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THE ROLE OF ACCESSIBILITY ASSESSMENT AUTOMATION TOOLS IN DESIGNING A POSITIVE EAA-COMPLIANT UX

ROLA NARZĘDZI AUTOMATYZUJĄCYCH OCENĘ DOSTĘPNOŚCI W PROJEKTOWANIU POZYTYWNEGO UX ZGODNEGO Z WYMOGAMI EAA

Piotr Curyl[1]

Abstract: The article examines the digital accessibility of websites through the lens of the European Accessibility Act. From June 2025, Poland must implement the EAA directive, which introduces a range of standards taking a horizontal and global approach to digital accessibility, both in making content available to people with disabilities and in raising public awareness. The directive creates a legal obligation to apply the WCAG 2.1 AA principles, extending the WCAG 2.1 standard currently in force. The study presents a qualitative analysis of automated digital-accessibility testing tools, using the most popular Polish websites as examples, and a quantitative analysis of the workload that website authors will face when migrating to WCAG 2.1 AA. The proposed solutions and improvements offered by automation tools are evaluated against positive UX criteria. The summary also assesses the prevailing standards in terms of fostering positive user experiences in human-computer interaction and analyses the quality of the proposed automated audits, paying particular attention to their compliance with accepted norms and their impact on interaction efficiency.

Streszczenie: Artykuł skupia się na dostępności cyfrowej witryn internetowych w ujęciu Europejskiego Aktu o dostępności. Od czerwca 2025 roku Polska będzie miała obowiązek stosowania dyrektywy EAA, która wprowadza szereg standardów obejmujących horyzontalne oraz globalne podejście do dostępności cyfrowej, zwłaszcza w zakresie udostępniania treści dla osób z niepełnosprawnościami, jak i pogłębienia świadomości społeczeństwa w tym zakresie. Dyrektywa ta wprowadza obowiązek prawny w postaci stosowania zasad WCAG 2.1 AA, które są rozszerzeniem obowiązującego dzisiaj standardu WCAG 2.1. Badania znajdujące się w artykule obejmują analizę jakościową aplikacji automatyzujących analizę dostępności cyfrowej na przykładzie najpopularniejszych polskich witryn internetowych oraz analizę ilościową pod względem oczekiwanej pracy, którą autorzy stron internetowych będą musieli wykonać ze względu na przejście do nowego standardu WCAG 2.1 AA. Zaproponowane rozwiązania oraz usprawnienia oferowane przez narzędzia automatyzujące zostały zbadane pod kątem pozytywnych kryteriów UX. Podsumowanie zawiera ponadto ocenę obowiązujących standardów w kontekście kształtowania pozytywnych doświadczeń użytkownika w interakcji człowiek-komputer oraz analizę jakości proponowanych audytów automatycznych, ze szczególnym uwzględnieniem ich zgodności z przyjętymi normami i wpływu na efektywność interakcji.

Keywords: *User Experience (UX), European Accessibility Act (EAA), Web Content Accessibility Guidelines (WCAG), automation tools, human-computer interaction, digital accessibility*

Słowa kluczowe: *User Experience (UX), European Accessibility Act (EAA), Web Content Accessibility Guidelines (WCAG), narzędzia automatyzujące, interakcja człowiek-komputer, dostępność cyfrowa*

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1. Introduction

Process automation has become one of the most significant topics, with Gartner estimating global spending on such solutions to reach 5.1 trillion US dollars in 2024 – an 8% increase compared to 2023[2]. As automation tools advance and are deployed across multiple industries, they hold particular promise in improving the digital accessibility of websites. Over time, various standards for digital accessibility have emerged and are governed by local legislation; however, conducting a preliminary manual audit of a site can be time-consuming. Additionally, Poland's forthcoming EAA requirements, which are due to take effect in 2025, can introduce further complexities to website evaluations. Against this backdrop, the present article explores the role of automated tools, programmed to verify current WCAG 2.1 standards as well as the forthcoming WCAG 2.2, in assessing website accessibility, and examines the impact of software-suggested improvements on positive user experience (UX). Section 2 offers an overview of digital accessibility standards and regulations, including EAA, which will be implemented in Poland from 2025 according to decisions by the European Union, while Section 3 delves into the most influential criteria for achieving a positive user experience. Section 4 describes an experiment comparing two automated accessibility assessment applications across three popular Polish websites, further evaluating how the improvement suggestions of each tool influence the end user's experience. Finally, Section 5 provides a summary of the article and highlights key research findings.

2. Digital accessibility standards and regulations

2.1. WCAG (Web Content Accessibility Guidelines)

The revolution in digital accessibility standards began back in 1994, first mentioned by Tim Berners-Lee[3]. The initial concept, raised at the World Wide Web conference[4], only fully matured into the WCAG 1.0 standard in 1999. This first standard defined the priorities and scope of accessibility. Its main guidelines included providing text alternatives, ensuring a monochromatic version of a webpage, and enabling website use without accompanying graphics[5]. The next standard took almost a decade to arrive: WCAG 2.0 was published only in 2008. Rapid technological development rendered the standards of the previous version inadequate for contemporary needs. WCAG 2.0 introduced several major changes that remain the foundation of digital accessibility principles to this day. One such change was the introduction of "success criteria", each with a specific label. The minimum accessibility level is denoted by 'A', the law-imposed level is 'AA', and the highest accessibility level is 'AAA'. Another key innovation in WCAG 2.0 was the set of accessibility principles, based on perceivability, operability, understandability, and robustness[6].

Subsequent versions of the standard did not introduce such dramatic alterations; rather, they added additional criteria intended to support new technologies and solutions. In 2018, a new

2 M. Cooney, *Gartner: IT spending to climb 8% to $5.1 trillion in 2024*, https://www.networkworld.com/article/957418/gartner-it-spending-to-climb-8-to-51-trillion-in-2024.html (on-line 8.05.2025).

3 J. Hoffmann, *Putting Web Accessibility First*, https://thehistoryoftheweb.com/putting-web-accessibility-first (on-line 8.05.2025).

4 *World Wide Web Consortium (W3C) Launches International Web Accessibility Initiative,* https://www.w3.org/press-releases/1997/wai-launch (on-line 8.05.2025).

5 *Historia WCAG. Główne wytyczne WCAG 1.0*, https://www.krakweb.pl/historia-wcag (on-line 08.05.2025).

6 *Ibidem*.

version known as WCAG 2.1 was released, which many countries continue to require by law. Its most significant enhancement was the introduction of criteria designed to support mobile devices and to increase accessibility guidelines for disabled users. The next version, WCAG 2.2, represents the ongoing effort to improve website accessibility standards. In the near future, it will become the legally recognised standard, superseding WCAG 2.1. This is currently the latest version developed by W3C, although work is already underway on the groundbreaking WCAG 3.0, in which the authors aim to introduce fundamental changes and adapt the criteria to current conditions.

2.2. ARIA (Accessible Rich Internet Applications)

The ARIA criteria[7] set is an extension of the WCAG standard created by W3C. These criteria were designed to standardise semantic attributes used on websites in HTML files. By employing ARIA attributes, people, for example, who use screen readers, can intuitively understand and navigate the structure of a website. The tools that read website content rely primarily on ARIA attributes, which enable the description of the properties, states, or roles of specific webpage elements. The main goal of the standard is to improve digital accessibility for both end users and people with disabilities by eliminating barriers to the use of information and communication technologies.

2.3. EAA (European Accessibility Act)

The European Accessibility Act is a 2019 directive of the European Parliament and the Council[8]. This directive is gradually being adopted by EU countries as a standard requirement for digital accessibility. In Poland, its implementation deadline has been set for 28 June 2025[9]. It seeks to harmonise standards in commercial digital products and services. Particular emphasis is placed on improving access to digital content for people with disabilities and raising social awareness. The Act includes an upgrade of the WCAG standards to version 2.1 at level AA. Once this directive is enforced, companies will be required to conduct compliance audits of any new restrictions, as well as design new solutions according to the applicable standards. A clear benefit of the directive is that it expands the audience and drives innovation in products and services.

3. Criteria for a positive user experience (UX)

Standards such as WCAG, ARIA, and various regulatory requirements are considered by many developers mere formalities that must be fulfilled due to legal mandates in areas like web design, mobile app creation, and digital services. However, end users need far more to freely use the product that they have been offered. The user experience (UX) goes beyond a simple list of mandatory rules. Although each person's experience can vary, there are certain principles that guide developers in creating products that meet not only legal requirements but also user expectations in terms of usability. Don Norman, in his book The Design of Everyday Things, introduced six concepts that can have a positive impact on user perception: affordances, signifi-

7 *Aria*, https://developer.mozilla.org/en-US/docs/Web/Accessibility/ARIA (on-line 8.05.2025).

8 *Directive (EU) 2019/882 of the European Parliament and of the Council of 17 April 2019 on the accessibility requirements for products and services*, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32019L0882 (on-line 08.05.2025).

9 *Polski Akt o dostępności – inauguracja*, https://www.gov.pl/web/fundusze-regiony/polski-akt-o-dostepnosci--inauguracja (on-line 08.05.2025).

ers, constraints, mapping, feedback, and the conceptual model[10]. The following brief overview explains their influence on publicly accessible websites.

3.1. Affordances

The term "affordances" was defined by the American psychologist James Gibson. In a 1977 article entitled The Theory of Affordances he described: "The affordance of anything is a specific combination of the properties of its substance and its surfaces taken with reference to an animal. The reference may be an animal in general as distinguished from a plant or to a particular species of animal as distinguished from other species"[11]. This definition can be interpreted to mean that affordances are all objective possibilities for action in our surrounding world, irrespective of individual differences. Norman sought to refine this definition by considering affordances as any actions an individual is capable of perceiving, thus introducing an element of subjectivity. One example in his book is a chair, which, despite its lack of personal attributes, affords being lifted; however, a person who is young or not physically strong might not perceive this affordance and thus would not be able to perform it[12]. A pertinent question is whether this concept applies to modern websites. Affordances can be crucial to the accessibility of a site. If a user does not perceive them, they will not know how to interact with the website or what it is for. Everyone has their own habits, and the world has taught us behavioural patterns that have developed over time. Poorly-planned features may confuse users and ultimately cause them to abandon a site they find cumbersome.

3.2. Signifiers

The concept of signifiers extends the notion of affordances, and these two ideas often overlap. This term is used when guiding the end user towards possible actions that may not be immediately apparent. In everyday life, there are many examples of signifiers, though not all are used correctly or are the result of thoughtful interface design. Signifiers are essentially clues about how a product is intended to function. In complex products, signifiers are very helpful and do not necessarily denote flawed interface design; however, in simpler systems, any functions should ideally be visible through affordances alone, so that the user knows how the product should work without guidance. In websites, examples of signifiers include tooltips[13], tutorials[14], or even the colour scheme of buttons. Whether these elements are used effectively from a UX perspective depends on the entire structure and specificity of a given site.

3.3. Constraints

Every product or system has constraints that should be designed so that the user is aware of them and follows them. Depending on the scope of the solution in question, there are many types of constraints, the most common being cultural, semantic, logical, and physical[15]. In websites, the designer is aware of the constraints placed on certain functions, but they should also convey

10 D. Norman, *Dizajn na co dzień*, trans. D. Malina, Kraków 2018, p. 28.

11 J. J. Gibson, *The theory of affordances* [in:] *Perceiving, acting, and knowing: Toward an ecological psychology*, W. R. Shaw, J. Bransford (eds.), London 2007, p. 68.

12 D. Norman, *op. cit.*, p. 29.

13 *What is a tooltip?*, https://learn.microsoft.com/pl-pl/office/vba/language/concepts/forms/what-is-a-tooltip (on-line 08.05.2025).

14 L. Khanh, *How to Create In-App Tutorials to Drive Product Adoption*, https://userpilot.com/blog/in-app-tutorials-adoption/ (08.05.2025).

15 D. Norman, *op. cit.*, p. 145.

these constraints appropriately to the user. An example might be a form that expects particular values (numbers, text, or dates) in its fields. One solution is to implement a validator that checks the entry for correctness and provides an error message if necessary.

3.4. Mapping

"Mapping" is a concept often overlooked in product design, but that does not mean that it is difficult to incorporate. It refers to natural human cognitive processes, or the intuitive perception of how a particular function should behave – known as "natural mapping"[16]. There are many examples of natural mapping in everyday life; one of the simplest is turning on a wheel of a car. It is perfectly natural for humans to assume that turning the wheel to the right makes the car turn right. Thus, an initiated action should naturally map to the expected outcome. The same principle can benefit website design. Positive user feedback arises from an intuitive and correct mapping of a site's functions. Paired with signifiers, a simple example of correct mapping is page scrolling. There are two ways in which it occurs commonly, depending on the user's preference. The first uses arrows to move the page up or down. Natural mapping dictates that scrolling goes in the direction of the arrow (the signifier). The second method uses a mouse with a scroll wheel, which moves forward or backward. Correct, natural mapping means that the page scrolls upward as the wheel is moved forward and downward as the wheel moves in the opposite direction.

3.5. Feedback

End users expect that every action produces a reaction. Unfortunately, many products overlook this principle, failing to inform customers about real-time results. Feedback allows the user to feel in control of what has happened or will happen. It is crucial for users to understand the current state of the system. Text-based, graphical, or even auditory messages have a positive impact on user reception. Without them, a user may become confused, frustrated, and ultimately cease using the product because it is too difficult. Examples of feedback in web applications include progress bars, success or error messages triggered by user actions, delivery or read receipts in messaging apps, and user availability status in a system.

3.6. Conceptual model

A conceptual model is essentially the presentation of complex processes that take place during a user action in the form of a user-friendly interface. It consists of the visible appearance of the product, shaped by the previously described concepts – affordances, signifiers, constraints, feedback, and mapping[17]. Creators of solutions intended for end users should understand that presenting functionalities in a way that is easy for the user to visualise will have a positive effect on perceived accessibility. An example of such a conceptual model in websites might be an extension of the form example from Section 3.3. Once the data have been validated, they are sent to the server, which processes them and returns a response to the website. In this process, the user does not see the entire data processing workflow; they only see the outcome, such as a success message or a refreshed list showing the newly added record.

16 *Ibidem*, p. 40.

17 *Ibidem*, pp. 44–45.

4. Automatic identification of digital accessibility

In today's environment, identifying digital accessibility is much simpler thanks to the availability of dedicated tools. This section focuses on reviewing existing applications that help to evaluate and pinpoint critical issues on websites. An experiment will then be carried out to assess whether the most popular Polish websites comply with current standards and how this compliance affects user perception. Lastly, the study's findings will highlight the impact that detected problems have on delivering a positive UX.

4.1. Overview of automation tools

There are numerous tools available for automated website verification against WCAG and EAA standards. However, one might ask how to identify which of them are the most popular and accurate. An official, regularly updated ranking of such tools is provided by an organisation called the World Wide Web Consortium (W3C)[18]. Known worldwide for maintaining and developing technical standards aimed at advancing the Internet and its accessibility, W3C was founded by Tim Berners-Lee, who ushered in a new online era in 1994. At present, W3C comprises the major players in the IT market, including Microsoft, Google, Apple, and IBM[19]. By using the database of W3C-recommended tools[20], several filters were applied that allow for:

- Free use of the tool,
- Full automation of the accessibility identification process,
- Support for HTML and CSS,
- The generation of reports directly from a web browser,
- Compatibility with WCAG 2.2.

Fig. 1. Applied filters in the W3C search engine. Screenshot of the W3C WAI tools

From the five filtered results, two applications – IBM Equal Access Accessibility Checker[21] and Accesible Web RAMP[22] – were selected. Both met the above criteria and are the most up-to-date in terms of WCAG specifications, particularly WCAG 2.2, as it includes WCAG 2.1 AA, which is required under the EAA.[23] These applications will be used in subsequent subsections to analyse and identify issues on selected websites.

18 *About W3C*, https://www.w3.org/about/ (on-line 08.05.2025).
19 *W3C membership list*, https://www.w3.org/membership/list/ (on-line 08.05.2025).
20 *W3C WAI tools for testing and evaluation*, https://www.w3.org/WAI/test-evaluate/tools/list/ (on-line 08.05.2025).
21 *Automated accessibility testing with the IBM Accessibility Toolkit*, https://www.ibm.com/able/toolkit/verify/automated (on-line 08.05.2025).
22 *RAMP – Web Accessibility Software for Agencies and Teams*, https://accessibleweb.com/ramp-web-accessibility-tools/ (on-line 08.05.2025).
23 EAA Audits, *Frequently Aked Questions,* https://www.eaaaudits.com/faqs (on-line 08.05.2025).

4.2. Identification of accessibility on the most popular Polish websites

Analysing the various WCAG criteria will involve three sites that are among the most visited in Poland. Numerous rankings exist to determine the popularity of a website in different categories. One of the most prominent is the MediaPanel ranking[24], which is regularly updated. As of the writing of this article, the ranking for November 2024 was examined. A general category, which includes personal computers and laptops, was taken into account. From the most popular Polish sites in this category, the following three were chosen for evaluation:

- wp.pl – 6,560,352 real users
- mediaexpert.pl – 4,261,572 real users
- przelewy24.pl – 3,057,750 real users

Google Chrome version 131 served as the test environment for detecting digital accessibility issues; it was run on an Apple MacBook M1 Air with Ventura 13.4. The screen resolution was set to 1920 × 1080 px. Each site was scanned for potential issues with respect to the WCAG 2.1 AA and WCAG 2.2 AA standards.

Tab. 1. Analysis of the wp.pl website in the WCAG 2.1 AA standard based on results from RAMP and IBM Accessibility Toolkit

	IBM Accessibility	**Accesible Web RAMP**
Percentage of elements with no detected violations or items to be reviewed	69%	51%
Number of critical errors	60	3
Number of errors being serious or to be verified	635	2
Number of minor errors	104	0

An initial analysis of wp.pl under WCAG 2.1 AA immediately revealed several observations. As shown in Table 1, there is a substantial discrepancy in the quality of the automated analyses. The IBM tool demonstrates a more thorough testing process, as indicated by the significantly higher number of detected issues. Furthermore, in IBM's tool, the percentage of elements that require review is 18% higher. After adjusting both tools to use WCAG 2.2 AA and rescanning the site, we obtained the results in the table below.

24 *Wyniki badania Mediapanel za listopad 2024*: *Internet,* https://media-panel.pl/pl/aktualnosci/wyniki-badania-mediapanel-za-listopad-2024-internet/ (on-line 08.05.2025).

Tab. 2. Analysis of the wp.pl website in the WCAG 2.2 AA standard based on results from RAMP and IBM Accessibility Toolkit

	IBM Accessibility	**Accessible Web RAMP**
Percentage of elements with no detected violations or items to be reviewed	69%	49%
Number of critical errors	60	3
Number of errors being serious or to be verified	640	2
Number of minor errors	104	0

Here, the Accesible Web RAMP application only differs in the percentage of elements with no detected violations or items to be reviewed. By contrast, the IBM tool still reports the same percentage of such elements, but detects five additional serious errors or items needing manual review compared to the WCAG 2.1 AA standard. The initial conclusion is that WCAG 2.2 AA does not radically deviate from the previous version, as the difference in detected issues between the two versions is marginal. With confidence that both IBM and Accesible Web RAMP are prepared to audit sites in accordance with WCAG 2.1 AA and WCAG 2.2 AA, it appears that the IBM tool offers higher precision. Two more analogous tests were conducted on different websites to verify this theory.

Tab. 3. Analysis of the mediaexpert.pl website in the WCAG 2.1 AA standard based on results from RAMP and IBM Accessibility Toolkit

	IBM Accessibility	**Accesible Web RAMP**
Percentage of elements with no detected violations or items to be reviewed	90%	72%
Number of critical errors	28	2
Number of errors being serious or to be verified	129	3
Number of minor errors	116	0

As seen in Table 3, the IBM application again proves to be more thorough. The gap between the two tools in the category of “elements with no detected violations or review items” is about 20%, which suggests that Accesible Web RAMP may lack some of the robust testing mechanisms found in the IBM tool, resulting in fewer accessibility issues detected.

Tab. 4. Analysis of the mediaexpert.pl website in the WCAG 2.2 AA standard based on results from RAMP and IBM Accessibility Toolkit

	IBM Accessibility	**Accesible Web RAMP**
Percentage of elements with no detected violations or items to be reviewed	90%	72%
Number of critical errors	28	2
Number of errors being serious or to be verified	139	4
Number of minor errors	116	0

Table 4 presents the results for mediaexpert.pl under WCAG 2.2 AA. Once again, the findings do not differ significantly from the 2.1 AA standard. IBM's tool detects 10 new issues requiring manual checks, while Accesible Web RAMP discovers only one new problem to be verified. This further supports the idea that the WCAG 2.2 AA requirements are not drastically different from the previous standard. Finally, a comparable analysis was conducted for przelewy24.pl, in order to confirm these observations conclusively.

Tab. 5. Analysis of the przelewy.pl website in the WCAG 2.1 AA standard based on results from RAMP and IBM Accessibility Toolkit

	IBM Accessibility	**Accesible Web RAMP**
Percentage of elements with no detected violations or items to be reviewed	83%	81%
Number of critical errors	38	3
Number of errors being serious or to be verified	265	1
Number of minor errors	134	0

Table 5 also shows that IBM's tool detects more accessibility problems. However, it is worth noting that in this instance, the percentage of elements with no violations or items to review aligns more closely between the two tools (83% vs. 81%). This minor difference of 2% implies that Accesible Web RAMP performs better on sites with less complex structures. In contrast, wp.pl is a large news portal, and mediaexpert.pl is a large online store, while przelewy24.pl has a simpler homepage that serves primarily an informational function. Another factor may be the significantly lower volume of advertisements on the site compared to the previous examples.

Tab. 6. Analysis of the przelewy.pl website in the WCAG 2.2 AA standard based on results from RAMP and IBM Accessibility Toolkit

	IBM Accessibility	**Accesible Web RAMP**
Percentage of elements with no detected violations or items to be reviewed	82%	81%
Number of critical errors	38	3
Number of errors being serious or to be verified	284	1
Number of minor errors	134	0

Table 6 does not reveal any changes for Accesible Web RAMP, while IBM's tool detects 19 new issues that require verification, lowering its percentage of elements with no violations by one point. The hypotheses formed following the results in Table 1 are therefore substantiated after examining additional websites with respect to WCAG 2.1 AA and WCAG 2.2 AA. The first conclusion is that WCAG 2.2 AA does not diverge significantly from its predecessor; the new additions remain compatible with the previous standard and, in many cases, sites properly designed for WCAG 2.1 AA require only minor adjustments to comply. The second conclusion is that there can be considerable differences in the range of functionalities tested by various website analysis tools, which may influence the final assessment of a site. It should also be noted that any automated accessibility scores merely serve as guidelines that should be considered in the context of the specific needs of the website in question.

4.3. The impact of identified issues on user experience (UX)

During the website analyses in Section 4.2, the most frequently recurring issues requiring manual verification were documented. This section discusses some of these and explores whether they represent genuine accessibility problems solely under the WCAG standards or also affect positive user perception (UX).

Tab. 7. Most frequent errors based on results from RAMP and IBM Accessibility Toolkit

Decription of the error	**Standard WCAG**
Buttons must have discernible text	WCAG 2.0 A
Images must have alternate text	WCAG 2.0 A
Zooming and scaling must not be disabled	WCAG 2.0 AA
Links must be distinguishable without relying on colour	WCAG 2.0 A

Table 7 lists four errors that occurred most often during the analysis, along with their respective WCAG standards. It was noted that the most frequent errors still arise from the older WCAG 2.0 version. The correlation between these errors and a positive user experience (UX) is minimal. Two of the issues, lack of alternative text for images that do not load and the fact that users

cannot zoom in on a page, marginally affect how users perceive the product. Addressing these issues could help people with vision impairments, those who rely on screen readers, or users with unstable Internet connections who cannot fully load all page content, including images. The next two errors concern the illegibility of the text on the buttons found on the page, as well as the links, which should not stand out from the rest of the text by colour alone. These issues can be classified as ones that affect the positive reception of the end user, since they significantly influence the readability of the page. Poor choice of colours and illegible text may cause confusion. Furthermore, the note concerning the poor choice of colours suggests that the website may have problems with using appropriate affordances and markers that directly indicate the intended actions. However, given the scale of the detected problems, this represents only a minimal contribution of the automation tools. Most of the issues that affect the positive experience of the end user tend to be overlooked by such applications, mainly because these types of rules are not encompassed by WCAG standards, especially WCAG 2.2 AA.

5. Conclusions

In summary, the role of automation tools can be considered an auxiliary; however, in many respects, they are underdeveloped with regard to current digital accessibility standards. The research conducted has shown that the IBM Accessibility and Accessible Web RAMP applications produce divergent results when automatically analysing the same pages and standards. It can also be observed that the results are merely guidelines that require manual verification, and the findings should be taken with a considerable degree of caution. Furthermore, applications that test the digital accessibility of websites are not designed to analyse them from a user experience perspective. Criteria influencing the positive reception of the end user depend on numerous factors, which significantly complicate the task for tool developers. At present, automating such processes is extremely difficult, especially due to the psychological aspects involved. Another conclusion that can be drawn is that most popular websites are already practically prepared for the new WCAG 2.1 AA standard, which introduces the EAA. The analysis of the websites indicates that these new regulations involve merely cosmetic changes, which are straightforward to implement. It is also worth noting that the accessibility assessment of a website should be carried out manually under the supervision of qualified specialists, and the available applications should serve only as tools to support manual analysis.

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16. *What is a tooltip?*, https://learn.microsoft.com/pl-pl/office/vba/language/concepts/forms/what-is-a-tooltip (on-line 08.05.2025).
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18. *Wyniki badania Mediapanel za listopad 2024: Internet*, https://media-panel.pl/pl/aktualnosci/wyniki-badania-mediapanel-za-listopad-2024-internet/ (on-line 08.05.2025).

THE IMPACT OF ARTIFICIAL INTELLIGENCE ON THE GAME DEVELOPMENT PROCESS

WPŁYW SZTUCZNEJ INTELIGENCJI NA PROCES TWORZENIA GIER

Mateusz Hyla[1]

Abstract: The development of artificial intelligence (AI) opens up new possibilities for the video game industry in terms of automation, personalization, and the quality of experiences offered to players. Thanks to advanced machine learning and deep learning algorithms, game developers can implement systems for dynamic content generation, more realistic non-player character (NPC) behaviours, and tailor gameplay based on the player's style. The paper will present both the specific applications of AI and the potential challenges related to integrating this technology into the production process. The first part of the article focuses on discussing the current state and predictions for artificial intelligence actors in games, including opponents, allies, and other non-player characters. Next, the development of artificial intelligence influencing the quality of gameplay is addressed. The following section presents artificial intelligence used for game content creation, along with a discussion of various models and their potential use in the production process. The conclusion highlights the ethical and technical challenges associated with the implementation of AI, including concerns about excessive computational resource consumption, user data privacy, and potential limitations arising from algorithmic imperfections. As a result, the article demonstrates how the responsible and thoughtful use of AI can revolutionise game production while supporting the development of the industry.

Streszczenie: Rozwój sztucznej inteligencji (AI) otwiera przed branżą gier wideo nowe możliwości w zakresie automatyzacji, personalizacji oraz podnoszenia jakości doświadczeń oferowanych graczom. Dzięki zaawansowanym algorytmom uczenia maszynowego i głębokiego uczenia deweloperzy mogą wdrażać systemy dynamicznego generowania zawartości, bardziej realistycznego zachowania postaci niezależnych (NPC) oraz dostosowywać rozgrywkę do stylu gracza. W niniejszym artykule zostaną zaprezentowane zarówno konkretne zastosowania AI, jak i potencjalne wyzwania wynikające z wykorzystania tej technologii w procesie produkcji gier. Pierwsza część tekstu koncentruje się na omówieniu aktualnej sytuacji oraz prognoz dotyczących funkcjonowania aktorów sztucznej inteligencji w grach, w tym przeciwników, sojuszników oraz pozostałych postaci niezależnych. Następnie zostanie poruszony temat rozwoju AI wpływającego na jakość rozgrywki. Kolejna część przedstawia sposób wykorzystania sztucznej inteligencji w tworzeniu zawartości gier, a także omawia różne modele i ich potencjalne zastosowanie w procesie produkcji. W podsumowaniu zostają opisane wyzwania etyczne i techniczne związane z wdrażaniem AI, obejmujące między innymi obawy o nadmierne zużycie zasobów obliczeniowych, kwestie prywatności danych użytkowników oraz potencjalne ograniczenia wynikające z niedoskonałości algorytmów. W efekcie artykuł wskazuje, w jaki sposób odpowiedzialne i przemyślane posługiwanie się sztuczną inteligencją może zrewolucjonizować produkcję gier, wspierając jednocześnie rozwój całej branży.

Keywords: *video games, artificial intelligence, game production*

Słowa kluczowe: *gry video, sztuczna inteligencja, produkcja gier*

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1. Introduction

Artificial intelligence has been associated with video games almost since their inception. For years, the benchmark for AI capabilities was competitions against grandmasters in chess[2]. In recent years, there has been a dynamic development of artificial intelligence – the most popular models have become available to all users, and AI is now implemented in virtually every electronic device – ranging from smartphones to cars, and even vacuum cleaners. The number of scientific papers and research focused on AI has also increased[3]. These changes have also impacted the video game industry – not only has the production process changed, but so have methods of data collection and processing, as well as the customisation of games to meet user needs. The artificial intelligence used in games is typically divided into the following elements[4]:

- NPCs (Non-Player Characters): These are characters in the game that are not directly controlled by the player. AI is used to manage their behaviour, making them authentic and responsive to player interactions.
- Enemies and adversaries: AI can control opponents or hostile entities in the game, determining their tactics, skills, and responses to the player.
- Allies: AI can control the players' allies, providing support and assistance during gameplay. This includes combat strategies, navigation, and other forms of help.
- System elements: AI can manage various system elements in the game, such as dynamic weather conditions, the economy, and others, to create a realistic environment.
- Procedurally generated elements: In some games, AI can randomly or procedurally generate units as part of the game, such as enemies, levels, or worlds.
- Game mechanics: Artificial intelligence can also be used to control different gameplay mechanics, such as physics, animations, and interactions with objects in the game.
- Customising player experiences: AI can analyse the player's behaviour and adjust the game to create personalised experiences, including adjusting the difficulty levels or game dynamics.
- Player behaviour analysis: AI can track and analyse the player's behaviour to develop statistics, recommendations, or challenges within the game.
- Player assistants: AI units can serve as guides or assistants for players, providing them with information, advice, or instructions during gameplay.
- Interactive dialogue: AI can control dialogue between players and NPCs, allowing diverse and dynamic conversations in the game.

Despite listing content-creating models, such as interactive dialogues, procedurally generated elements, and system elements, these are presented as an integral part of the game. The emergence of widely accessible models such as Midjourney, Luna AI, and Suno AI has led to the establishment of a new type of artificial intelligence, used exclusively in the game production process, but not forming an integral part of the final production. Therefore, AI in the game production industry can be divided into three categories: artificial intelligence of actors and games (NPCs, allies, opponents), artificial intelligence improving gameplay quality (analysing player behaviour), and artificial intelligence used to generate game content (whether as an integral

2 C. E. Shannon, *Programming a Computer for Playing Chess*, [in:] *Computer Chess Compendium*, D. Levy (ed.), New York 1988, pp. 2–13.

3 J. P. Sousa, R. Tavares, J. P. Gomes, V. Mendonça, *Review and analysis of research on Video Games and Artificial Intelligence: a look back and a step forward*, "Procedia Computer Science" 2022 (204), pp. 315–323.

4 A. Filipović, *The Role of Artificial Intelligence in Video Game Development*, "Kultura polisa" 2023 (3), pp. 54–55.

part of production or as external tools allowing the creation of content elements). The proposed division is presented below:

Tab. 1. Division of artificial intelligence according to its use in video games

AI of actors and the game	AI affecting gameplay quality	AI generating game content
NPC Opponents and enemies Allies Player assistants System elements Game mechanics	Customising player experiences Analysis of player behaviour	Procedurally generated elements Interactive dialogue Game elements generated by external tools

This article discusses the changes, development directions, and potential applications of each of the indicated types of AI.

2. Artificial Intelligence of actors and the game

Now we have increasingly advanced AI models. Creating new artificial intelligences is certainly easier than it was a decade ago. Basic machine learning methods are an integral part of many academic curricula[5]. Computers have more processing power and are able to analyse an increasing number of parameters; opponents can learn from mistakes and adapt to the player's strategies, forcing them to employ diverse approaches. AI is capable of anticipating the player's moves in advance, as seen in chess where millions of combinations can be examined. Stockfish is able to predict 15–20 moves for both sides, while grandmasters can predict 4–6 moves[6]. According to the latest research, however, it is a less effective algorithm, often defeated by neural networks[7].

It must be remembered that in video games, AI has to share computational resources with graphics, physics, player input, and other processes. Therefore, it is unrealistic to expect the opponent to foresee many moves ahead. However, we can create artificial intelligence capable of always defeating the player. As Sid Meier, the creator of the Civilisation series, pointed out years ago, game developers had already reached such a level of AI development that the player had no chance of winning against artificial intelligence. Meier's experience demonstrated that players prefer to have an advantage. They prefer that, even in situations with low probability, the game ends with their success. On the contrary, they expect artificial intelligence to occasionally lose, even when it has greater chances of winning[8].

Therefore, it can be assumed that despite the fact that modern technologies allow the creation of highly advanced AI actors in games, no one actually does it. This is neither the goal of the

5 Cf. *Machine Learning – nowy kierunek na studiach II stopnia*, https://www.mimuw.edu.pl/pl/studia/machine-learning-nowy-kierunek-na-studiach-ii-stopnia/ (on-line: 05.03.2025).

6 A. Manzo, P. Cianciarini, *Enhancing Stockfish: A Chess Engine Tailored for Training Human Players*, [in:] *Entertainment Computing – ICEC*, P. Cianciarini, A. Di Iorio, H. Hlavacs, F. Poggi (eds.), Berlin 2023, pp. 275–289.

7 E. Modi, K. Acuna, *The Effects of Computer and AI Engines on Competitive Chess*, "Journal of Student Research" 2023 (3), pp. 1– 9.

8 S. Meier, *Sid Meier przedstawia. Wspomnienia*, Kraków 2021, pp. 297–300.

developers nor the expectation of the audience. Despite the growing possibilities in this field, game developers do not opt for a significant expansion of this AI segment, and it can be assumed that there will be no substantial changes in the future.

3. AI influencing gameplay quality

In the segment of artificial intelligence influencing gameplay quality, a significant increase in interest in the use of such solutions can be observed. Developers are increasingly opting to support artificial intelligence in order to better understand players, as well as optimise gameplay mechanics and improve user interaction, aiming to influence an even deeper immersion in the game world[9].

Game developers, with the help of artificial intelligence, can analyse not only basic game data, such as the frequency of using specific mechanics, the moment when the player abandons the game, and the complexity of individual levels, but they are also capable of collecting and processing physiological or environmental data. It is possible to study the player's perception of the game by measuring and analysing heart rate, skin resistance, muscle activity, chair acceleration and rotation, eye movement, and mouse movement[10].

It is worth noting Unity's report (one of the largest game engine providers), which highlights that more than 71% of studios used AI in 2023. According to the study, the primary reason for adopting AI is to accelerate the production process. As the market demands larger and more complex games, the average development time has increased by 86 days in a year. In response, developers are expanding their R&D departments and integrating artificial intelligence, which is most commonly used for[11]:

- Improving character animations – 46%
- Writing code/speeding up code writing – 37%
- Generating artwork and game levels – 36%
- Writing and narrative design – 36%
- Automated play testing – 36%
- Adaptive difficulty – 35%
- In-game text and voice chat moderation – 33%
- In world building itself, AI is most often used for[12]:
- Non-playable characters (NPCs) – 64%
- Creating one-of-a-kind experiences – 54%
- Speech recognition and natural language processing – 52%
- Body/object detection or classification – 43%
- Image, video, or 3D model classification – 39%
- User-generated content – 34%

9 K. Ravichandran, S. K. Ilango, *Influence of AI Powered Gaming Developers and Analyzing Player Behavior and Enhancing User Experience*, "First International Conference on Advances in Electrical, Electronics and Computational Intelligence (ICAEECI), Tiruchengode, India" 2023.

10 A. Smerdov, A. Somov, E. Burnaev, *AI-enabled prediction of video game player performance using the data from heterogeneous sensors*, "Multimedia Tools and Applications" 2022 (82), pp. 11021–11046.

11 *2025 Unity Gaming Report*, https://unity.com/resources/gaming-report (on-line: 05.03.2025).

12 *Ibidem*.

3.1. Industry leaders

Artificial intelligence aimed at enhancing gaming quality is being developed by major corporations and made available to game creators. One of the most widely adopted solutions today is Deep Learning Super Sampling (DLSS) by Nvidia. This technology improves graphical performance while maintaining high image quality by leveraging deep neural networks. These networks analyse visuals and perform adaptive upscaling in real-time: games are rendered at a lower resolution, and AI upscales them to the native resolution of the monitor. As a result, the number of frames per second (FPS) increases without compromising graphical fidelity, even with ray tracing enabled. Recent data indicates that DLSS is implemented in more than 540 games and applications, including 15 of the top 20 most-played PC games of 2024[13].

Another example of AI-driven game development is the Muse system of Microsoft and Xbox Game Studios' Ninja Theory. Designed to support the recreation of classic games on modern hardware, Muse also streamlines the prototyping phase for game developers[14].

Muse is built upon another Microsoft innovation, World and Human Action Models (WHAM). Utilising a transformer-based architecture, WHAM is an advanced sequential model capable of generating dynamic and diverse gameplay scenarios. This AI model not only predicts game developments based on initial input data, but also allows developers to implement and test new mechanics without manual intervention. Consequently, AI can analyse fundamental human behaviour patterns while capturing contextual and nuanced dependencies, significantly improving realism and flexibility in game simulations[15].

Electronic Arts (EA) is also advancing AI applications in gaming. In particular, during the GENEA Challenge 2023, teams were tasked with developing a model capable of generating gestures based on speech. The study evaluated the likelihood of human movement, the appropriateness of gestures in relation to spoken content, and their alignment with conversational partner behaviours[16].

Additionally, EA is working on AI-driven animation generation without relying on motion capture (MoCap). By using a robust character model trained via reinforcement learning, followed by progressively weaker versions, AI can simulate realistic animations, such as a character recovering from a fall using a ragdoll physics approach. This method could also enable animations for injured characters or those with plaster casts on specific limbs[17].

Furthermore, AI is being used to optimise game testing processes. EA researchers propose shifting from reinforcement learning-based approaches to adversarial imitation learning, incorporating discriminators as reward models. This method, referred to as Multimodal Generative

13 *C. Guyton, Nvidia releases stats that prove DLSS and Frame Generation are here to stay – sorry, angry gamers,* https://www.techradar.com/computing/gpu/nvidia-releases-stats-that-prove-dlss-and-frame-generation-are-here-to-stay-sorry-angry-gamers (on-line: 05.03.2025).

14 *Introducing Muse: Our first generative AI model designed for gameplay ideation,* https://www.youtube.com/watch?v=c15vxDHJ2lU&t (on-line: 03.03.2025).

15 A. Kanervisto, D. Bignell, L. Wen *et al.*, *World and Human Action Models towards gameplay ideation*, "Nature" 2025 (638, 656–663), pp. 1–23.

16 T. Kucherenko, R. Nagy, Y. Yoon *et al.*, *The GENEA challenge 2023: a large-scale evaluation of gesture generation models in monadic and dyadic settings* [in:] *Proceedings of the 25th International Conference on Multimodal Interaction*, E. André, M. Chetouani, D. Vaufreydaz *et al.* (eds.), New York 2023, pp. 792–801.

17 T. Tao, M. Wilson, R. Gou, M. van de Panne, *Learning to Get Up* [in:] *ACM SIGGRAPH 2022 conference proceedings*, M. Nandigjav, N. J. Mitra, A. Hertzmann, New York 2022, pp. 1–10.

Adversarial Imitation Learning (MultiGAIL), could significantly enhance AI-driven testing efficiency[18].

Another example of leading gaming companies actively exploring AI applications to enhance game development processes is CD Projekt Red. It has established a dedicated team to investigate broader AI integration to improve production workflows[19].

The company has been developing proprietary AI-driven technologies for years, including City Creation – an advanced system designed to construct expansive, real-time playable urban environments. This technology relies on AI principles and automation, incorporating innovative tools to support the creation of large-scale, open-world games. The technology enabling the generation of urbanised environments in video games will be characterised by vast, fully interactive areas with a high degree of infrastructural complexity. This system facilitates the design of multi-level playable spaces (both terrestrial and aerial) that collectively form virtual cities. By leveraging advanced algorithms, the system autonomously generates and distributes content, dynamically shaping the game world without the need for manual creation of all elements. Developers emphasise that this approach will enhance immersion and exploration dynamics, which makes it particularly valuable for games with nonlinear gameplay. Additionally, the system incorporates audiovisual modules that accurately replicate the atmosphere and structural complexity of real-world cities. The creators anticipate that this technology will significantly expand the freedom of exploration in video games[20].

Square Enix also adopts a similar approach to artificial intelligence, with its president stating that the studio intends "to be aggressive in applying AI and other cutting-edge technologies to both our content development and our publishing functions"[21].

3.2. Medium companies

Medium-sized enterprises are also striving to develop their own AI technologies that improve game quality or optimise the production process. For instance, Kinetix created the AI-UGC Fund, aimed at engaging creators in utilising their Generative AI technology – the AI Emote Creator. In games that use this artificial intelligence, players can create their own custom 3D animations using in-game video. This type of gameplay modification enables players to become creators of the game themselves, enriching the game. This initiative also has a marketing aspect, as the best animations are shared by users on social media and have the potential to go viral[22].

The first studio to benefit from the fund was SmokeSpot Games, the creators of the game Dropcult. Their game offers character customisation and supports mods, making it an ideal environment to test the new AI. SmokeSpot could receive up to $75,000 to cover the costs of

18 W. Ahlberg, A. Sestini, K. Tollmar, L. Gisslén, *Generating Personas for Games with Multimodal Adversarial Imitation Learning*, https://arxiv.org/abs/2308.07598 (on-line: 05.03.2025).

19 A. Ebert, *CD Projekt aims to start production phase of 'Polaris' in 2024*, https://www.reuters.com/technology/cd-projekt-aims-start-production-phase-polaris-2024-2024-01-22/ (on-line: 05.03.2025).

20 *City Creation – kompleksowa technologia służąca do kreacji "żywego", grywalnego w czasie rzeczywistym, miasta o wielkiej skali, która bazuje na zasadach, sztucznej inteligencji i automatyzacji oraz uwzględnia opracowanie innowacyjnych procesów i narzędzi wspierających tworzenie najwyższej jakości gier z otwartym światem*, https://mapadotacji.gov.pl/projekty/743661/?lang=en (on-line: 05.03.2025)

21 T. Kiryu, *A New Year's Letter from the President*, https://www.hd.square-enix.com/eng/news/2024/html/a_new_years_letter_from_the_president_4.html (on-line: 05.03.2025).

22 *Kinetix launches $1M fund to accelerate AI-UGC in gaming*, https://www.gamedeveloper.com/press-release/kinetix-launches-1m-fund-to-accelerate-ai-ugc-in-gaming (on-line: 05.03.2025).

implementing this technology. The fund's founders expect this to accelerate the introduction of user-generated content features[23].

Another example might be QEDgames, developing the Grail system – an artificial intelligence framework designed for seamless transfer between different projects. This solution enables game studios to reduce costs by eliminating the need to develop AI systems from scratch for each new production. Grail incorporates a multi-agent system, allows for AI preference modeling using mathematical curves, supports long-term sequence planning, and facilitates AI behavior simulation within a simplified game model[24].

Another noteworthy example is Jabali, a company that develops artificial intelligence capable of generating entire games. Currently, the company claims its AI can create games across more than ten different genres[25].

Among such AI solutions, it is worth highlighting Polish companies that are attempting to develop their own technologies. An example is the platform for automating the generation, gameplay, and difficulty level determination of blast levels, based on AI and Machine Learning, developed by Vivid Games[26] or the project aimed at creating an innovative system for optimizing user and revenue parameters in games through artificial intelligence—the Automatic Parameterization and Optimization System developed by T-BULL[27]. Artifex Mundi, on the other hand, has been working on a system that enables the automatic generation of new levels for "match-3" type games, while simultaneously enhancing the quality of these levels through self-learning capabilities and player behavior prediction[28]. CI GAMES developed an innovative technology based on advanced artificial intelligence algorithms, dedicated to generating the player's environment, including crowds and animal herds[29].

An alternative approach is being pursued by ECC Games with their GearShift project. The studio developed a behaviour engine for wheeled motor vehicles and map generation based on artificial intelligence algorithms using the Unreal Engine platform. This is the first technology to integrate a vehicle physics engine with a dynamic map generation module. The engine allows for the customization of vehicle physics according to the environmental conditions on the generated map, taking into account game mechanics elements such as suspension physics, tire behaviour physics, engine models that consider power, torque, friction, and engine type characteristics (e.g., inline engines, V engines, electric motors), braking systems that account for brake temperature, differential systems with adjustable parameters, and driving assistance systems such as ABS, ESP, and TRC[30].

23 *Ibidem*.

24 *Grail whitepaper June 2021*, https://grail.com.pl/media/Grail_Whitepaper_June_2021.pdf (on-line: 05.03.2025).

25 *Introducing Jabali, the AI Engine for Aspiring Game Developers*, https://www.gamedeveloper.com/press-release/introducing-jabali-the-ai-engine-for-aspiring-game-developers (on-line: 05.03.2025).

26 *Vivid Games otrzyma 3,8 mln zł dofinansowania NCBiR*, https://www.biznesradar.pl/a/115290,vivid-games-otrzyma-3-8-mln-zl-dofinansowania-ncbir (on-line: 05.03.2025).

27 K. Pieczonka, *75 mln dofinansowania na gry, NCBiR wspiera innowacje cyfrowe*, https://antyweb.pl/ncbir-przyznalo-75-mln-dofinansowania-na-gry (on-line: 05.03.2025).

28 *NCBR wybrało 27 projektów do dofinansowania w ramach programu GAMEINN*, https://www.money.pl/gielda/ncbr-wybralo-27-projektow-do-dofinansowania-w-ramach-programu-gameinn-6429062445454977a.html (on-line: 05.03.2025).

29 *Lista ocenionych projektów złożonych w ramach Programu Operacyjnego Inteligentny Rozwój 2014–2020 działanie 1.2,* https://archiwum.ncbr.gov.pl/fileadmin/gfx/ncbir/userfiles/_public/fundusze_europejskie/inteligentny_rozwoj/gameinn/lista_rankingowa_3_1.2_2016_poir__gameinn.pdf (on-line: 05.03.2025).

30 *Silnik fizyki*, https://eccgames.com/ecc-uslugi/silnik-fizyki/ (on-line: 05.03.2025).

3.3. Indie studios

Developing proprietary AI models involves significant costs. It is necessary to establish an R&D department and conduct a series of research and tests to develop a new solution. This means spending resources for several years before the benefits of the new models can be realised. In the case of small indie game studios, their own funds are typically insufficient to develop proprietary solutions. In Poland within the development of AI, significant opportunities for the gaming industry are provided by competitions organised by the Polish Agency for Enterprise Development (Polska Agencja Rozwoju Przedsiębiorczości) and the National Centre for Research and Development (Narodowe Centrum Badań i Rozwoju), which mediate the financing of R&D projects from European Funds.

A good example of AI development in an indie studio using this type of subsidy could be Jujubee. The first research project from this company was an AI that manages the computational power consumption of the computer and decides how to allocate resources to various AI actors. This was carried out within the project titled "Development of a framework for building artificial intelligence behavior systems in multi-actor real-time 'Grand Strategy' games – GS-AIM (Grand Strategy Artificial Intelligence Mechanism)"[31]. One of the outcomes of the project was the creation of a completely new category of games – 'Real Time Grand Strategy' mobile games, using the developed GS-AIM system. The project solved a research problem related to ensuring proper game performance when developing real-time strategy games with multiple actors from a technical perspective. Until then, this involved excessive usage of computational power and memory, leading to prolonged interval calculations and a decrease in frame rate per second. The problem was associated, on the one hand, with the variety of available behavioural options that each AI actor could use and, on the other hand, with the management of the units by each actor.

The second Jujubee's project from this area focused on enhancing the capabilities of artificial intelligence and integrating it with a new environment, additionally supporting the work of developers. This project was titled "Development of the Grand Strategy Engine tool for designing multi-actor real-time or turn-based Grand Strategy games and integrating it with the Grand Strategy Artificial Intelligence Mechanism"[32]. The goal of the project was to create an independent Grand Strategy Engine (GSE) tool for designing real-time Grand Strategy games. The development of GSE reduced the involvement of developers in game creation, accelerated game production, and decreased the frequency of issues related to faulty code functioning. Optimisation in this regard allowed games to be created for less powerful devices. GSE enables game production for computers and mobile devices, contributing to the development of the type of games known as Real-Time Grand Strategy mobile games, initiated by the company.

31 The project was part of Action 1.2: "Sectoral R&D Programs" – GameINN, within the Operational Program Intelligent Development 2014–2020, co-financed by the European Regional Development Fund. The value of the project was 1,946,295 PLN, of which the contribution from the European Funds covered 1,341,171 PLN.

32 The project was part of Action 1.1: R&D Projects for Enterprises, part of the Operational Program Intelligent Development 2014–2020, co-financed by the European Regional Development Fund. The value of the project was 3,535,000 PLN, of which the contribution from the European Funds covered 2,585,500 PLN. Project co-financed by the European Union from the European Regional Development Fund under the Smart Growth Operational Programme. Project implemented as part of the National Centre for Research and Development competition: Fast Track.

Another example of companies of this size developing their own AI technologies with the support form EU Founds might be[33]:

- Esports Lab with their Better Games project – development and validation of an AI-based tool for psychological profiling and player segmentation
- Symbiote Sp. z o.o. with their INVICTUS – a modular solution utilising artificial intelligence for the expansion of games.
- 4Gate with their *Chowaniec* – a tool for creating and managing AI-based animal companions in video games.
- Games Operators with their project of development of advanced algorithms for generating game world AI based on map data using reinforcement learning methods for innovative modules in the game tentatively titled *Urban Warfare*.
- All Investments with their FinAISym project – a playable financial market simulator based on multi-agent AI/RL algorithms with a high degree of real-world replication in a digital twin model, enabling the study of market behaviours and participants under various market and economic parameters.
- Baad Games Studio with their project of development of algorithms and models in the field of artificial intelligence using behavioural tree methods for implementation in Real-Time Strategy games.
- Silver Bullet Solutions with their project of development of an external modular tool for the implementation and optimisation of advanced artificial intelligence with broad applications in video games.

In conclusion, within the segment of AI that improves gameplay quality, a significant technology development of the technology is visible. However, it requires substantial financial investment, which makes it primarily the domain of larger enterprises. For smaller companies, European Funds present an opportunity to acquire the necessary resources for technology development.

4. Artificial Intelligence for the creation of game content

The creation of game content is typically managed by generative AI, represented by a class of models that generate new data based on the patterns and structures of the data analysed by them[34]. Thanks to the rapid development of natural language processing and deep learning techniques in neural networks, models have been created that allow the generation of text, images, music, sound, 3D models, and other elements[35].

4.1. Content generation models

Content generation models are responsible for creating content and data that are difficult to distinguish from those generated by humans. The idea of such artificial intelligence dates back to the 1970s when methods like ELIZA and MYCIN were developed, allowing pattern matching with scripted responses. Currently, advanced language models are used, which have been trained

33 K. Pieczonka, *op. cit. Lista ocenionych projektów złożonych w ramach Programu Operacyjnego Inteligentny Rozwój 2014–2020 działanie 1.2*, *op. cit.*

34 R. W. McGee, *A. Chan. Three Short Stories Written with Chat GPT*, 2023, pre-print, (on-line: 05.03.2025).

35 E. N. Naumova, *A mistake-find exercise: a teacher's tool to engage with information innovations, ChatGPT, and their analogs*, "Journal of Public Health Policy" 2023 (44), pp. 173–178.

on massive datasets, enabling significant development of this segment and potential applications of artificial intelligence in fields such as medicine, education or arts[36].

An example of a content generation model is ChatGPT. This model operates based on the Generative Pre-trained Transformer (GPT) architecture[37]. The idea behind creating this model was to support a variety of tasks, including not only text generation but also text translation and data analysis[38].

In game production, the model can be used for text correction. It can analyse a submitted text for spelling and punctuation accuracy, and even for readability, appropriately shortening sentences.

In line with the aforementioned idea, it is also useful for text translation. In the video game industry, localisation can consume a significant portion of the budget, especially in independent productions. The use of content-generating AI allows for considerable cost reductions, and in some cases, even facilitates the release of the game in new languages. This is particularly important for small studios or games created by a single individual, often semi-amateur productions. Utilising content-generating models opens new markets for them. It is worth noting that introducing additional languages also increases the accessibility of games, especially for those who do not speak English – many interesting, yet niche productions miss out on this player type due to lack of translation.

However, content-generating models can substitute more advanced services provided by localisation companies – cultural context analysis and the detection of sensitive content. For example, analysing reviews of the game *Realpolitiks II* on the Steam platform shows considerable dissatisfaction with certain geographical names – some countries do not recognise universally accepted terms and use names valid only within specific regions. Using, for instance, ChatGPT for translation analysis in terms of cultural adaptation would help avoid such issues. Content-generating models can also be used to check the accuracy of translations, particularly with regard to tailoring them for specific markets.

The core functions of content-generating models, namely text creation, can also be employed in game production as a source of inspiration. Models have not only analysed large quantities of game reviews, design guides, and other cultural works, but can also help find ideas for quests, mechanics, events, and characters in a game. They can directly generate in-game text, both on a creative level, where the model can realistically simulate dialogue between two NPCs based on the characters' traits and the topic of conversation, and on a generative level, creating secondary texts, such as numerous item descriptions or location overviews. Models can also be useful in creating various forms of documentation, from shortening or extending texts for funding applications, to generating reports, creating checklists, documenting best practices, generating presentation content, and producing test scripts.

Artificial intelligence, such as ChatGPT, can also aid in the analysis of documentation. Newer models allow for the creation of custom bots based on supplied data. In game production, one can upload the Game Design Document (GDD), game script, mechanics descriptions, marketing documents, or company strategies, and use the bot created in this way to analyse game information. This is an efficient way to find inconsistencies between documents or current actions. It is also very useful for searching for specific information, by simply asking a question about

36 P. Gupta, B. Ding, C. Guan, D. Ding, *Generative AI: A systematic review using topic modelling techniques*, "Data and Information Management" 2024 (8), pp. 1–66.

37 F. Y. Wang, Q. Miao, X. Li, X. Wang, Y. Lin, *What does ChatGPT say: the DAO from algorithmic intelligence to linguistic intelligence*, "IEEE/CAA Journal of Automatica Sinica" 2023 (10), pp. 575–579.

38 P. Ray, *ChatGPT: A comprehensive review on background, applications, key challenges, bias, ethics, limitations and future scope*, "Internet of Things and Cyber-Physical Systems" 2023 (3), pp. 121–154.

a particular mechanic, character, or item, one can obtain all the necessary data without having to search through hundreds of pages of documentation across multiple documents. Such actions not only accelerate conceptual work, but also prevent errors that would only become apparent after the implementation of mechanics – significantly shortening the number of iterations in the project and reducing the number of mistakes.

Another function of content-generating models is to assist in programming. Artificial Intelligence manages secondary changes in code or simple solutions. In more complex problems, the code may not work, but it may serve as a good inspiration for finding a solution.

4.2. 2D graphics generation models

Artificial intelligence dedicated to 2D graphics is responsible for creating graphic data, both abstract and spatial. Thanks to this technology, it is possible to generate diverse content, such as sequential data (ordered texts, codes, music, videos, time series), tabular data (structured rows and columns, as seen in spreadsheets and databases), or graphs (modelled network structures – social networks, molecular structures, or recommendation systems). In video games the most significant aspect is the creation of 2D images, which involves representing spatial data (including pixels, voxels, or points with 2D coordinates) within Euclidean spaces. This allows, through the use of such processes as Data enhancement, Visual mapping generation, Stylisation and Interaction, to create, among others, visualisation images, sketches and natural images. The same methods are also responsible for creating QR codes, volumetric data or density maps. The AI that generates 2D graphics uses methods such as image synthesis, style transfer, and digital visual art creation[39].

An example of such a model is Midjourney – artificial intelligence based on Dall-E technology, built on a version of GPT-3 containing 12 billion parameters and trained to generate images using a text-image dataset[40].

2D graphics generation models can be used in the process of creating conceptual artwork. These are simple drawings, often sketches, aimed at finding the right graphic direction or presenting an initial design of a character or a game element.

The traditional process involves the design team specifying the requirements for a given game element and describing it. Then, a 2D artist prepares several versions of the drawing for that element. Typically, this process takes 2 to 3 days. With the use of 2D graphics generation models, it is possible to obtain dozens of proposals in 15–20 minutes. It is worth noting that the graphics can reflect typical concept art in the form of drawings or sketches, or they may already be more advanced graphics, including colours. Conceptual graphics are created exclusively for internal use by the studio, so the presence of typical artifacts, such as excessive fingers or distorted proportions, is not problematic. On the other hand, AI cannot yet make specific corrections to graphics – for example, if we want to replace a sword with an axe, a beard with a moustache, or even red hair with grey hair, an artist is still needed to finish the image. However, it should be emphasised that with the use of artificial intelligence, studios can now produce 1–2, sometimes even 3 graphics per day, resulting in productivity increases of 100% to 900%.

A much simpler task for this type of AI model would be the creation of moodboards – fundamental tools in the design industry that encompass a wide range of boards with reference

39 Y. Ye, J. Hao, Y. Hou *et al*., *Generative AI for visualization: State of the art and future directions*, "Visual Informatics" 2024 (8), pp. 43–66.

40 D. Hanna, *The Use of Artificial Intelligence Art Generator "Midjourney" in Artistic and Advertising Creativity*, "Journal of Design Sciences and Applied Arts" 2023 (4), pp. 42–58.

graphics[41]. Therefore, this is an element that does not require any corrections, as it serves solely to convey references, mood, and the atmosphere of the production.

Another use of this kind of artificial intelligence in the game production process may occur during the prototyping phase or internal demo creation. In the traditional process, when developing an early version of a game for investors, publishers, or management, placeholder elements are used, typically with text that indicates what should appear in a given place. Thanks to the new AI models, studios can now provide graphics close to the final effect, helping to better understand the game, especially for those not directly involved in the production process. It is worth noting that artificial intelligence is ineffective when it comes to generating UI elements or icons. There are also certain elements that it often struggles with – for example, bows.

The use of 2D graphics generation models for the full version of a game delivered to the customer raises ethical concerns, especially regarding proper labeling of such productions. The quality of the generated graphics is often high enough that it could potentially be used in the full game version as the main elements, after reducing artifacts – such as poorly generated hands, incorrectly placed eyes, or distorted proportions. However, it must be remembered that for independent creators or very small teams, often working on semi-amateur productions, even raw AI-generated graphics can be the deciding factor in completing the project – hence, it should not be surprising that such raw graphics can be found in games.

The last example of using these models is in marketing materials – preparing newsletters, distributor website materials, devblogs, social media posts, forum contributions, servers, and other places where developers communicate with players may require significant processing power, which could otherwise be needed for other areas of production. Depending on the strategy adopted by the studio and the reach of the campaign, the materials may require more or fewer corrections by artists – but in any case, this approach speeds up the work. This type of artificial intelligence is used, among others, by Activision in *Call of Duty: Black Ops 6*. However, it is important to note that the use of generative AI in games is often met with negative reactions from players, which is why studios tend to conceal this fact[42].

4.3. Sound generation models

Among the numerous technologies for sound generation, not all can be fully classified as artificial intelligence. An example is the Markov chain, which models event sequences based on the probabilities of subsequent states that depend only on the previous state, indicating what is possible or impossible in the ensuing sequence – chord by chord, beat by beat. However, the chain can be integrated with a neural network, thus becoming AI. We can also mention evolutionary algorithms that modify musical fragments according to harmonic rules and adjust the output through an adaptation function. Among neural networks, architectures such as Feedforward Networks, Recurrent Neural Networks, Generative Adversarial Networks, Variational Autoencoders, and Transformers are commonly cited[43]. Among these models, one can distinguish models that generate music, ambient sounds, or speech.

41 T. Cassidy, *The Mood Board Process Modeled and Understood as a Qualitative Design Research Tool*, "Fashion Practice" 2011 (3), pp. 225–252.

42 C. Kerr, *Players lambast Activision after publisher confirms generative AI was used in Black Ops 6*, https://www.gamedeveloper.com/production/players-lambast-activision-after-publisher-confirms-generative-ai-was-used-in-black-ops-6 (on-line: 05.03.2025).

43 M. Civit, J. Civit-Masot, F. Cuadrado, M. J. Escalona, *A systematic review of artificial intelligence-based music generation: Scope, applications, and future trends*, "Expert Systems with Applications" 2022 (209), pp. 1–16.

An example of a music-generating model is SunoAI. This model also has a text-generation function, focused on generating song lyrics. The user can input their own text and specify the type of music, such as: "Hip hop R&B, Electronic synths, 80s retro, fast paced" or more specifically: "Cyberpunk, Soviet Pop, dubstep, voodoo, death metal, [tempo: 150–259 BPM], acid glitch, mechanical, melancholy, dirty, duet, female singer, female backup vocals". The second option is simply providing a description of the song – the artificial intelligence will then generate both the lyrics and the music. For example, one could enter the phrase: "A song about rain in the park; piano; nostalgic" and within minutes receive two versions of a four-verse, nearly four-minute piece on the specified theme. The AI can sing in many languages, but with Polish it often produces incorrect pronunciation. A downside is the frequently audible autotune effect. Sometimes the song is unable to fully generate and abruptly cuts off or turns into an entirely different piece. Nevertheless, of 10 attempts, or 20 generated songs, 6 are generally of good quality.

The model also has an "instrumental" option, which generates only the music, without lyrics. Due to this, music-generating models can be used to create background music for games, trailers, and other marketing materials. The tracks can serve as a basis or reference for musical artists creating game soundtracks or even as a complete soundtrack for smaller productions.

An example of a model that generates dialogue could be Play HT. Improving models allow for the use of various voices or even mimic real voices based on a sound sample. The user has the ability to adjust emotions and speak in different languages. This technology can primarily be used for voice-overs, which have often represented a very significant cost. It is also important to note the accessibility aspect. The model can read text in most languages. In addition, it can be implemented as a support for people with disabilities, particularly those with reading difficulties. For example, in Jujubee, a system is being developed where an AI voiceover reads every clicked text – menu elements, UI, or dialogues – to assist individuals who have difficulty with large amounts of text in the game. An example of the use of this type of AI can be seen in the dubbing of the character Viktor Vektor in the *Phantom Liberty* expansion for *Cyberpunk 2077* after the death of the actor who originally voiced the character[44]. Another example of AI usage for voice-overs is demonstrated by Paradox in the game *Stellaris*. In *The Machine Age* expansion, which introduces a new faction consisting of artificial intelligence, the developers utilized AI to generate the voices of the characters from this group[45].

4.4. Models generating 3D elements

Artificial intelligence models generating 3D elements utilise machine learning, primarily networks such as GAN and VAE, capable of creating three-dimensional structures based on available input data. These models recognize characteristics of shapes, textures, and spatial relationships, enabling them to generate new forms[46].

An example of such a model is LumaAI – Genie. In this model, it is enough to input a simple prompt, such as "slavic young warrior, t-pose" to generate a preliminarily textured, optimised model within a few minutes. However, the quality of the models is very low – there are many

44 J. Henry, *CD Projekt Red Wants to Use AI for Future Game Development – Will We See It for New Witcher, Cyberpunk Games?*, https://www.techtimes.com/articles/300902/20240123/cd-projekt-red-use-ai-future-game-developmentwill-see-new.htm (online 05.03.2025).

45 M. Jarvis, *Stellaris director insists "ethical use of AI is very important to us" after generating voices in latest DLC*, https://www.rockpapershotgun.com/stellaris-director-insists-ethical-use-of-ai-is-very-important-to-us-after-generating-voices-in-latest-dlc (online 05.03.2025).

46 Q. C. Xu, T. J. Mu, Y. L. Yang, *A survey of deep learning-based 3D shape generation*, "Computational Visual Media" 2023 (9), pp. 407–442.

artefacts, and the models often lack symmetry. The AI does not understand many terms and tends to generate rather generic, very stereotypical characters. After entering the prompt, four model proposals are provided, with few details, very simple meshes, and angular shapes. It is possible to select the Hi-Res option, which in theory should improve the quality of the textures and character mesh. In practice, however, the process textures the model in a different way, introducing variations that distort the idea of improving the resolution of the already selected model. The model contains more details, and its resolution increases, as seen by the file size – from 2.24MB in the case of the basic model to 3.02MB in the case of the file with the improved resolution. An example comparison of a generated character along with a character whose resolution has been enhanced by the model is shown in Figure 1.

Fig. 1. Comparison of a low-resolution model with a model of improved resolution

The model encounters significant issues when generating animal models, often producing highly distorted shapes. Sample glitches are presented in Figure 2. One can observe additional stands, elements unrelated to the character, generation of material instead of the entire character, errors in the limbs, model duplication, lack of proportion, or incorrect interpretation of prompts.

Fig. 2. An example of artefacts in models generated by artificial intelligence

In the case of 3D elements, it is therefore impossible to directly use AI-generated content in a game. Each model must undergo processing by a 3D artist, who will refine the mesh, remove unnecessary elements, and create new textures. An example of a model generated by artificial intelligence and modified by a 3D artist, along with its use in a game engine, is shown below.

Fig. 3. Comparison of an AI-generated model with a model modified by an artist and placed in the game engine

Models generated by artificial intelligence can thus only serve as a basis for further work, but this is sufficient to speed up the pace of character production. The scope of necessary changes depends not only on the quality of the generated model but also on the type of game and camera settings. In strategy games, where units are usually depicted from a large distance, the amount of modifications will be significantly smaller than in RPGs with an isometric camera angle and a closer view of the character. In TPS or FPS games, AI-generated models would require so many changes that they could only serve as conceptual art or model elements – at the current stage of AI development, the artist would need to make such substantial modifications that creating the model from scratch could be a faster process. Therefore, such 3D models are more suitable for prototyping stages, internal demos, or games with a considerably distant camera angle from the units.

5. Challenges

The development of artificial intelligence offers significant opportunities to streamline the game production process. However, it also requires changes in studio strategy and current workflow. Before implementing artificial intelligence, it will be necessary to address a series of challenges, among which concerns can be defined about the potential replacement by AI. There are many movements opposing the use of artificial intelligence in art.

Another challenge may be the lack of knowledge about how to teach the use of AI. Professionals need to face the task of acquiring knowledge and experience in artificial intelligence on their own. AI is evolving so rapidly that it is difficult to answer questions such as: “should we teach AI?”, “how should we teach about AI?”, “what should we teach about it?”, and “how should we combat AI-assisted plagiarism?”.

There are also issues related to AI legislation. Most countries are still developing regulations regarding artificial intelligence. Creators are uncertain about how to properly label products that use AI, what restrictions should be imposed on AI, and what the copyright situation is for elements, as well as entire games, that use AI-generated content.

The issue of legal regulation, education, and the use of AI in different countries must also be considered. There are concerns about overly restrictive approaches to using and developing artificial intelligence, especially in heavily regulated markets. Countries with a more liberal approach to the development and use of AI may significantly accelerate progress, improve product quality, and lower costs.

Ethical challenges may also arise, particularly concerning how AI is used to influence users, the proper labelling of AI-utilising projects, and the databases employed by artificial intelligence.

The resistance to AI should not be overlooked: many users, employees, and creators oppose the use of artificial intelligence in artistic productions, including video games. Negative review bombing can be observed in the case of games using AI-generated elements.

Furthermore, the issue of excessive computational power and energy consumption by artificial intelligence must be addressed. Currently, most popular models use neural networks that have high resource demands. AI developers must focus on creating more optimised network architectures, improving the transfer of complex knowledge from larger models to smaller ones, and using energy-efficient components.

6. Conclusions

The development of artificial intelligence opens new opportunities for game developers. Among the greatest benefits, one can mention the increased accessibility of technology for game creators, the acceleration of the production process, which translates into reduced production costs, or the ability to create larger games within the same budget. Artificial intelligence does not develop uniformly, and some areas remain untapped – therefore, there is a perspective for the emergence of more advanced AI models that will change the way games are produced and the operating principles within the market. However, the use of artificial intelligence in games and its development have led to new problems that must be addressed not only by developers, but also by players, businesses, educators, and governments.

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THE APPLICATION OF LEAN MANAGEMENT IN THE WORK OF IT TEAMS: A CASE STUDY OF THE SPOTIFY SERVICE AND INTEL COMPANY

ZASTOSOWANIE LEAN MANAGEMENT W PRACY ZESPOŁÓW IT CASE STUDY SERWISU SPOTIFY I FIRMY INTEL

Natalia Przybylska-Curyl[1]

Abstract: In the face of challenges related to the execution of IT projects, companies are looking for ways to improve the efficiency of their teams' work. This text presents the impact of the Lean methodology on the functioning of project teams, as well as the process of implementing its principles using the examples of the Spotify service and the Intel corporation. A case study method was employed, allowing for the depiction of complex processes in their natural context, along with an analysis of the relevant literature. Particular attention was paid to the implementation of tools and practices such as value stream mapping and Kanban boards. The introduction of Lean Management in the organisations analysed demonstrated that the application of this methodology can support IT teams to eliminate waste, increase work flexibility, and pursue continuous improvement.

Streszczenie: W obliczu wyzwań związanych z realizacją projektów informatycznych przedsiębiorstwa poszukują sposobów na zwiększenie efektywności pracy zespołów. W tekście przedstawiono wpływ metodyki Lean na funkcjonowanie zespołów projektowych oraz proces wdrażania jej założeń na przykładzie serwisu Spotify i firmy Intel. Zastosowano metodę studium przypadku, która pozwala na ukazanie złożonych procesów w ich naturalnym kontekście, a także przeprowadzono analizę literatury przedmiotu. Szczególną uwagę zwrócono na implementację narzędzi i praktyk takich jak mapowanie strumienia wartości oraz tablice Kanban. Wdrożenie Lean Management w analizowanych organizacjach pokazało, że stosowanie tej metodyki może wspierać zespoły IT w eliminowaniu marnotrawstwa, zwiększaniu elastyczności pracy oraz ciągłym doskonaleniu.

Keywords: *Lean Management, Lean, IT project, Kanban, VSM, Spotify, Intel*

Słowa kluczowe: *Lean Management, Lean, projekt informatyczny, Kanban, VSM, Spotify, Intel*

1. Introduction

Contemporary organisations are increasingly confronted with challenges related to the speed of product delivery, product quality, and flexibility, all of which enable dynamic growth through the adaptation of tasks carried out by teams responsible for product creation. An approach that supports these aspects is Lean Management – a concept whose key principles include continuous improvement, the elimination of so-called bottlenecks, and the provision of products of the highest possible value to customers.

The purpose of this article is to analyse the application of Lean Management beyond the traditional industrial production sector, particularly in the IT industry. The main research question focuses on how Lean Management tools and practices, such as value stream mapping and Kanban boards, can be effectively implemented in IT teams to improve their efficiency, work quality and flexibility. The analysis is based on the case study method, which enables a practical illustration

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of these processes. Using examples from Spotify and Intel, the article presents the deployment of Lean Management as a strategy for enhancing the performance of IT teams by pinpointing bottlenecks that adversely affect workflow and contribute to waste. The structure of the article is as follows: the first part presents the essence of Lean Management and its key principles. Next, the possibilities of adapting this approach in project teams operating within the IT sector are discussed. The final part contains an analysis of the cases of Spotify and Intel, illustrating the practical implementation of Lean Management. The conclusion provides the main findings, identifies the limitations of the study, and outlines potential directions for future research on the adaptation of Lean Management within IT environments.

2. Lean Management

The pursuit of ever-improving results by companies, whether in the context of projects or processes, is due to the need for effective management of the teams responsible for their execution. A core goal of organisations is to achieve better outcomes, become more efficient, and produce increasingly high-quality products. Focusing on quality and satisfying customer needs is a standard requirement – every enterprise can identify areas that, if improved, will help deliver higher quality[2]. In line with the Kaizen philosophy, they should strive to become ever better: "Something is always changing; in improving one thing, we notice further elements that can be enhanced. A continuous search for improvements and gradual process refinement step by step"[3].

Identifying the steps that require corrective measures is necessary to implement improvements within enterprises. The concept of Lean Management was developed in response to these needs. The methodology originated from the Toyota Production System. Its principal assumption is "to produce more and more with ever-decreasing resource consumption"[4]. The essence of Lean Management is to create a work culture in the organisation in such a way that everyone responsible for particular tasks strives to reduce the costs of the endeavour, shorten the time needed to deliver the product, and improve quality. These measures enable enterprises to satisfy customer expectations and adapt to the ongoing changes imposed by the business environment[5]. Lean Management holds that anything that does not contribute value is waste; hence, the focus should be on actions that lead to the elimination of it.

According to Taiichi Ohno, a pioneer of Lean Management, it is possible to identify the basic examples of waste[6] – *muda* (無駄) in Japanese – occurring in the manufacturing industry:

- Production of goods without a customer order (leading to an increase in finished products)
- Idle waiting of people/machines for delayed deliveries or subsequent process steps
- Unnecessary transportation of materials between functional areas
- Excessively long operating times due to poor product or tool design
- Inventories larger than the absolute minimum required

2 A. J. Blikle, *Doktryna jakości: rzecz o skutecznym zarządzaniu*, Gliwice 2014.

3 K. Kaczor, *Scrum i nie tylko, teoria i praktyka w metodach Agile*, Warszawa 2016, p. 62.

4 J. P. Womack, D. T. Jones, *Lean thinking – szczupłe myślenie*, transl. M. Wąsiel, R. Muszyński, S. Kubik, Wrocław 2008, p. 15.

5 P. Jóźwiakowski, *Lean management – metoda racjonalnego zarządzania produkcją*, "Zeszyty Naukowe DWSPiT. Studia z Nauk Technicznych" 2015 (4), p. 35.

6 Taiichi Ohno (1912–1990) is the father of the Toyota Production System (TPS) and one of the main architects of the organisational revolution in industry. He created an innovative system based on the principles of just-in-time (JIT), so-called *jidoka* method and new management principles, which are the first historical layers of Lean manufacturing.

- Workers' movements in search of parts, tools, instructions, or assistance
- Defects and errors that require repairs or corrections[7].

Although Taiichi Ohno's original observations on waste were focused on the industrial sector, they have subsequently been translated into issues related to the management of IT teams.

3. Application of Lean Management in the work of IT teams

IT teams, which strive to perform their tasks efficiently, face daily problems that, to some extent, mirror those found in industry. It is thus unsurprising that ever-changing client requirements and the desire to reduce the related costs make Lean Management methods potentially valuable in this context[8]. As researchers state, "Although the use of Lean practices and principles in IT projects managed by IT managers is currently limited, it is nonetheless needed"[9]. As the literature review indicates, organizations adapt Lean principles within their software development processes to eliminate waste, reinforce learning, make decisions before the latest feasible moment, deliver tasks at the earliest possible moment, delegate authority and give authorisation, ensure the integrity of the software, think holistically about the entire system and solution[10].

IT teams usually work on developing software products of a certain complexity, so identifying types of waste that can affect both team efficiency and product quality can be challenging. Value stream mapping (VSM) has proven helpful in characterising potential waste in the IT sector. VSM can be applied in IT processes in nearly the same way as in manufacturing. "The main difficulty for VSM in IT lies in the need to map processes that often do not result in a tangible product and are not visible. VSM begins, as in manufacturing, by identifying the process that is a potential source of waste. Next, the process must be broken down into tasks, measured by their expected completion time. In the next step, the waiting times (between the completion of consecutive tasks) are determined. It is crucial for the map to start and end with the customer or be as close as possible to the actual customer"[11]. Another Lean Management principle states that, once the sources of waste are known, one should ensure a smooth workflow free from delays. An example of such a disruption is having to wait for another team member to finish their work or for a task to be approved by a different entity. These occurrences can complicate task management. It is thus necessary to organise work so that bottlenecks do not impede progress on subsequent tasks. When introducing Lean to IT teams, it is also important to consider work overload. Tools designed to report work hours or display the status of ongoing tasks can be helpful. The most common of them, used for visualising workflow in software development, is the Kanban board, considered as an excellent example of applying Lean it IT[12]. This tool helps to represent the process by identifying interruptions and bottlenecks and also allows setting a limit on the amount of work in progress[13]. The board should indicate which tasks are most critical in terms of priority and should be updated regularly by the team. Depending on the project, Kanban boards may differ. The figure below presents an example of a Kanban board[14].

7 T. Ohno, *Toyota Production System: Beyond Large-Scale Production*, New York 1988, p. 37.
8 J. Łojewski, *Lean IT w praktyce – krótki przewodnik co to jest Lean*, https://itwiz.pl/lean-praktyce-krotki-przewodnik/ (on-line 24.04.2025).
9 G. Kundu, B. Manohar, *How do the practitioners perceive relevancy of lean practices in IT support services?*, "TQM Journal" 2015 (5), pp. 648–668.
10 M. Poppendieck, T. Poppendieck, *Lean Software Development:An Agile Toolkit*, Boston 2003. M. Poppendieck, T. Poppendieck, *Implementing Lean Software Development: From Concept to Cash*, Upper Saddle River 2006.
11 B. Gładysz, *Zastosowanie wybranych technik Lean Management w* projektach, "Przegląd Organizacji" 2019 (1), s. 54.
12 *Ibidem*, p. 57.
13 K. Kaczor, *op. cit.*, p. 64.
14 *Jira Kanban Board*, https://kanbanboard.co.uk/jira-kanban-board (on-line 08.05.2025).

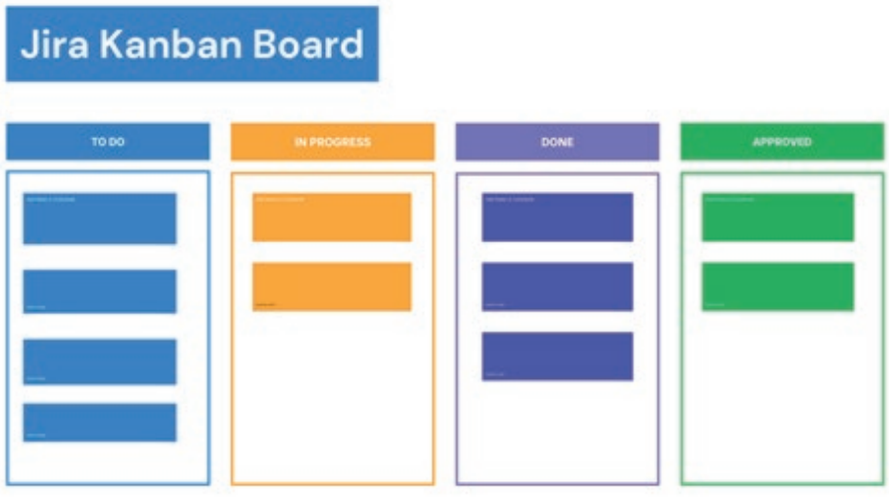

Fig. 1. Sample Kanban board

Another example of the use of Lean in IT is the pursuit of continuous improvement through ITIL. "ITIL is a reference model, a set of detailed practices used in IT service management, comprising five areas: (1) strategy, (2) design, (3) transition, (4) operation, and (5) continuous service improvement"[15]. By employing ITIL, organisations can benefit from better financial results and ongoing process enhancements. Table below, proposed by Bartłomiej Gładysz and based on the concepts of Zoltán Vajna, provides an overview of Lean tools in IT that originate from industry[16].

Tab. 1. Lean in IT versus Lean in production

Action	**Production**	**IT**	**Benefits in IT**
Value stream analysis	Value analysis VoC (Voice of Customer) VSM (Value Stream Mapping		Less complex systems Lower costs Task division Waste elimination
Elimination of waste	5S JiT (Just in Time) Kanban One-piece flow SMED (Single Minute Exchange of Die)	5S in the office Agile methodologies Outsourcing "Roadrunner", handing over tasks immediately upon completion)	Better alignment with needs Improved planning and delivery Greater flexibility
Elimination of variability	Heijunka	CFD (Cumulative Flow Diagrams) Agile methodologies Kanban in IT	More efficient use of resources Higher quality

15 *What Are ITIL Best Practices*, https://www.itsm-docs.com/blogs/itil-faq/what-are-itil-best-practices (on-line 08.05.2025).
16 B. Gładysz, *op. cit.*, p. 57.

Action	Production	IT	Benefits in IT
Pull system	Kanban	Iterative software development Kanban in IT Customer-tailored software	Lower working capital freeze and reduced work in progress Greater customer involvement Increased revenue
Focus on quality	Six Sigma Andon (visual control) CtQ (Critical to Quality) Poka-yoke (error-proofing) SPC (Statistical Process Control)	CtQ (Critical to Quality) SOA, modular software Monitoring systems Automated tests Automated data validation	Faster system delivery Higher software quality
Continuous improvement	Kaizen	CMMI ITIL	Cost savings Process improvements Increased knowledge

As the literature review shows, IT companies have long been adapting Lean practices from manufacturing systems to improve their processes and overall efficiency. This may suggest certain similarities in the challenges faced by organisations in different sectors and the shared roots of these problems. Since IT enterprises, like those in manufacturing, are characterised by high variability and susceptibility to external factors, the implementation of Lean Management practices can be an effective way to improve their operations. The following section of the article discusses examples of implementation of Lean methods in practice.

4. Case study: Spotify and Intel

The first organization analysed is Spotify, a Swedish company that offers digital platform providing music, podcast, and video streaming from around the globe. The second organisation under discussion is Intel, an American multinational corporation and technology enterprise that designs, manufactures, and sells computer hardware components. Both companies have long used Lean Management to improve work organisation. Spotify adopted the Lean Management approach to increase flexibility in its product development process. The company's primary objective was to rapidly introduce new solutions that would give its products an innovative edge to customers. "The company uses Lean thinking to eliminate unnecessary steps in its workflows, allowing cross-functional teams to focus on delivering value rapidly. Spotify's Lean-agile integration enhances its ability to respond swiftly to market demands, leading to better user satisfaction and engagement (Kniberg & Ivarsson, 2012). This approach ensures that teams are continuously improving processes, maintaining flexibility, and staying aligned with customer needs"[17]. In addition, Spotify introduced the Kanban method, which streamlines its software development process. By employing Kanban boards, teams can easily visualise their work, track progress, and detect potential workflow disruptions. Implementing Kanban boards has enabled Spotify to respond more quickly to customer feedback and

17 J. Chukwunweike, O. E. Aro, *Implementing agile management practices in the era of digital transformation*, "World Journal of Advanced Research and Reviews" 2024 (1), pp. 2234.

consequently introduce new features faster than its competitors[18]. The table below presents the primary improvements in these areas related to Lean[19].

Tab. 2 Spotify – Lean Key Performance Indicators

Area	Description	Reference to Lean
Organisational structure	Around 70–80 self-organizing, interdisciplinary squads functioning as "mini-startups" with end-to-end responsibility.	Small, autonomous teams with clear goals and responsibilities foster efficiency and rapid value delivery, eliminating the need for a large hierarchy
Culture and people	Emphasis on adaptability during hiring, strong relationships in teams, knowledge sharing in chapters and guilds	Engaged and skilled employees in a flexible structure encourage continuous improvement and innovation
Continuous development	Regular retrospectives at multiple levels, coaches identifying bottlenecks, TPD Operations team eliminating waste	An iterative approach to problem identification, resolution, and waste elimination
Innovation and market responsiveness	The "Discover Weekly" feature reached one billion streams in 10 weeks with high user engagement	Autonomous teams can rapidly experiment and implement innovations in response to user needs, basing on continuous feedback and frequent iterations

Table 2 shows that from the very beginning, Spotify built its organisation on Lean and Agile principles, as evidenced by its structure of small, autonomous teams, culture of continuous improvement, and strong focus on people. This approach allowed Spotify to grow rapidly, remain innovative, and respond effectively to market demands, exemplified by the tremendous success of its "Discover Weekly" feature.

Like Spotify, Intel also applies Lean Management, which in Intel's case has primarily been translated into optimising production processes by increasing operational flexibility and improving efficiency. The company's main goal was to implement improvements in production-line management and reduce the turnaround time on customer orders. Its continuous drive to improve processes and increase flexibility in managing organizational tasks has helped Intel solidify its leadership position in the semiconductor market[20]. Intel likewise adopted Kanban to visualize and manage processes. By depicting each production stage and controlling work-in-progress (WIP) limits[21], Intel improved its order delivery process while ensuring the quality of its products[22]. The table below illustrates the most significant improvements achieved through Lean[23].

18 *Ibidem*.

19 Author's own compilation based on K. Lindwall, *How music streaming giant Spotify stays successful*, https://www.planet-lean.com/articles/spotify-agile-leadership-lean, and M. Cagan, J. Sundén, *The Product Model at Spotify*, https://www.svpg.com/product-model-at-spotify/ (on-line 24.04.2025).

20 See J. Flinchbaugh, B. Carlino, *The Hitchhiker's Guide to Lean: Lessons from the Road*, Society of Manufacturing Engineers, Dearborn 2005.

21 WIP – a restriction on the amount of work that can be carried out at one time. Problems can be identified in the of tasks in terms of bottlenecks that hinder further stages of work.

22 J. Chukwunweike, O. E. Aro, *op. cit*.

23 Author's own compilation based on: *Inside Intel's Lean Manufacturing: How the Semiconductor Giant Stays Ahead of the Competition*, https://www.orcalean.com/article/inside-intel's-lean-manufacturing:-how-the-semiconductor-gi-

Tab. 3 Intel – Lean Key Performance Indicators

Area	Description	Reference to Lean
Production efficiency	62% decrease in production cycle time, 33% reduction in inventories (raw materials, work in progress, and finished goods)	Eliminating waste and optimising production processes directly contributed to reducing production time and lowering the capital tied up in inventory.
Supply chain responsiveness	Increase in confirming order changes within one business day, from 21% to over 70%, and reduction of order fulfilment lead time (OFLT) to one day	Initiatives such as "Just Say Yes", focused on rapid response to customer needs and the removal of bureaucratic barriers in order processing, thereby boosting supply chain responsiveness.
Quality and reliability	Achieving 96% perfect orders; 30% reduction in unplanned lithography tool downtime, enabled by predictive maintenance	Ongoing process refinement and a proactive approach to machine maintenance improved operational quality and reliability. The use of AI further supports these initiatives.
Process optimisation	25% reduction in wafer transport time through AMHS optimisation, 95% elimination of manual data entry in the planning process	Visualising workflow and automating processes contributed to better operational efficiency and reduced the risk of errors from manual work

The table illustrates how Intel's implementation of Lean Manufacturing has led to significant improvements in production efficiency, supply chain responsiveness, quality, and process optimisation. By focusing on waste elimination, rapid response to customer demands, and continuous improvement, Intel has solidified its status as a leader in the semiconductor market.

5. Conclusions

Lean Management is a method focused on eliminating waste, delivering high-quality products, and increasing organisational flexibility. Although its principles originate in the manufacturing sector, they are now applied across various industries, including IT. A review of the literature indicates that many types of waste found in manufacturing have parallels in the IT sector. As a result, numerous Lean tools have been adapted to the specific demands of IT teams. One of the key tools for Lean Management used in IT is the Kanban board, which helps teams to visualise work, set limits and identify potential issues in task execution. The Lean Management approach also appears in other popular IT management models. An example is ITIL (Information Technology Infrastructure Library), which emphasises the continuous improvement of processes – a principle that aligns with Kaizen philosophy, promoting the ongoing pursuit of process enhancement and elimination of inefficiency. An analysis of the Spotify and Intel case studies suggests that Lean Management provides tools enabling non-industrial companies to manage resources and projects more effectively. However, it is important to note certain limitations of this review

ant-stays-ahead-of-the-competition, and *Through Its Complete Cultural Shift, Intel Takes Top Spot in Supply Chain* Innovation Awards, https://www.supplychainbrain.com/articles/6789-through-its-complete-cultural-shift-intel-takes-top-spot-in-supply-chain-innovation-awards (on-line 24.04.2025).

of the literature. The analysis did not encompass all research on the implementation of Lean Management in the IT sector. Moreover, the case studies of Spotify and Intel address specific principles and tools, which may limit the generalisability of the results to other organisations. In addition, the effectiveness of the implementation of Lean Management can be influenced by individual factors, such as leadership commitment to change or employee resistance to the new approach, further complicating any broad conclusions. However, the use of Lean Management elements by companies with a well-established position in the IT sector suggests that the tenets of this methodology allow companies to enhance their ability to implement changes, rapidly react to emerging challenges, and adapt to dynamic market conditions – factors crucial for success in the modern world.

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QUANTUM INFORMATION SCIENCE AND THE MIND: STRUCTURAL MODELS OF CONSCIOUSNESS

INFORMATYKA KWANTOWA I UMYSŁ: STRUKTURALNE MODELE ŚWIADOMOŚCI

Agnieszka Matylda Schlichtinger[1]

Abstract: Consciousness remains an unresolved challenge in both science and philosophy, defying conventional physicalist explanations. Classical neuroscience, despite its advances in correlating brain activity with behaviour, fails to address the "hard problem" – why and how subjective experiences arise from physical processes. This study explores the potential of quantum information science to bridge this explanatory gap. Building on Orch-OR theory, which posits that consciousness emerges from quantum coherence in neuronal microtubules, this paper evaluates its feasibility in light of critiques concerning rapid quantum decoherence. Structural and mathematical models, including set theory, topology, and Clifford algebras, are examined for their capacity to model cognitive systems. Additionally, computational approaches, such as GPU-based simulations and quantum neural networks, are considered for their relevance to cognitive modelling. Although quantum theories of consciousness remain controversial, this interdisciplinary study synthesises insights from physics, mathematics, and neuroscience to assess their plausibility. It highlights the necessity for further empirical investigation and the development of hybrid quantum-classical models that might better encapsulate the complexity of conscious processes. Ultimately, this research contributes to ongoing efforts to integrate quantum mechanics and computational neuroscience in redefining the relationship between consciousness and physical reality.

Streszczenie: Świadomość wciąż stanowi nierozwiązane wyzwanie zarówno dla nauki, jak i filozofii, wymykając się konwencjonalnym, fizykalistycznym wyjaśnieniom. Klasyczna neuronauka, mimo postępów w łączeniu aktywności mózgu z zachowaniem, nie odpowiada na „trudny problem" – dlaczego i w jaki sposób subiektywne doświadczenia wyłaniają się z procesów fizycznych. Niniejsze opracowanie bada potencjał informatyki kwantowej w przezwyciężeniu tej luki eksplanacyjnej Bazując na teorii Orch-OR, która zakłada, że świadomość powstaje dzięki kwantowej koherencji w mikrotubulach neuronów, artykuł ocenia jej realność w świetle krytyki dotyczącej szybkiej dekoherencji kwantowej. Analizowane są również modele strukturalne i matematyczne – teoria mnogości, topologia oraz algebry Clifforda – pod kątem ich przydatności do modelowania systemów poznawczych. Dodatkowo rozważane są podejścia obliczeniowe, takie jak symulacje GPU oraz kwantowe sieci neuronowe, istotne dla modelowania poznawczego. Chociaż kwantowe teorie świadomości pozostają kontrowersyjne, niniejsze interdyscyplinarne studium syntetyzuje ustalenia z fizyki, matematyki i neuronauki, aby ocenić ich wiarygodność. Podkreśla ono również konieczność dalszych badań empirycznych i rozwoju hybrydowych modeli kwantowo-klasycznych, mogących lepiej uchwycić złożoność procesów świadomości. Ostatecznie praca ta wzbogaca trwające wysiłki na rzecz integracji mechaniki kwantowej z neuronauką obliczeniową w przeformułowaniu relacji między świadomością a rzeczywistością fizyczną.

Keywords: *Quantum information science, consciousness modelling, Orch-OR theory, quantum neural networks, computational neuroscience*

Słowa kluczowe: *Informatyka kwantowa, modelowanie świadomości, teoria Orch-OR, kwantowe sieci neuronowe, neuronauka obliczeniowa.*

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1. Introduction

Consciousness remains one of the most profound challenges in contemporary science and philosophy, raising questions that traditional frameworks have yet to answer. While classical neuroscience has significantly advanced our understanding of brain functions by correlating neuronal activity with behaviours, it has not addressed the "hard problem of consciousness"[2]. This problem probes why and how subjective experiences, or qualia, emerge from physical processes and why certain neural states are accompanied by these experiences while others are not[3]. This challenge underscores a conceptual divide between objective, measurable processes, such as synaptic activity, and subjective, first-person experiences, such as the perception of colour or the sensation of pain. Physicalist frameworks describe behaviour through causal closure within the physical domain, represented as $P_1 \rightarrow P_2$, where P_1 and P_2 denote successive physical states. However, the function $f: P \rightarrow E$, which would map physical states P to experiential states E, remains not only undefined but may also be fundamentally inaccessible within the framework of physicalist explanations. This mirrors Gödel's incompleteness theorems[4], which establish that any sufficiently expressive formal system contains true statements that cannot be proven within the system itself. Analogously, the explanatory gap between physical processes and subjective experience suggests that consciousness may reside in a domain that inherently transcends the descriptive power of physicalist models.

Quantum mechanics provides a promising avenue to bridge this explanatory gap. Penrose and Hameroff's Orchestrated Objective Reduction (Orch-OR) theory suggests that quantum coherence within neuronal microtubules underpins consciousness[5]. This model describes qua,ntum superpositions collapsing into conscious states through gravitational thresholds: $T \sim \hbar / E_G$, where T is the superposition lifespan, $\hbar$ is the reduced Planck constant, and E_G is the gravitational self-energy. These states are expressed as $\Psi = \alpha |P\rangle + \beta |Q\rangle$, with $|P\rangle$ and $|Q\rangle$ denoting physical and experiential states, respectively. This approach situates consciousness as an intrinsic aspect of quantum processes.

Beyond physics, structural models have emerged as complementary tools. Król and Schumann employ Zermelo-Fraenkel set theory (ZFC) to model consciousness as layered structures interacting within spacetime, presenting these as dynamically shifting systems influenced by both local and global interactions within physical reality[6].

Other contributions have built on the idea of dynamic interplay between mind and matter. John Bell's advocacy for incorporating real-time events into quantum theory, particularly through his emphasis on "beables" - things that fundamentally "are" - and the necessity of explicitly describing the flow of information within quantum systems, has laid the groundwork for exploring consciousness as a physically instantiated phenomenon[7]. These ideas align with Schlichtinger's

2 D. Chalmers, *Facing up to the problem of consciousness*, "Journal of Consciousness Studies" (3), 1995, pp. 200–219.

3 It is worth noting that the so-called "hard problem of consciousness" implicitly presupposes a particular ontological stance – namely, that consciousness arises from physical processes and is intrinsically linked to specific neurobiological states. In this sense, the question may be seen as somewhat question-begging, insofar as it assumes as given what remains philosophically and empirically contested: that consciousness is an emergent property of material complexity, rather than a fundamental or irreducible aspect of reality.

4 K. Gödel, *Über formal unentscheidbare Sätze der Principia Mathematica und verwandter Systeme I*, "Monatshefte für Mathematik und Physik" 1931, pp. 173–198.

5 S. Hameroff, R. Penrose, *Orchestrated reduction of quantum coherence in brain microtubules: A model for consciousness*, "Mathematics and Computers in Simulation" 1996 (3–4), pp. 453–480.

6 J. Król, A. Schumann, *The formal layer of {brain and mind} and emerging consciousness in physical systems*, "Foundations of Science" 2023, pp. 1–30

7 J. S. Bell, *On the impossible pilot wave*, "Foundations of Physics", vol. 12, no. 10, 1982, pp. 989–999.

perspective, which interprets consciousness and time as inherently relational constructs. Schlichtinger emphasises their co-evolutionary dynamics, suggesting that consciousness cannot be understood apart from its interaction with temporal and structural properties of reality[8].

Insights from neuroscience and computational models further deepen this perspective. Studies on neural engrams highlight parallels between memory encoding in neuronal ensembles and state preservation in quantum systems[9]. Similarly, cortical neurones have been likened to deep artificial neural networks, demonstrating computational complexity akin to quantum systems[10]. Quantum computational models, such as the Quantum Relief Algorithm[11], support the potential of quantum frameworks for simulating cognitive processes.

This study aims to critically evaluate these interdisciplinary approaches to consciousness, integrating quantum mechanics, mathematical models, and neuroscience to address the limitations of reductionist paradigms. Specifically, it seeks to examine the role of quantum processes in bridging the physical and experiential domains and to explore the potential of quantum information systems as analogues for cognitive and conscious processes. By synthesising these perspectives, the study proposes alternative frameworks that redefine the relationship between consciousness and the physical universe.

The methodology integrates critical analysis of existing theories with mathematical formalism and conceptual exploration. It examines the plausibility of quantum coherence in biological systems, evaluates mathematical models for emergent phenomena, and explores the integration of quantum information science into consciousness studies. Rather than advocating for a specific position, this work aims to assess the applicability of these interdisciplinary frameworks to bridge the gap between physical and experiential domains. The study ultimately seeks to provide a comprehensive overview of current approaches to consciousness, offering insight into their relevance for both natural and artificial systems.

2. Quantum approaches to consciousness

This section examines selected approaches to modelling consciousness on the grounds of quantum mechanics.

2.1 The Orch-OR theory: a foundation

The Orch-OR (Orchestrated Objective Reduction) theory establishes a framework where consciousness is rooted in quantum coherence and objective self-collapse of superpositions within neuronal microtubules. These microtubules, structured as crystalline lattices composed of tubulin dimers, are posited to act as quantum processors, enabling large-scale quantum coherence across neurones.

Quantum states in tubulins are maintained in superposition, allowing simultaneous potential states. The coherence grows over pre-conscious periods (up to 500 milliseconds), with the system collapsing when mass-energy differences between states reach a gravitational threshold. This collapse, termed Objective Reduction (OR), is intrinsic and non-random, marking the

8 A. M. Schlichtinger, *O koncepcjach czasu w neoplatonizmie i chrześcijaństwie oraz ich wpływie na współczesną fizykę: analiza strukturalna i relacyjna* "Theologica Wratislaviensia" 2024, pp. 157–186.

9 S. A. Josselyn, S. Köhler, P. W. Frankland, *Finding the engram*, "Nature Reviews Neuroscience" 2015 (9), pp. 521–534.

10 D. Beniaguev, I. Segev, M. London, *Single cortical neurons as deep artificial neural networks*, "SSRN Electronic Journal" 2020 (17), pp. 2727–2739.

11 W. J. Liu, P. P. Gao, Y. Wang *et al.*, *A unitary weights based one-iteration quantum perceptron algorithm for non-ideal training sets*, "IEEE Access" 2019, pp. 36854–36865.

transition from quantum pre-conscious computation to classical conscious experience. The unique integration of gravitational self-collapse prevents spatial-temporal anomalies, linking the phenomenon to quantum gravity.

Microtubule-associated proteins (MAPs) play a critical role by tuning and orchestrating quantum oscillations. These proteins act as nodes, influencing collapse probabilities and regulating information processing. This orchestration not only ensures coherent states but also connects pre-conscious quantum computations with neural activities like synaptic regulation and intra-neuronal signalling[12].

Orch-OR situates microtubules as quantum information processors that introduce non-computable elements into consciousness, bridging the explanatory gap between the physical processes of the brain and the subjective experience. By integrating principles of quantum mechanics, this theory provides a unique foundation for understanding consciousness as a fundamental and intrinsic aspect of the universe.

2.2. Critiques of the Orch-OR theory

Physicist Max Tegmark conducted calculations indicating that quantum states in the brain would decohere extremely rapidly, on the order of seconds, far shorter than the timescales required for neural processing[13]. This rapid decoherence challenges the plausibility of sustained quantum coherence as posited by the Orch-OR model; however, recent proposals explore whether certain biological mechanisms might mitigate this effect. One such hypothesis, proposed by Fisher, suggests that nuclear spins of phosphorus atoms in biochemical environments could maintain entanglement for biologically relevant timescales, potentially enabling quantum information processing in neural systems[14].

Furthermore, some studies speculate that microtubules might possess structural properties that shield quantum states from rapid decoherence through specific geometric configurations or interactions with surrounding biomolecules. While these hypotheses remain speculative, further experimental investigations into the persistence of quantum coherence in biological systems are necessary to assess the plausibility of quantum contributions to cognitive processes.

However, despite these theoretical possibilities, there remains skepticism within the neuroscience community. Researchers such as Christof Koch and Klaus Hepp argue that quantum mechanics does not play a significant role in neurophysiology. They contend that classical processes provide a sufficient basis for explaining neural activity associated with consciousness, making quantum explanations redundant[15]. This divergence of perspectives highlights the ongoing debate between proponents of quantum theories of mind and advocates of classical computational models.

Further experimental investigations have failed to provide evidence supporting the Orch-OR model. For instance, a 2022 study by Derakhshani *et al*. tested predictions of the theory related to spontaneous radiation but found no supporting data, thereby weakening the case for a quantum basis of consciousness[16].

12 This entire description is based on: S. Hameroff, R. Penrose, *op. cit*.

13 M. Tegmark, *Importance of quantum decoherence in brain processes*, "Physical Review E" 2000 (4), pp. 4194–4206.

14 M. P. A. Fisher, *Quantum cognition: The possibility of processing with nuclear spins in the brain*, "Annals of Physics" 2015 (362), pp. 593–602.

15 C. Koch, K. Hepp, *Quantum mechanics in the brain*, "Nature" 2006 (440), p. 611.

16 M. Derakhshani *et al*., *At the crossroad of the search for spontaneous radiation and the Orch OR consciousness theory*, "Physics of Life Reviews" 2022 (42), pp. 8–14.

These critiques highlight substantial challenges to the Orch-OR theory, emphasising the need for empirical validation and raising questions about the role of quantum mechanics in explaining consciousness.

2.3 Alternative quantum perspectives: insights for consciousness studies

Quantum mechanics, challenging classical determinism and locality, has inspired theories linking consciousness with quantum phenomena. Eugene Wigner's hypothesis posits that consciousness collapses the wavefunction, integrating subjective experience into physical theory, but lacks empirical support and a clear mind-matter interaction mechanism, relegating it to philosophical speculation[17].

The self-simulation hypothesis by Irwin *et al*. views the universe as a self-actualising informational loop, with consciousness both creating and emerging from recursive processes. This informational paradigm departs from materialism but faces limitations due to its lack of testable predictions[18].

Quantum information science advances computational models, applying concepts like entanglement and superposition to consciousness as emergent from formal systems, independent of biological substrates. Although innovative, these models face challenges in empirical validation and in capturing subjective experience.

3. Structural and mathematical models

Mathematics provides a rigorous framework for exploring consciousness by formalising its structural, dynamic, and informational aspects. This section discusses set-theoretic, algebraic and topological models of consciousness.

3.1. Set-theoretic modelling of conscious systems

Conscious systems can be effectively described using Zermelo-Fraenkel set theory with the axiom of choice (ZFC). A core concept of this approach is forcing extensions, which model the system's response to external stimuli. Forcing modifies a model M_i into a new model $M_i[G]$, where:

$$M_i[G] \supseteq M_i,$$

with G representing a generic ultrafilter. This extension captures how systems dynamically integrate new information from their environment[19]. Additionally, the system can be spatially distributed using regions, $U_i \subset \mathbb{R}^3$, with corresponding ZFC models:

$$S = \{(U_i, M_i) : i \in I\}.$$

Here S lescribes the global system, and M_i formalises the cognitive processes localised within each region.

17 E. P. Wigner, *Physics and the Explanation of Life*, "Foundations of Physics"1970 (1), pp. 35–45.

18 K. Irwin, M. Amaral, D. Chester, *The Self-Simulation Hypothesis Interpretation of Quantum Mechanics*, "Entropy" 2020 (22), pp. 1–26.

19 J. Król, A. Schumann, *op. cit*.

3.2. Topology and neural dynamics

Topology provides tools for understanding the structural properties of neural networks. Homology groups measure the topological features, such as loops or voids, in a space X:

$$H_k(X) = \frac{\ker(\partial_k)}{\mathrm{im}(\partial_{k+1})},$$

where ∂_k is the boundary operator acting on k-dimensional simplices. These groups are critical for identifying persistent patterns in neural dynamics. To study the evolution of these features over time, we use persistent homology, summarised in a persistence diagram:

$$D = \{(b_i, d_i) : i \in \mathbb{N}\},$$

where b_i and d_i represent the birth and death times of specific topological features. This approach enables the analysis of how neural activity changes dynamically.

3.3. Clifford algebras in microtubule modelling

Microtubules, hypothesised as computational units, can be mathematically described using Clifford algebras. Each tubulin dimer in a microtubule is modelled as a binary unit ("0" or "1"):

$$Cl(16) \cong Cl(8) \otimes Cl(8).$$

The Clifford algebra structure satisfies:

$$\{e_i, e_j\} = 2\delta_{ij},$$

where e_i and e_j are basis elements, and δ_{ij} is the Kronecker delta. This encoding allows the system to represent logical operations and computations, supporting the hypothesis of microtubules as quantum computational substrates[20].

3.4. Computational models and system dynamics

Information flow in neural networks is described by linear differential equations:

$$\frac{d\mathbf{x}}{dt} = A\mathbf{x},$$

where $\mathbf{x}$ represents the state vector, and A is the connectivity matrix. The eigenvalues of A determine the system's behaviour, such as stability or oscillations, aligning with patterns observed in conscious states. Integrated information theory (IIT), however, quantifies consciousness by measuring system integration:

$$\Phi = \sum_{S \subseteq N} I(S; N \backslash S),$$

20 T. D. Smith, *World-Line String Bohm Quantum Potential, E8, and Consciousness*, "viXra" 2015, paper no. 1512.0300, p. 1–17.

where $I(S; N\backslash S)$ is the mutual information between subsystems S and $N\backslash S$. A higher Φ value indicates greater system integration and complexity, characteristic of conscious processes[21].

3.5. Simplifying mathematical formalisms: intuitive explanations

While mathematical models provide a rigorous formalism for studying consciousness, some sections – particularly those involving set theory, topology, and Clifford algebras – may be challenging for readers unfamiliar with these fields. To clarify their relevance, a brief and intuitive explanation is warranted.

Set-theoretic models conceptualise consciousness as a structured hierarchy of interacting subsystems, where forcing extensions simulate cognitive adaptation to new information. Intuitively, this can be compared to how neural networks update their states in response to external stimuli, dynamically reorganising cognitive structures. *Topological approaches* capture the geometry of neural dynamics. Homology groups, for example, track the emergence and disappearance of patterns in neural activity over time, akin to how stable thought patterns form and dissolve in cognition. *Clifford algebras* model microtubule-based computations by representing tubulin dimers as binary units, enabling logical operations similar to those in artificial neural networks. This perspective suggests that microtubules might function as quantum information processors, potentially linking microscopic quantum states with macroscopic cognitive processes. From the perspective of category theory, consciousness can be seen as an emergent colimit in a higher-order category, where cognitive states are objects and their transformations form morphisms. Quotient categories naturally arise in the study of equivalence relations in cognitive state spaces, where distinct but functionally identical mental representations collapse into equivalence classes under categorical adjunctions. The transition between states, modelled as functors between categories, can be interpreted as cognitive state transitions driven by neural plasticity. Although these approaches remain highly abstract, they provide a mathematically rigorous framework that could, with advances in computational technology, inform practical implementations in neuromorphic computing, quantum-enhanced AI, and biologically inspired cognitive models. The integration of category-theoretic, algebraic, and topological structures into machine learning and quantum computation might eventually allow for a formalised, computationally viable model of consciousness, bridging the gap between abstract mathematical formalism and real-world cognitive systems.

4. Computational modelling of consciousness

Quantum computing introduces superposition, entanglement, and non-classical correlations into cognitive modelling. Quantum Neural Networks (QNNs) and Variational Quantum Eigensolvers (VQE) provide new frameworks for processing and optimising cognitive states. These approaches may bridge classical computation and quantum-enhanced models of consciousness.

4.1. Structural parallelism of CUDA cores and biological neural networks

In contemporary high-performance computing (HPC), parallel architectures, particularly those based on Graphics Processing Units (GPUs), provide an effective analogue to biological neural networks. Unlike traditional Central Processing Units (CPUs), which follow a von Neumann

21 G. Tononi, *Consciousness as Integrated Information: A Provisional Manifesto*, "The Biological Bulletin" 2008 (3), pp. 216–242.

architecture[22] and execute instructions sequentially, GPUs leverage a Single Instruction, Multiple Threads (SIMT) model, enabling large-scale parallel computations across thousands of cores[23].

This parallel structure closely resembles the way cortical neurones process information, where each neuron functions as an independent computational unit, exchanging data via synapses in a massively interconnected network. Formally, a GPU-based neural model can be described using a matrix-vector formulation:

$$\boldsymbol{Y} = f(\boldsymbol{X} \cdot \boldsymbol{W} + \boldsymbol{B}),$$

where $\boldsymbol{X} \in \mathbb{R}^{N \times M}$ is the input matrix (sensory data or activation potentials), $\boldsymbol{W} \in \mathbb{R}^{M \times K}$ represents synaptic weight matrices, $\boldsymbol{B}$ is the bias vector and $f(x)$ is a nonlinear activation function, such as the ReLU (Rectified Linear Unit):

$$f(x) = max(0, x).$$

This operation is highly optimised for CUDA-based tensor cores, enabling efficient execution of deep learning models in frameworks like TensorFlow or PyTorch, which utilise cuDNN (CUDA Deep Neural Network library) to accelerate forward and backward propagation[24]

A crucial metric for assessing computational efficiency is Floating Point Operations per Second (FLOPS), which serves as a standard benchmark for comparing CPUs, GPUs and Quantum Processing Units (QPUs). CPUs, traditionally optimised for sequential processing, exhibit lower parallel throughput compared to GPUs, which leverage massively parallel architectures. Unlike CPUs, which are designed for general-purpose computing with high clock speeds and complex instruction sets, GPUs excel in highly parallel computations, making them particularly effective for matrix operations, neural network training, and large-scale data processing. GPUs efficiently model neural computations due to their ability to handle sparse matrix multiplications using block-sparse kernel decompositions, a technique that significantly enhances computational efficiency in large-scale synaptic connectivity simulations. This is particularly relevant for deep learning applications, where optimised GPU kernels exploit sparsity in weight matrices to reduce memory overhead and improve computational speed. Research on block-sparse architectures has demonstrated significant gains in efficiency, particularly in training deep neural networks with structured sparsity, which reduces the number of active parameters while maintaining performance[25].

22 The von Neumann architecture is still the foundation of most modern computers, including multicore and multiprocessor systems. However, its limitations are leading to the search for alternative models, such as Harvard architecture, GPU or quantum computing. Ultimately, it is the way in which memory is organised and instructions are processed that determines whether a system can be considered compatible with the von Neumann model or whether it should be classified as a separate computing paradigm.

23 E. Lindholm, J. Nickolls, S. Oberman, J. Montrym, *NVIDIA Tesla: A Unified Graphics and Computing Architecture*, "IEEE Micro"2008 (2), pp. 39–55.

24 CUDA remains the foundational framework for GPU-accelerated computing, though its implementation has evolved with successive NVIDIA architectures. From Fermi and Kepler to Ampere, Ada Lovelace, and Blackwell, each generation has enhanced CUDA's capabilities while preserving its core conceptual foundation. Though newer architectures refine and extend CUDA's functionality, the term itself continues to define the overarching paradigm for parallel computing on GPUs.

25 A. Narang, G. Diamos, S. Sengupta, *Block-Sparse Recurrent Neural Networks*, "arXiv" 2017, pre-print, paper no.1711.02782, pp. 1–12.

Further, NVIDIA has pioneered the use of block-sparse formats in matrix multiplications, utilising Tensor Cores to accelerate deep learning workloads by efficiently computing structured sparse multiplications[26]. These techniques allow deep learning models to be trained with significantly reduced computational complexity, which is particularly relevant for high-performance computing (HPC) and artificial intelligence (AI) applications.

In contrast, QPUs provide an entirely different computational paradigm, leveraging quantum superposition and entanglement to perform certain types of computations exponentially faster than classical architectures. While still in the early stages of practical application, QPUs have demonstrated quantum supremacy in highly specialised tasks, such as simulating quantum mechanical systems and solving complex combinatorial optimisation problems[27]

As computational hardware evolves, the integration of GPU-accelerated deep learning with quantum-enhanced computation may unlock new capabilities for neuromorphic computing and large-scale cognitive simulations, bridging the gap between classical and quantum machine learning paradigms.

4.2. Extended explanation of CUDA, abstraction classes, and quotient categories in the context of consciousness

Let $C(i,j)$ represent the CUDA kernel computation executed on the thread (i,j). The computation given by:

$$C(i,j) = \sum_{k=1}^{M} X_{ik} \cdot W_{kj} + B_i.$$

represents a generalised matrix-vector computation, a fundamental operation in scientific computing, deep learning, and numerical simulations. The efficient execution of this operation in CUDA relies significantly on its structured memory hierarchy and the deployment of warps, where 32 threads function in unison. Within this execution paradigm, warp-level primitives, such as __shfl_sync and __ballot_sync, play a crucial role in facilitating seamless intra-warp communication, minimising the need for costly global memory accesses.

This can be interpreted categorically using the concept of quotient categories, where we treat each warp as an equivalence class of threads that behave as a single computational unit modulo synchronisation constraints. More formally, given a category C (representing all threads), we can define an equivalence relation ~ over morphisms (representing computation paths) such that $C/\sim$ denotes the quotient category, where individual threads collapse into equivalence classes defined by their warp-level synchronisations.

This quotient structure abstracts away individual thread interactions and allows us to study the computation at a higher level of abstraction, focusing on the warp as a whole rather than its individual components.

From the perspective of topos theory, we can view CUDA computations as objects in a categorical topos, where:

- Objects represent computational states,
- Morphisms model kernel transformations,

26 T. Yamaguchi, F. Busato, *Accelerating Matrix Multiplication with Block-Sparse Format and NVIDIA Tensor Cores*, https://developer.nvidia.com/blog/accelerating-matrix-multiplication-with-block-sparse-format-and-nvidia-tensor-cores/ (on-line 24.04.2025).

27 F. Arute *et al*., *Quantum Supremacy Using a Programmable Superconducting Processor*, "Nature" 2019 (574), pp. 505–510.

- Sheaves can encode distributed memory states.

In this setting, intra-warp communication corresponds to colimits (i.e., gluing of local computational structures), ensuring coherence in distributed execution.

The use of topos-theoretic models allows us to extend CUDA computation beyond classical von Neumann architectures into the realm of higher-order logic, intuitionistic mathematics, and even categorical formulations of consciousness.

By leveraging quotient categories, CUDA computation can be studied as a model of emergent behaviour, where threads form higher-order abstractions, much like neurones forming functional clusters in the brain. In this way, CUDA's execution model provides a concrete computational analogy to consciousness, where:

- Threads (neurones) synchronise via shared memory (synaptic transmission),
- Warps (functional clusters) act as emergent computational entities,
- Quotient categories model the abstraction process in cognition.

By extending this analogy to topos theory, we can explore consciousness as a logical structure emerging from distributed computational processes, drawing deeper connections between GPU architectures, categorical logic and emergent cognition.

4.3. Quantum information processing and its relevance to cognitive modelling

In contrast to classical parallel architectures, quantum computing leverages qubits, which exist in superposition states:

$$|\psi\rangle = \alpha\,|0\rangle + \beta\,|1\rangle,$$

where the probability amplitudes α, β satisfy:

$$|\alpha|^2 + |\beta|^2 = 1$$

Computation in a quantum processor is governed by unitary transformations:

$$|\psi'\rangle = U\,|\psi\rangle,$$

where U is a unitary matrix satisfying $U^\dagger U = I$. Unlike classical logic gates, quantum computation is represented via quantum circuits, using gates such as[28]:

- **Hadamard Gate (H)**:

$$H = \frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\ 1 & -1\end{bmatrix},$$

which enables superposition.

- **CNOT Gate (Controlled-NOT)**:

$$CNOT = \begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\\ 0 & 0 & 0 & 1\\ 0 & 0 & 1 & 0\end{bmatrix},$$

which entangles qubits.

28 M. A. Nielsen, I. L. Chuang, *Quantum Computation and Quantum Information*, Cambridge 2010.

4.4. Quantum algorithmic models for consciousness

Quantum-enhanced cognitive models can leverage several quantum algorithms:

- Grover's algorithm – associative memory search

Grover's search reduces search complexity from $O(N)$ to $O(\sqrt{N})$. It employs an oracle-based iteration:

$$G = (2|\psi\rangle\langle\psi| - I)O,$$

which amplifies the probability of correct solutions. This can be adapted to model associative memory retrieval in neural networks[29].

- **Quantum neural networks (QNN)**

A Quantum onvolutional Neural Network (QCNN) is defined as:

$$|\psi_{out}\rangle = U_{QCNN}|\psi_{in}\rangle,$$

where U_{QCNN} is a trainable quantum gate sequence analogous to weight matrices in classical deep learning[30].

- **Variational Quantum Eigensolver (VQE) for energy-based neural networks**

The VQE algorithm minimises quantum states to approximate eigenvalues, a mechanism suitable for energy-based consciousness models[31].

4.5. Hierarchical computation and quantum mechanics: toward a unified theory of cognition

The discussion of CUDA-based computation highlights how hierarchical parallelism and quotient categories enable efficient data processing, drawing parallels between GPU execution models and neural architectures. By interpreting warp-level synchronisation as a form of categorical abstraction, we gain insight into how complex systems, including biological cognition, can emerge from structured computational interactions. Furthermore, the application of topos theory suggests that CUDA execution can be framed within higher-order logical structures, providing a formal foundation for reasoning about distributed computation and its relevance to emergent cognitive processes.

Extending these principles into quantum computing, we recognise the potential of superposition, entanglement, and quantum parallelism in modelling cognitive states beyond classical architectures. Quantum associative memory, variational eigensolvers, and quantum neural networks (QNNs) offer novel frameworks for capturing probabilistic and non-local features of cognition. As computational paradigms evolve, the integration of GPU-accelerated deep learning with

29 L. K. Grover, *A Fast Quantum Mechanical Algorithm for Database Search*, "Proceedings of the 28th Annual ACM Symposium on Theory of Computing (STOC)", 1996, pp. 212–219.

30 S. Oh, C. Jaeho, K. Joongheon, *A Tutorial on Quantum Convolutional Neural Networks (QCNN)*, "IEEE Access", 2020 (8), pp. 188922–188940.

31 A. Peruzzo, J. McClean, P. Shadbolt *et al.*, *A variational eigenvalue solver on a photonic quantum processor*, "Nature Communications" 2014 (5), pp. 1–7.

quantum information processing may bridge the gap between classical and quantum machine learning, potentially unlocking new insights into the mathematical modelling of consciousness.

5. Conclusions

This study has examined the intersection of quantum information science, mathematical modelling, and neuroscience in addressing the limitations of reductionist approaches to consciousness. By integrating these perspectives, we have explored the potential for quantum processes to bridge the explanatory gap between the physical and experiential domains, evaluating whether quantum information systems could serve as computational analogues for cognitive and conscious processes. The findings suggest that consciousness may not be merely an emergent property of classical computation but could be deeply interwoven with quantum principles, challenging traditional assumptions in cognitive science.

A major insight of this research is the fundamental difference between classical and quantum computation in their ability to model cognitive processes. GPUs have been shown to effectively implement classical parallelism, facilitating large-scale artificial neural network computations, particularly in models of perception and memory encoding[32]. However, these architectures remain fundamentally deterministic and bitwise, which limits their capacity to capture non-local, probabilistic, and indeterminate aspects of cognition. In contrast, Quantum Processing Units (QPUs) introduce a paradigm shift by utilising superposition and entanglement, enabling exponentially parallel processing that classical systems cannot replicate efficiently. This computational advantage aligns with theoretical frameworks suggesting that cognitive states may operate as complex quantum systems, dynamically collapsing into classical experience through mechanisms akin to Orchestrated Objective Reduction (Orch-OR).

The consequences of this quantum paradigm for computational neuroscience extend beyond theoretical considerations. The integration of GPU-QPU hybrid architectures presents a promising approach for modelling large-scale cognitive systems, where classical processors handle deterministic, large-scale computations akin to synaptic weight adjustments, while quantum processors simulate probabilistic decision-making, non-local information integration, and high-level abstraction. This framework finds computational support in the development of Quantum Boltzmann Machines (QBMs) and Variational Quantum Neural Networks (VQNNs), which allow for adaptive learning in quantum-inspired cognitive models. Moreover, advancements in quantum programming frameworks, such as Qiskit, Pennylane and TensorFlow Quantum, facilitate the development of hybrid classical-quantum machine learning models, bridging the divide between traditional deep learning and quantum-enhanced cognition[33].

A crucial question remains regarding the physical realisation of quantum effects in biological systems, particularly whether quantum coherence can persist in the warm, noisy environment of the brain. While empirical studies have yet to definitively confirm the presence of sustained quantum states in microtubules or neural processes, models based on quantum brain dynamics and non-classical signal propagation continue to gain theoretical support. This suggests that future research must prioritise experimental validation of quantum effects in cognition, alongside the continued refinement of quantum-classical hybrid computational models.

32 N. P. Jouppi, C. Young, N. Patil *et al.*, *In-datacenter performance analysis of a tensor processing unit*, "Proceedings of the 44th International Symposium on Computer Architecture (ISCA'17)", 2017, pp. 1–12.

33 K. Mitarai, M. Negoro, M. Kitagawa, K. Fujii, *Quantum circuit learning*, "Physical Review A" 2018 (3), pp. 032309-1–032309-6.

Ultimately, this study highlights the emerging role of quantum information science in redefining consciousness as a computational phenomenon, moving beyond classical reductionist models towards a framework that integrates quantum principles into theories of cognition. While many challenges remain, particularly in empirical verification and computational scalability, the fusion of quantum mechanics, mathematical formalism, and computational neuroscience offers a non-reductionist yet rigorous approach to studying consciousness. The synthesis of quantum and classical models may represent a crucial step towards understanding consciousness as an emergent, self-organising system, leveraging the computational power of quantum mechanics to simulate the complexity of conscious experience.

While this study explores various quantum approaches to consciousness, a definitive conclusion on their validity remains elusive. The Orch-OR theory presents an intriguing framework linking quantum mechanics with cognitive processes, yet it faces significant challenges, particularly regarding the feasibility of sustained quantum coherence in biological environments. The critiques by Tegmark and others highlight the rapid decoherence timescales, which undermine the model's viability unless compensatory mechanisms exist. On the contrary, emerging quantum information models and hybrid quantum-classical architectures offer promising directions for computational simulations of cognitive processes.

Future research should focus on empirically testing the presence of quantum effects in neural processes, as well as refining mathematical and computational frameworks to determine whether quantum information can genuinely bridge the explanatory gap between physical processes and subjective experience. A more rigorous integration of classical and quantum paradigms may ultimately provide a more comprehensive model of consciousness, one that neither discards quantum principles outright nor assumes their necessity without experimental validation.

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