

Solving Industry 4.0 scheduling tasks

Doctoral (PhD) Theses

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Abstract

This dissertation investigates advanced scheduling techniques for dynamic manufacturing environments, focusing on the integration of reactive adaptability, intermediate storage management, and multi-objective optimization within a unified framework. Motivated by the increasing complexity and real-time variability of production systems in the context of Industry 4.0 and 5.0, the research addresses two core scheduling paradigms: reactive scheduling under dynamic order arrivals, and deterministic scheduling with due date and storage constraints.

The first part of the research formulates a reactive branch-and-bound scheduling model based on the S-graph framework, capable of adapting to new job arrivals through policy-driven rescheduling strategies. A comparative analysis of different rescheduling policies demonstrates that full rescheduling consistently yields the best makespan

performance, albeit with higher computational cost. Novel mechanisms such as zero-wait arcs, task sequence preservation, and partial solution reuse are introduced to enable efficient real-time adaptation.

The second part of the dissertation presents a deterministic scheduling model that integrates intermediate storage policies with due date adherence. A multi-objective cost function is proposed to minimize both earliness/tardiness penalties and storage time, incorporating dynamic schedule adjustments via local search. This approach significantly improves schedule quality in storage-constrained environments by ensuring that equipment blocking is minimized without violating precedence or timing constraints.

Finally, a comprehensive multi-objective scheduling framework is introduced, synthesizing the strengths of the reactive and deterministic approaches. It unifies policy-aware rescheduling, storage-aware placement, and due date optimization in a single S-graph-based model. The framework is supported by theoretical formulations, algorithmic procedures, and illustrative benchmark examples.

Thesis Statements

1st thesis group: *Reactive scheduling in flexible job shops minimizes makespan by applying targeted S-graph modifications—zero-wait arc insertion and selective release-node locking—under three policies (append-only, partial insertion with strict or flexible delay, and full rescheduling), seamlessly integrated via equipment- or task-based branching.*

(Own publications regarding this thesis group: [P1], [P2])

This approach allows for dynamic order integration while maintaining computational efficiency and makespan optimization. The methodology classifies tasks into started, unscheduled, and new sets, constructing a root subproblem by inserting zero-wait arcs to fix start times where required. Policy-specific graph edits preserve or free task sequences and timings: the append-only policy locks all unscheduled tasks; strict insertion allows idle-gap placement only; flexible delay insertion shifts existing tasks to create slots; and full rescheduling frees all pending tasks. Equipment-based branching handles machine assignments sequentially, while task-based branching leverages activity lists, both requiring only minimal adaptation—such as gap constraints—to enforce policy rules. By unifying release-node locking, zero-wait arcs, and precedence arcs within the S-graph framework, the approach enables dynamic order integration with controlled flexibility, balancing computational efficiency and makespan optimization.

2nd thesis group: *The extended S-graph framework jointly minimizes earliness/tardiness penalties and intermediate storage*

time in flexible job shop scheduling with due-date constraints, leveraging zero-wait arc adjustments, equipment- and recipe-arc sequencing, and hybrid integration with an LP solver to balance timeliness and material handling under NIS and UIS policies.

(Own publications regarding this thesis group: [P3])

This framework extends the S-graph model to address both due-date adherence and intermediate storage minimization in flexible job shop scheduling. It employs zero-wait arc adjustments to enforce strict start-time locking for in-progress tasks, while recipe- and schedule-arcs capture precedence and resource constraints. The dual-objective function combines total earliness, tardiness, and intermediate storage, guiding branching decisions. Local schedule adjustments reduce idle storage when feasible, and a hybrid approach transforms each partial S-graph into an LP model to compute tight lower bounds and refine task timings. This integrated strategy ensures feasible, compact schedules that respect due dates and minimize holding costs, offering a modular, adaptable solution for complex scheduling environments.

3rd thesis group: *A unified reactive S-graph framework integrates due-date optimization and intermediate storage management for flexible job shops, enabling dynamic order integration under NIS/UIS policies through policy-driven graph augmentations and branch-and-bound search with storage-aware conflict resolution.*

(Own publications regarding this thesis group: [P4])

This framework extends the S-graph model to simultaneously address due-date optimization and intermediate storage management in flexible job shop scheduling. It employs policy-driven graph augmentations—such as zero-wait arcs for strict start-time locking and selective release-node locking—to enable dynamic order integration under both NIS and UIS policies. The branch-and-bound search incorporates storage-aware conflict resolution, redistributing storage slack to resolve conflicts while maintaining schedule feasibility. By integrating reactive adaptability with multi-objective optimization, this framework provides a robust solution for managing dynamic manufacturing environments characterized by uncertainty and competing objectives.

Publications of the author

The core results of this doctoral research have been disseminated through peer-reviewed international journals and presented at both national and international conferences. This section lists the author's publications, grouped according to their relevance to the thesis. The thesis group associated with each publication is indicated in parentheses. Publications are arranged in chronological order of appearance. A complete and up-to-date list of publications is available on the author's public profile in the Hungarian Collection of Scientific Works (MTMT) database:

<https://m2.mtmt.hu/api/author/10071598>

Publications directly related to the thesis:

[P1] **Krisztián Attila Bakon**, Tibor Holczinger, Zoltán Süle, Szilárd Jaskó, and János Abonyi: *Scheduling Under Uncertainty for Industry 4.0 and 5.0*, IEEE Access, vol. 10, pp. 74977–75017, 2022. DOI: 10.1109/ACCESS.2022.3191426.

Impact Factor: 3.367

[P2] **Krisztián Attila Bakon**, Tibor Holczinger: *S-Graph-Based Reactive Scheduling with Unexpected Arrivals of New Orders*, Machines, 2024. DOI: 10.3390/machines12070446.

Impact Factor: 2.1

[P3] **Krisztián Attila Bakon**, Tibor Holczinger: *Addressing Due Date and Storage Restrictions in the S-Graph Scheduling Framework*, Machines, 2025. DOI: 10.3390/machines13020131.

Impact Factor: 2.1

[P4] **Krisztián Attila Bakon**, Tibor Holczinger: *Reactive Scheduling under Due-Date and Intermediate Storage Constraints: A Conceptual Multi-Objective Approach*, in Proceedings of the Central European Conference on Information and Intelligent Systems (CECIIS), Varaždin, Croatia, 2025.

Other publications by the author (not directly related to the dissertation):

- [N1] **Krisztián Attila Bakon**, Tibor Holczinger, Szilárd Jaskó:
Demonstration of Maturity Questions with Multipurpose Digital Factory, Logistics – Information Technology – Management, Abstract book of conference presentations, p. 13, 2021.
- [N2] **Krisztián Attila Bakon**, Tibor Holczinger, Szilárd Jaskó, Nikoletta Kaszás: *Tourism 4.0 and the Path of Achievement*, VI. International Scientific Conference on Tourism and Security, pp. 225–237, 2022. ISBN: 9789633962237
- [N3] **Krisztián Attila Bakon**, Tibor Holczinger, Szilárd Jaskó:
Production Flow of Customized Products in a Digital Factory, Procedia Computer Science, vol. 200, pp. 1201–1208, 2022. DOI: 10.1016/j.procs.2022.01.320.
- [N4] Máté Hegyháti, **Krisztián Attila Bakon**, Tibor Holczinger:
Optimization with Uncertainties: A Scheduling Example, Central European Journal of Operational Research, 2023. DOI: 10.1007/s10100-023-00854-4.
Impact Factor: 2.407
- [N5] **Krisztián Attila Bakon**: *Agile Circularity: Reactive Scheduling Approaches*, in Mastering Time, Chapter 5, IntechOpen, Rijeka, 2025. DOI: 10.5772/intechopen.1006167.