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EVALUATING REQUIRED VALIDITY AND GRANULARITY OF DIGITAL TWINS FOR OPERATIONAL PLANNING IN ROLL-ON ROLL-OFF TERMINALS

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ABSTRACT

Digital twins (DTs) are increasingly used in large container ports to support decision-making during operations. However, building and maintaining a full-scale DT involves significant effort and costs, which smaller roll-on roll-off terminals often cannot justify. This study asks how much granularity and accuracy a DT actually needs while providing meaningful decisions to the port. The focus lies on two planning tasks: minimizing vessel turnaround time through online scheduling and predicting departure times to support berth and shore power planning. The DT here mirrors a pseudo-analog twin and applies discrete event-based simulations based on data from the Port of Kiel (Germany). Several experiments test different levels of model validity and granularity. The DT's performance is measured through accuracy in predicting departure time and the efficiency of engine preheating.

EXTENDED ABSTRACT

Digital twins (DTs) mirror physical spaces or products into a virtual, digital space and are connected through data and information exchange (Grieves 2023). Unlike traditional simulation models, DTs are continuously synchronized with their physical twin through real-time data streams, enabling them to reflect system states and act as (semi-)autonomous decision-support tools (Mihai et al. 2022). DTs often apply a methodological mix of simulation, optimization, and machine learning to make decisions. As such, they enable what-if analyses during ongoing operations and enhance transparency in complex environments such as ports. Large container ports, e.g., Singapore, Rotterdam, and Zhoushan, already deploy DTs for tasks such as operational planning of terminal processes, strategic planning on new ports, energy management, and analyzing traffic flow (Neugebauer et al. 2024). They also are the groundwork for future autonomous shipping (Port of Rotterdam 2025).

However, a DT requires massive investments in (hardware) infrastructure and (software) development. Furthermore, they must be validated online over time (Marquardt et al. 2021), resulting in additional maintenance costs. For smaller terminals, such as roll-on roll-off (RoRo) short-sea shipping terminals, which often have low berth utilization density, these costs are hardly manageable. Clearly, such terminal operators might have less sophisticated use cases than the listed ports above, but they could still benefit from some applications performed by a DT.

In this study, I am thus stepping back and asking: How "much" of a DT does a small port operator actually need to balance costs and benefits? I aim to answer this question by conducting experiments that focus on the DT requirements defined by industry experts (Marquardt et al. 2021): validity, granularity, and agility. Validity refers to the ability to reflect and simulate the analog system accurately. Granularity is the level of detail as well as the update frequency of the DT. Agility, i.e., the speed of the DT in making decisions, is not considered in this study, since it relies heavily on the used hardware and software configurations, limiting the generalizability of experimental results.

I am considering a small RoRo terminal, following a case study in the Port of Kiel, Germany, that operates one vessel at a time. Heterogeneity in cargo here leads to a higher planning complexity than in container terminals, and more human employees are required in the terminal. Thus, RoRo terminal operators face many unpredictable factors in their daily operations. A DT of such a system could be meaningful in serving as a decision-making agent that considers two aspects of terminal operations planning: First, the DT shall estimate the time of departure as close as possible. A reliable estimated time of departure (ETD) is necessary when employing shore power systems, as the vessel's engines must be preheated at a set time before departure. Underestimating the time left in stevedoring leads to unnecessary vessel engine running at the berth, and overestimating it results in unnecessary stay time at the berth. Both misjudgments lead to increased fuel consumption and emissions. Predicting a reliable ETD is, therefore, a critical task in terminal operations management that is becoming increasingly relevant. Additionally, reliable ETDs also facilitate efficient online berth planning, avoiding congestion at the shore and within the terminal.

Second, while predicting ETD, it shall also reduce vessel turnaround time. After berthing a vessel, many sub-processes run in series or in parallel, and each of them could be optimized to reduce the turnaround time. However, the most promising sub-process to consider is stevedoring, i.e., the unloading and loading of goods, which determines the vessel service time at a berth. In stevedoring, port employees in tugs move cargo units between the vessel and the yard. Driver-handled cargo units also travel simultaneously. By minimizing the makespan of this scheduling problem, tug empty trips are reduced, saving emissions and increasing capacity. In addition, ships can spend more time at sea rather than at berth, allowing them to steam at a slower speed, which in turn reduces emissions while maintaining schedules.

The DT mirrors the analog twin and considers both aspects through (re-)planning the stevedoring process heuristically online and by predicting the ETD using real-time information on stevedoring. The planning heuristics consider expected processing times of the cargo units. The underlying rules applied are introduced in Marquardt et al. (2025). For predicting the ETD, it simulates the makespans of the resulting schedule under uncertain processing times multiple times and then decides about the vessel engine based on the resulting makespans. It then transfers the decision and schedule back to the analog twin. In the study design, the physical port is purely simulated, which is why I refer to it as a pseudo-analog twin. The pseudo-analog twin and the simulations within the DT are modeled using discrete event simulation based on data from the Port of Kiel.

To investigate DT requirements, I conduct experiments that manipulate processing time assumptions and apply tug breakdowns in the pseudo-analog twin (validity), as well as update the DT at fixed intervals rather than in real time (granularity). I also combine both aspects. DT performance is evaluated by comparing predicted departure times against the realized and by measuring the lack or excess in preheating time for the vessel engine after stevedoring. I benchmark the results against the initial ETD prediction prior to operations (i.e., if no replanning takes place), and a fixed-rule-based engine start triggered by a remaining cargo threshold.

In conclusion, this study examines the level of detail and accuracy required for a digital twin of a RoRo terminal to provide a reasonable level of guidance. Preliminary results will be presented at the conference.

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