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Referee Report
on the PhD Dissertation of

Krisztián Attila Bakon

entitled

Solving Industry 4.0 scheduling tasks

The Choice of Topic and Theoretical Background

The choice of the topic is good and well justified. The dissertation deals with a modern and important research area that is both relevant in theory and useful in practice. Scheduling in dynamic manufacturing systems is a current and significant topic, a modern production systems need flexible and adaptive solutions. The issues studied in the thesis, such as reactive scheduling, due dates, and intermediate storage, are closely connected to real problems in modern manufacturing. In my opinion, the candidate has chosen a timely and valuable topic for doctoral research.

The theoretical background of the dissertation is appropriate. It is based on well-known results from scheduling theory, optimization, and graph-based modeling.

Summary of the Research Goal

The primary goal of the research is to develop advanced scheduling models and solution approaches for flexible job shop manufacturing systems. The problem statement considers that the operative environment is dynamic.

A key objective of the dissertation is to extend classical scheduling formulations by the typical scheduling policies. In particular, the research aims to design reactive scheduling methods that can efficiently update production schedules



when new orders arrive, while preserving the operations already started or finished.

Another research goal is to optimize performance measures, including earliness, tardiness, and intermediate storage time. To cope with this the formulation of multi-objective scheduling models that balance delivery performance with feasible scheduling is presented. The work aims to unify these aspects into an integrated scheduling framework, combining dynamic order arrivals, due-date optimization, and storage constraints within a single model.

Structure of the Dissertation

The thesis begins with an abstract, a Hungarian summary, acknowledgements, and lists of figures and tables. The main body of the dissertation is organized into seven chapters.

Chapter 1 introduces the research topic, presenting the motivation and the broader research context of manufacturing scheduling in dynamic production environments. It highlights the increasing complexity of modern manufacturing systems and the limitations of traditional static scheduling approaches. The chapter also outlines the objectives of the research and presents the structure of the dissertation.

Chapter 2 provides a comprehensive literature review of manufacturing scheduling methodologies. The chapter discusses different scheduling problem types, sources of uncertainty in production environments, and existing solution approaches, including exact optimization methods, heuristic techniques, and metaheuristic algorithms. Special attention is given to reactive scheduling strategies and S-graph-based scheduling models, which form the theoretical foundation of the proposed methods.



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Chapter 3 formulates the scheduling problems addressed in the dissertation. The author defines the investigated problem classes, including reactive scheduling with dynamic order arrivals, deterministic scheduling with due-date and intermediate storage objectives, and an integrated scheduling problem that combines these aspects within a unified framework.

Chapter 4 presents the proposed approach for reactive scheduling with makespan minimization. The chapter introduces the methodological framework, describes the S-graph representation of the manufacturing system, and discusses the implemented policy variants and algorithmic solution strategies. The effectiveness of the proposed methods is evaluated through computational experiments and comparisons with existing approaches.

Chapter 5 addresses deterministic scheduling problems that incorporate due-date constraints and intermediate storage objectives. The author extends the S-graph framework to include earliness and tardiness minimization and integrates linear programming techniques to improve solution quality and computational efficiency. The chapter presents numerical results and discusses their implications.

Chapter 6 introduces an integrated reactive scheduling framework that simultaneously considers due-date compliance and intermediate storage constraints. The chapter presents the algorithmic procedures and discusses trade-offs between competing objectives in the scheduling process.

Finally, *Chapter 7* summarizes the main scientific contributions of the dissertation, discusses its practical implications, identifies limitations, and outlines directions for future research. The thesis concludes with a nomenclature section, bibliography, and a list of the author's related publications.



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Reviewer Evaluation Points

The research topic of the dissertation is a good choice, as it addresses a relevant and important research challenge with both theoretical and practical significance.

The originality of the dissertation lies in:

a) the proposed extensions of the S-graph scheduling framework and b) the integration of multiple scheduling objectives within a unified methodological approach.

It combines reactive scheduling mechanisms with deterministic optimization objectives such as due dates and intermediate storage constraints. The author proposes a framework that addresses several practical challenges simultaneously. This integrated approach represents an important contribution to the field of production scheduling.

Evaluation of the Quality of the Literature Review

The literature review presented mainly in Chapter 2 of the dissertation. It provides a good overview of scheduling problems in modern manufacturing systems and the methodological approaches used to address them. The chapter covers the relevant research directions, including classical manufacturing scheduling models, uncertainty in production environments, exact optimization methods, heuristic and metaheuristic algorithms, multi-objective optimization, and reactive scheduling strategies. It also introduces the S-graph scheduling framework, which serves as the theoretical foundation of the dissertation.

From a quantitative perspective, the dissertation cites 158 references, which indicates a wide overview of the scientific literature. The references are consistently cited throughout the document. They are integrated into the overview of the different scheduling approaches and methodological developments.



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The cited literature appears to be recent. Based on the reference list a significant share of the references originates from the last decade, with many sources published after 2018. This demonstrates that the author is familiar with current developments in scheduling theory, Industry 4.0 production systems, and modern optimization methods.

In terms of relevance, the cited works are largely appropriate for the research topic. The literature review includes foundational studies in manufacturing scheduling, as well as more recent research addressing reactive scheduling, multi-objective optimization, and dynamic production environments. The discussion shows a good understanding of the relationships between different scheduling paradigms.

Another positive aspect of the literature review is that the references are not only listed but are actively used to underline the motivation of the research problem and methodological choices. The author frequently refers to previous studies when discussing algorithmic approaches, uncertainty sources in scheduling, and trade-offs between scheduling objectives. This indicates that the literature is used not only descriptively but also analytically.

Research methodology

The research methodology applied in the dissertation is clearly structured and is consistent with the objectives of the study. The author adopts a model-based and algorithmic approach to address scheduling problems in dynamic manufacturing environments. The methodological framework is primarily built upon the S-graph scheduling representation, which is a well-established approach in the field of production scheduling and combinatorial optimization.

The dissertation follows a logical methodological flow. First, the scheduling problems are formally defined, including reactive scheduling with dynamic order arrivals, deterministic scheduling with due-date and intermediate



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storage objectives, and an integrated scheduling framework that combines these aspects. This clear problem formulation provides a solid foundation for the development of the proposed models and algorithms.

The core methodological contribution lies in the extension of the S-graph framework to address several practical scheduling challenges simultaneously. The author develops algorithmic procedures based on branch-and-bound method combined with the graph-based modeling techniques. The proposed methods incorporate mechanisms such as policy-based reactive rescheduling, due-date optimization, and intermediate storage management. These extensions demonstrate a good understanding of both theoretical scheduling models and practical production constraints.

The dissertation also includes computational experiments designed to evaluate the performance of the proposed algorithms. The experimental setup illustrates the behavior of the scheduling methods under different policy variants and scheduling objectives. The presented examples and comparisons help to demonstrate the applicability of the proposed approach and provide insights into the trade-offs between scheduling performance and computational complexity.

From a methodological perspective, the research is supported by mathematical modeling and algorithm design, which is appropriate for the field of production scheduling and operations research.

At the same time, some aspects of the methodology could be further elaborated. In particular, the scalability of the proposed algorithms for large-scale industrial scheduling problems could be discussed in more detail.



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Presentation and Structure

The dissertation is generally well organized and follows a clear and logical structure that guides the reader from the research motivation through the theoretical background, methodological development, and experimental validation to the final conclusions. The overall structure of the thesis is appropriate for a doctoral dissertation. The progression of chapters—from the introduction and literature review to the problem formulation, methodological contributions, experimental evaluation, and conclusions—supports a coherent presentation of the research work.

The text is written in a clear and generally understandable academic style. The author consistently uses appropriate terminology from the fields of scheduling theory, operations research, and manufacturing systems. The explanations of the models, algorithms, and scheduling concepts are mostly precise and technically accurate. In some sections, particularly those describing algorithmic procedures and mathematical formulations, the presentation becomes relatively dense; however, this level of technical detail is expected in a doctoral dissertation dealing with combinatorial optimization and scheduling algorithms.

The logical structure of the dissertation is well designed. The literature review provides a solid theoretical background and positions the research within the existing body of work. The subsequent chapters build upon this foundation by first defining the investigated scheduling problems and then presenting the proposed methodological solutions. The separation of the contributions into chapters addressing reactive scheduling, deterministic scheduling with due-date and storage objectives, and their integrated treatment helps to clearly distinguish the different aspects of the research.



The quality of figures and tables is generally satisfactory. The figures, including scheduling graphs and illustrative Gantt charts, support the explanation of the proposed methods and help the reader understand the underlying scheduling models and algorithmic procedures. Tables presenting computational results are informative and allow comparison of different scheduling strategies and policy variants.

Review on Mathematical Formulation

From a mathematical perspective, the formulations presented in Chapters 3 to Chapter 6 are appropriate and consistent with established scheduling theory. The problem is formulated having features such as dynamic order arrivals, precedence constraints, and equipment assignment flexibility, and policies. The modeling framework defines the fundamental components of the scheduling problem clearly: the set of products, the associated task sets, the equipment units capable of executing each task, and the processing times associated with each task–equipment pair. These elements correspond to the standard representation used in combinatorial optimization models for production scheduling.

The feasibility of schedules is ensured through several well-known constraint types. First, precedence constraints guarantee that tasks belonging to the same product are executed in the correct technological order. Second, resource constraints ensure that each equipment unit processes at most one task at any given time. Third, release time constraints guarantee that tasks belonging to newly arriving orders cannot begin before their specified arrival time. These constraints collectively define the feasible solution space of the scheduling problem and are consistent with classical job shop scheduling formulations.

The algorithm also incorporates mechanisms required for reactive scheduling, where new production orders may arrive during schedule execution. The model



handles such events by partitioning the existing schedule into tasks that have already started and tasks that have not yet begun. Tasks that are already in execution remain fixed, while the remaining tasks may be rescheduled.

An aspect that could be expanded is the algorithmic complexity analysis. Branch-and-bound algorithms for flexible job shop scheduling are known to have exponential worst-case complexity, and a discussion of the expected computational behavior of the proposed approach would help clarify its scalability for larger problem instances.

Critical remarks

The dissertation is overall well prepared; however, there are several critical remarks concerning the formulation, presentation, and evaluation of the proposed methods.

Page 31 “Among all feasible schedules satisfying the above constraints, S_{k+1} should minimize the makespan.” should have been mathematically formalized.

Page 33 Equation (3.3) uses β as a common weight coefficient for earliness and tardiness penalty. Equation (3.1) had a separated, product specific weight, w_p^E and w_p^T respectively. From a modeling perspective, the latter formulation is more general and more expressive, since it allows different products to have different penalty structures for early or late completion. For this reason, the product-specific weighting scheme would have been preferable in the later formulation as well.

Page 42 “Add zero-wait arcs from global node Z”- This chapter referenced global node as n_0 . This is a minor notation inconsistency.

Page 48. In figure 4.8 (A) the length of task 9:1 is different to that of (B), (C), (D).



Page 59. The internal storage reduction algorithm explained in the first paragraph may break objective function (5.8)

Scientific Contributions

The dissertation presents several scientific contributions related to scheduling problems in dynamic manufacturing environments, particularly within the context of Industry 4.0 production systems. The main contributions are connected to the development and extension of scheduling models based on the S-graph framework and to the integration of multiple scheduling objectives within a unified optimization approach.

The dissertation presents three main thesis groups, each addressing a different aspect of scheduling optimization in flexible manufacturing systems.

Thesis 1 – Reactive scheduling with makespan minimization

The first thesis proposes a reactive scheduling method for flexible job shop environments based on extensions of the S-graph framework. The method integrates new production orders into an already executing schedule using several rescheduling policies (append-only insertion, partial insertion, and full rescheduling). These policies are implemented through graph modifications such as zero-wait arc insertion and release-node locking, enabling dynamic adaptation of schedules while minimizing makespan.

Thesis 2 – Multi-objective scheduling with due dates and intermediate storage

The second thesis extends the S-graph framework to address simultaneous minimization of earliness–tardiness penalties and intermediate storage time in flexible job shop scheduling. The proposed approach integrates storage policies, due-date optimization, and hybrid LP-based bounding techniques, allowing the scheduling algorithm to balance delivery performance with material handling constraints.



Thesis 3 – Integrated reactive multi-objective scheduling framework

The third thesis develops a unified scheduling framework that combines the reactive scheduling approach with the due-date and storage optimization model. The resulting method enables dynamic integration of new orders while simultaneously considering delivery deadlines and storage limitations, using policy-driven S-graph transformations and branch-and-bound search procedures.

Final recommendation

In summary, the dissertation presents a well-structured and methodologically solid investigation of scheduling problems in dynamic manufacturing environments. The work demonstrates a deep understanding of the relevant theoretical background and proposes meaningful extensions of S-graph-based scheduling methods to address reactive and multi-objective optimization challenges. The results are supported by appropriate modeling demonstrated by examples, and the contributions are relevant to both the academic field and practical applications. The thesis statements are supported by appropriate number of scientific publications.

I declare that the three thesis statements formulated in the dissertation are accepted by me without modification.

The candidate can discover new and complex research problems, find appropriate solutions, and understandably present them through systematic analytical and empirical approaches.

Based on the presented results and scientific contributions, I recommend the dissertation to be accepted on public defense and I consider it suitable for the award of the PhD degree.



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Questions

1. The method proposed in this document is based on a branch-and-bound search over S-graph representations. Given that flexible job shop scheduling is an NP-hard problem, how does the worst-case computational complexity of your algorithm scale with the number of tasks and machines? Additionally, can you identify the dominant factors that most significantly influence the growth of the search space in the presented approach?
2. The introduced policy-based restrictions (e.g., append-only, partial insertion, full rescheduling), effectively constrain the search space. How do these policies influence the theoretical and practical complexity of the algorithm? In particular, can you characterize whether these restrictions reduce the problem size in a provable way, or do they primarily act as heuristics without guarantees on complexity reduction?
3. What are the limitations of applying S-graph framework to more general or heterogeneous production systems, such as those with sequence-dependent setup times or transportation delays?

Miskolc, 29 March 2026.

A handwritten signature in blue ink, appearing to be 'OH' with a long horizontal stroke extending to the right.

Oliver Hornyák