Inclusive Pedagogical Architecture in Action: Teaching Complex Systems to Visually

Arquitetura Pedagógica Inclusiva em Ação: Ensinando Sistemas Complexos a Pessoas com Deficiência Visual

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Abstract. This article presents an inclusive pedagogical architecture to support the learning of complex systems by visually impaired and/or blind students (VI). The framework utilizes the accessible virtual laboratory Netvoice, an extension of NetLogo, which incorporates auditory feedback and artificial intelligence (AI). Organized into five stages, the pedagogical architecture (PA) was tested with five students, including two with VI. Using Design Science Research (DSR) methodology, qualitative data analysis showed that the PA significantly contributed to the learning of complex systems concepts, enabling both sighted and VI students to independently explore computational models and promoting autonomy in the learning process.

Keywords: *Complex systems. Inclusive education. Visual impairment. Pedagogical architecture. Multi-Agent simulation.*

Resumo. *Este artigo apresenta uma arquitetura pedagógica inclusiva voltada para a aprendizagem de sistemas complexos por estudantes com deficiência visual (DV). A proposta utiliza o laboratório virtual acessível Netvoice, uma extensão do NetLogo, com recursos de sonificação e inteligência artificial (IA). A arquitetura foi organizada em cinco etapas e testada com cinco estudantes, incluindo dois com DV. Com base na metodologia Design Science Research (DSR), a análise qualitativa dos dados demonstrou que a arquitetura contribuiu* *significativamente para a compreensão dos conceitos de sistemas complexos e para o desenvolvimento da autonomia dos alunos, possibilitando a exploração independente dos modelos computacionais.*

Palavras-chave: *Sistemas complexos. Educação inclusiva. Deficiência visual. Arquitetura pedagógica. Simulação multiagente.*

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1. Introduction

Inclusive education seeks to provide a learning environment that meets the needs of all students, regardless of their physical or sensory limitations. However, in the context of science education, particularly in the learning of complex systems (CS), the inclusion of students with visual impairments (VI) still represents a significant challenge.

CS, characterized by the interdependence of their components and the emergence of collective behaviors (Garcia, 2006), require pedagogical approaches that allow for visualization and intuitive understanding of complex dynamics. Traditionally, this learning process is mediated by graphical representations and interactive visual simulations. In this scenario, the central problem arises: how can we ensure that students with VI are able to access, interpret, and interact with CS simulations under equitable conditions compared to their sighted peers?

This study addresses this problem by proposing a solution: an inclusive pedagogical architecture that integrates agent-based simulations with assistive technologies to support the learning of CS by students with VI. Agent-based simulation is particularly effective in representing the dynamics of CS, as it allows students to manipulate variables and observe the emergence of collective behaviors.

However, such simulations must be adapted to provide accessible resources that ensure not only participation but also the autonomy of students with VI in exploratory activities.

Thus, the research seeks to respond to a concrete educational need: the development of strategies that guarantee equitable access for students with VI to the study of CS.

Enabling them to interact with materials, collect data, make adaptations, and take an active role in their learning process. To achieve this, the study adopts the Design Science Research (DSR) methodology, which guides the design and evaluation of innovative educational artifacts.

Based on this proposal, the article is structured as follows: Section 2 presents the theoretical framework, covering the concepts of CS, agent-based simulation, inclusive education, pedagogical architecture (PA), and the assistive technologies employed. Section 3 details the research methodology, the application of DSR, the study participants, and the data collection procedures. Section 4 describes and discusses the results, highlighting the observed challenges and benefits. Finally, Section 5 presents the study's conclusions and its implications for educational practice.

2. Theoretical Framework

The theoretical framework of this study is grounded in inclusive education, artificial intelligence (AI), agent-based simulation, and the applied study of complex systems (CS).

2.1 Complex Systems

Complex systems are composed of interconnected components that exhibit unpredictable emergent behaviors. They are found in various fields of knowledge such as physics, biology, ecology, economics, and computer science, and are characterized by interactions among their components, which makes their behavior difficult to analyze using conventional methods (Holland, 1999).

These systems are adaptable and resilient, adjusting to environmental changes and recovering from external disturbances through feedback mechanisms (Nussenzveig, 1999). Understanding complex systems is essential for addressing social challenges such as climate change, pandemics, and economic crises (Yoon; Goh e Park, 2018).

Studying the emergent patterns and interaction processes within these systems helps to understand how they adapt, self-organize, and maintain balance in the face of disruptions. Due to their nonlinear and decentralized nature, these problems are particularly challenging (Bar-Yam, 2016). Agent-based simulation is an effective strategy for exploring the behavior of complex systems through computational models based on the interaction of multiple agents.

2.2 Agent-Based Simulation

Agent-based simulation enables the creation of models in which multiple agents interact in a decentralized manner, representing entities ranging from simple to more complex ones (Bordini; Vieira e Moreira, 2001). These agents follow internal behavioral rules, allowing for the simulation of an artificial world to explore hypotheses and repeat experiments in a safe and efficient way (Ferber, 1999). This approach facilitates the modeling of complex behaviors by considering both quantitative and qualitative properties of the system being represented, and it helps to understand dynamic processes (Wilensky e Rand, 2015).

2.3 Inclusive Education for Students with Visual Impairments

Inclusive education aims to ensure that all students, regardless of their abilities, have equal access to education. For students with visual impairments (VI), this involves adapting instructional materials and using assistive technologies such as screen readers, magnification software, and tactile devices.

Digital technologies are transforming pedagogical practices, especially in science education, by offering new forms of experimentation and hands-on learning. However, for students with VI, it is essential that resources are accessible and that pedagogical planning is adapted to ensure true inclusion.

Assistive Technology (AT) is defined as a range of services and resources that enhance the functional capabilities of people with disabilities, promoting independent living and social inclusion (Brasil, 2004). In educational contexts, AT addresses functional difficulties and promotes the active participation of students with disabilities (Bersch, 2008). Technology plays a fundamental role in people's lives, especially for those with visual impairments (Borges, 2003).

2.4 Pedagogical Architectures

Pedagogical Architectures represent structured learning proposals that integrate technologies to enhance teaching and learning processes. As defined by Menezes *et al*. (2013), Pedagogical Architectures (PA) are "structuring supports" for learning, combining genetic epistemology and pedagogical conception with technological tools, within an ecosystemic perspective. They support learners' development through the convergence of different components, such as pedagogical approaches, educational software, the Internet, artificial intelligence (AI), distance education, and conceptions of time and space.

According to Carvalho, Nevado and Menezes (2005), the curricular foundations of PA include open pedagogies that allow for adjustable and adaptable teaching proposals suited to different thematic approaches. In this sense, PA promotes learning through action and reflection, and the organization of learners' thinking through interaction with research objects and collaboration with peers. In this process, the teacher acts as a mediator, while students take on the role of protagonists in their own learning journey.

2.5 Design Science Research (DSR)

Design Science Research (DSR), proposed by Herbert Simon, is a research methodology focused on the creation and evaluation of innovative artifacts to solve practical problems. In the educational context, DSR can be used to develop and test new tools and teaching methods that promote inclusion and accessibility. DSR involves an iterative cycle of design, implementation, and evaluation, allowing for continuous adjustments based on user feedback. This ensures that the developed solutions are effective and meet the real needs of students and educators (Simon; Pereira, 2006).

2.6 NetLogo

NetLogo is a programming and modeling environment designed to study the behavior of decentralized complex systems. According to Wilensky *et al*. (2015), it is particularly well-suited for modeling systems that evolve over time, offering an easy-to-use approach for creating agent-based models.

NetLogo is composed of three types of agents: turtles, patches, and observers. Modelers can provide instructions to hundreds or even thousands of independent agents simultaneously, enabling the exploration of connections between micro-level behaviors and macro-level patterns that emerge from the interactions among these individuals. It uses its own modeling language, derived from the Logo programming language developed at the MIT Media Lab. As a free and open-source tool, it is highly accessible for academic and educational contexts

2.7 Artificial Intelligence

Artificial Intelligence (AI) has its roots in the pioneering work of Alan Turing in the 1950s, which explored the idea of machines being capable of thinking. Over the decades, AI has evolved into an interdisciplinary field that seeks to perform complex tasks that were traditionally reserved for humans. According to Baker *et al*. (2019), AI can be defined as the ability of computers to carry out tasks that simulate human cognitive processes in solving problems. This definition encompasses various techniques, such as machine learning, natural language processing, data mining, and neural networks.

Among the models and structures developed for implementing AI, generative models stand out. Generative Artificial Intelligence is a type of neural network capable of learning to generate text, images, and sounds based on user specifications. One example of Generative AI is the system developed by OpenAI, based on large language models (LLMs), which provides APIs for creating intelligent solutions.

An API (Application Programming Interface) is a set of rules and tools that enables organized communication between different software systems. The OpenAI API, as described by Catalano and Lorenzi (2023), defines a specification of the available functionalities to access and use OpenAI's natural language model. Through this interface, developers can integrate intelligent actions into their own systems.

3. Methodology

This research adopted the theoretical-methodological approach of Design Science Research (DSR), aiming to develop and evaluate the pedagogical architecture. Data collection was conducted in the Support Center for People with Special Needs (CAPNE) at the institution public technical high school located in the northern region of Brazil. The participants included three sighted students and two students with visual impairments (VI) from the integrated high school program, along with two science teachers who supported the evaluation of the learning process.

The study received approval from the Research Ethics Committee, under Opinion No. 6.761.359, with all participants and/or their guardians providing informed consent. Each student used an individual computer. Students with VI used computers equipped with the NVDA 2023.1 screen reader (NVDA, 2023) to access the activities, which were made available through online spreadsheets and text editors.

3.1 Data Collection and Recording Procedure

Data were collected through systematic observation, questionnaires, interviews, and audiovisual materials produced by the students. An interview protocol was also used to assess student learning regarding complex systems.

3.2 Research Stages

The implementation of the study followed a structured activity guide, including stages, challenges, and questions designed to support students' understanding of the content. To ensure accessibility for students with VI, Google Forms was used, enabling the use of screen readers, keyboard navigation, and the inclusion of image and table descriptions, as well as specific instructional prompts.

Instructions regarding how to interact with the pedagogical architecture were integrated into the activities, specifying what students could modify or activate within the simulation. All materials were made available in a virtual classroom hosted on Google Classroom, titled "Complex Systems Workshop". The process was carried out in five stages, as described below.

3.2.1 Stage 1 – Diagnostic Assessment

Two questionnaires were applied in this stage:

•A socioeconomic questionnaire, with ten questions (three open-ended and seven closed-ended), addressing personal information and the use of simulations in learning.

•A prior knowledge questionnaire, consisting of ten open-ended questions aimed at identifying students' understanding of complex systems (CS). The responses were classified into three categories: Adequate (A), Partially Adequate (PA), and Inadequate (I).

3.2.2 Stage 2 – Experimentation in the Accessible Virtual Laboratory

The teacher introduced the simulation using the Accessible Virtual Laboratory Netvoice (jacaúna *et al*., 2024). After the presentation, students received an activity guide containing questions and challenges to be completed individually.

Both sighted and VI students interacted with the virtual environment and recorded their observations. To ensure accessibility, VI students received auditory feedback indicating the values of variables in the simulation graphs. These data were automatically saved in a file, which could then be analyzed using a generative AI model from OpenAI.

To discourage students with VI from simply copying the activity questions into the AI prompt to obtain direct answers, 21 fixed questions were provided. These were designed to help them interpret the data from the "Simulação.csv" file generated by Netvoice. These questions aimed to make inaccessible information more understandable to VI students. During analysis, student responses were categorized in the same way as in Stage 1.

3.2.3 Stage 3 – Peer Review

Students assumed the role of reviewers, analyzing the arguments of two peers and providing constructive feedback to promote reflection and idea reconstruction. This process placed students in the role of mediators, a task typically performed by the teacher.

The peer reviews were classified according to Silva *et al*. (2021) into the following types:

• Agreement without suggestions for further development

• Agreement with suggestions for further development

• Disagreement without revision guidance

• Disagreement with revision guidance

• Attempted correction and/or presentation of a ready-made response

3.2.4 Stage 4 – Rebuttal

After the review cycle, each student resumed the role of argument presenter, analyzing the feedback received and elaborating a revised response.

Participants could either fully or partially accept the reviewer's suggestions, or disagree and justify their position. This process promoted critical reflection and encouraged students to reassess their arguments. The evaluation of changes in students' reasoning was conducted based on the framework proposed by Silva *et al*. (2021), which includes the following categories:

- Inclusion of new arguments
- Removal of arguments
- Argument elaboration
- Complete argument reconstruction
- No significant changes

3.2.5 Stage 5 – Collective Debate

During synchronous sessions, students presented their understanding of complex systems concepts, under the moderation of the teacher. Each participant had approximately five minutes to share their reflections. After the presentations, a collective debate was conducted, allowing all students to share insights and engage in collaborative discussion, thereby reinforcing the construction of shared knowledge.

Analysis and Categorization

The responses were transcribed, analyzed, and categorized according to predefined categories, such as understanding of interactions, system interconnections, critical thinking, understanding of unpredictability, and practical application. These categories were based on the conceptual framework proposed by Thurner, Hanel, and Klimek (2018), allowing for a comprehensive examination of how students' understanding of complex systems evolves throughout the process

4. RESULTS AND DISCUSSION

To analyze the implementation of the pedagogical architecture (PA), participants were invited to access the learning guide available in the virtual classroom, carry out the simulations, and record their observations in the corresponding forms for each stage.

4.1 Stage 1 – Initial Class Analysis

The responses obtained from the diagnostic questionnaire provided relevant information for the subsequent application of activities within the PA, which involved adapted computer simulations.

To assess students’ understanding of the relationships among system components, emergence, feedback, non-linearity, interaction, and self-organization, questions were designed to encourage reflection and the application of these concepts to real-life situations.

To protect the identity of participants, each student was assigned a code composed of the letter "A" (for "Aluno" – student) followed by a number. For example, the question “How does the individual behavior of an ant contribute to the collective behavior of the ant colony when searching for food?” was designed to prompt students to explain how individual ant behaviors interact to generate a collective outcome greater than the sum of its parts (Wilensky e Rand, 2015).

Most students demonstrated a solid understanding, with three students highlighting the interaction among ants in the search for food. For example:

A01: “It communicates through communication sensors or the trails it leaves behind.”

In the partially adequate category, two students identified relationships among the ants but attributed their behavior to a commanding figure, reducing the idea of emergent behavior. For example:

A04: “When an ant (the king) goes after food, most of the others follow, because walking in groups increases their chances of survival.”.

These responses served as an important starting point for later pedagogical interventions aimed at deepening scientific concepts. On the other hand, inadequate responses revealed the need to create learning situations that allow students to modify elements of the environment and integrate new concepts into their cognitive structure, thereby promoting conceptual change.

4.2 Stage 2 – Experimentation in the Accessible Virtual Laboratory

This stage addressed the concept of ecosystems, which are considered complex systems (Gkiolmas *et al*., 2013). Using the model “Wolf Sheep Simple 5” (Wilensky, 2007), the study evaluated whether participants understood the characteristics of complex systems. During the activity, students observed the simulation and the data generated, using the AI module to support and synthesize their observations.

In response to the question “How did the populations of prey and predators change over time?

Was there any observable pattern?", students provided responses that were categorized as adequate according to Wilensky e Rand (2015). For example - A04:

"The more the predators increase, the more the prey decreases, increasing the energy. The more the prey increases, the more the energy decreases. The more the energy increases, the more the prey increases. The more the energy decreases, the more the prey decreases, and so do the predators".

Students highlighted interdependent relationships and observed emergent patterns and feedback processes. These findings are consistent with Wilensky and Reisman (2006), who stated that predator-prey populations in such models tend to exhibit cyclical patterns over time.

In the partially adequate category, two responses described the relationship between species but did not fully address how population interactions and prey adaptation relate to system complexity. For instance:

A03: "As the populations decrease, new ones emerge to replace those that disappeared, and the same happens with the prey—they adapt.".

One inadequate response failed to consider the complexity of species interactions and the influence of environmental factors:

A02: "The wolves on the grassland left, and then only the sheep were left.".

The proposed challenges allowed students to explore different scenarios and observe, in real time, the consequences of changes within the ecosystem. This investigative approach contributed to the construction of complex systems concepts, helping students develop observation, data recording, reflection, and critical analysis skills. The activity aligns with Jean Piaget's theory of genetic epistemology, which emphasizes the active construction of knowledge through interaction with the environment.

4.2.1 Technical Challenges and Solutions

During the activity, one visually impaired student encountered difficulty using the AI query module, especially in accessing responses on the system interface. She did not realize that it was necessary to press the ESC key to exit the text input box and use the keyboard navigation keys to read the output.

4.3 Stage 3 – Peer Review

In this stage, we analyzed the peer review contributions submitted by students. In the first review task, five reviewers partially agreed with the arguments presented, but only one provided suggestions for improvement. The others did not offer additional insights. For example:

Reviewed: A01 – Reviewer 01: "I agree. When there is nothing left to consume, the wolves are forced to look for another area.".

Although the reviewer agrees with the student's observation and adds the idea of predator movement in search of food, they do not suggest a deeper exploration using the simulation tool.

The peer review process played an essential role in helping students analyze and enrich their observations on complex systems. Of the ten reviews examined, nine contributed to discussions that triggered cognitive disequilibrium. The remaining reviews had little effect, likely due to a more prescriptive tone or the presentation of ready-made answers, which limited further reflection. This highlights the importance of cooperative peer review as a valuable strategy for critical analysis and argumentative development.

4.4 Stage 4 – Rebuttal

We analyzed the evolution of the students' reasoning during the rebuttal stage. Four out of five students modified their initial arguments after receiving feedback, while one made no significant changes. The following is an example of a student's progression:

A03 – Initial observation: "As the populations decrease, new populations emerge to replace those that disappeared, and the same happens with the prey—they adapt.".

Rebuttal – Reviewer 2: "Yes, I agree... the dependency relationship is clear. In my view, my answer was correct but incomplete.".

Evolution of the response: inclusion of new arguments.

In the 80 rebuttals analyzed (two for each student), we observed that regardless of agreement or disagreement from the reviewers, most students enhanced their final responses with additional elements.

The frequency of each evolution category was as follows:

- Inclusion of new arguments: 41.67 percent
- Elaboration of arguments: 25 percent
- No significant changes: 33.33 percent
- General reconstruction of the argument: 16.67 percent

These results indicate that most students revised and improved their arguments after the peer review process, demonstrating the significant impact of this step on the development of reasoning. Although a few students maintained their original positions, in several cases the reviewers offered insights that led to a deeper or entirely reconstructed argument.

This underscores the active role of the student in knowledge construction, reflecting the constructivist perspective that learning is built through interaction with the environment and others (Piaget, 1986).

4.5 Stage 5 – Debate

Key insights from the participants regarding complex systems and their component interactions were highlighted. While all students contributed valuable perspectives, the following examples illustrate the diversity of experiences and understandings within the group.

Question: “After interacting with the predator-prey model in Netvoice, how did this experience help illustrate the concepts and interactions among individual components? Was there any specific insight you would like to share?” (Adapted from Mitchell, 2009).

A04 (17 years old, visually impaired):

“Using Netvoice with sound feedback and AI support was a really cool experience! It helped me understand how the components' actions affect the ecosystem. I was able to participate, control variables, and check the results. It was important to show how things are always changing. For example, when the whole sheep herd was there, then a wolf appeared, causing an imbalance because one wolf with another wolf produces a little wolf, and it needs to feed, so more wolves are generated”.

After the individual presentations, participants engaged in a collective discussion of the topics raised.

A01: “I found it amazing how small changes can affect the entire ecosystem. Small variations in the number of prey or predators can cause major imbalances. It all seems to come down to interactions among system members.”.

A03:

“I agree with A01. The importance of interactions among individual components is evident in all these examples. For instance, when there were many sheep and few wolves, the sheep population grew. But when there were too many wolves, the sheep population declined. This created a cycle of population highs and lows”.

Based on the analysis, participants' responses were found to be appropriate, meeting the established criteria. All students demonstrated a good level of understanding of complex systems interactions, applied critical thinking, and made connections with other complex systems, suggesting practical applications in real-life contexts.

5. Final Considerations

This study presented an Inclusive Pedagogical Architecture for the learning of complex systems, implemented through an accessible virtual laboratory called Netvoice, designed for students with visual impairments (VI) and/or blindness.

The results indicate that the pedagogical architecture significantly contributed to students' understanding of complex systems concepts. Both sighted students and those with visual impairments were able to explore computational models independently, benefiting from simulations in the virtual laboratory supported by artificial intelligence (AI) tools. These simulations proved effective in promoting student autonomy and fostering educational inclusion.

Future studies may explore the application of this architecture in other educational contexts and with a larger number of participants, in order to validate and expand upon the findings of this research.

A key aspect of the study was its alignment with inclusion and accessibility standards. The reflection on conducting laboratory experiences in science education using an inclusive approach highlighted the importance of considering the students' profiles, the available technologies, the content covered, the methodology adopted, the time required, and the sociopedagogical context.

This approach reinforces the importance of active exploration and inquiry-based learning in developing a solid understanding of the principles that govern complex systems in an inclusive manner. The use of accessible technologies and inclusive pedagogical methodologies is essential to ensure that all students, regardless of their visual limitations, have equitable access to knowledge and real opportunities to develop essential skills in the field of Science.

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