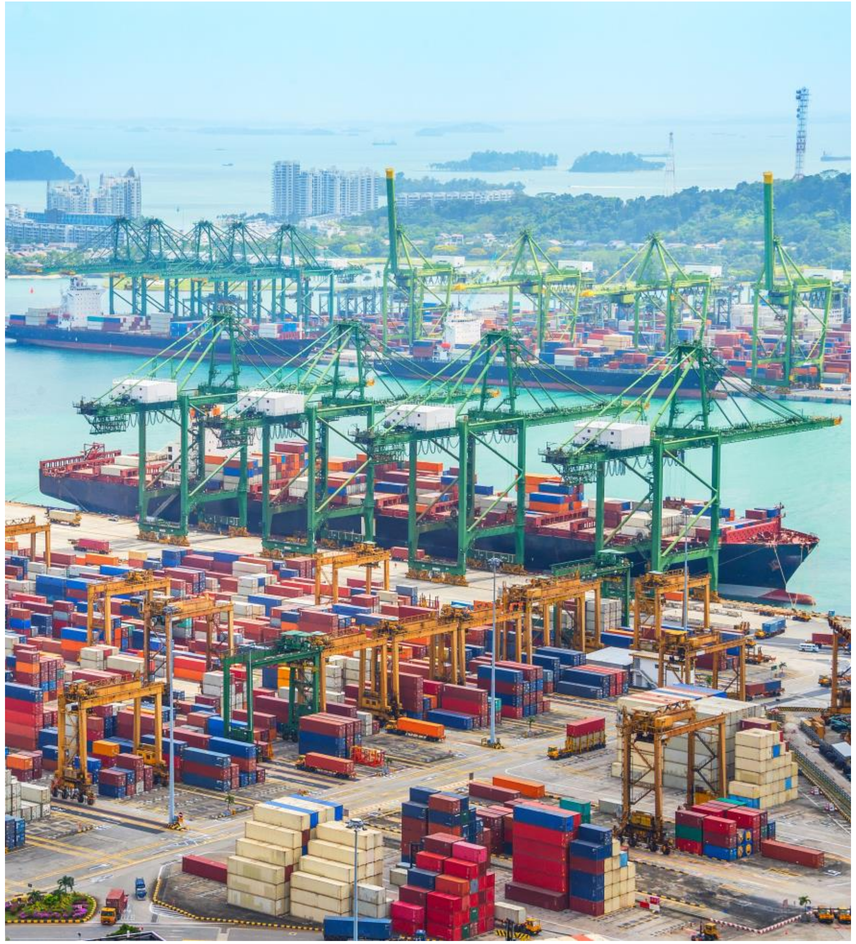
BALTIC-FIT Summer School 2025

Outline

- Ports
- Digital Twins in Industry 4.0
- Research questions
- Overview of papers and contributions
- Conclusion
- Future work

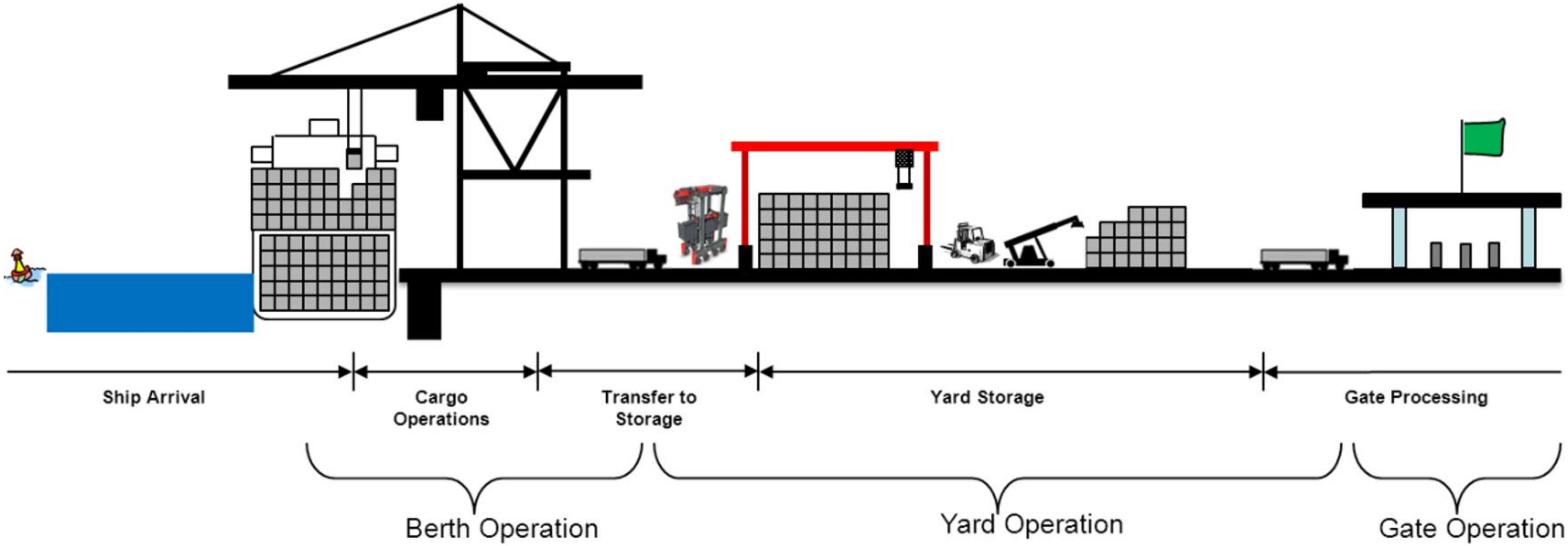
Ports as part of supply chains

- Multi-modal hubs of trade
  - 90% of world trade passes through ports
- Connect different modes of transport
- Provide temporary storage
  - 80% of containers are temporarily stored
- Accommodate a large number of interlinked processes and actors
- Space, time and cost constraints



Picture taken from VTI ImageVault

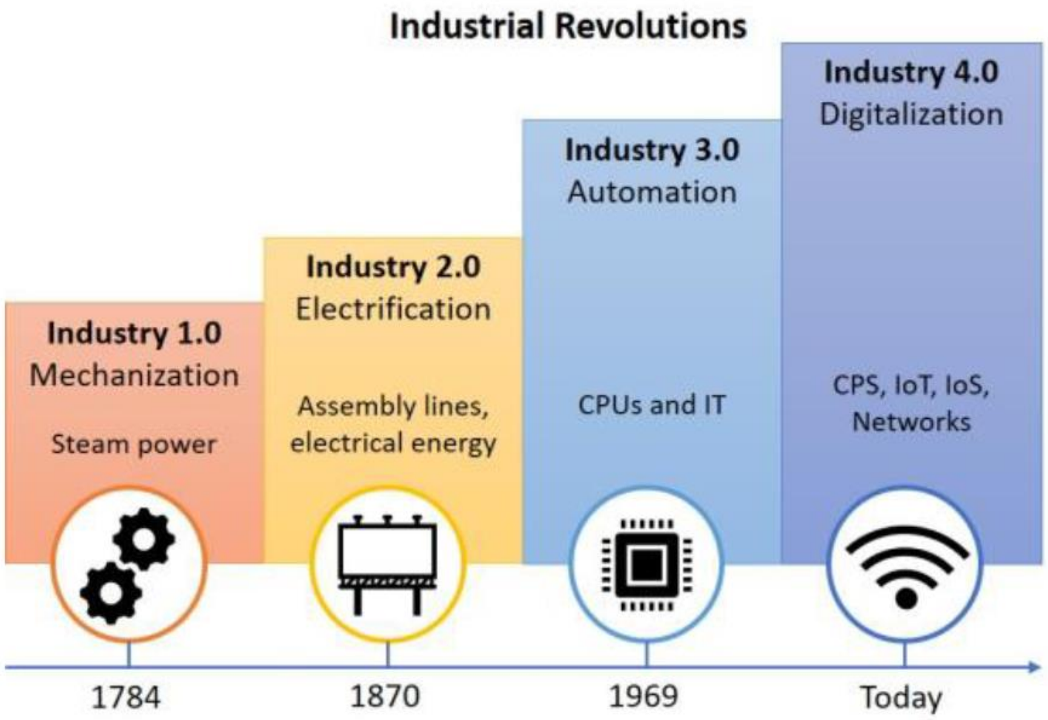
Overview of ports



International Maritime Organization (IMO) (2016). Module 5 – Ship Port Interface for Energy Efficiency.

Digital Twins in Industry 4.0

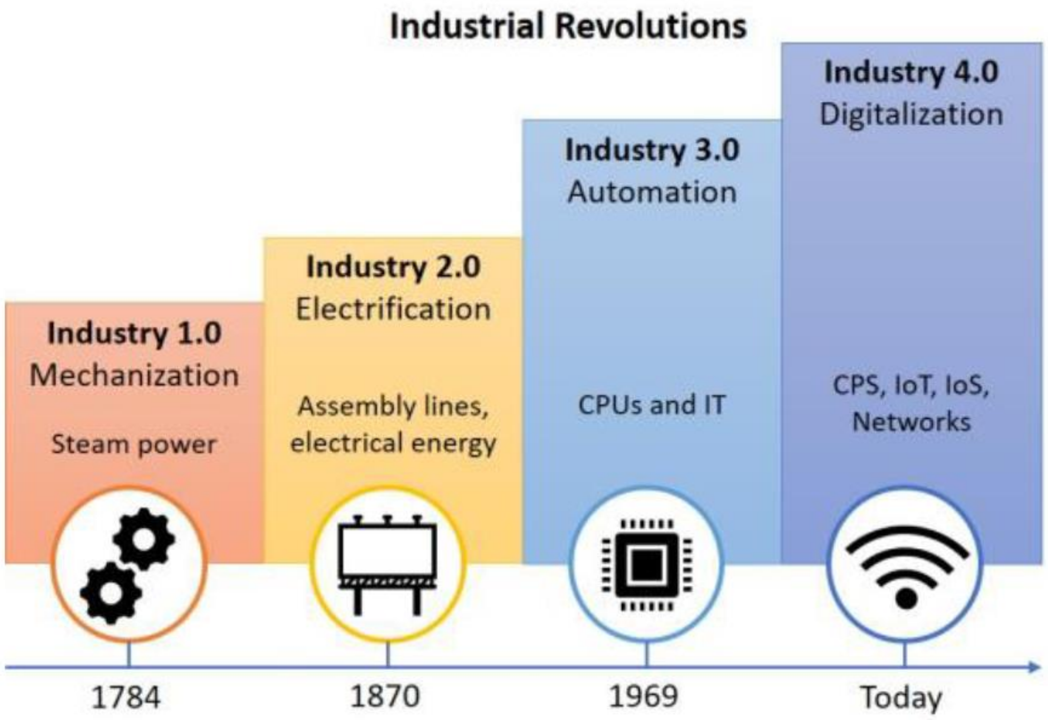
- Industry 4.0 refers to the wide range of new technologies and digital advances altering production by integrating the physical and virtual worlds



Gutiérrez, I., Ponce, P., Balderas, D., Khakifirooz, M., & Molina, A (2021). **Automation Taxonomy for Industry 4.0 based on human features: A Sensing Smart and Sustainable approach**. In proc. of ICMEAE 2021.

Digital Twins in Industry 4.0

- Industry 4.0 refers to the wide range of new technologies and digital advances altering production by integrating the physical and virtual worlds
- Digital Twins (DT) clone a physical object into a software counterpart
- Digital Twins considered one of the pillars of Industry 4.0
    - They comprise Industry 4.0 tech such as: CPS, IoT, AI, etc.



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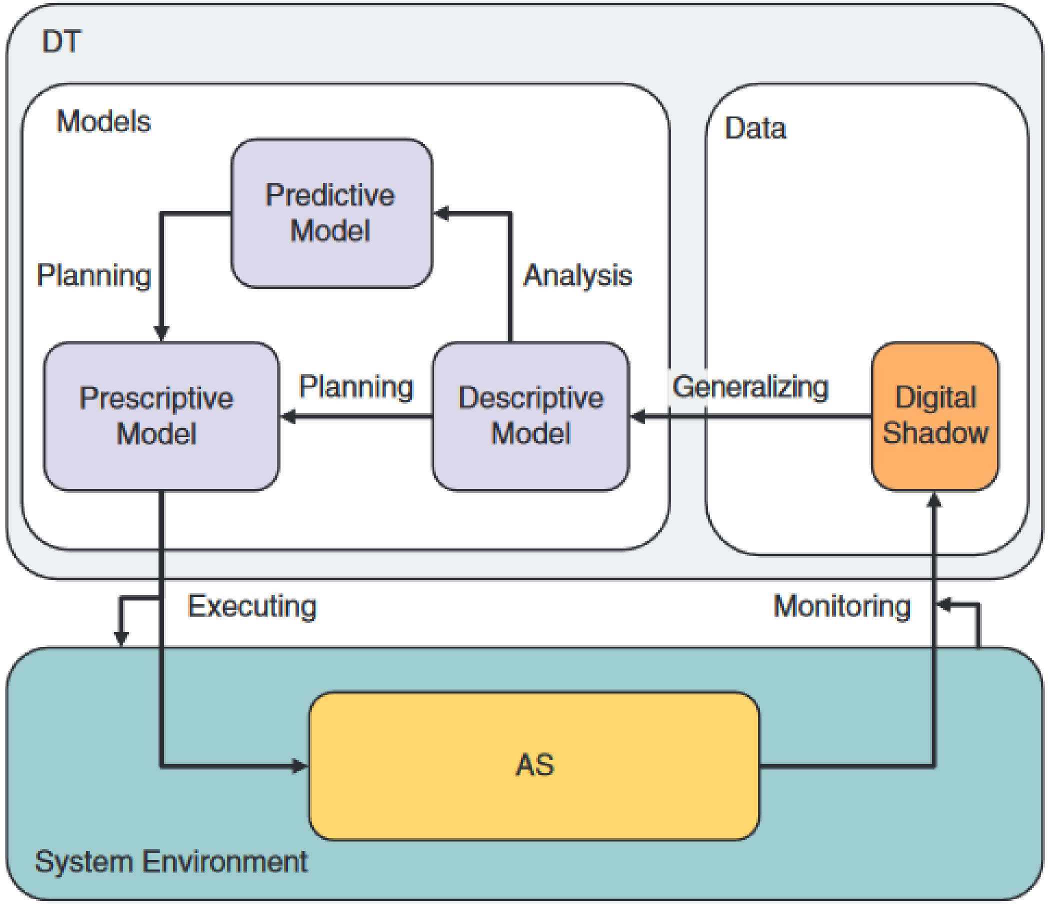
Digital Twins in Industry 4.0

- “the one” definition of DTs does not exist
- DT solutions share some common characteristics
  - ➢Actual Twinned System
  - ➢Virtual Representation
  - ➢(Real Time) Data Collection
  - ➢Modeling
  - ➢Bi-directional data exchange
  - ➢Automation

… and more in paper 2 of the thesis



Eramo, R., Bordeleau, F., Combemale, B., van Den Brand, M., Wimmer, M., & Wortmann, A. (2021). **Conceptualizing digital twins**. *In IEEE Software*, *39*(2)

Research Questions

- **RQ-1:** What are the key characteristics of cross-domain digital twinning solutions, and to what extent can they be transferred to the port?

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- **RQ-2:** How mature are existing digital twinning solutions in ports and how can their maturity be evaluated?

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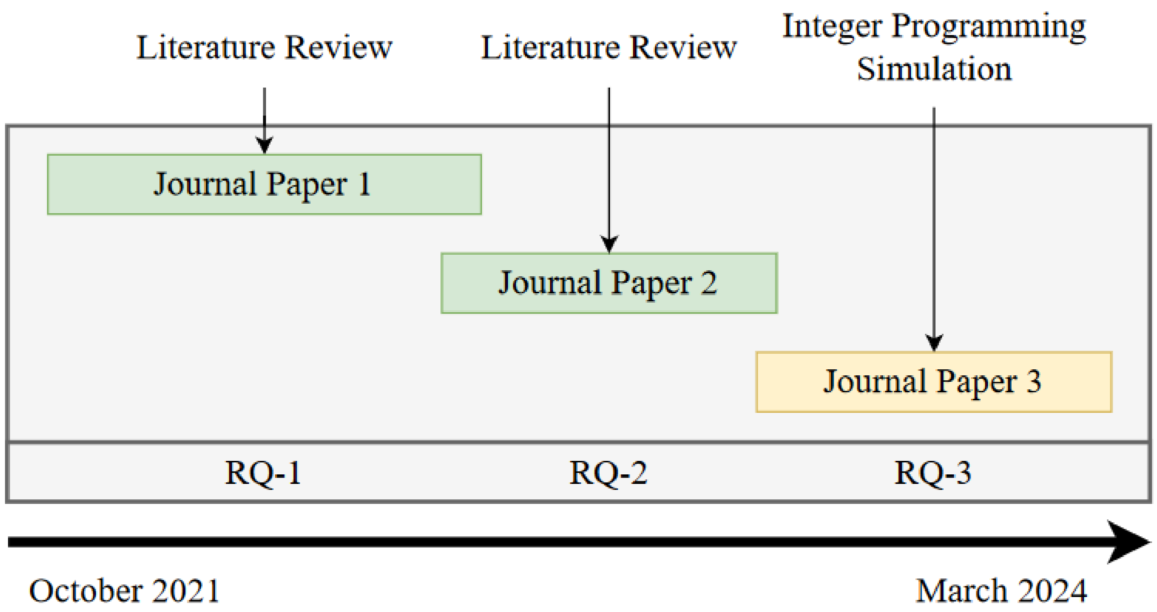
- **RQ-1:** What are the key characteristics of cross-domain digital twinning solutions, and to what extent can they be transferred to the port?
- **RQ-2:** How mature are existing digital twinning solutions in ports and how can their maturity be evaluated?
- **RQ-3:** How can digital twin components be designed that could facilitate the effectiveness of multimodal transportation using ports to reduce the carbon footprint of cargo?

Papers and contributions

- Paper 1
  - ➢Identifies port DT requirements
  - ➢Outlines a port DT
- Paper 2
  - ➢Provides a tool to assess DT maturity
  - ➢Emphasizes the importance of interoperability
- Paper 3
  - ➢Links two important port problems
  - ➢Provides a model suitable for integration into a DT



Paper 1

Digital Twins for Ports:
Derived From Smart City and Supply Chain Twinning Experience

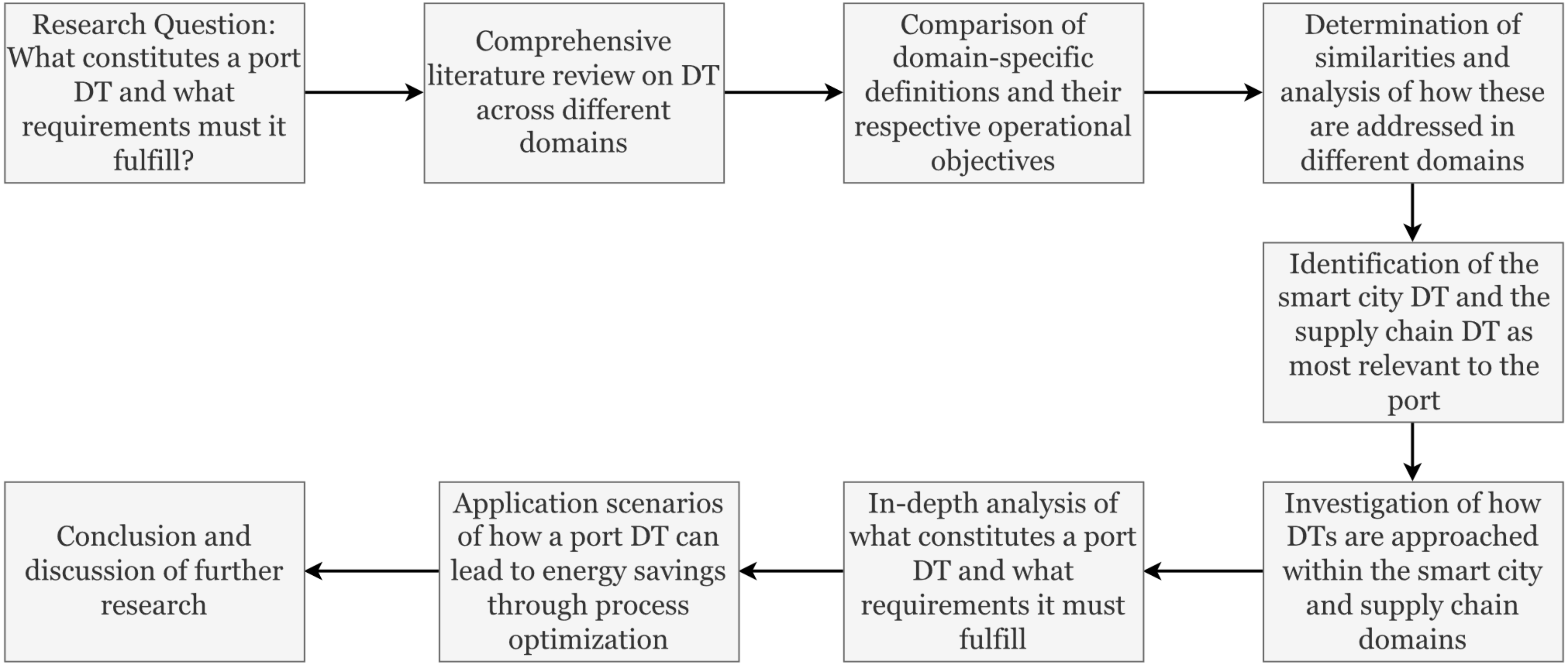
Authors: **Robert Klar**, Anna Fredriksson and Vangelis Angelakis
in *IEEE Access*, vol. 11, pp. 71777-71799, 2023
doi: 10.1109/ACCESS.2023.3295495.

Paper 1: Background

- Lack of research that uses the DT as a tool to optimize the entire port
  - ➢A port is a system of systems
- Existing DT research in ports is limited to twinning assets in isolation
  - ➢E.g., twinning of quay cranes
- Cities and supply chains are very relevant systems of systems
  - ➢Both interact with ports and have more DT-related research
    - How can ports draw from their digital twinning experience? (RQ1)

R. Klar, A. Fredriksson and V. Angelakis (2023)
Digital Twins for Ports: Derived From Smart City and Supply Chain Twinning Experience,
in *IEEE Access*, vol. 11, pp. 71777-71799

Paper 1: Methodology



Paper 1: Results

- Port DTs are very close to those of smart cities and supply chains
- Key requirements for port DTs:
  - (Real-time) Situational awareness
  - Data-driven (joint) decision making
  - Facilitation of multi-stakeholder governance and collaboration
- A port DT
  - Is a grouping of models and algorithmic components
  - Enables a complete view of past and current operating conditions
  - Allows the prediction of the most efficient operations
  - May act autonomously while providing full transparency across actors

Paper 2

Digital Twins' Maturity: The Need for Interoperability

Authors: **Robert Klar**, Niklas Arvidsson and Vangelis Angelakis

in *IEEE Systems Journal*, vol.18, no.1, pp.713-724, 2024.

doi: 10.1109/JSYST.2023.3340422.

Paper 2: Background

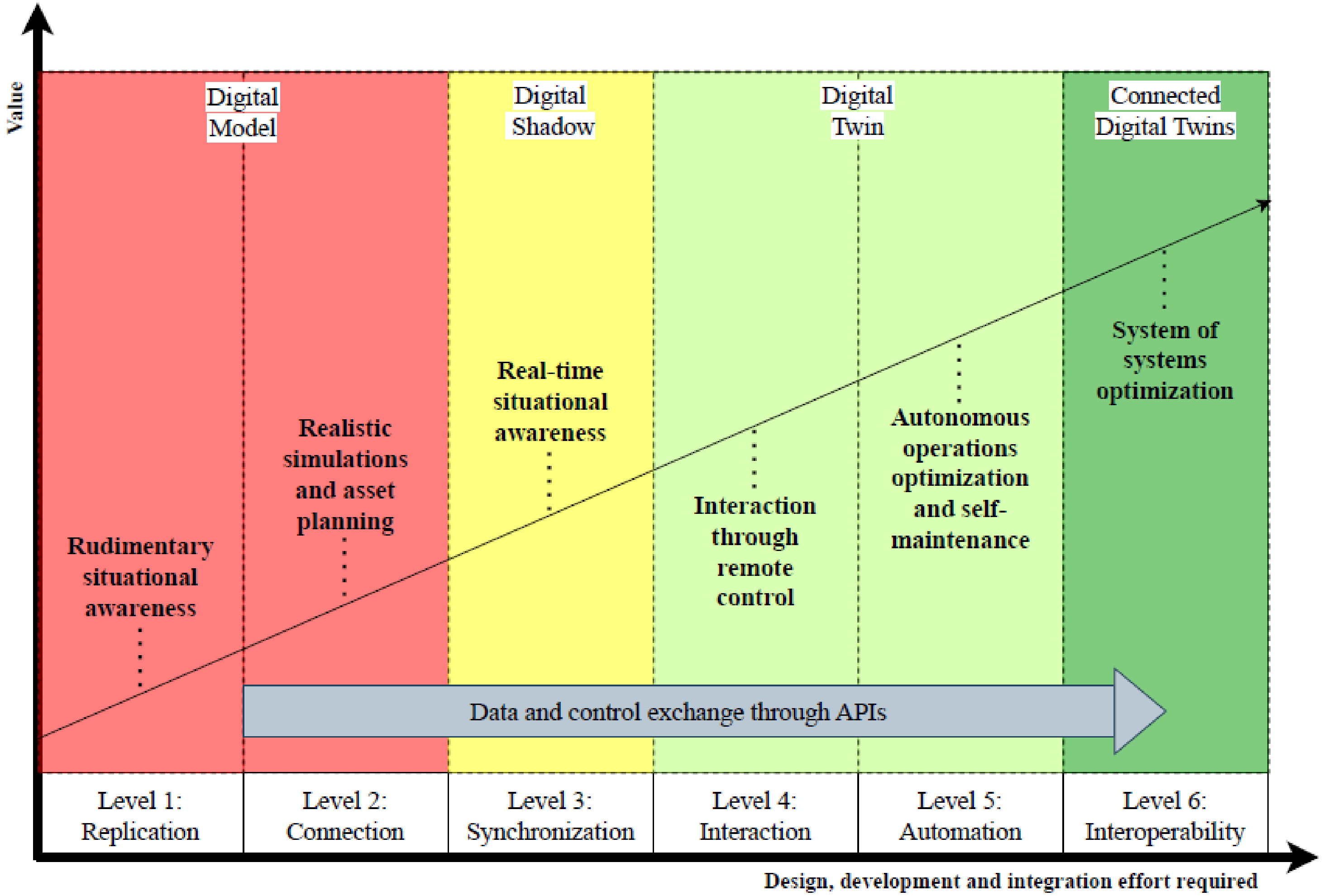
- Growing number of DT solution providers
  - ➢How to compare and benchmark offerings of different DT solutions? (RQ2)
- Existing DT assessment tools are domain specific
  - ➢There is a lack of domain-independent tools to assess DT maturity
- Most existing DTs act in isolation
  - ➢Interoperability is crucial for system of systems, e.g., ports (RQ2)

R. Klar, N. Arvidsson and V. Angelakis, (2024) **Digital Twins' Maturity: The Need for Interoperability** in *IEEE Systems Journal*

Paper 2: Methodology

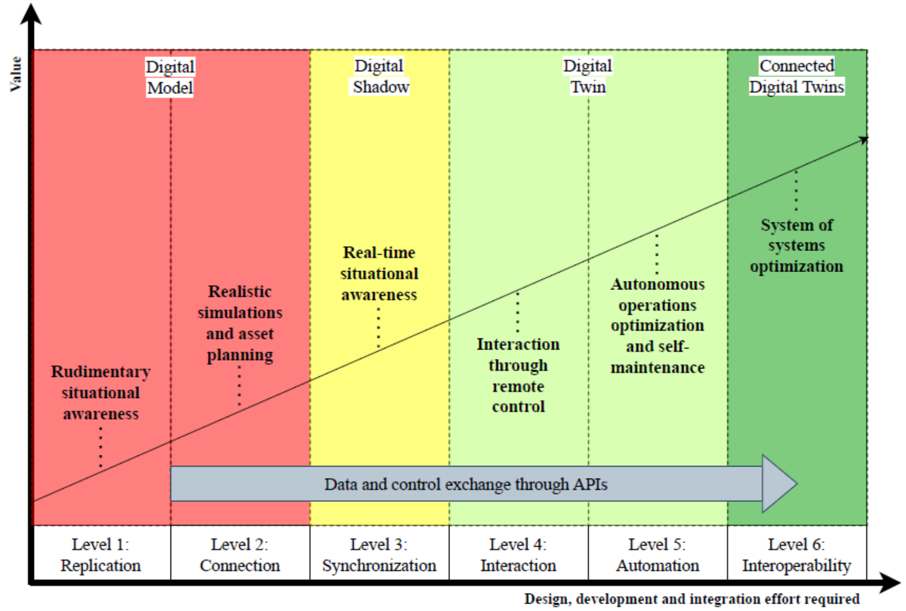
- Systematic literature review to identify
  - Existing domain-specific DT maturity assessment tools
  - Best practices for assessing DT maturity
  - Barriers that hinder the development of DTs towards higher DT maturity
- Maturity characterization derivation
- Application of the derived tool to assessing maturity of existing port DTs

Paper 2: Results – the tool



Paper 2: Results – using the tool

- Innovation-leading ports have already sophisticated DT solutions
- Most ports are still in the initial phase
  - ➢ Have maturity level up to 3 (Synchronization)
- Existing DT solutions are restricted by lack of
  - Standardization
  - Trust
- DTs reach full potential through joint decision-making (requires interoperable DTs)



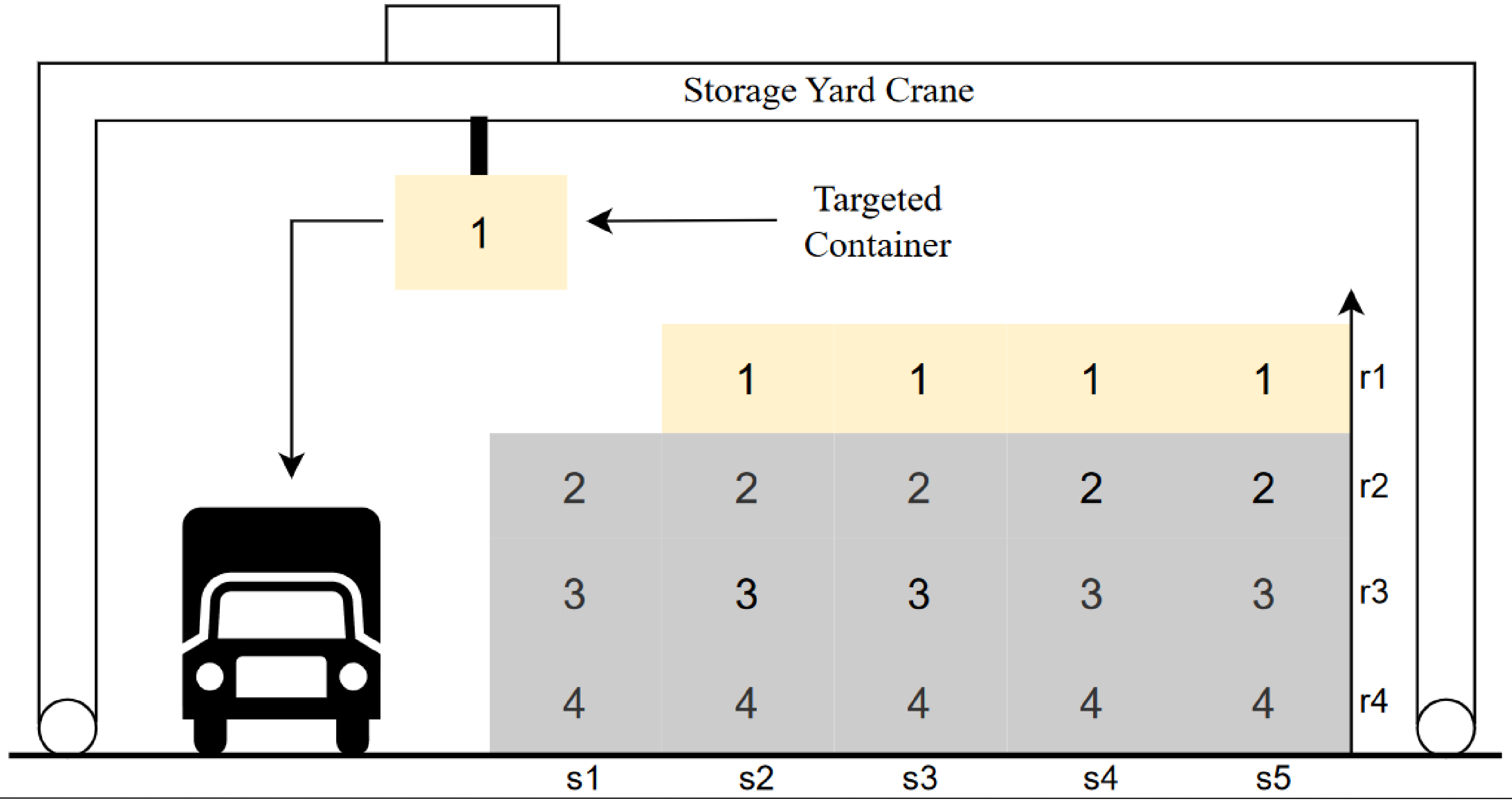
Paper 3

Container relocation and retrieval tradeoffs minimizing schedule deviations and relocations

Authors: **Robert Klar**, Niklas Arvidsson and Vangelis Angelakis

in *IEEE Open Journal of Intelligent Transportation Systems*, vol. 5, pp. 360-379, 2024, doi: 10.1109/OJITS.2024.3413197.

What we hope for



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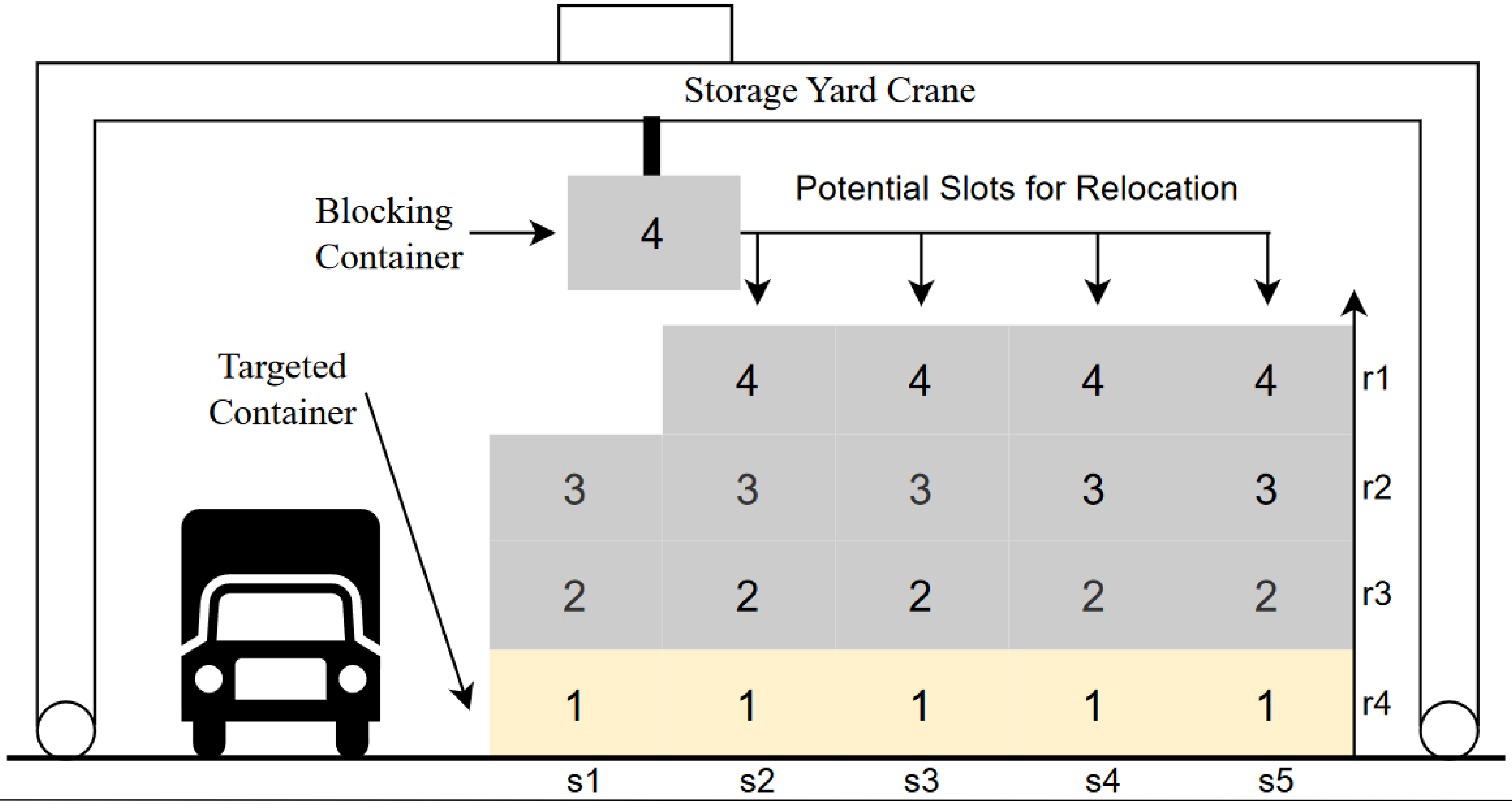
What occurs in reality



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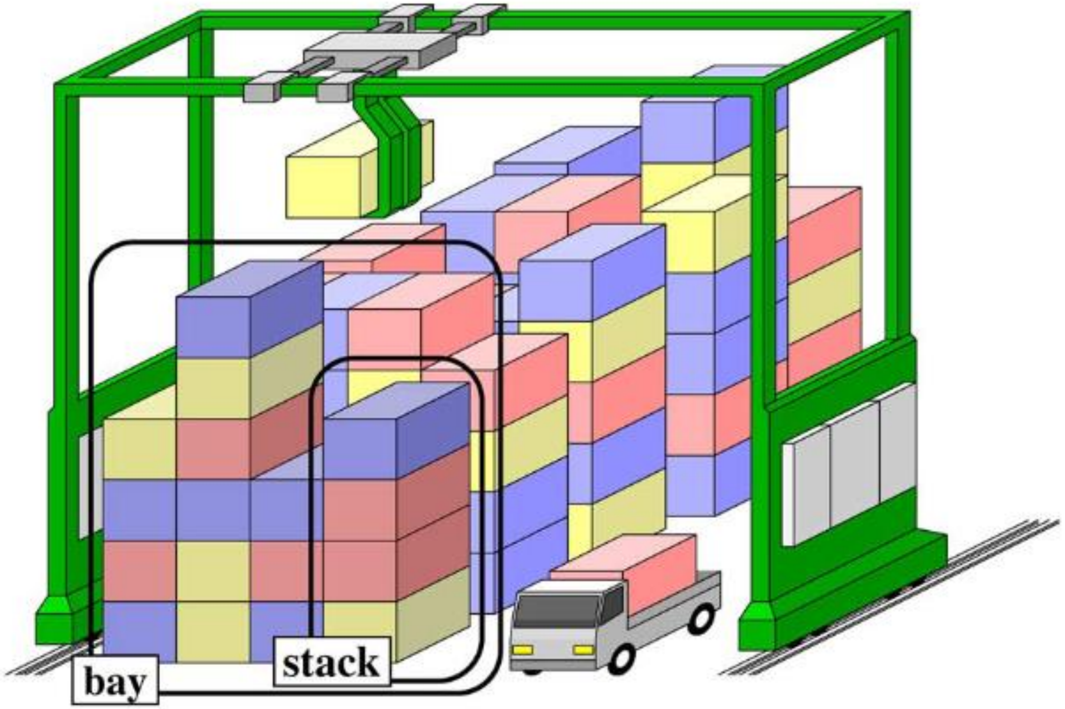
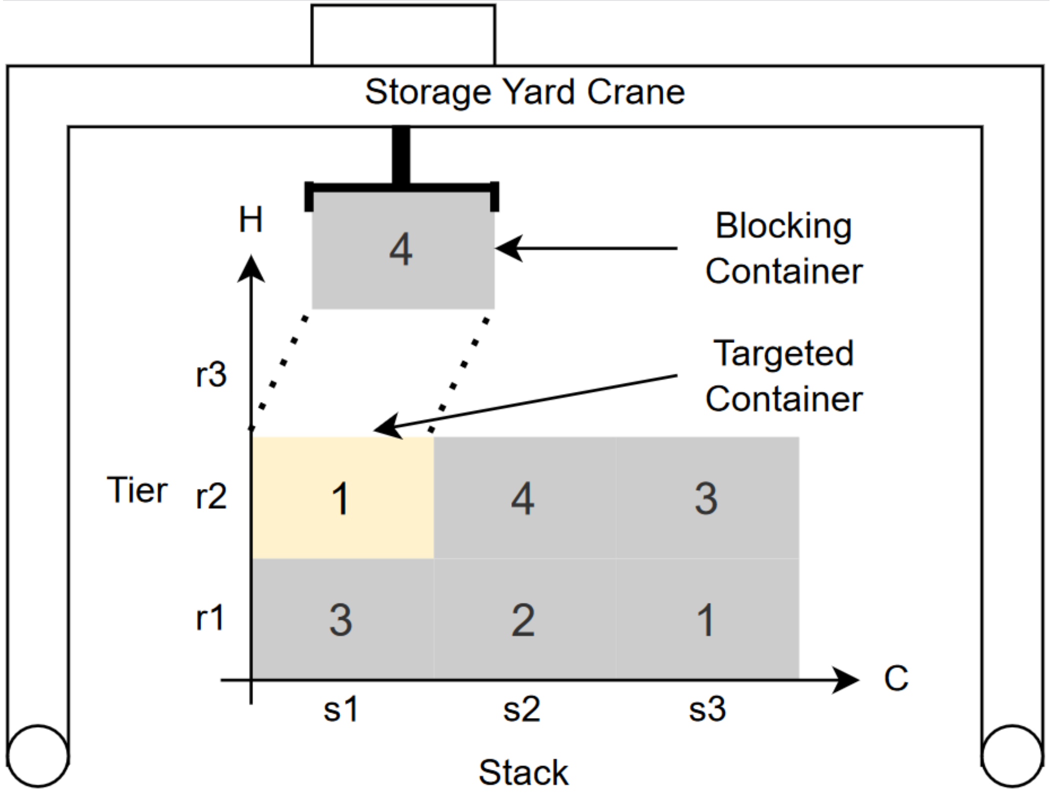
Background

- Two major challenges in a port storage yard
  - ➢Minimize crane movements (BRP)
  - ➢Maintaining tight truck retrieval schedules
- Existing literature considers each of the problems in isolation
- Improving overall system efficiency requires addressing both jointly



Tanaka, S., & Takii, K. (2015). **A faster branch-and-bound algorithm for the block relocation problem**. *IEEE Transactions on Automation Science and Engineering*, *13*(1)

Block Relocation and Schedule Reliability Problem (BRSRP)



Only the topmost container can be accessed

Current problem configuration:
7 Containers (N)
3 Stacks (C) and 3 Tiers (H)
4 Time Windows (T)

In each Time Window t ∈ T,
3 Crane Movements (G) are available to serve 2 Trucks (L)

How can we retrieve all containers while minimizing crane relocations and schedule deviations?

Problem formulation

BRSRP Model:

minimize z :

$$\alpha\left(\sum_{i\in N}\left(\sum_{s\in C}\sum_{r\in H}\sum_{k\in G}\sum_{t\in T}((|t-p[i]|)\cdot v[i,s,r,k,t])\right)\right) + \beta\left(\sum_{i\in N}\sum_{s\in C}\sum_{r\in H}\sum_{k\in G}\sum_{t\in T} y[i,s,r,k,t]\right) \quad (1)$$

Subject to:

$$p[i]-\sum_{s=1}^{C}\sum_{r=1}^{H}\sum_{k=1}^{G}\sum_{t=1}^{T}(t\cdot v[i,s,r,k,t]) \le \delta, \forall i\in\{1,...,N\} \quad (2)$$

$$\sum_{s=1}^{C}\sum_{r=1}^{H}\sum_{k=1}^{G}\sum_{t=1}^{T}(t\cdot v[i,s,r,k,t]) \le \delta + p[i], \forall i\in\{1,...,N\} \quad (3)$$

$$\sum_{i=1}^{N}\sum_{s=1}^{C}\sum_{r=1}^{H}\sum_{k=1}^{G} v_{isrk}^{t} \le L, \forall t\in\{1,...,T\} \quad (4)$$

$$\sum_{i=1}^{N}\sum_{s=1}^{C}\sum_{r=1}^{H} v_{isrk}^{t} + \sum_{i=1}^{N}\sum_{s=1}^{C}\sum_{r=1}^{H} x_{isrk}^{t} \le 1, \forall k\in\{1,...,G\}, t\in\{1,...,T\} \quad (5)$$

$$\sum_{i=1}^{N} x_{isrk}^{t} \le \sum_{i=1}^{N}(u_{isrk}^{t}-u_{is(r+1)k}^{t}), \forall s\in\{1,...,C\}, r\in\{1,...,H-1\}, k\in\{1,...,G\}, t\in\{1,...,T\} \quad (6)$$

$$\sum_{s'=1,s'\neq s}^{N}\sum_{r=1}^{H} y_{is'rk}^{t} \ge \sum_{r=1}^{H} x_{isrk}^{t}, \forall i\in\{1,...,N\}, s\in\{1,...,C\}, k\in\{1,...,G\}, t\in\{1,...,T\} \quad (7)$$

$$\sum_{i=1}^{N} v_{isrk}^{t} + \sum_{i=1}^{N} y_{isrk}^{t} + \sum_{i=1}^{N} x_{isrk}^{t} \le 1, \forall s\in\{1,...,C\}, k\in\{1,...,G\}, t\in\{1,...,T\} \quad (8)$$

$$u_{isr1}^{1} = I_{isr}, \forall i\in\{1,...,N\}, s\in\{1,...,C\}, r\in\{1,...,H\} \quad (9)$$

$$u_{isrk+1}^{t} = u_{isrk}^{t} + y_{isrk}^{t} - x_{isrk}^{t} - v_{isrk}^{t}, \forall i\in\{1,...,N\}, s\in\{1,...,C\}, r\in\{1,...,H\}, k\in\{1,...,G-1\}, t\in\{1,...,T\} \quad (10)$$

$$u_{isr1}^{t} = u_{isrG}^{t-1} + y_{isrG}^{t-1} - x_{isrG}^{t-1} - v_{isrG}^{t-1}, \forall i\in\{1,...,N\}, s\in\{1,...,C\}, r\in\{1,...,H\}, t\in\{2,...,T\} \quad (11)$$

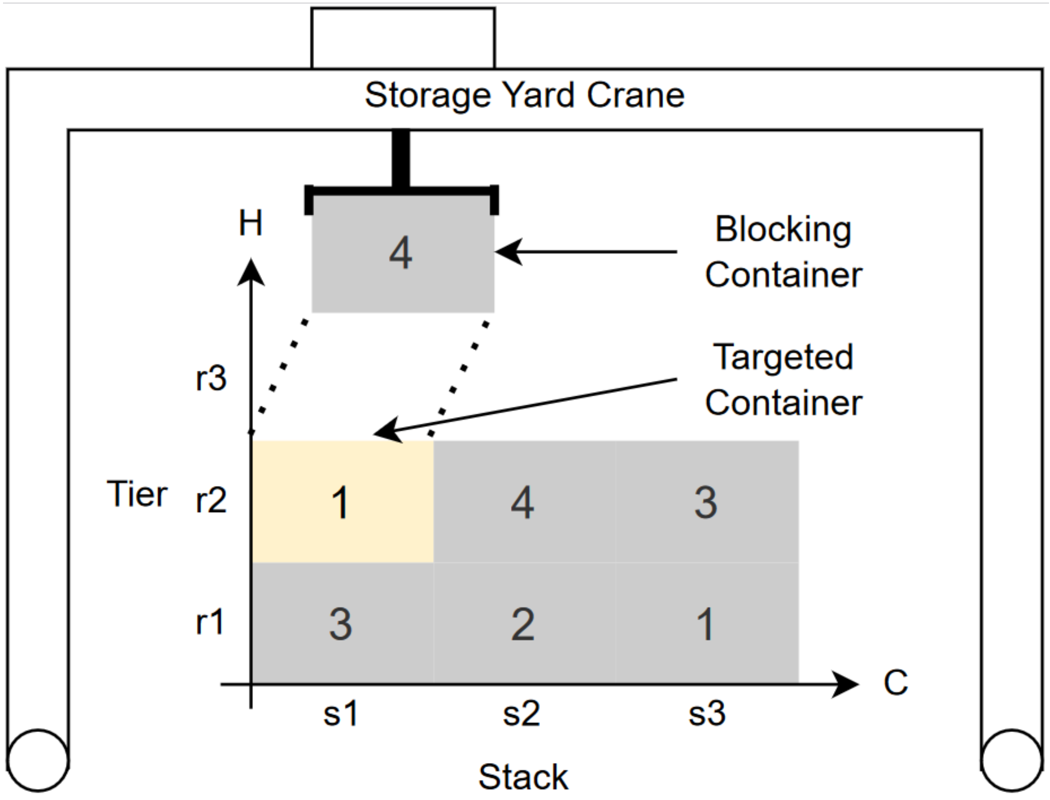
$$\sum_{i=1}^{N}\sum_{r=1}^{H}\sum_{k'=k+1}^{G} u_{isrk'}^{t} + \sum_{i=1}^{N}\sum_{r=1}^{H}\sum_{k'=k+1}^{G}\sum_{t'=t+1}^{T} u_{isrk'}^{t'} \le G*T(1-\sum_{s=1}^{C}\sum_{r=1}^{H} v_{isrk}^{t}), \forall i\in\{1,...,N\}, k\in\{1,...,G\}, t\in\{1,...,T\} \quad (12)$$

$$\sum_{s=1}^{C}\sum_{r=1}^{H}\sum_{k=1}^{G}\sum_{t=1}^{T} v_{isrk}^{t} = 1, \forall i\in\{1,...,N\} \quad (13)$$

$$\sum_{i=1}^{N} u_{isrk}^{t} \le 1, \forall s\in\{1,...,C\}, r\in\{1,...,H\}, k\in\{1,...,G\}, t\in\{1,...,T\} \quad (14)$$

$$\sum_{s=1}^{C}\sum_{r=1}^{H} u_{isrk}^{t} \le 1, \forall i\in\{1,...,N\}, k\in\{1,...,G\}, t\in\{1,...,T\} \quad (15)$$

$$u_{isrk}^{t}, x_{isrk}^{t}, y_{isrk}^{t}, v_{isrk}^{t} \in \{0,1\}, \forall i\in\{1,...,N\}, s\in\{1,...,C\}, r\in\{1,...,H\}, k\in\{1,...,G\}, t\in\{1,...,T\} \quad (16)$$



Problem formulation – Objective Function

	Notation	Explanation
Parameters	N	Number of containers in the initial configuration of the bay
	C	Number of stacks
	H	Maximum allowed height of bay
	G	Maximum allowed container moves (either retrievals or relocations) per time window
	L	Maximum queue length at bay (appointments per time window)
	T	Number of time windows
	p_i	Scheduled container pickup time window, $i \in 1, ..., N$
	δ	Maximum allowed container pickup time window shift
	I_{isr}	Whether container i occupies slot (s,r) in the initial bay layout, $I_{isr} \in 0, 1$
Indices	i	Index of container, $i \in 1, ..., N$
	s	Index for stack, $s \in 1, ..., C$
	r	Index for tier, $r \in 1, ..., H$
	k	Index of the stage, $k \in 1, ..., G$ where each stage k represents one possible container move
	t	Index for time window, $t \in 1, ..., T$
Variables	u^t_{isrk}	$\begin{cases} 1, & \text{if container i occupies the slot (s, r) at stage k of time window t} \\ 0, & \text{otherwise} \end{cases}$
	x^t_{isrk}	$\begin{cases} 1, & \text{if container i is relocated from slot (s, r) at stage k of time window t} \\ 0, & \text{otherwise} \end{cases}$
	y^t_{isrk}	$\begin{cases} 1, & \text{if container i is relocated to slot (s, r) at stage k of time window t} \\ 0, & \text{otherwise} \end{cases}$
	v^t_{isrk}	$\begin{cases} 1, & \text{if container i is picked up from slot (s, r) at stage k during time widow t} \\ 0, & \text{otherwise} \end{cases}$

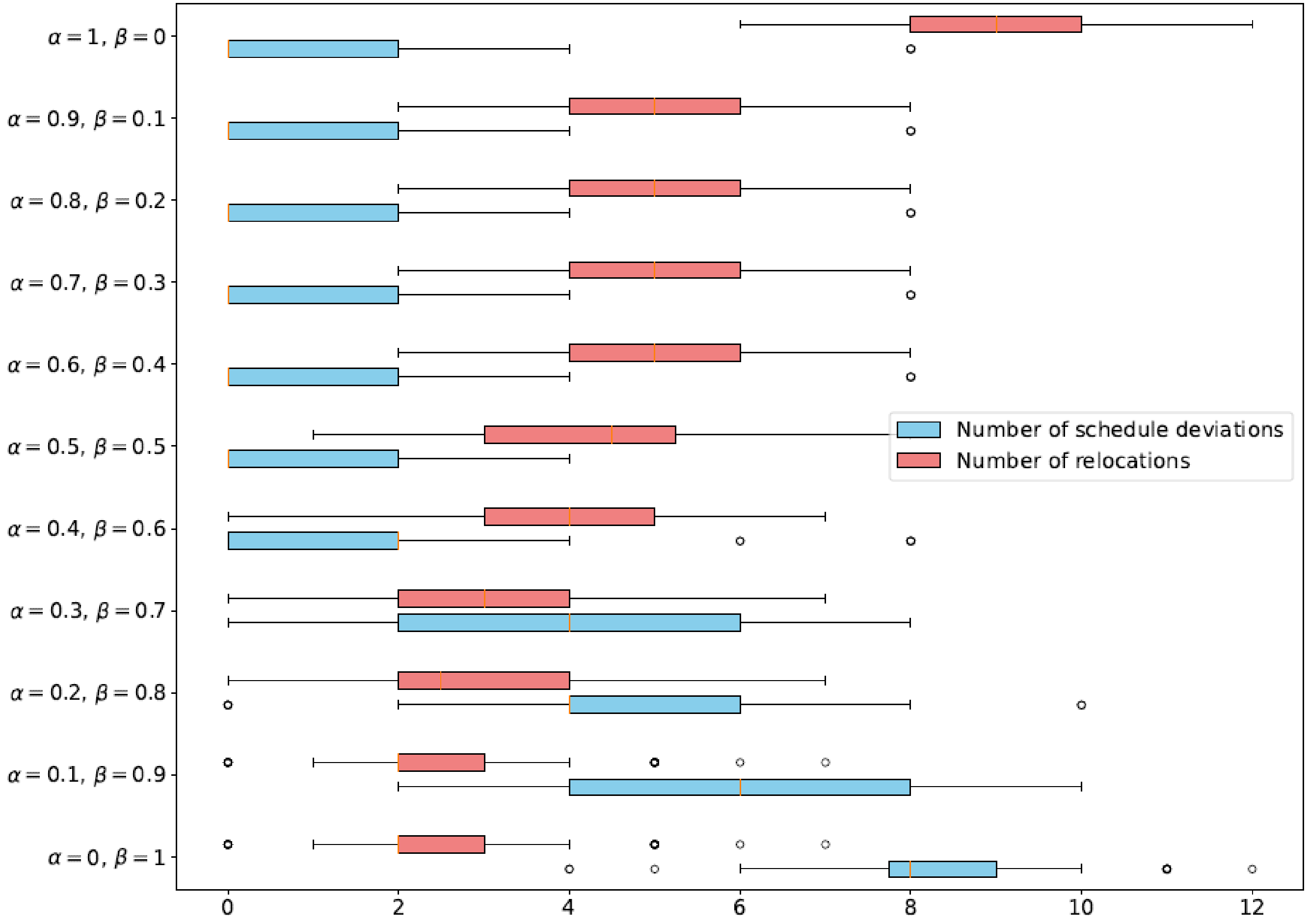
u^t_{isrk}, x^t_{isrk}, y^t_{isrk}, v^t_{isrk} are the decision variables.

minimize z :

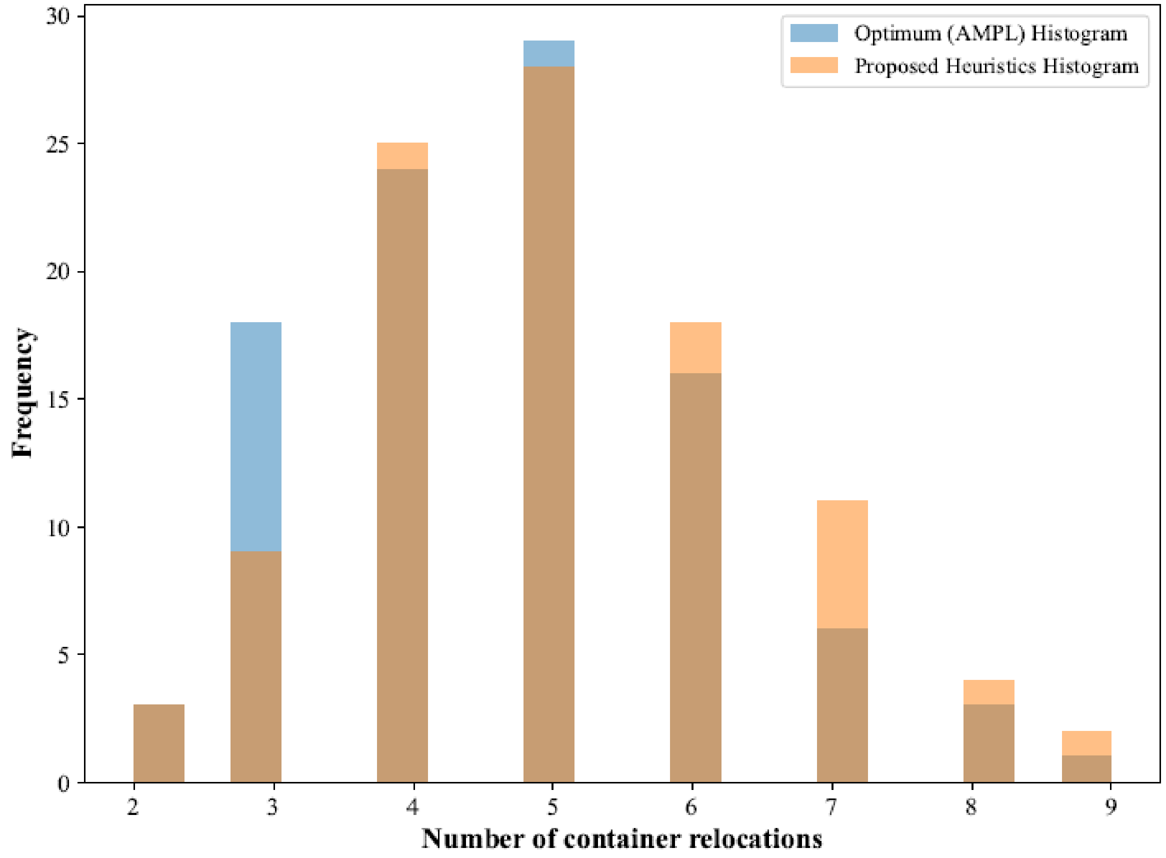
$$\alpha\left(\sum_{i\in N}\left(\sum_{s\in C}\sum_{r\in H}\sum_{k\in G}\sum_{t\in T}((|t-p[i]|)\cdot v[i,s,r,k,t])\right)\right)$$

$$+\beta\left(\sum_{i\in N}\sum_{s\in C}\sum_{r\in H}\sum_{k\in G}\sum_{t\in T}y[i,s,r,k,t]\right)$$

Results – impact of (α,β) weights



Paper 3: Results –exact vs. heuristic



Example run time for 15 containers:

Exact solution: 199.9 seconds
Heuristic solution: 0.019 seconds

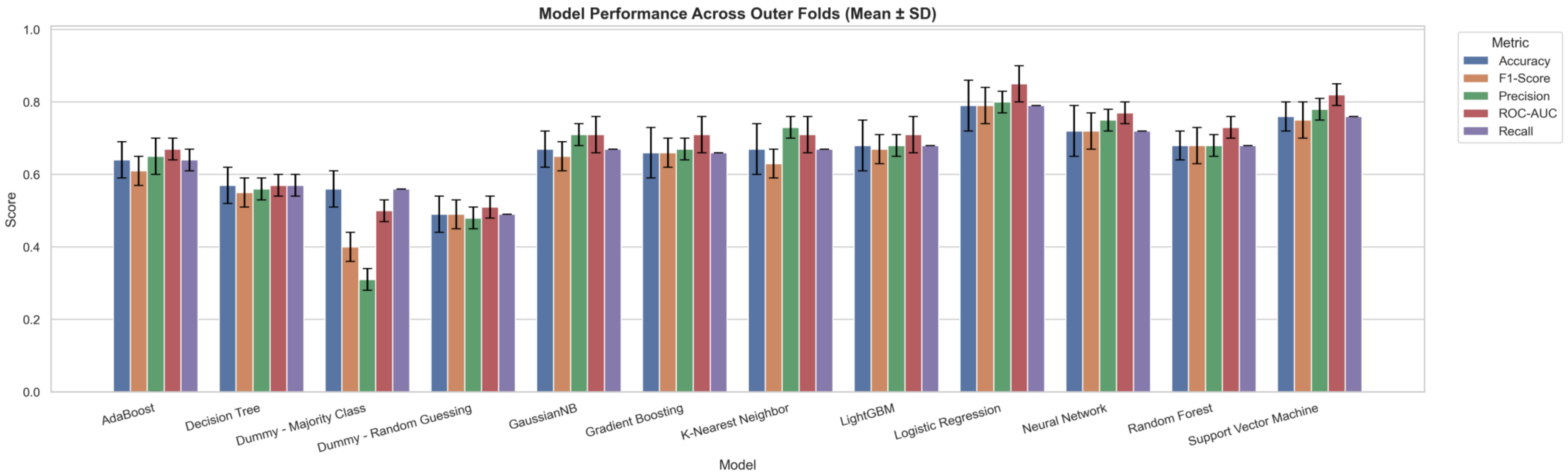
Conclusion

- From a port perspective, this thesis provides:
  - ➢An overview of the potential, challenges, and practical use cases of how digital twins lead to overall port efficiency
  - ➢A tool for DT users (ports) to assess the maturity future and current DTs
  - ➢A multi-objective optimization model suitable for integration into a port DT

- From a digital twin development perspective, this thesis outlines:
  - ➢The characteristics and requirements of ports
  - ➢The need for interoperability

Future work

- ➢Provide further modeling components of a port digital twin
- ➢Involve real operational data into our models
- ➢Dive into the predictive maintenance aspect of port equipment



Many thanks for your attention!