氏 名 （ 本 籍 ）	KURSAT KILIC (キリツククルサト)
専攻分野の名称	博士（資源学・理学・工学）
学 位 記 番 号	国博甲第　20　号
学位授与の日付	令和　6 年　3 月　22 日
学位授与の要件	学位規則第 4 条第 1・2 項該当
研 究 科 ・ 専 攻	国際資源学研究科・資源学専攻
学位論文題目（英文）	Enhancing Tunnel Boring Machine Performance Prediction and Optimization with Artificial Intelligence Models: Insights from Operational Data (人工知能モデルによるトンネルボーリングマシンのパフォーマンス予測と最適化の強化: 運用データからの洞察)
論 文 審 査 委 員	（主査）教授　TSUYOSHI ADACHI （副査）教授　TADAO IMAI （副査）教授　ATSUSHI SHIBAYAMA

論文内容の要旨

Throughout human civilization, the construction of underground spaces has been pivotal in advancing transportation, energy production, and infrastructure development. Tunnel boring machines (TBMs) have become increasingly prevalent in tunnel construction projects, significantly departing from traditional drilling and blasting methods. Integrating artificial intelligence (AI) techniques into TBM operation has shown remarkable promise in forecasting and enhancing TBM performance. Several models have emerged to dissect and predict TBM performance, aiming to expedite excavation processes and boost tunnelling efficiency. These models fall into three broad categories: empirical, probabilistic, and AI-based approaches. Empirical models, often rooted in laboratory-scale tests like Linear Cutting Machines (LCM) and Intermediate Linear Cutting Machines (ILCM), have traditionally focused on limited parameters and specific conditions. However, they struggle to account for the complexity of real-world scenarios.

The second conventional approach involves probabilistic techniques that establish relationships among TBM parameters, cutter head conditions, and geological formations. Yet, these methods face challenges when dealing with extensive datasets and nonlinear parameters, limiting their effectiveness. In response to these limitations, this thesis aims to develop an AI-driven model for TBM performance prediction. The model's foundation is built upon the fusion of TBM operational parameters, lithology data, and TBM operator decisions alongside resultant force data. These elements are the basis for creating deep neural networks and machine learning models. Using TBM operational datasets, a one-dimensional convolutional neural network (1D CNN) is tailored to predict cutter tool wear. This predictive model can estimate cutter tool wear from measurements taken at four distinct inspection points, effectively creating a tool life prediction model. The importance of this capability cannot be overstated, as it enhances maintenance planning by reducing downtime and improving operational efficiency. Additionally, the thesis incorporates a clustering-guided Light Gradient Boosting Machine (LightGBM) for precise tunnelling lithology identification based on TBM propulsion parameters. This approach optimizes accuracy and addresses issues related to a class imbalance in tunnel lithology identification. Furthermore, this clustering-guided LightGBM is integrated into an automatic machine-learning library, automatic data preprocessing and model hyperparameter tuning. Leveraging data from the TBM control panel, including operator decisions and resultant forces, this study delves into predicting specific energy consumption and the autonomous control of TBM jack speed and torque. These predictions are achieved through the transparent application of neural networks and random forests, empowered by Optuna automatic hyperparameter tuning and Shapley additive explanations (SHAP) for feature engineering.

The power of these advanced techniques is evident when considering the role of TBM operator decisions in energy consumption monitoring. Integrating neural networks and random forests allows for a comprehensive analysis of extensive and complex datasets, a necessity for understanding the intricacies of TBM operation. Neural networks excel in uncovering intricate patterns and relationships within the data, providing precise predictions, while random forests handle nonlinearity and variability inherent in real-world scenarios. The synergy between these models forms a robust framework for comprehending and forecasting energy consumption. The value of Optuna automatic hyperparameter tuning is clear when addressing the complex task of configuring models for optimal performance. Hyperparameters govern the behaviour of machine learning algorithms, and finding the right combination can be akin to solving a complex puzzle. Optuna automates this process, systematically exploring various hyperparameter configurations to identify the optimal set, resulting in finely tuned models that deliver highly accurate energy consumption predictions. SHAP, or Shapley additive explanations, is crucial in feature engineering. This technique enables predictions while providing a deep understanding of the contribution of each feature to those predictions. SHAP dissects the complex web of features and their impact on the model's output, providing transparency and interpretability essential in applications like TBM energy consumption monitoring.

In summary, this research leverages the potential of AI to revolutionize TBM performance prediction and tunnelling efficiency. While acknowledging the historical importance of

underground construction in human progress, it also recognizes the limitations of traditional tunnelling methods and existing empirical or probabilistic models. This thesis aims to develop an AI-powered model capable of predicting TBM performance precisely.
In conclusion, this abstract serves as an introduction to a mission to redefine tunnel construction through the power of AI. It emphasizes the transformative potential of this research in enhancing TBM performance prediction and facilitating more efficient tunnel construction projects. The fusion of AI and TBM technology marks a significant step forward in the construction industry, and this thesis aspires to lead this exciting journey.

論文審査結果の要旨

This academic degree review committee will hold an international resource screening meeting on Monday, February 5, 2024, from 13:00 to 14:00.
Thesis hearing was held in Classroom S301, International resource sciences bulding,

1. Tsuyoshi Adachi, Chief Examiner,
2. Tadao Imai, Examiner
3. Atsushi Shibayama, Examiner

In the presence of reviewer Histoshi Toriya, Brian Bino Sinaice, reviewer Hajime Ikeda (participating via Zoom), we discussed matters related to the paper. A detailed question-and-answer session and an oral academic confirmation were held.
Regarding enhancing tunnel boring machine performance prediction and optimization with artificial intelligence models: insights from operational data have been described in my doctoral thesis.

(1) Do you think the AI controller can operate the TBM without human intervention in the future?
(2) What is the difference and orginality of your research compared to the previous applications?
(3) How to apply real time data using your model?
(4) How do you understand difficulties and anomalies in data and TBM operation in real-time excavation?
(5) Regarding correlation matrix, can you obtain the TBM features on time (real-time)?
(6) How do you understand data synchronization between machine and operator? How many operators work or drive the machine?
(7) How do you validate your data synchronization?

Questions and comments were raised, and the applicants provided clear answers based on academic considerations.
Therefore, the degree examination committee held after the public hearing determined that Mr. Kursat Kilic passed the final examination and was fully qualified for the doctoral degree (engineering).