Theses of PhD dissertation

Machine learning-based industry 4.0 solutions for tool management

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Introduction to the topic

A flexible manufacturing system uses multifunctional machines and a variety of tools to guarantee its flexibility. The set of tools used is immense, and their location is subject to constant change. Hence, ensuring that the right tool is in the right place at the right time is a challenge. Tool management is a complex task that must manage many interdependencies, constraints, and stochastic processes. It includes the allocation of tools between different machines or tasks. An appropriate maintenance plan should be developed to maintain the functionality of the tools. To be aware of the manufacturing processes, tools must be tracked and their history documented. Traditional tool management relies heavily on manual processes and is not sufficiently documented, leading to inefficiencies and increased costs. The advent of Industry 4.0 has introduced new opportunities for data-driven decision-making, allowing manufacturers to leverage machine learning and digitalization to minimize downtime, optimize resource allocation, and enhance productivity. Effective tool management involves complex mathematical algorithms that model the intricate dependencies between machines, tools, and tasks. Due to the stochastic nature of manufacturing processes, tool wear, and constantly changing production demands, planning and design are extremely difficult, and providing optimal solutions is a challenging task where simple, data-sparse methods often fall short. Advanced and data-driven probabilistic modeling and heuristic and metaheuristic optimization techniques, allow for the creation of robust, scalable solutions that adapt to real-time production constraints. These mathematical frameworks are essential to reduce inefficiencies, optimize resource allocation, and minimize operational risks, ensuring that modern manufacturing systems remain competitive in an Industry 4.0 environment.

Goals

The primary objective of this research is to develop data-driven Industry 4.0 solutions for tool management that enhance efficiency and reduce operational costs. The specific goals include:

- Development of an effective and scalable tool allocation optimization method to reduce downtime due to changeovers.
- Development of a complex monitoring procedure capable of extracting reliable information about tool utilization and exploring the relevant locations in the production area from noisy data from an uncertain production area.
- Development of a predictive, risk-based maintenance optimization methodology that schedules and aligns maintenance tasks in accordance with fluctuating production.
- Demonstrating the applicability of these methodologies through industrial case studies or reasonable, realistic, synthesized examples.

Methodology

The research methodology is structured around three core components, each addressing a critical aspect of tool management:

Tool allocation

The proposed tooling allocation methodology is based on grouping technology. Products are grouped according to their similarity in tooling requirements, taking into account the capacity of tool magazines. This grouping problem is formulated and solved as a hierarchical clustering procedure, where the two objectives, such as groups should be as similar as possible in tooling requirements to reduce changeovers, and groups should be as small as possible to avoid exceeding capacity, are considered by easily interpretable heuristic rules. This heuristic product grouping technique provides feasible solutions that approximate the optimum, while its computational requirements are low, making it suitable for industrial applications. To demonstrate its applicability, the proposed multiobjective hierarchical method was compared in terms of goodness of the solution provided and computational demand with a linear programming method solving the same problem.

Tool utilization monitoring

The proposed utilization monitoring method uses a supervised fuzzy clustering technique to build a probabilistic model on the noisy tool position data. By processing the raw data, informative features regarding the spatial distribution of tools and their activity are obtained. The basis of the method is a probabilistic model, namely Gaussian mixture model, where elementary normal distributions are fitted to the tool data. By using the spatial and activity features, the obtained elementary normal distributions represent such data clusters where the probability of spatial proximity and functional similarity is maximized. The main merit of the model is that it indicates the probability of occurrence of a tool at a specific point in space in a specific activity state, which can be used to determine the utilization of an asset at that location. The background probabilistic model is combined with fuzzy logic to form easily interpretable rules for parameter identification. The method is demonstrated on industrial data.

Risk-based tool maintenance

The developed risk-based tool maintenance optimization method aims at assigning different tools to maintenance opportunity windows in such a way that risks to the system are minimized over the entire planning horizon. An effective operation time formula is developed to take into account the history of tool operating time and the impact of maintenance activities. Failure probability is modeled using the Weibull Accelerated Failure Time model, which describes tool reliability as a function of operating time and changing operating conditions. Different costs and production values are also considered to quantify the consequences of failures and maintenance activities. These probabilities and financial values are the input to the risk evaluation model which includes terms for the risk of both insufficient and excessive maintenance, thus aiming to find the trade-off between the over and under maintenance The genetic algorithm is used to find the maintenance plan that has the minimum risk to the system. The risk model and the maintenance optimization based on it are demonstrated by a synthetic example.

As a graphical summary, Figure 1 shows the discussed theoretical and practical sections of my research.

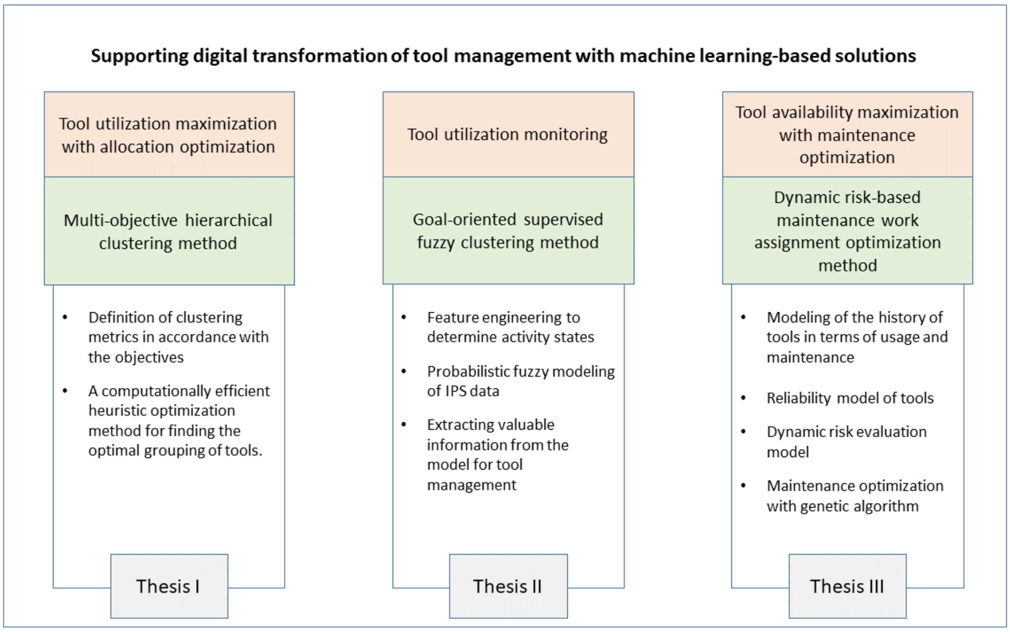

Figure 1: The graphical summary of thesis findings. The orange boxes represent the problem areas and the green boxes represent the solutions developed for them. Gray boxes indicate which thesis (see below) belongs to which area.

Structure of the thesis

The thesis is divided into five primary chapters. The first chapter introduces the topic of tool management. It discusses the challenges of tool management, its digital transformation, and the proposed framework. The next three chapters describe the research related to the three aforementioned aspects of tool management, namely tool allocation, tool usage monitoring, and tool maintenance. These chapters are organized in the same way: after a brief introduction, the mathematical formulation of the method is presented, followed by a demonstration study. The last section summarizes the results and gives some concluding remarks.

Results

The scientific results of my research are summarized in three thesis findings:

Thesis I.

I developed a heuristic multi-objective optimization-based clustering method for the tool allocation problem, which provides a feasible solution that approximates the result of the full optimization algorithm with lower computational requirements [1].

Due to the limited tool magazine capacities of machines, time-consuming tool changeovers result in inefficient equipment utilization. A method is developed to minimize the changeovers by optimizing the allocation of the tools to the machines. The proposed algorithm is efficient as it approaches the tool assignment task as a multi-objective hierarchical clustering problem where the products are grouped based on the similarity of the tool demands. During the agglomerative clustering process, two objectives are pursued: the size of the resulting product group should be as small as possible, and the overlap between the tool requirements of the group members should be as large as possible. The novelty of the goal-oriented agglomerative clustering algorithm is that it is based on the Pareto optimal selection of the merged clusters. The tool assignment problem has also been formulated as a bin-packing optimization task, and the results of the related linear programming were used as a benchmark reference. The comparison highlighted that the proposed method provides a feasible solution for large real-life problems with low computation time.

Thesis II.

I developed a location-based utilization monitoring methodology that can be implemented based on position data, using information revealed by clustering algorithms [2].

Indoor positioning systems allow real-time tracking of tool locations. Tool utilization can be calculated based on positional data of the storage and manufacturing areas. Due to the uncertainty of the position measurements, estimation of the state of the tools is problematic when the distance between the examined zones is less than the estimation error. I proposed a goal-oriented supervised fuzzy clustering algorithm that utilizes the activity state of the tool, as the algorithm simultaneously maximizes the spatial distribution probability and the probability of a specific activity state occurring in a cluster. By weighting the data points according to the time spent in the associated states and positions, valuable information can be extracted. The resulting clusters represent relevant locations on the shop floor. They can be categorized based on the temporal probabilities of different activity states of the cluster. The temporal probability of finding a tool in an active state can be interpreted as its utilization, which can be calculated both in general and for location.

Thesis III.

I developed a maintenance optimization methodology that can optimize maintenance under changing manufacturing conditions with a risk evaluation model that considers dynamic failure probability and criticality.

Flexible manufacturing systems represent a rapidly changing environment in which a large number of manufacturing tools are used for production, with multiple interdependencies between them. As a result, the improper condition of any tool can pose a significant risk to the performance and availability of the system. Risk-based maintenance approaches seek to minimize the risks of both over- and under-maintenance. Traditional methods assume that the assessed risks are constant, which in many cases does not reflect the dynamic nature of flexible manufacturing systems. On the one hand, the probability of adverse events increases due to tool wear which is a function of the operating times and conditions, and on the other hand, the severity of the consequences of these events depends on the current production schedule. I proposed an optimization algorithm to find the optimal selection and allocation of maintenance work that minimizes the overall risk. The objective function includes the probabilities of adverse events, obtained from tool reliability models, and the costs of lost production, over-maintenance, and under-maintenance as a result of these events, taking information about the system and current production orders into account. A genetic algorithm is used to find the best solution, where the fitness function is based on the risk evaluation function.

References

[1] A. Darányi, T. Czvetkó, A. Kummer, T. Ruppert, J. Abonyi, Multi-objective hierarchical clustering for tool assignment, CIRP Journal of Manufacturing Science and Technology 42 (2023) 47–54.

[2] A. Darányi, G. Dörgő, T. Ruppert, J. Abonyi, Processing indoor positioning data by goal-oriented supervised fuzzy clustering for tool management, Journal of Manufacturing Systems 63 (2022) 15–22.