

THESES OF THE DOCTORAL (PHD) DISSERTATION

# Development of machine learning, process modeling and optimization algorithms for supporting Industry 4.0

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# 1 Introduction and the aim of the work

Positioning data analysis plays a critical role in understanding and optimizing spatial and temporal processes across various domains. Despite its potential, traditional methods often struggle to address inefficiencies and workflow optimization comprehensively. To overcome these challenges, this thesis introduces five algorithms that integrate positioning data with data science, enabling more effective analysis and decision-making. Through diverse case studies, the proposed algorithms demonstrate their adaptability and potential to support decision-making systems in logistics, manufacturing, urban transportation, and resource allocation scenarios. The first approach highlights the practical utility of RTLS positioning data for manufacturing environments. Using data mining and statistical methods, patterns and inefficiencies in internal logistics are uncovered, facilitating actionable insights that enhance workflow efficiency and resource allocation. The second approach addresses the critical issue of data accuracy by proposing a data reconciliation method that improves the reliability of RTLS positioning data. Improved accuracy ensures better process monitoring and supports more effective operational decisions. The third approach focuses on identifying value-added and non-value-added activities using positioning data through a multi-layer network framework. Applied to taxi route optimization in New York City, the method leverages temporal network modeling to analyze resource flows, significantly reducing waiting times, and can be adapted to address intralogistics challenges in similar contexts. The fourth approach employs advanced clustering algorithms, specifically a modified DBSCAN, to classify and optimize resource activities in logistics environments. By analyzing UWB-based positioning data from a warehouse, the method reduces idle time, improves resource utilization, and supports supply chain efficiency. The fifth approach explores the use of RTLS positioning data for micro-logistics and material handling processes, focusing on the potential application of Reinforcement Learning and Markov Decision Process (MDP) techniques. Demonstrated in a real industrial scenario, the approach improves task scheduling, reduces idle times, and maximizes resource efficiency. Together, these methods demonstrate the transformative potential of positioning data and data science techniques in addressing complex challenges in logistics and manufacturing. Through real-world case studies, this dissertation highlights the effectiveness and adaptability of the proposed algorithms in improving resource management, operational efficiency, and decision-making processes.

## 2 Experimental tools and technologies

The efficiency of the algorithms developed based on positioning data is demonstrated through various case studies, highlighting their applicability in different domains. The methods have been applied to analyze the following:

1. The use of RTLS (Real-Time Location System) positioning data to improve the efficiency of manufacturing processes.
2. Improving the accuracy of positioning data using a data reconciliation approach.
3. Identifying value-added and non-value-added activities based on position data using a multi-layer network approach.

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4. Identifying value-added and non-value-added activities based on position data using a DBSCAN-based clustering and network analysis approach.
  5. Exploring the optimization of micro-logistics and material handling processes using real-time positioning data, applying reinforcement learning and Markov decision process frameworks.

These studies use multiple algorithms to analyze positioning data and demonstrate their effectiveness in improving efficiency and optimizing processes in a variety of applications. The algorithms have been implemented and tested in a MATLAB environment.

### 3 Theses

#### 1. I developed a data science approach for utilizing RTLS positioning data in manufacturing environments for process optimization and decision support.

- I demonstrated how RTLS positioning data can be integrated into manufacturing workflows to provide real-time insights for process optimization and decision-making.
- I presented case studies where RTLS data has been applied to improve operational efficiency through better tracking and monitoring of assets.
- I introduced a framework for using data-driven decision support systems based on RTLS data to streamline processes and resource allocation.

Related publications:

1. András Rácz-Szabó, Tamás Ruppert, László Bántay, Andreas Löcklin, László Jakab, and János Abonyi. "Real-time locating system in production management." *Sensors* 20, no. 23 (2020): 6766. [1]

#### 2. I developed a data reconciliation approach for enhancing the accuracy of RTLS position data for improved process insights.

- I demonstrated how data reconciliation techniques can improve the precision of RTLS position data in manufacturing environments.
- I presented examples of how more accurate position data leads to better process monitoring and error reduction in real-time operations.
- I introduced an approach for integrating data reconciliation into RTLS systems to continuously enhance data accuracy and reliability.

Related publications:

1. András Rácz-Szabó, Tamás Ruppert, and János Abonyi. Data reconciliation of indoor positioning data: Improve position data accuracy in warehouse environment. *MethodsX*. 2024 Dec 1;13:102838. [2]

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**3. I developed a multilayer-based algorithm for identifying value-added and non-value-added activities using position data.**

- I demonstrated how position data can be used to distinguish between value-added and non-value-added activities through a multi-layer network approach.
- I presented case studies analyzing urban mobility patterns and traffic flows, which provided insights for balancing and optimizing resource flows.
- I introduced an analysis of urban mobility patterns and traffic flows to better understand and optimize resource utilization.

Related publications:

1. András Rácz-Szabó, Tamás Ruppert, and János Abonyi. "Multilayer Network-Based Evaluation of the Efficiency and Resilience of Network Flows." *Complexity* 2025, no. 1 (2025): 6940097. [3]

**4. I developed a DBSCAN-based approach for identifying value-added and non-value-added activities using position data in an intralogistics environment.**

- I demonstrated how position data, processed through a DBSCAN-based clustering algorithm, can differentiate between value-added and non-value-added activities within intralogistics operations.
- I presented case study focusing on the movement patterns of forklifts in a warehouse setting, providing insights into optimizing resource allocation and reducing idle times.
- I introduced a modified DBSCAN algorithm for refining the identification of non-value-added activities through position data analysis. This algorithm improved clustering precision by incorporating additional movement data and conditions, facilitating better task scheduling and resource utilization in manufacturing systems.

Related publications:

1. András Rácz-Szabó, Tamás Ruppert, and János Abonyi. "Clustering and network analysis of mobility patterns as an analysis tool for lean project." *Emerging Science Journal* 2024 Volume 9, Issue 01 [4]

**5. I developed a framework for utilizing RTLS positioning data in manufacturing environments to support micro-logistics and material handling processes.**

- I demonstrated how RTLS positioning data can be leveraged to improve the scheduling and coordination of automated guided vehicles (AGVs) in complex manufacturing systems.
- I presented case studies where reinforcement learning and Markov Decision Process (MDP) models were applied to optimize AGV scheduling, resource utilization, and task execution.

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- I introduced a framework that integrates RTLS data with advanced algorithmic techniques to provide actionable insights and improve decision-making in material handling operations.

Related publications:

1. András RÁCZ-Szabó, Tamás Ruppert, and János Abonyi. "Enhancing material supply for an automated production line by implementing a Markov Decision Process model for AGV-based material handling." In 2024 IEEE 22nd World Symposium on Applied Machine Intelligence and Informatics (SAMI), pp. 000193-000198. IEEE, 2024. [5]
2. András RÁCZ-Szabó, Tamás Ruppert, and János Abonyi. "Improving micrologistics processes by indoor positioning system and the tools of data science." In PCS Science, ISBN 978-615-01-9235-2, published by Eclipse Solutions Ltd, 2023. Available at: <http://pcsmeeting.hu/science/>. [6]

## 4 Utilization of results

Positioning data analysis is a key methodology for understanding and optimizing spatial and temporal processes across multiple domains. However, traditional approaches often fall short in accurately identifying inefficiencies and optimizing workflows. Therefore, this thesis presents five algorithms that integrate positioning data with data science.

The applicability of the proposed algorithms is demonstrated through various case studies. These applications serve as prototypes for the development of decision support systems in logistics and manufacturing scenarios.

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# Publications by András Rácz-Szabó

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Current h-index: 1

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## Publications related to theses

1. András Rácz-Szabó, Tamás Ruppert, László Bántay, Andreas Löcklin, László Jakab, and János Abonyi. "Real-time locating system in production management." *Sensors* 20, no. 23 (2020): 6766.
2. András Rácz-Szabó, Tamás Ruppert, and János Abonyi. Data reconciliation of indoor positioning data: Improve position data accuracy in warehouse environment. *MethodsX*. 2024 Dec 1;13:102838.
3. András Rácz-Szabó, Tamás Ruppert, and János Abonyi. "Multilayer Network-Based Evaluation of the Efficiency and Resilience of Network Flows." *Complexity* 2024, no. 1 (2024): 6940097.
4. András Rácz-Szabó, Tamás Ruppert, and János Abonyi. "Clustering and network analysis of mobility patterns as an analysis tool for lean project." *Emerging Science Journal* 2025 Volume 9, Issue 01.
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6. András Rácz-Szabó, Tamás Ruppert, and János Abonyi. "Improving micrologistics processes by indoor positioning system and the tools of data science." In *PCS Science*, ISBN 978-615-01-9235-2, published by Eclipse Solutions Ltd, 2023. Available at: <http://pcsmeeting.hu/science/>.