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PhD THESIS
– SUMMARY –

STUDIES AND RESEARCH ON SERIAL PRODUCTION MANAGEMENT

PhD Student:
Mircea TEODORESCU

Scientific Supervisor:
Professor Dr. Eng. Florin LUNGU

PhD Thesis Evaluation Committee:

Chair: Professor Dr. Inf, Ec. Emilia Ciupan - Technical University of Cluj-Napoca
Scientific Supervisor: Professor Dr. Eng. Florin Lungu - Technical University of Cluj-Napoca

Reviewers:
- Professor Dr. Eng. Liviu Moldovan - University of Medicine, Pharmacy, Science, and Technology “G.E. Palade” Târgu-Mureș
- Professor Dr. Eng. Gabriela Proștean - Politehnica University of Timișoara
- Professor Dr. Eng. Nicolae Ungureanu - Technical University of Cluj-Napoca

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INTRODUCTION, STRUCTURE, AND METHODOLOGY

Motivation and Necessity of the Approach (Argument)
In today's globalized market, optimizing production scheduling is not only a necessity but also an imperative for companies aiming to remain competitive. The increasing complexity of supply chains, diversification of customer demands, and constant pressure to reduce costs necessitate the adoption of advanced technological solutions. In this context, artificial intelligence (AI) and optimization algorithms offer immense potential to improve operational efficiency. Utilizing these technologies enables companies to plan more accurately, reduce production cycles, and minimize errors, thereby enhancing product quality and profitability.
Furthermore, in the era of digitalization, adopting AI in production management is becoming a critical differentiator. Companies that delay implementing such solutions risk falling behind, losing their competitive edge. Therefore, the research and application of optimization algorithms in production scheduling are not only relevant but essential for ensuring long-term sustainability and success. This effort not only supports the improvement of internal performance but also contributes to rapid market changes, thus securing the future of organizations in today's dynamic business environment.

Relevance and Importance of the Topic. The topic of optimizing production scheduling through AI algorithms is undeniably relevant in the context of the digital transformation dominating contemporary industry. In a time when technological innovation is redefining production processes, adopting these methods is essential to address economic and operational challenges. Optimization algorithms, including genetic and hybrid ones, provide efficient solutions for managing the complexity of production processes, reducing execution times, minimizing resource usage, and enhancing product quality.
The importance of this topic lies not only in its ability to increase companies' competitiveness but also in its potential to revolutionize production management globally. As companies increasingly adopt AI to optimize their processes, the capacity to implement and integrate these technologies becomes a crucial criterion for long-term success. Thus, research in this field significantly contributes to the development of an economy based on efficiency and innovation, reinforcing the importance of this topic in the current industrial landscape.

Thesis Objectives.
The primary aim of the research undertaken in this thesis is to investigate and evaluate the application of artificial intelligence (AI) algorithms, especially genetic and hybrid ones, in optimizing serial production scheduling. Given the complexity and dynamism of today's industrial environment, the thesis aims to achieve the following objectives:

1. Identify innovative elements that contribute to improving the serial production planning and scheduling process. This objective targets the discovery and analysis of new methods emerging in production scheduling, with a focus on AI applications.
2. Optimize production processes through the implementation of advanced AI techniques, particularly genetic and hybrid algorithms. This aims to explore how these techniques can bring improvements in the efficiency and accuracy of production scheduling.

3. Evaluate the applicability of AI in production management by analyzing how various types of AI algorithms can be used to increase efficiency and adaptability in production processes.
4. Identify key trends in serial production scheduling management. This objective aims to study and understand recent developments and future directions in this field, proposing relevant and up-to-date solutions.

These objectives are essential for providing a clear picture of the impact and potential of AI technologies in optimizing production processes, thereby making a significant contribution to the development and efficiency of production management.

The thesis is structured into three main parts, each organized into chapters that aim to achieve the research objectives.

The **General Part** begins with Chapter 1, which provides an overview of the fundamentals of production management, including essential aspects such as production planning and scheduling, the diversity of production types, and recent innovations, such as the impact of IoT technology and approaches to Job Shop Scheduling problems.

Chapter 2 continues with a comparative study of production scheduling methods based on AI algorithms, analyzing planning strategies, scheduling techniques, and the theoretical foundations of AI.

The **Specific Part** opens with Chapter 3, which presents the applied research methodology and discusses in detail the modeling of serial production scheduling. This chapter includes the analysis of guided interviews and a case study on ABC Company, exploring the integration and implementation of AI technologies, as well as a comparison between exact and heuristic methods.

The **Experimental Part** is addressed in Chapter 4, which focuses on consolidating the results from the application of the objective function, discussing the results obtained, cause-effect analysis, and SWOT evaluation. The thesis concludes with a summary of the main contributions and the research's impact on the field.

Methodology (Research Question, Hypotheses, and Research Methods)

The methodology of this thesis is based on an integrated approach that combines theoretical analysis with applied research to address the main research question: “To what extent do the application of artificial intelligence algorithms (genetic and hybrid) and other optimization techniques contribute to improving the serial production scheduling process?”

To address this question, the following research hypotheses were formulated:

- Hypothesis 1: Exact methods provide superior results to heuristic methods in serial production scheduling.
- Hypothesis 2: Hybrid genetic algorithms provide better results than classic genetic algorithms in terms of solution accuracy in serial production scheduling.
- Hypothesis 3: Classic genetic algorithms produce varying and inconclusive results in successive runs for serial production scheduling.
- Hypothesis 4: Applying the Guinet model in production scheduling will lead to significant improvements in reducing production cycles.
- Hypothesis 5: The results of applying hybrid algorithms have the potential to approach those of exact methods in the future for serial production scheduling.

The quantitative and qualitative research methods used will be:

- Literature review – Analysis of statistical data obtained from secondary sources, including scientific articles, industry reports, and existing case studies, to identify trends and recent developments in the application of AI algorithms and optimization techniques in serial production.
- Guided interview – Conducting interviews with industry experts and researchers to gain in-depth insights into the applicability and effectiveness of optimization techniques and AI algorithms in production scheduling.
- Cause-effect analysis – Identifying and analyzing the factors contributing to challenges and opportunities in serial production scheduling, facilitating an understanding of the complex relationships between the different elements involved.
- Importance of case study – Identifying and analyzing relevant case studies to demonstrate the practical applicability of optimization techniques and AI algorithms in various industrial contexts. Case studies will provide practical insights into how these techniques can be implemented and adapted to meet the specific requirements of each industry.
- Mathematical solution of the objective function problem – Applying exact methods (CPLEX/OPL Mixed Integer Linear Programming and CPLEX Constraint Programming) and heuristic methods (Genetic Algorithm GA and Hybrid Algorithm GA + PSO) to solve optimization problems in serial production scheduling. This involves formulating the objective function and constraint set, followed by analyzing and comparing the solutions obtained.
- SWOT analysis – Associated with the application of AI algorithms and optimization techniques in serial production scheduling. This will help in developing informed strategies and making strategic decisions to improve operational performance.

CONFIRMATION OF RESEARCH HYPOTHESES BASED ON INTERVIEWS

Hypothesis 1: Exact methods provide superior results to heuristic methods in serial production scheduling. The conducted interviews reveal a variable interest in using AI algorithms for production optimization, with most companies not yet employing these technologies. However, those who have started to explore AI usage note clear benefits in error reduction and efficiency gains. A significant portion of respondents emphasizes the need for a detailed cost-benefit analysis before implementation, which supports the idea that while exact methods yield superior results, they may involve considerable costs and integration challenges. This suggests that despite the effectiveness of exact methods, companies are hesitant to adopt them without a clear assurance of profitability, thus confirming the hypothesis that exact methods offer superior results but are more difficult to implement without strong management commitment and dedicated resources. Hypothesis confirmed.

Hypothesis 2: Hybrid genetic algorithms provide superior results to classic genetic algorithms in terms of solution accuracy in serial production scheduling. The interviews reveal a general perception that hybrid genetic algorithms, although not widely explored in practice, have the potential to offer more accurate solutions in serial production scheduling compared to traditional methods. However, acceptance of these technologies depends on how their benefits are presented and on employee training for efficient use. Companies that have begun testing or considering implementing these technologies acknowledge the need for strong managerial support and cross-departmental collaboration to ensure their success. This confirms the hypothesis that hybrid genetic algorithms can provide considerable advantages in production scheduling but require rigorous preparation and a deep understanding of the technology. Hypothesis confirmed.

Hypothesis 3: Classic genetic algorithms yield inconsistent and inconclusive results in successive runs in large-scale serial production scheduling. The interviews indicate that most companies are not yet using genetic algorithms, whether classic or hybrid, in production scheduling. Among those experimenting with AI technologies, there is recognition of their limitations, particularly regarding result consistency. Several companies highlighted that the lack of concrete and reliable data makes implementing these algorithms challenging, suggesting that results obtained through classic genetic methods may be uneven and difficult to replicate. This confirms the hypothesis that classic genetic algorithms do not always provide conclusive results, which may discourage their widespread use in large-scale serial production scheduling. Hypothesis confirmed.

Hypothesis 4: The application of the Guinet model in production scheduling will lead to significant reductions in production cycles. Interview analysis reveals that managerial support and technological infrastructure are essential for successful AI implementation, suggesting that complex models like Guinet’s require substantial commitment and resources for effective implementation. Companies emphasized the importance of appropriate modeling and adapting technology to their specific needs to achieve a significant reduction in production times. This confirms the hypothesis that applying the Guinet model can bring significant improvements but requires thorough planning, rigorous execution, a solid infrastructure, and continuous support from all involved parties. Hypothesis confirmed.

Hypothesis 5: The results of applying hybrid algorithms are likely to approach those of exact methods in large-scale serial production scheduling in the future. Interviews suggest a positive perception of the potential of hybrid algorithms, although they are not yet widely adopted. Many companies are open to investing in AI, recognizing that these technologies could become as efficient as exact methods in the future. The gradual acceptance of these technologies, supported by investments and proper training, could lead to increased accuracy and efficiency in large-scale serial production scheduling. This supports the hypothesis that, as technology advances and becomes better understood, hybrid algorithms could offer solutions comparable to those of exact methods, making them a viable alternative in the near future. Hypothesis confirmed.

EXPERIMENTAL PART

Our research partner is ABC Company from Cluj-Napoca, a DEF subsidiary and a member of the XYZ group, with a turnover exceeding 14 million euros. The company has 8,000 square meters of production halls, produces over 350 products monthly, exports to 8 countries, and invests 0.5 million euros annually.

Areas of Activity:

- Production of metal subassemblies for the household electrical appliances industry.
- Electromechanical assembly and testing.

Organizationally, the company operates 17 production centers, with machines grouped into centers specific to certain operations. The overall importance of the study area is crucial for optimizing and increasing the efficiency of the entire production process, directly contributing to reduced delivery times and enhancing the company's competitiveness in the market.

Improving Production Scheduling. The technological processes within ABC Company require improvements in production scheduling, as described in the following table. The use of the Pegasus system leads to situations in production centers equipped with cutting and bending machines where "bottlenecks" appear, representing critical points in the production flow (see Table No. 3.1.). These bottlenecks limit the capacity of production centers to complete all scheduled orders within the allotted time frame, resulting in delays and reduced operational efficiency. This issue highlights the need for optimizing production flows and appropriately managing resources to minimize the impact of these constraints and ensure adherence to delivery schedules without significantly increasing cost impact.

The initial dataset used for this analysis includes a production scheduling period of three weeks, corresponding to 280 orders for 353 products manufactured by ABC. Each of these products is associated with a specific technological itinerary, detailed.

The application of the Guinet model within the production process led to the elimination of bottlenecks, thereby optimizing the production flow. This intervention enabled efficient production scheduling, ensuring a continuous flow and minimizing waiting times. As a result, product delivery delays were eliminated, significantly improving operational performance and the ability to meet delivery deadlines.

In conclusion we obtain the following objective function

$$f = min \sum_{i=1}^{I} T_{in,M_p} \tag{1}$$

The constraints related this functions objective are :

$T_{in,m_p} - T_{jn,m_p} + KZ_{in,jn,m_p} \geq d_{jn,m_p} \quad \forall n \in [1, N]; \forall i, j \in [1, I];\ i \neq j; \forall\ m_p \in [1, M_P]$ (2)

$T_{jn,m_p} - T_{in,m_p} + K\left(1 - Z_{in,jn,m_p}\right) \geq d_{in,m_p} \quad \forall n \in [1, N]; \forall i, j \in [1, I]\ ; i \neq j; \forall\ m_p \in [1, M_P]$ (3)

$T_{in,m_p+1} - T_{in,m_p} \geq d_{in,m_p} \quad \forall i, \in [1, I]; \forall n \in [1, N]; \forall\ m_p \in [1, M_P - 1]$ (4)

$T_{in,1} \geq dint_i \quad \forall i \in [1, I]; \forall n \in [1, N]$ (5)

$T_{in,m_P} \leq dl_i - d_{in,m_P}\ \forall\ i \in [1, I]; \forall n \in [1, N]$ (6)

where:

$T_{in,mp} -$ a variable that indicate the time(moment) when job "in" was schedule on machine "p" from machine center "m"

$T_{jn,mp} -$ a variable that indicate the time(moment) when job "jn" was schedule on machine "p" from machine center "m"

$Z_{in,jn,m} -$ Variable with value 1 when operation "in" is scheduled before operation "jn" on machine "p" from machine center "m"

$Z_{in,jn,m} -$ Variable with value 0 when operation "jn" is scheduled before operation "in" on machine "p" from machine center "m"

$d_{in,mp} -$ Processing time of operation "in" on machine "p" from machine center "m"

$d_{jn,mp} -$ Processing time of operation "jn" on machine "p" from machine center "m"

$dint_{in} -$ The moment from which the order "in" can be programmed

$dl_{in} -$ The time when the order must be delivered to client

$K -$ the constant that has a large value($1 * 10^7$)

$M -$ Number of production centers

$In, Jn -$ the number of orders . (In and Jn are 2 different orders.)

$P -$ the number of machines in each production center

N- The number of products

With the limits values:

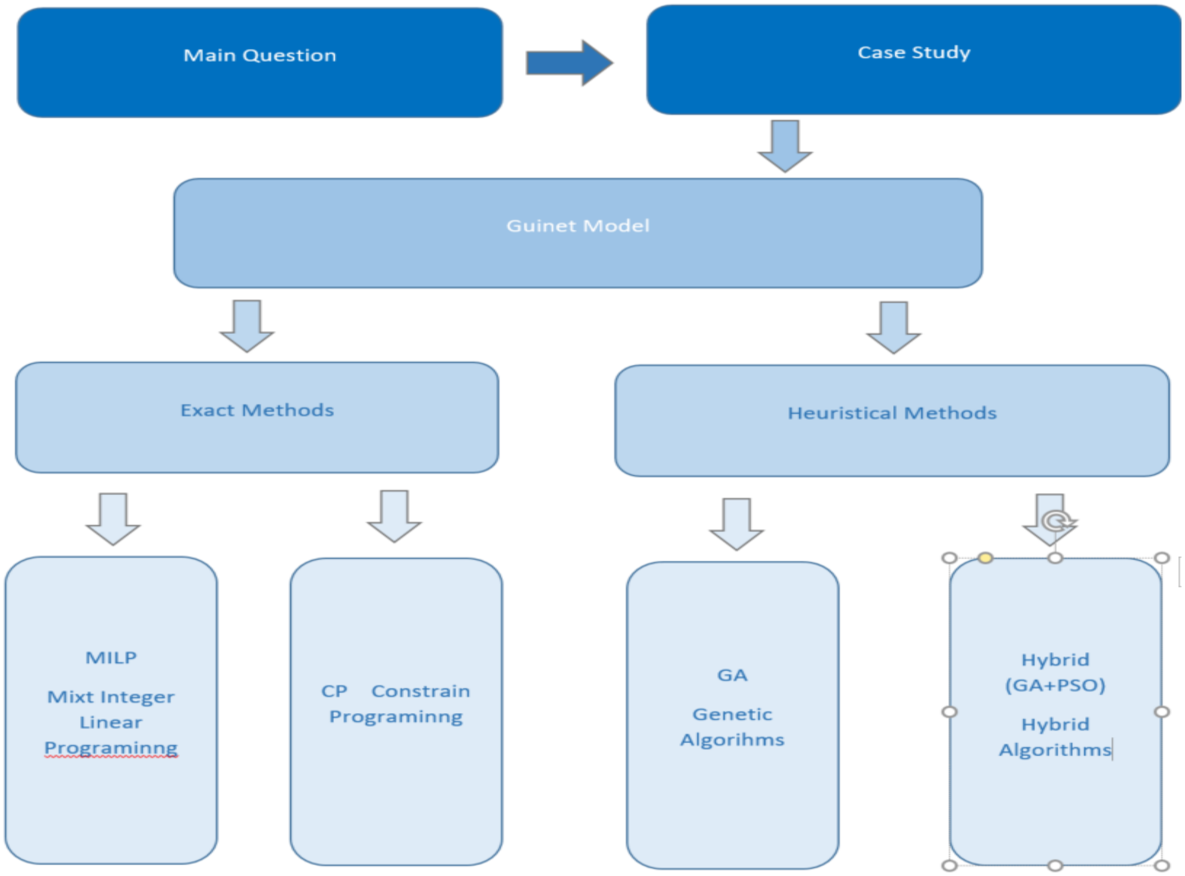
i,j ∈ [1 , 5000]

m ∈ [1 , 17]

p ∈ [1 , 51]

p ∈ [1 , 353]

The main objective function aimed to minimize the total time required to complete the orders, an essential aspect in an industry where timely delivery is a key factor for customer satisfaction and for maintaining long-term business relationships. A systematic presentation of this analysis might appear as follows:



Solution Approach Using the Adapted Guinet Function

The solution provided by the adapted Guinet function was achieved through four methods:

I. Exact Methods:

1.1) CPLEX/OPL Mixed Integer Linear Programming (MILP)

Exact methods, such as Mixed Integer Linear Programming (MILP) used in CPLEX/OPL, rely on rigorous mathematical models to find optimal solutions. These methods are deterministic, meaning that for a specific problem and set of parameters, the solution will always be the same. Linear programming involves formulating an objective function and a set of constraints, which are solved to find the optimal values of decision variables. In the variant developed using the MILP technique, the software ran for over 29 hours without generating a solution due to the complexity of the involved matrix – see the newly added Appendices. The matrix comprised the number of orders (280), the number of products (353), and the number of machines required for processing (51), resulting in an immense number of solution variants (5,040,840). This highlights the limitations of exact methods for large and complex problems.

1.2) CPLEX Constraint Programming (CP)

Constraint Programming (CP) is an exact method used to solve complex problems that cannot be easily formulated in terms of linear programming. CP uses a set of variables, domains, and constraints to model the problem, and the solution is found by systematically exploring the space of possible solutions. CP methods are particularly useful for complex combinatorial problems, such as scheduling and resource allocation.

Using the solution approach provided by CPLEX Constraint Programming, the objective function was optimized to yield a value below the maximum permissible time for product delivery. This performance demonstrates not only the effectiveness of the Guinet model but also the superior capacity of CPLEX Constraint Programming to manage complex production scheduling problems. According to the data presented in Table 3.7 above, the runtime to find the optimal solution was significantly reduced, reaching only 12.55 seconds. This extremely short processing time demonstrates the computational efficiency of the CPLEX Constraint Programming method compared to other traditional methods.

II. Heuristic Methods:

2.1) Genetic Algorithm (GA)

The Genetic Algorithm (GA) is an evolutionary optimization technique that uses processes inspired by natural biology, such as selection, crossover, and mutation, to evolve solutions to complex problems. GA starts with a population of possible solutions (chromosomes), each representing a potential solution to the problem. Solutions are evaluated based on an objective function, and the best solutions are selected to generate new solutions through crossover and mutation.

Genetic Algorithms, implemented in Matlab [123], yielded mixed results. Although they ran in a relatively short time, they failed to provide a solution within the contractual six-week timeframe. The lowest objective function value obtained from this type of Genetic Algorithm run was 516 production hours, well above the contractual delivery deadline. In conclusion, although Genetic Algorithms are powerful in exploring the search space and can find good solutions to complex problems, their performance may be limited by the nature of the objective function or the way constraints are set. In this context, fine-tuning algorithm parameters, such as the mutation rate and crossover rate, might improve performance, but a combined model may also be necessary to meet the imposed objectives.

2.2) Hybrid Algorithm (GA + PSO)

The hybrid algorithm combines the Genetic Algorithm (GA) with Particle Swarm Optimization (PSO) to improve performance and solution diversity. PSO is inspired by the collective behavior of bird flocks or fish schools, where each particle in the population moves through the solution space, guided by its own experience and that of its neighbors. Combining GA and PSO allows the hybrid algorithm to benefit from both the genetic diversity offered by GA and the fast convergence provided by PSO.

The hybrid approach, which combines Genetic Algorithms with Particle Swarm Optimization (PSO), showed improved performance compared to the use of Genetic Algorithms in isolation. In the experiments, hybrid algorithms provided solutions meeting the time requirement for product delivery in three out of sixty cases, yielding production cycles of 352, 446, and 480 production hours.

These results suggest that integrating two optimization methods can provide significant benefits, leveraging the strengths of each method to overcome individual limitations. In this case, PSO contributed to improved search space exploration, but it was insufficient to fully meet the contractual time terms, indicating that while hybrid approaches can yield better solutions, they still require fine-tuning and in-depth analysis of method interactions to maximize efficiency.

Table of results

CPLEX -MILP Mixt Integer Linear	Contract Production Time					Real Production Time		
	Weeks	Days	HRS 2*16	Min	Sec	Hrs	Sec	Running time
	6	30	480	28800	1728000	na	na	>14400
CPLEX CP - Constrain Programinng	Contract Production Time					Real Production Time		
	Weeks	Days	HRS 2*16	Min	Sec	Hrs	Sec	Running time
	6	30	480	28800	1728000	303.3	1091828	12.55
Matlab GA	Contract Production Time					Real Production Time		
	Weeks	Days	HRS 2*16	Min	Sec	Hrs	Sec	Running time
	6	30	480	28800	1728000	516	1857600	21
Matlab Hybrid (GA+PSO)	Contract Production Time					Real Production Time		
	Weeks	Days	HRS 2*16	Min	Sec	Hrs	Sec	Running time
	6	30	480	28800	1728000	352	1267200	111

RESULTS AND DISCUSSIONS

Comparison of Exact and Heuristic Methods:

A) **Regarding Precision and Optimization:**

- Exact methods, such as Mixed Integer Linear Programming (MILP) and Constraint Programming (CP), are capable of finding optimal solutions for well-defined problems with clear constraints. These methods are highly accurate and guarantee finding the best possible solution. However, they can be inefficient for very large or computationally complex problems.
- Conversely, heuristic methods, such as Genetic Algorithms (GA) and hybrid algorithms, do not guarantee an optimal solution but can find very good solutions within a reasonable time frame. These methods are more flexible and can address problems for which exact methods would be impractical due to complexity or the large size of the solution space.

B) **Regarding Flexibility and Adaptability:**

- Exact methods are less flexible because they require a strict mathematical formulation of the problem. Any change in the problem necessitates a complete reformulation of the mathematical model. In contrast, heuristic methods are much more adaptable and can easily adjust to changes in the problem parameters or the operating environment.

C) **Regarding Implementation Complexity:**

- Exact methods can be complex to implement and require advanced mathematical and programming knowledge. Proper problem formulation and parameter setup are crucial for the success of these methods. On the other hand, heuristic methods are generally easier to implement and adapt to various problems. Genetic and hybrid algorithms can be implemented using existing code libraries and can be adjusted easily to improve performance.

D) **Regarding Computational Performance:**

- Exact methods can become very slow for large-scale problems due to the need to exhaustively explore the solution space. This can lead to long computation times and require significant computational resources. Although heuristic methods may be faster, they often require multiple iterations and can also consume considerable computational resources, but in a more manageable and scalable way.

E) **Regarding Solution Capability:**

- Exact methods provide highly precise and deterministic solutions but can be sensitive to minor changes in input data or problem formulation. Heuristic methods are more robust to data variations and can find good solutions even when the data are incomplete or inaccurate.

Both exact and heuristic methods have strengths and weaknesses in the context of production planning. The choice of method depends on the specific nature of the problem, available resources, and requirements for precision and efficiency. Exact methods are ideal for well-defined problems requiring maximum precision, while heuristic methods are more suitable for complex problems where flexibility and adaptability are essential. Combining both types of methods, depending on the context, can provide the best solutions for optimizing production planning.

Objective Function Solution Process Using the Guinet Method: The solution process for the objective function formulated through the Guinet method included implementing four distinct approaches. Each approach was selected based on its ability to address the problem's complexity and deliver optimal results within the imposed constraints.

- The first approach was Linear Programming, implemented via CPLEX OPL, a traditional yet efficient method for optimization problems, though it has limitations in contexts with multiple constraints in the objective function.
- The second approach, Constraint Programming, also implemented through CPLEX OPL, provided increased flexibility in modeling problems and allowed easier integration of complex constraints. The adapted Guinet model, resolved using the CP method, which included the objective function along with its constraints and conditions, and effectively ordered production activities, resolved the bottlenecks presented in Table 3.1 of the study.

Next, Genetic Algorithms (GA) were evaluated, implemented in Matlab. Known for their ability to efficiently explore the search space and find near-optimal solutions in complex problems, GAs face challenges in quickly converging to optimal solutions within a restricted time frame. Finally, a hybrid approach between Genetic Algorithms and Particle Swarm Optimization (PSO), also implemented in Matlab, was tested to assess the potential of this combination to enhance both exploration and exploitation of the solution space, maximizing the chances of finding the optimal solution within the set limits.

Each of these approaches was rigorously evaluated based on its ability to meet imposed constraints and minimize production time within established limits. These analyses highlighted that the choice of optimal method depends on the problem's specifics and each method's capacity to integrate and resolve the complex constraints of the production process. This underlines the need for a flexible and adaptable approach in production optimization, especially in dynamic and competitive industries.

CONCLUSIONS, CONTRIBUTIONS, LIMITATIONS, AND FUTURE RESEARCH DIRECTIONS

In a constantly changing industrial world with increasing competitiveness, optimizing batch production processes becomes essential. Artificial Intelligence (AI) provides a powerful set of tools and techniques to tackle the complex and varied challenges in this field. This paper explored various optimization approaches and algorithms, highlighting how they can be applied to enhance the efficiency and productivity of industrial processes.

Production scheduling is one of the most complex functions in managing production processes. The choice of technology and technological routing, along with defining the manufacturing process, is crucial for achieving production goals. These decisions depend on the characteristics of the workpiece, such as shape, dimensions, material, tolerances, and functionality. By using AI, these variables can be analyzed and optimized efficiently, contributing to an overall improvement in the production process.

The objective function optimizes a system's performance by minimizing a combination of maximum cost and weighted time, reflecting René Guinet's innovative approaches in operations research. Guinet played an essential role in developing these mathematical models, profoundly influencing optimization methods and efficient resource management, thereby advancing industry through advanced production planning and control techniques.

In the context of batch production, the objective function may include minimizing costs, maximizing resource utilization efficiency, or reducing production time. The choice of an objective function and an appropriate optimization method is crucial for achieving the best results.

Genetic algorithms (GA), inspired by natural processes of evolution and selection, are an example of a heuristic optimization technique that can be successfully applied in batch production. GA starts with a population of possible solutions, each representing a potential solution to the problem. Solutions are evaluated based on an objective function, and the best solutions are selected to generate new solutions through crossover and mutation processes. This method allows for exploring a vast solution space and finding efficient configurations for production lines.

Particle swarm optimization (PSO) is another effective heuristic technique. Inspired by the social behavior of bird flocks or fish schools, PSO involves moving particles in the solution space, guided by their own experience and that of their neighbors. This allows for rapid convergence to optimal solutions, especially useful in problems where production process dynamics are complex and variable.

The combination of these two methods, hybrid algorithms (GA + PSO), offers significant benefits. By combining the genetic diversity provided by GA with PSO's rapid convergence, hybrid algorithms can improve both the speed and quality of final solutions. For example, in assembly line optimization, GA can generate various initial configurations, and PSO can refine these configurations to account for dynamic factors such as product demand or equipment availability. This combined approach enables the rapid discovery of efficient and adaptable solutions.

Exact methods, such as Mixed-Integer Linear Programming (MILP) used in CPLEX/OPL, are fundamental for well-defined and linearizable problems. MILP involves formulating an objective function and a set of constraints, solved to find the optimal values for decision variables. In batch production, MILP is vital for resource optimization and cost minimization, ensuring precise and efficient solutions. In this case, given the complexity of the three-dimensional matrix underlying the objective function, the running times were too long to continue executing the algorithm.

On the other hand, Constraint Programming (CP), another exact method, is ideal for complex combinatorial problems, such as planning and resource allocation. CP uses a set of variables, domains, and constraints to model the problem, systematically exploring the space of possible solutions. In batch production, CP can optimize scheduling and task sequencing, ensuring feasible solutions that meet all requirements.

In conclusion, optimization techniques and algorithms, whether exact or heuristic, play a crucial role in enhancing the efficiency and productivity of batch production processes. Exact methods offer precise and reliable solutions for well-defined problems, while heuristic methods offer flexibility and adaptability in addressing complex and dynamic problems. Integrating these techniques into production planning and scheduling strategies is essential for maintaining competitiveness and operational performance in modern industry.

The detailed analysis of the four methods for solving the production scheduling problem provided valuable insights into the efficiency and applicability of each in the specific context of this problem. Each method was evaluated based on its ability to meet time constraints and deliver an optimal solution within a reasonable timeframe.

The results obtained varied considerably between methods. CPLEX OPL, using Mixed-Integer Linear Programming, failed to provide a solution within a reasonable time, suggesting that the problem's complexity exceeds this model's capacity to find an optimal solution within a practical computation time. In contrast, using Constraint Programming in CPLEX OPL produced much more favorable results, meeting the six-week deadline and providing an optimal solution within the specified terms.

The methods implemented in Matlab also highlighted notable differences. Although Genetic Algorithms ran efficiently, they failed to meet the imposed time constraints, indicating a need for further exploration of algorithmic parameters or a potential combination with other methods to improve performance.

In the conducted experiments, it was observed that hybrid algorithms (GA+PSO) demonstrated a limited ability to meet the strict conditions regarding the time required for product delivery. Out of a total of sixty runs performed, only in 3 cases did the hybrid algorithms succeed in generating viable solutions within the established time limits. These solutions resulted in production cycles of 352 hours, 446 hours, and 480 hours, respectively, thus highlighting an inconsistency in the algorithm's performance.

It is important to note that, although these results align with the established objectives, the low frequency of success suggests the need for further optimization of the hybrid algorithm parameters. This finding underscores the importance of a continuous research approach to improve the consistency and reliability of the algorithms so that they can consistently provide efficient solutions within production requirements. The results indicate promising potential for the hybrid method but also the need for a more in-depth analysis to understand the factors contributing to performance variability.

Therefore, these observations highlight the importance of selecting the optimization method based on the specific characteristics of the problem. They also suggest that in situations where time constraints are critical, advanced constraint-based optimization techniques may offer more efficient solutions than traditional linear models. Additionally, the results suggest the need for fine-tuning the algorithmic parameters and possibly a reevaluation of the problem model to improve the success rate in using optimization methods.

In conclusion, this study emphasizes the importance of choosing the optimization method according to the specific nature of the problem and imposed constraints. Traditional methods, such as Linear Programming, can become inefficient when facing complex problems with multiple constraints, whereas advanced approaches, such as Constraint Programming, offer viable alternatives but require careful parameter settings to achieve optimal results.

Hybrid approaches, such as combining Genetic Algorithms with PSO, present significant potential in optimizing complex problems by balancing exploration and exploitation. However, the success of these methods is limited and inconsistent and largely depends on how they are integrated and their ability to adapt to the problem's specifics.

Own Contributions. One of the most important contributions of the thesis lies in the integration and comparative analysis of exact and heuristic methodologies in production scheduling. The study offers a valuable perspective on how these two approaches, each with its advantages and limitations, can be used to optimize production in various industrial contexts. By using genetic and hybrid algorithms, the effectiveness of these methods in reducing processing times and optimizing resources was demonstrated, while also providing a flexible framework adaptable to the specific needs of each industry.

Another remarkable contribution of the thesis is the development of a detailed analytical framework for applying the Guinet model. It was demonstrated how this model can bring significant improvements in reducing production cycles, offering clear and applicable solutions for companies seeking to optimize processes through advanced technologies such as AI algorithms. This contribution supports not only the efficiency of production processes but also their adaptability to various industries.

A third noteworthy contribution is the development of a method for solving the Guinet model through CPLEX OPL Constraint Programming, which provided minimization of the objective function, a detailed solution for order scheduling, and achieved the shortest running time.

A. Theoretical Contributions

1. **Integration of Exact and Heuristic Methodologies:** The thesis explores how exact and heuristic methodologies can be integrated for production optimization. Through a comparative analysis, it demonstrates the advantages of each approach, such as reducing processing times and optimizing resources. Genetic and hybrid algorithms prove effective in this context, providing a flexible and adaptable framework for various industries. This integration allows companies to use tailored methods for their specific needs, ensuring more efficient and competitive production in today’s industrial environment.
2. **Development of an Analytical Framework for the Guinet Model:** The thesis offers a detailed analytical framework for applying the Guinet model in production optimization. It demonstrates that the model brings significant improvements in reducing production cycles, offering clear solutions for companies aiming to enhance process efficiency. By using advanced technologies, such as artificial intelligence algorithms, this model supports not only production efficiency but also adaptability across different industries, contributing to a modern and competitive operational framework.

3. **Comparison of Exact and Heuristic Methods:** The thesis provides a comparative analysis of exact and heuristic methods, highlighting the advantages and disadvantages of each in production optimization. Algorithms like CPLEX/OPL Constraint Programming and the Hybrid Genetic Algorithm (GA + PSO) are used to demonstrate the flexibility and efficiency of these methods in various industrial contexts. This comparison underscores the importance of choosing the appropriate methodology to achieve optimal production scheduling results and improve operational efficiency.
4. **Integrated Approach to Theoretical and Applied Research:** The work is distinguished by its integrated approach to theoretical and applied research, contributing to the advancement of knowledge in production optimization. Validating the utility of AI algorithms in the industrial sector is based on a balance between theory and practice. This holistic approach provides a solid framework for researchers and practitioners in understanding and applying AI in production.
5. **Analysis of Trends and Challenges in AI Adoption:** The thesis analyzes the main trends and challenges that companies face in adopting AI technologies. This analysis offers a valuable guide for managers and decision-makers, facilitating a better understanding of the complexities involved in implementing AI in operational and strategic processes. By addressing these challenges, companies can remain competitive in the global market, better understanding how to combine human and technological resources to maximize efficiency and improve production processes.
6. **Modeling of Batch Production Scheduling:** Chapter 3 represents the central contribution of the thesis, focusing on the modeling of batch production scheduling through artificial intelligence algorithms. Through a detailed analysis, practical solutions for batch production optimization are offered. Aspects such as reducing wait times and improving production flows are addressed, demonstrating how AI can contribute to more efficient operations in the industrial environment, providing a solid foundation for implementing these technologies in companies.
7. **Use of Genetic and Hybrid Algorithms:** The thesis explores the use of genetic and hybrid algorithms for production optimization. These algorithms have proven efficient in reducing processing times and optimizing resources, offering a flexible framework that can adapt to the specific needs of each industry. This allows companies to optimize processes, reduce costs, and improve operational efficiency, thus contributing to increased competitiveness in today's industrial environment.
8. **Adaptability to Various Industries:** The thesis emphasizes the adaptability of AI algorithms and the Guinet model to various industries. By offering a flexible and customizable framework, companies can implement these technologies according to their specific needs, ensuring efficient production process optimization. This allows companies to adapt more quickly to changes in the business environment and remain competitive in a dynamic market.
9. **Applied Research Methodology:** The thesis presents a rigorous methodology for analyzing the application of AI in batch production scheduling. Through guided interviews with industry experts, a deep understanding was gained of how these technologies can be integrated into local industries. This methodological approach highlighted the link between theoretical research and practical applications, providing a solid foundation for implementing AI in production processes.

10. **Guide for Managers and Decision-Makers:** The thesis offers a valuable guide for managers and decision-makers in implementing AI technologies in production. By highlighting challenges, benefits, and practical solutions, the work facilitates an understanding of the complexity and opportunities associated with AI in operational processes. This helps companies make informed decisions to remain competitive and improve operational efficiency and flexibility.

B. Practical Contributions

1. **Solving the Guinet Model with CPLEX OPL:** The thesis presents a method for solving the Guinet model using CPLEX OPL Constraint Programming. This approach allowed for minimizing the objective function value and optimizing order scheduling, achieving the shortest runtime. This is a major contribution to the production field, demonstrating how advanced programming tools can solve complex problems, enabling companies to optimize the production process, reduce costs, and improve operational efficiency.
2. **Validation of AI Algorithms in Industrial Production:** The case study on ABC Company validates the effectiveness of artificial intelligence algorithms in Romanian industrial production. This validation goes beyond theory, demonstrating the practical application of these technologies and highlighting their benefits in today's industrial context. Through guided interviews and practical applications, it offers relevant insights for companies planning to implement AI technologies, contributing to increased competitiveness and improved operational processes.
3. **Practical Solutions for AI Implementation:** Beyond academic contributions, the thesis offers practical solutions for implementing AI in production management. These solutions are applicable and adaptable for various types of companies, allowing for process optimization, cost reduction, and improved operational flexibility. Thus, the work serves as a useful guide for both researchers and practitioners, demonstrating how AI technologies can be effectively integrated into production processes to achieve significant competitive advantages.
4. **Case Study: ABC Company:** The case study of ABC Company provides a practical example of implementing exact methods in batch production. Through guided interviews and production data analysis, the research demonstrates the applicability of AI algorithms in production processes. It highlights how these technologies can be adapted and applied in a company's specific context, offering valuable insights for other organizations aiming to improve production efficiency.
5. **Integration of Advanced Technologies:** The thesis examines the integration of advanced technologies into operational processes, emphasizing both the advantages and challenges encountered in adopting these innovative solutions. This analysis provides a valuable guide for managers, helping them understand the risks and opportunities associated with using AI in production. By adopting these technologies, companies can improve operational efficiency and flexibility, becoming more competitive in the global market.
6. **Reducing Wait Times:** By applying the Guinet model, the thesis demonstrates how companies can reduce wait times in production. The model offers advanced solutions for optimizing production cycles, allowing companies to improve production flows and use resources more efficiently. This contributes to increased operational efficiency, cost reduction, and improved competitiveness in the global market.

7. **Cost Reduction through AI:** The thesis demonstrates how AI algorithms can contribute to cost reduction in production. By optimizing processes and improving resource utilization, companies can reduce operational expenses and increase profitability. This approach offers a significant competitive advantage, allowing companies to adapt their production strategies to better meet market demands and improve operational efficiency.
8. **Minimizing the Objective Function Value:** Through the use of CPLEX OPL Constraint Programming, the thesis successfully minimizes the objective function value in the context of order scheduling. This minimization is essential for improving production process efficiency, allowing companies to optimize production scheduling, reduce wait times, and improve workflow. This leads to more efficient production and better utilization of available resources.
9. **Operational Flexibility:** By implementing AI technologies, companies can increase operational flexibility. This allows for quick adjustments in production processes based on market demands and changes in the business environment. The work demonstrates how companies can use these technologies to enhance their responsiveness to customer requirements, optimizing production and maximizing efficiency.
10. **Production Process Efficiency:** The thesis contributes to improving the efficiency of production processes by solving the Guinet model in CPLEX. By reducing wait times, optimizing production flows, and efficiently utilizing resources, companies can significantly enhance operational efficiency. This has a direct impact on global market competitiveness, allowing companies to deliver products more quickly and efficiently.

Thus, through the case study on ABC Company, the thesis validates the effectiveness of the adapted Guinet model in Romanian industrial production. This validation is not limited to a theoretical approach but is supported by practical applications and guided interviews, offering relevant insights for companies seeking to implement cutting-edge technologies.

The research highlights the main trends and challenges companies face in adopting AI technologies. This analysis provides a valuable guide for managers and decision-makers, facilitating an understanding of the complexities involved in implementing AI within operational and strategic processes to remain competitive in the global market.

In addition to enriching the specialized literature, the thesis offers practical solutions for implementing AI in production management. These solutions are applicable and adaptable, enabling companies to optimize processes and improve operational efficiency and flexibility. Thus, the thesis becomes a useful guide for both researchers and practitioners.

Future Research Directions

In the current context, where market demands are continuously changing and production process efficiency and optimization are becoming critical priorities, further research is needed on optimizing parameters for production scheduling algorithms. We recommend continuing investigations in adjusting and optimizing the parameters governing the behavior of Genetic Algorithms (GA) and advanced hybrid methods, such as the combination of Genetic Algorithms and Particle Swarm Optimization (PSO).

Regarding Parameter Optimization in Genetic Algorithms (GA):

One of the essential aspects influencing the performance of Genetic Algorithms is the correct choice of basic parameters, such as population size, crossover rate, and mutation rate.

- **Population Size:** This parameter determines the total number of potential solutions (chromosomes) evaluated at each iteration. A larger population may lead to more efficient exploration of the search space, reducing the risk of getting stuck in local optima. However, a larger population also requires additional computational resources and can increase algorithm runtime. Future research should focus on identifying an optimal population size that maximizes algorithm performance without excessively increasing computational demands.
- **Crossover Rate:** The crossover rate, which controls how often pairs of chromosomes are combined to generate new solutions, plays a crucial role in maintaining population diversity. A high crossover rate can disrupt good solution structures, while a low rate can lead to premature convergence. Future research directions should explore how dynamically varying the crossover rate based on the algorithm stage could improve its efficiency and effectiveness.
- **Mutation Rate:** Mutation introduces additional variation in the population, allowing the algorithm to explore new areas of the solution space. Similar to the crossover rate, the mutation rate must be carefully adjusted. A high mutation rate can turn the algorithm into a random process, while a low rate can limit the algorithm's ability to avoid local optima. Research should focus on developing adaptive mutation schemes that adjust the rate according to the dynamics of the evolutionary process.

Regarding Parameter Optimization in Hybrid Algorithms (GA + PSO):

For hybrid algorithms that combine Genetic Algorithms with Particle Swarm Optimization, other key parameters require adjustment and optimization.

- **Swarm Size:** Similar to population size in GA, swarm size in PSO influences the balance between exploration and exploitation. A larger swarm may provide a more thorough exploration of the solution space but also increases computational complexity. Future research should analyze the impact of swarm size on overall hybrid algorithm performance and identify optimal sizes for different types of production problems.
- **Inertia Factor (w):** The inertia factor controls the influence of particles' previous velocity on their current speed. A high inertia factor favors exploration, while a low factor favors exploitation. Future studies should investigate the use of a variable inertia factor that gradually decreases as the algorithm approaches convergence to ensure an optimal balance between exploration and exploitation.
- **Cognitive and Social Coefficients (c1 and c2):** These coefficients determine how much particles are attracted to their previous successful positions and the swarm's global success position. Research should focus on optimizing these coefficients to maximize hybrid algorithm performance. For example, dynamically adjusting the cognitive and social coefficients based on the search process's progress could be investigated.
- **Particle Velocity:** Controlling velocity is essential to avoid particles overshooting areas of interest in the search space. Limiting particle speed, known as velocity clamping, can improve algorithm stability and efficiency. Future research should explore the impact of different velocity clamping strategies on hybrid algorithm performance.

Influence of Constraints on Algorithm Performance

Another critical aspect that requires special attention is how constraints imposed on production problems influence algorithm performance. A detailed analysis is needed of how various types of constraints (time, resources, quality, etc.) affect algorithms' ability to find optimal solutions. This may involve developing more robust optimization models that can adapt to various production scenarios.

Additionally, it could be beneficial to explore other advanced optimization techniques, such as evolutionary algorithms or other metaheuristic methods. These methods have shown promising results in other fields and may offer innovative and efficient solutions for complex production scheduling problems.

Importance of an Iterative Testing and Adjustment Process

Finally, it is essential that any optimization method used is supported by an iterative process of testing and adjustment. This process allows for the continuous refinement of the model and performance improvement in line with established objectives. An iterative approach ensures that algorithms can be adjusted based on obtained results, enabling the development of optimized solutions that can effectively meet market demands and ensure the organization's long-term success. In this regard, close collaboration between researchers and practitioners will play a crucial role in achieving significant advancements in production scheduling optimization.

Research Limitations

In this research, several limitations were identified that influenced both the process of obtaining results and their quality. These limitations are essential for a comprehensive understanding of the context in which the experiments were conducted and for an accurate interpretation of the obtained results. They also provide a clear direction for future research, which should address these challenges to improve the performance of algorithms and the relevance of proposed solutions:

a) **Size of the Three-Dimensional Matrix:** The first major limitation of the research was imposed by the considerable size of the three-dimensional matrix used in the objective function implementation. This matrix is essential for complex modeling of the search space and ensuring that all constraints are considered in the optimization process. However, its large size led to an excessively long runtime to find a viable solution through CPLEX OPL Mixed Integer Linear Programming.

Specifically, the computational complexity associated with this matrix required significant computing resources, making the execution time impractical for real-world applications. This is particularly problematic in an industrial environment where speed and efficiency are critical. This limitation thus highlighted the need for more efficient methods to reduce the problem's size, either by simplifying the mathematical model or by implementing advanced parallel computing techniques or distributing tasks across multiple computational resources. Addressing these aspects could lead to a significant improvement in response time and, consequently, better applicability of the solution in real contexts.

b) **Variability of Results in Genetic Algorithms (GA):** The second significant limitation was observed in using GAs. Although these algorithms are known for their ability to efficiently explore large and complex search spaces, the results obtained showed considerable variability from one run to another. This variability is problematic because it reduces the predictability and reliability of the obtained solutions, making it difficult to stay within the time frame set for product delivery.

Moreover, GAs did not consistently meet the imposed time constraints, which raises questions about the accuracy and relevance of the output data. This aspect indicates a possible need to adjust algorithmic parameters, such as population size, mutation rate, or crossover rate, to improve algorithm performance. It may also be necessary to integrate additional optimization methods or hybridize GAs with other techniques to stabilize results and ensure compliance with time requirements. This limitation also highlights the importance of proper calibration of the algorithm based on the specific optimization problem being addressed.

c) **Inconsistency of Results in Hybrid Algorithms:** Although the use of hybrid algorithms, combining Genetic Algorithms with Particle Swarm Optimization (PSO), showed promising potential in tackling complex problems, the results were, unfortunately, inconsistent. In the experiments, only three out of sixty runs succeeded in providing solutions that met the time frame requirement for product delivery. This highlights another level of variability, raising questions about the robustness and reliability of these methods.

The inconsistency of results depending on the run suggests that hybrid algorithms are sensitive to initial parameter settings, such as swarm size, inertia factor, and cognitive and social coefficients. This implies a need for further research to better understand the dynamics of these algorithms and to develop strategies for automatic parameter adjustment during runtime, based on observed performance. Additionally, the accuracy of the output data from hybrid algorithms was considered unsatisfactory in some cases, indicating the need for refinement in the solution evaluation method.

This limitation also underscores the need for more advanced testing and validation methods for hybrid algorithms to ensure that results are consistent and reliable, regardless of minor variations in initial conditions. Possible solutions could include implementing feedback mechanisms that allow the algorithm to learn from its past performance and adjust its behavior accordingly.

In conclusion, the limitations identified in this research provide an important starting point for future research directions. The need to optimize algorithm performance through parameter adjustment and the implementation of more robust and efficient methods is evident. Addressing these challenges will contribute not only to improving existing algorithms but also to the development of new optimization techniques capable of meeting the complex and varied requirements of modern production.