Transilvania
University
of Brașov

INTERDISCIPLINARY DOCTORAL SCHOOL
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# COMPUTATIONAL METHODS FOR CHESS

## SUMMARY

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Brașov, 2025

# Acknowledgements

First and foremost, I would like to express my gratitude to my supervisor, Prof. Dr. Marius-Sabin Tăbîrcă, for the guidance and support offered throughout my doctoral studies. I am also grateful to the members of the advisory committee, Prof. Dr. Dorin Bocu, Assoc. Prof. Dr. Lucian Sasu and Prof. Dr. Eleonor Ciurea, whose valuable suggestions and availability for discussions contributed to the development of the research topic.

Furthermore, I wish to express my appreciation to the members of the review committee, who will dedicate their time to reading this summary of the thesis.

Last but not least, I am grateful to my family for their understanding, unconditional support and patience during these years. Their moral support has been my main motivation and source of balance in completing this academic journey.

# Research Motivation

In recent decades, computer-based strategic games have contributed to a deeper understanding of how both humans and computers make decisions under conditions of uncertainty. They have represented a fertile ground for the development of computational methods and software applications. Moreover, strategic games and advances in computational methods have exhibited a relationship of mutual influence ([26], [53]). In this context, chess has become a classical example of a domain in which decision-making complexity continuously interacts with computational methods. Why uncertainty in the case of chess? Although chess is a game of perfect information, in which both players have access to the same board configuration and the same information throughout the entire game, the number of possible moves is estimated to exceed $10^{120}$ [78]. Furthermore, the possibility of repeating positions through moves that return to previous configurations creates an infinite number of options, making a complete evaluation of all possible variations infeasible. Even with substantial computational resources, such as those employed by programs developed by DeepMind [74], uncertainty remains inevitable, and determining the optimal move continues to represent an ongoing challenge.

This doctoral work was approached with equal passion for computer science and chess, seeking to highlight the reciprocal influence of technology within the field of strategic games, with a particular emphasis on chess. The evolution and diversification of computational methods applied to chess were analyzed, along with the educational value of chess, the various types of notation used in the game, and the automatic recognition of pieces on the chessboard.

Over the years, chess has served as a testing ground for various computational methods that were later applied in other domains [58]. The present research aims to explore the use of computational methods for the evaluation of chess diagrams and their automatic composition.

A composed chess diagram is considered valuable if it possesses specific attributes that are taken into account by nearly every member of a chess jury involved in the composition and solving of chess problems. Certain computational approaches have been attempted in the past; however, they did not lead to practical results suitable for inclusion in the daily judging of chess diagrams ([82], [20]).

The ultimate goal of this thesis is to develop a system capable of automatically composing chess diagrams, which will also be used to evaluate and optimize the generated diagrams. Subsequently, a chess book containing the most remarkable automatically generated diagrams, together with their solutions, could be published.

# Personal Contributions

Within the doctoral work to which this summary refers, particular attention was devoted to the automatic composition of chess diagrams, with a specific focus on two-move checkmate problems. Based on the system developed for generating chess diagrams, the subsequent step of the research consisted in exploring the possibility of automatically evaluating such diagrams. Metrics were defined in order to determine the degree of beauty of an already composed or automatically generated diagram. A valuable chess problem is one that possesses multiple qualities, such as, for example, material economy or a subtle key move for the verification of the mentioned criteria). Another criterion for diagrams in which White moves and delivers checkmate in n moves is related to the defensive variations and does not consist solely in the number of defensive responses available to Black, but also in the uniqueness of White's mate against each of these defenses. These criteria make the diagram more highly appreciated by jury members, as well as by solvers. Furthermore, it is desirable for a diagram to contain a theme or an element that creates a distinctive artistic impression. For instance, if the apparent play[1] includes the moves a–b and each of these moves leads to the mate c–d, and in the solution there exists a key move X that changes the order of Black's defenses and leads to the mate d–c, a pleasing artistic impression is thus created.

The idea of automatically composing chess diagrams remains largely unexplored. A recent example is the article [50], in which so-called "puzzle" positions[2] are generated using genetic algorithms and the Stockfish engine. The generated positions cannot be regarded as compositions, since they fail to satisfy, among other criteria, legal constraints related to the pieces, such as the maximum number of pawns per color. In the model proposed in what follows, these constraints are implicitly enforced already at the diagram composition interface, which guarantees the structural validity of each position. Moreover, the approach described in [50] does not implement evaluation criteria for diagrams and does not pursue aesthetic or thematic optimization, as Stockfish is used solely to verify the existence of a checkmate within a specified number of moves.

A methodology for the composition and evaluation of chess diagrams based on a list of criteria was proposed, and a system for optimizing the generated diagrams was developed. The proposed methodology may have multiple practical applications, such as judging chess composition competitions, selecting diagrams for publication, or developing databases (which may lead to the publication of books) containing automatically generated chess diagrams, classified and evaluated according to multiple criteria.

The ideas presented in this work were disseminated at several CORE-listed and indexed conferences, such as the International Conference on Information and Software Technologies (ICIST) and the Advanced Information Networking and Applications Conference (AINA, CORE B listed). In addition, several articles were published in journals indexed by Web of Science (WOS), including one single-author publication [21].

[1]Apparent play refers to what would occur on the board if Black were to move in the initial position of the composition, although in reality the move belongs to White. It is frequently used to highlight thematic ideas, such as White's responses to various Black moves, and serves as a contrast or prefiguration of the actual play that follows after the key move of the problem.

[2]The term "puzzle" in the context of chess refers to positions similar to those arising in practical chess games, analyzed with the purpose of tactical solving, often containing many superfluous pieces, as opposed to chess diagrams that must comply with strict rules and aesthetic criteria in order to be considered artistic compositions.

**Papers published in journals with impact factor**

1) Publication as sole author of an ISI-indexed article:
"The Impact of Artificial Intelligence on the Chess World"[21]
Author: DM Duca Iliescu
Journal: JMIR Serious Games – Impact factor 3.8
WOS No.: 000632268800010
https://www.webofscience.com/wos/woscc/full-record/WOS:000632268800010
https://www.doi.org/10.2196/24049

2) Co-author of an ISI-indexed article:
"Personal Health Metrics Data Management Using Symmetric 5G Data Channels"[13]
Authors: R Bocu, A Vasilescu, DM Duca Iliescu
Journal: Symmetry-Basel, Impact factor 2.2
WOS No.: 000831607000001
https://www.webofscience.com/wos/woscc/full-record/WOS:000831607000001
https://www.doi.org/10.3390/sym14071387

**Papers presented at indexed conferences**

1) Paper presented at the Scopus-listed Conference "International Conference on Information and Software Technologies" (ICIST) 2024, with the paper subsequently published by Springer: "Efficient Didactic Methods Used in Modern E-Learning and Traditional Environments"
Authors: Constantin Lucian Aldea, Razvan Bocu, Delia Monica Duca Iliescu, Anca Vasilescu
https://www.webofscience.com/wos/woscc/full-record/WOS:001481366300022
https://www.doi.org/10.1007/978-3-031-84263-4_22
Springer link: https://link.springer.com/chapter/10.1007/978-3-031-84263-4_22 [5].

2) Paper presented at the Core-listed Conference (category B) "Advanced Information Networking and Applications Conference" (AINA), 2024 – with the paper subsequently published by Springer: "Health Parameters Monitoring Through an Integrated Multilayer Digital Twin Architecture"
Authors: Constantin Lucian Aldea, Razvan Bocu, Delia Monica Duca Iliescu
Proceedings of the 38th International Conference on Advanced Information Networking and Applications (AINA-2024), Volume 1
https://www.webofscience.com/wos/woscc/full-record/WOS:001264727500027
https://www.doi.org/10.1007/978-3-031-57840-3_27
Springer link: https://link.springer.com/chapter/10.1007/978-3-031-57840-3_27

3) Paper presented at the Scopus-listed Conference "Elearning and Software for Education" (eLSE) 2023 with the paper "Applied Research Concerning the Aspects and Methods Used in Modern Learning Environments"
Authors: Constantin Lucian Aldea, Razvan Bocu, Delia Monica Duca Iliescu, Anca Vasilescu
https://www.scopus.com/pages/publications/85219122571

4) Invited speaker at the Core-listed Conference (category C) "Conference on Games" (CoG), 2022 – with the paper: "The Impact of Artificial Intelligence on the Chess World"
Author: Delia Monica Duca Iliescu
Conference program: https://ieee-cog.org/2022/ProgramOfCoG2022-Formal.pdf (pp.37)

**Accepted paper**

1) Constantin Lucian Aldea, Razvan Bocu, Delia Monica Duca Iliescu. “On the analysis and prediction of chess diagram scores using artificial neural networks”. In: The 40-th International Conference on Advanced Information Networking and Applications 2026 – Section Intelligent Computing and Machine Learning (AINA, 2026). https://voyager.ce.fit.ac.jp/conf/aina/2026/program [4]

**Other conference and workshop participations**

1) Invited speaker at the TEDx "Simplicity. Less is More" Conference, Braşov, 2025
https://youtu.be/TtY0AISJDLI

2) Poster presentation “Magne 2D Chess Scan” at the “AFCO” Conference organized by Transilvania University of Braşov, 2022
https://afco.unitbv.ro/2022/images/Documente/Lucrarile_AFCO_2022.pdf

3) Invited speaker at the “Artificial Intelligence meets Big Data” Conference, London, 2021
https://chessconference.org/sunday-6th-dec/

4) Invited speaker at the “London Chess Conference” – joint session with the authors of the AlphaZero algorithm and presentation of the individual chess study board in 2D format, London, 2020
https://youtu.be/wvgSqN6M9L8

5) Workshop attendance at “Machine Learning and Applications Summer School” (MLASS), Braşov, 2019
https://www.unitbv.ro/cercetare/evenimente/3148-mlass-2019.html

6) Invited speaker at the BookLand Evolution Conferences, Braşov, 2019
https://youtu.be/AXrBIFmmy2M

7) Presentation at the “MACOS” Conference (organized by Transilvania University of Braşov) with the paper “Search Optimization in Chess”, Braşov, 2018
https://mateinfo.unitbv.ro/en/macos/macos-2018.html

# Thesis Structure

The structure of the doctoral thesis referred to in this summary is as follows:

**Chapter 1 - Introduction**
The introductory chapter presents the motivations underlying the initiation of this research, together with an overview of the published articles and participation in relevant conferences and workshops. Furthermore, the main personal contributions of this work are briefly highlighted, as well as the overall structure of the thesis.

**Chapter 2 - Related research in the scientific literature**
This chapter explores relevant research from the scientific literature in the field of strategic games. In addition, existing studies on the educational value of strategic games are presented, with a particular focus on chess, highlighting their impact on cognitive development and strategic thinking skills. Studies and works addressing similar aspects or related topics are examined, emphasizing the research opportunities that are addressed in this thesis.

**Chapter 3 - The impact of computational evolution in the world of chess**
Chapter 3 analyzes the fundamental concepts underlying strategic games. In addition, the evolution and diversification of computational methods used in the context of chess are investigated, as well as possible directions for technological development in the context of strategic games. New methods for automatic recognition of the chessboard are also explored, and the conversion between different types of chess notation is analyzed using the Magne 2D App.

**Chapter 4 - Proposed directions for chess diagram generation**
Chapter 4 defines criteria for the evaluation of chess diagrams, describes the concept of automatic generation of a chess diagram book, and proposes a methodology for the automatic composition and evaluation of chess diagrams.

**Chapter 5 - Conclusions**
Chapter 5 presents a series of conclusions regarding the impact of technology on the world of chess, new directions, and the methodologies proposed in this work.

The final objective was to propose a system for the composition and evaluation of chess diagrams. Thus, the intention was to bring significant contributions to the field of chess composition. The development of a system capable of automatically generating chess diagrams and evaluating them using a set of characteristics represents an important step in the field of chess composition. The system can be used both to create new chess diagrams and to evaluate existing ones. After a chess diagram has been generated, the system uses a set of features to evaluate its aesthetic quality. The evaluation can be performed by the system in real time, providing immediate feedback on the quality of the generated chess diagram, and, ultimately, the diagram can be optimized.

# Summary of the Research on the Evaluation of Chess Diagrams Presented in the Thesis

The main objective of the research was to develop a methodology for evaluating chess diagrams based on a set of multiple “beauty” criteria, as well as to explore the possibility of automatically generating and optimizing chess compositions.

The first study presented in the thesis is that of Dobrescu [20], who proposed an evaluation model based on static criteria (material size, piece arrangement, balance of forces, initial level of tension) and dynamic criteria (an unconventional key move, its strategic impact, and aesthetic quality. Subsequently, the author introduced additional criteria such as the depth of variations and the difficulty of finding the solution, which added a new dimension to the aesthetic evaluation of chess problems.

Iqbal [49] continued research in this field by focusing on the concept of economy in chess compositions and proposing a computational function capable of distinguishing economic differences between positions. The results confirm that the evaluation of compositions can be formalized and translated into an algorithmic framework.

Building on these contributions, in Section 4.5 of the thesis I proposed a methodology designed to integrate multiple criteria: from material economy to the symmetry of defensive variations [82], adherence to established themes [85], and the uniqueness and diversity of mates. These criteria reflect both the objective dimension of evaluation (positional balance) and the aesthetic and creative dimension of compositions.

Specialized literature confirms that a composed chess problem is considered a genuine artistic creation that must meet strict requirements. Ianovcic [47] emphasizes the need to respect principles such as maximum material economy, uniqueness of the solution, subtlety of the key move, and diversity of Black’s defenses. Similarly, Toth [83] highlights the importance of including well-established compositional themes, which give identity and artistic value to a diagram.

Beyond traditional analysis, recent research also addresses the potential of artificial intelligence in relation to creativity. Grassini [38] compared the generative flexibility of ChatGPT-4 with human creativity, finding that although artificial intelligence can produce diverse and innovative interpretations, the subjectively perceived creativity of humans remains superior. Watkins [86] reinforces this observation, arguing that artificial intelligence can broaden the scope of possible ideas, but expressiveness and artistic depth remain primarily human attributes.

In conclusion, the evaluation of chess diagrams is an interdisciplinary field situated at the intersection of sport, science, and art. While practical play has already been transformed by algorithms such as AlphaZero and MuZero, artistic composition remains an area in which human intuition and creativity retain a significant advantage. Nevertheless, through the proposed methodologies and recent advances in artificial intelligence, the possibility emerges—perhaps for the first time—that computers may learn aesthetic criteria and contribute to the generation of compositions with artistic value, opening a new chapter in the history of the relationship between chess and technology.

# Summary of Research on the Educational Value of Chess presented in the thesis

The specialized literature has consistently highlighted the educational role of strategy games, whose use in teaching has become increasingly common. By integrating them into classroom activities, strategy games can support content consolidation and develop both cognitive and social skills in an attractive and responsible way [56]. Their practice fosters planning, analysis, and decision-making abilities, which are transferable to other domains. Gibson *et al.* [33] show that games can effectively support online learning, provided that their design aligns with learning objectives and is adapted to the students' skills and levels. Technology, they argue, should enhance the learning process but not become an end in itself.

Recent studies confirm the potential of modern games in supporting mathematics education and other subjects. Kebritchi *et al.* [51] demonstrated significant improvements in students' mathematical performance and motivation through the use of educational games, findings that are also supported by [5]. With regard to chess, research emphasizes its extensive academic literature, being noted that more books have been written about chess than about any other game [23], a claim historically supported by Murray [62].

Ferguson [27] synthesized studies showing that chess enhances critical thinking, spatial reasoning, problem-solving, and mathematical skills, while Reyes-Joa *et al.* [68] confirm its role in developing both cognitive skills (strategic thinking, memory, problem-solving) and social ones (rule compliance, collaboration, tolerance to failure). Similarly, Garate-Quispe *et al.* [32] found significant gains in abstract reasoning and school motivation after chess training programs.

Research also compares chess with other types of games. Anderson *et al.* [7] indicate that violent games can increase aggression and reduce empathy, while chess, as a strategic and non-violent game, supports positive educational outcomes. Krebs [76] highlights the potential of serious games to promote ethical decision-making, whereas Trinchero *et al.* [84] and Gliga *et al.* [34] demonstrate that chess enhances abstract reasoning, critical thinking, attention, and school performance.

Nonetheless, some research stresses methodological limitations. Gobet *et al.* [36] and Sala *et al.* [72] argue that findings are sometimes inconclusive or dependent on sample size and study design. Schultetus *et al.* [77] underline the role of memory and position recognition, suggesting that chess expertise cannot be explained solely by calculating optimal moves. The question of knowledge transfer remains open. Franklin [28], also discussed in [48], argued that chess has formative value beyond entertainment, but more recent studies caution that benefits may be limited to the game itself, requiring further research to assess long-term effects across different domains.

In conclusion, most studies confirm the positive effects of chess on cognitive and social development, even though more rigorous research is needed to evaluate the consistency and transferability of these outcomes. In particular, abstract reasoning, memory, and attention have been consistently improved, confirming the educational value of chess and reinforcing its position as a valuable tool for education and cognitive development.

# Summary of Research Related to the Security of Strategic Games in the Online Context presented in the thesis

The COVID-19 pandemic had a significant impact on online strategic games, driving their rapid rise in popularity and bringing new concerns regarding data security and digital well-being. In [13], technological solutions are presented showing how 5G networks can enhance player experience while ensuring the protection of personal information. At the same time, Han *et al.* [42] demonstrated that social isolation, anxiety, and intensive use of digital devices have contributed to increased gaming addiction among children and adolescents, emphasizing that prevention efforts should focus on improving social and emotional life, reducing isolation, and promoting a balanced lifestyle.

In this context, the programming of strategic games could include mechanisms such as monitoring playing time, issuing warnings when the duration becomes excessive, mandatory breaks, bonuses for time spent away from the game, and even educational or social mini-games.

A relevant example is chess, whose popularity increased significantly during the pandemic [21]. The transition of competitions to the online environment allowed a much larger global participation but also brought new challenges, such as the risk of players using computer programs to enhance their performance at the expense of fair play. The online experience differs from face-to-face play, affecting skill development, but it enabled the continuation of national and international tournaments despite the cancellation of traditional events. In parallel, strategic games were incorporated into education, fostering critical thinking and social skills [51].

The massive increase in online gaming also amplified vulnerabilities in data protection. According to [13], 5G technology can enable secure collection and management of player data, but Zhao [89] highlights that cybersecurity issues such as attacks and fraud remain frequent, noting that more than 50 countries have already published official strategies in this regard ([89], [55]). Cybersecurity, once primarily associated with protecting critical infrastructures, now extends to the domain of strategic games, where it concerns not only the confidentiality of data but also the fairness of competitions [69].

Fair-play has become a central challenge in online chess. Numerous disqualification cases have demonstrated the need for advanced technological solutions, including artificial intelligence and analytical algorithms capable of distinguishing human-like moves from those generated by external programs ([75], [21], [8]). Although FIDE has issued anti-cheating guidelines, the online environment remains difficult to regulate. Platforms such as Chess.com and Chess24 employ statistical models and machine-learning algorithms to detect improbable moves and protect the integrity of competitions.

Within this framework, the concept of a digital twin [25], [3] has been proposed as an innovative solution for monitoring player behavior by creating a virtual replica and comparing it in real time with actual data. Complementary research on privacy and immersive technologies [66] further highlights both the opportunities and risks of hybrid physical–digital environments.

In conclusion, the pandemic not only accelerated the global popularity of online strategic games but also raised major challenges regarding gaming addiction, data security, and the preservation of fair play. Technologies such as 5G, artificial intelligence, and digital twin open new pathways for transforming strategic games into a domain with educational, social, and cybersecurity implications.

# Summary of the Evolution of Computational Methods used for Chess

This section examines the evolution and diversification of computational methods applied to strategic games, with a special focus on chess, where such approaches have played a central role in advancing artificial intelligence. Beyond position evaluation and the search for optimal moves, computational techniques have been extended to applications such as cheating detection – increasingly necessary in light of the rapid growth of online chess after 2020.

Theoretical foundations include concepts such as decision-making, risk analysis, and resource management. Strategic games rely on decision-tree processes [24], where each choice generates multiple possible branches. Players must evaluate costs and benefits and allocate limited resources efficiently, including time [1]. In chess, these elements are complemented by long-term planning and the use of intuition, which is particularly important under time constraints [35].

The development of search algorithms such as Minimax and Alpha-Beta Pruning marked major steps in optimizing game-tree exploration. Chess became a benchmark for artificial intelligence research as early as the mid-20th century, with a key milestone being Deep Blue's 1997 victory over world champion Garry Kasparov ([46], [21], [61]). While this achievement relied mainly on brute-force computation, subsequent progress brought a paradigm shift: in 2017, AlphaZero surpassed all existing engines after only four hours of self-learning [80], and in 2019 MuZero advanced further by reaching exceptional performance without being explicitly provided with the rules of the game ([74], [71], [79]). These breakthroughs demonstrated that chess is an ideal testbed for measuring advances in artificial intelligence [2].

Educational applications are equally significant. Strategic games can be used to reinforce knowledge through interactive exercises or mathematical testing [19], while modern platforms such as chess.com foster collaboration, teamwork, and constructive competition [5]. At the same time, scholarship highlights the educational value of chess, which disciplines thinking, improves concentration, and encourages reflection before decision-making [15]. Research by Holding [44] and Gobet [35] emphasizes how chess blends logical reasoning with intuition, making it a powerful tool for cognitive development.

In recent years, debates have also expanded toward artificial creativity. Studies show that artistic productions generated by artificial intelligence can be perceived as indistinguishable from human creations [43], raising questions about originality and authenticity [9], as well as about the redefinition of creativity in an age increasingly shaped by technological systems [60]. The concept of creativity, traditionally considered an exclusively human attribute [16], is now critically reexamined in light of the ability of artificial intelligence to generate outputs that may be perceived as original.

In conclusion, the evolution of computational methods applied to chess – from classical algorithms to advanced systems such as AlphaZero and MuZero – demonstrates the decisive role of strategic games in advancing artificial intelligence. At the same time, the educational potential and the ongoing debates about algorithmic creativity confirm chess as a privileged platform for research, innovation, and the exploration of the intersection between human reasoning and artificial computation.

# Different Types of Algorithms Tested with the Help of Strategy Games

Strategic games provide an excellent framework for testing and evaluating algorithms, allowing decision-making under uncertainty and with incomplete information. Artificial intelligence systems have achieved remarkable performance in complex games such as chess and GO ([11], [30], [31], [80], [67]).

Evolutionary algorithms, inspired by the biological metaphor of species adaptation, have proven effective in search and optimization problems where an optimal solution is not required [12]. The early contributions of Box [14], Fraser [29], and Holland [45] laid the foundation for genetic algorithms, later widely applied in artificial intelligence [22]. Although these methods do not guarantee convergence to the optimal solution, several improvements have been proposed for specific contexts [22]. High computational costs and the need for many iterations remain challenges, but technological advances are increasing their efficiency and accessibility.

Machine learning, another key branch of artificial intelligence, also benefits greatly from strategic games, which provide clear rules and objectives. Algorithms can be trained to recognize patterns and develop strategies. Three main approaches are distinguished: feature-based algorithms (with features manually extracted by experts), supervised algorithms (trained on labeled datasets, such as chess diagrams evaluated for aesthetics), and unsupervised algorithms (which discover hidden structures through clustering).

A reference example is MuZero, developed by DeepMind, which combined unsupervised learning with reinforcement learning [74]. In its initial stage, the program played millions of games against itself without labels or explicit rules, autonomously discovering strategic patterns and even original opening variations [71]. By using neural networks and self-play, MuZero achieved superhuman performance, surpassing both elite players and existing engines. These results confirm the extraordinary potential of machine learning in complex games and suggest promising applications in other fields as well [67].

In conclusion, strategic games, due to their complexity and structured nature, have become experimental laboratories for testing and refining evolutionary and machine learning algorithms, decisively contributing to the progress of artificial intelligence.

# Possible Directions of Technological Development in the Context of Strategy Games

Strategic games have proven to be a fertile ground for exploring computational methods, with applications extending beyond the gaming industry into education and research [58]. Modern techniques such as machine learning, neural networks, augmented reality (AR), and virtual reality (VR) have opened new perspectives in the educational field. Augmented reality enables the integration of digital elements into the real world, while virtual reality creates immersive environments with applications ranging from scientific explorations to historical contexts. Recent studies highlight the educational potential of these technologies; Yu *et al.* [88], through a meta-analysis of 43 studies, emphasized the positive impact of virtual reality on learning, with the exception of primary education.

In chess-related research, the use of a digital twin architecture was proposed in [3], where the MyMLTwin model integrates machine learning and deep learning algorithms. This approach allows the evaluation of chess compositions according to criteria such as originality and complexity, offering objective assessments and detailed feedback, adaptable to community standards. Thus, digital twins not only support chess but also contribute to technological progress in a reciprocal manner [21].

At the same time, the proliferation of artificial intelligence tools has sparked pedagogical and ethical debates. Some studies have raised concerns about a potential decline in critical thinking [81], while others have discussed whether such tools should be restricted in academia [37], [87]. On the other hand, generative applications such as ChatGPT can be constructively integrated into education [5]. The emergence of these systems has triggered discussions about creativity ([60], [86]), the labor market ([54], [63], [6]), and legal issues including copyright [41], [73].

Creativity, defined as the ability to generate ideas that are both novel and useful ([39], [70]), is linked to cognitive flexibility [17] and to associative theory [59], supported by computational studies [52] and brain imaging research [65]. The incursion of artificial intelligence into the arts has resulted in high-quality works [64], though critics argue these may lack authentic originality [57]. Nonetheless, recent research suggests that artificial intelligence may achieve levels of creativity comparable to human output [40].

In conclusion, computational methods and emerging technologies – from augmented reality and virtual reality to digital twins and generative artificial intelligence – have transformed the role of strategic games, including chess, into platforms for testing and innovation. They confirm the central role of these games in technological progress and open new horizons for education and creativity.

# Research Conclusions

In this thesis, it was examined the progress of computational methods in the context of strategic games and explored their implications for the future of artificial intelligence. For example, advances in computational techniques used by chess engines have paved the way for numerous improvements in artificial intelligence. Strategic games have long been a subject of interest for AI researchers. One of the main reasons is that these games offer a perfect environment for testing and improving various artificial intelligence techniques and algorithms. Strategic games have played a significant role in technological progress, particularly in the development of AI algorithms. Chess, as well as other strategy games, has been used as a benchmark for developing and testing artificial intelligence algorithms [26]. These games have helped researchers understand both the limitations and the capabilities of AI algorithms and have led to substantial advancements in machine learning, neural networks, and related fields. Computational methods have been applied to strategic games to analyze complex strategies, optimize decision-making processes, and create game-playing agents capable of defeating human experts. Chess is one of the most extensively studied strategic games in this regard.

The use of strategic games in education has also been a significant topic of interest. In [5], I proposed approaches that combine various learning techniques, including the teaching of strategic games such as chess, with the aim of analyzing and improving educational processes.

Studies have shown that practicing strategic games can offer numerous benefits for cognitive development, including improved memory, problem-solving skills, and spatial reasoning. Strategic games may also enhance social skills such as teamwork, communication, and sportsmanship. Moreover, chess has been used as a teaching tool for subjects such as mathematics and has been integrated into school and university curricula in many countries. Research on the educational benefits of chess has attracted considerable interest in recent decades. A variety of studies have examined the impact of chess on children's cognitive and educational development. Many researchers argue that chess may offer benefits for strategic thinking, decision-making, problem-solving, and the development of mathematical abilities. Chess requires anticipation, evaluation of consequences, and adaptation to change, all of which can strengthen strategic thinking. Therefore, chess has been considered a valuable tool for improving problem-solving skills, as players must identify and apply strategies to overcome obstacles during the game. Regarding decision-making, some research suggests that chess may improve the ability to evaluate options, anticipate outcomes, and make informed decisions, and that these skills may transfer to other contexts in real life, supporting effective learning and decision-making. Additionally, several studies indicate that practicing chess may contribute to the development of mathematical skills, proposing that the problem-solving abilities required in chess may transfer to mathematics, supporting the understanding of mathematical concepts and the solving of complex mathematical problems ([34], [84]).

This doctoral work sought to investigate the role of strategic games in the development and testing of artificial intelligence algorithms. Throughout the research, I showed that strategic games have been an important reference point in the development and testing of AI algorithms for several decades. Their importance within AI research was also analyzed, and the findings indicate that strategic games have played a significant role in recent advances in machine learning, deep neural networks, and related domains. Another major objective of the research was to analyze the impact of strategic games on the development of new AI algorithms and their application in various fields. The results show that strategic games can be a valuable tool in developing new artificial intelligence algorithms and in applying these algorithms across diverse areas. The analysis of the potential of strategic games as an instrument for enhancing cognitive abilities in education was also one of the objectives. It was found that strategic games can be successfully used in educational contexts to improve students' cognitive skills.

Regarding the analysis of factors that significantly influence the value of a composed chess diagram, the research focused on designing an algorithm capable of generating and evaluating chess diagrams automatically. The ability to automatically evaluate chess diagrams would represent a significant breakthrough in both gaming and artificial intelligence. As shown in Chapter 4, through precise formulations we can define and automatically verify the presence of certain "beauty" criteria in chess compositions. These definitions enabled the implementation of automatic verification algorithms for the stated criteria, including the detection of themes present in diagrams, thus facilitating the analysis and appreciation of chess problems. Furthermore, by analyzing the strategies and techniques used by the algorithm to generate diagrams and their solutions, it becomes possible to gain insights into the thought processes and decision-making strategies used by human composers ([18], [10]). This may lead to a better understanding of the fundamental principles of chess composition and contribute to the development of new techniques and strategies. Thus, the process of automatically composing chess diagrams has the potential to revolutionize the field of chess composition.

The final step will be writing a book containing the automatically composed chess diagrams and their likewise automatically generated solutions. The book will be organized beginning with diagrams containing fewer pieces and gradually increasing the level of complexity, up to more sophisticated compositions featuring diverse themes.

Due to its complex but well-defined nature, chess has proven to be a perfect environment for testing machine learning algorithms and for evaluating progress in artificial intelligence [26]. It is important to highlight that, although the results may appear similar—both Deep Blue and Google's AlphaZero managed to play chess more strongly than any human—the processes used to achieve these results were entirely different. Google DeepMind's AlphaZero learning process emulated "human-like" learning. To clarify this distinction, consider the following example: If we design a robot's software to answer a question in a particular way merely because it happens to be one of the million question-answer pairs stored in a database, this is brute force. But designing a robot's software to "learn" how to answer any question based on the conversations available on the internet—similar to the way humans learn through observation, interaction with the environment, and imitation—so that it becomes capable of formulating a response to any question, is a completely different process. Even if the outcome might be the same, such as replying "I'm fine, thank you!" to the question "How are you feeling?", the underlying mechanism is fundamentally distinct.

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