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SYSTEM SIMULATION AND MACHINE LEARNING-BASED MAINTENANCE OPTIMIZATION FOR AN INLAND WATERWAY TRANSPORTATION SYSTEM

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ABSTRACT

To keep an inland waterway transportation system (IWTS) up and running, the interconnected infrastructure, including lock and dam systems, must remain in good operating condition. However, unexpected disruptions often occur, causing significant transportation delays and economic losses. To evaluate the impacts of such disruptions, a Python-enhanced NetLogo simulation tool is developed, in which extreme natural events are considered and characterized by a spatiotemporal model. With this tool, optimal maintenance strategies that maximize the total cargo throughput of the IWTS are determined via deep reinforcement learning. A case study of the lower Mississippi River system and the McClellan-Kerr Arkansas River Navigation System is conducted to illustrate the capability of the developed simulation and machine learning-based method for IWTS maintenance optimization.

1 INTRODUCTION

The inland waterway navigation system is a critical component of the United States (U.S.) transportation network and contributes to the safe and efficient freight movement of agricultural, coal, petroleum, and chemical commodities (US Department of Agriculture 2019). In certain regions of the inland waterway navigation system, lock and dam systems are utilized to uphold the required navigation channel depths, enabling towboats and barges to navigate from their origins to destinations along the rivers. Since the malfunction of a lock can considerably interrupt barge movements, it is imperative to tackle this challenge by leveraging cutting-edge technologies, such as preventive maintenance, to avoid potential lock failures, thereby mitigating the negative impact of unscheduled outages of lock and dam systems(US Department of Agriculture 2019).

This work develops a Python-enhanced NetLogo simulation tool to evaluate the effects of disruptions caused by lock closures and proposes a deep reinforcement learning (DRL) method for maintenance optimization. A case study on the lower Mississippi River and the McClellan–Kerr Arkansas River Navigation System (MKARNS) is conducted to illustrate the capability of the developed simulation and machine learning-based method for IWTS maintenance optimization.

2 PROBLEM DESCRIPTION, PRACTICAL CONSIDERATIONS

This work considers the operation of an IWTS involving waterways, ports and locks. Through simulation and optimization, the optimal sequence of maintenance and repair actions on these locks over a specific planning horizon is determined to maximize the throughput of the IWTS for the same period.

It is worth pointing out that along navigable waterways, there are several sites where the gage heights are checked for measuring water levels in real time. The measurements help operators make informed decisions about vessel movement (i.e., proceed or halt based on the current water level).

Another set of key considerations is related to repairs and preventive maintenance of locks. In this work, a repair crew responsible for repairs, preventive maintenance, and inspections of locks is considered under various practical aspects. An intuitive logic was included to handle situations where multiple lock failures occur simultaneously. In such cases, an automatic assignment mechanism is employed, which prioritizes repair on a lock with the highest importance. This prioritization strategy ensures that critical lock failures are fixed promptly with the goal of minimizing the downtime and potential disruptions of the system. Another consideration is the minimum time interval between consecutive preventive maintenance actions on each lock. Moreover, the repair and preventive maintenance times are random due to the unpredictable nature of these tasks.

The study considers a fixed annual budget for preventive maintenance and repair tasks. This budget constraint adds another layer of complexity to the repair and maintenance planning problem. Indeed, to maximize the throughput of the entire IWTS, repair and preventive maintenance need to be considered in a comprehensive manner by incorporating a collection of critical information, such as the available resources and criticality of different locks.

3 METHODOLOGY

At the core of the simulation tool is its capability to predict the gage height at a measurement site. A Spatio-Temporal Bayesian Modelling (spTimer) method was utilized to capture the complex interplay of spatial and temporal correlations among the selected measuring sites considering seasonal variations. One advantage of this method is its potential to infer gage height data from sites of interest where actual measurements are not available (Azucena et al. 2021).

To reduce the negative impact of lock failures on the throughput of IWTS, preventive maintenance can be performed before locks fail. Such actions may reduce the ages and/or failure rates of locks to different extents. Especially, a perfect preventive maintenance action (or repair) will make a lock go back to its good-as-new state, while an imperfect preventive maintenance action (or repair) will bring the lock to somewhere between its good-as-new state and bad-as-old state.

DRL combines deep learning and reinforcement learning, allowing intelligent agents to learn decision-making through environment feedback. By treating the environment as a Partially Observable Markov Decision Process (POMDP), DRL enables adaptability in uncertain situations. OpenAI Gym (Brockman et al. 2016) provides a standardized platform for experimenting with reinforcement learning algorithms, offering varied complexity levels and customizable simulations. A unique environment is crafted for evaluating and training a Maskable Proximal Policy Optimization (M-PPO) algorithm (Huang and Ontañón 2020), using flags to identify feasible actions based on simulation constraints. These constraints, including resource allocation and budget limits, are translated into action masks to ensure valid actions during simulation.

4 CONCLUSION

The developed Python-enhanced NetLogo simulation tool provides a realistic and flexible way to study the operation of an IWTS and reduce the negative economic impact of disruptions. Especially, by taking advantage of a spatiotemporal model capable of describing water level variation and probabilistic models for lock failures, the simulation tool can assess the performance of the IWTS under various scenarios. Moreover, the DRL approach is indeed an efficient alternative for solving the optimal maintenance planning problem involving a series of actions. In our future research, more advanced maintenance strategies involving multiple maintenance crews and different effects of maintenance actions will be studied.

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