Adaptive Educational Content Generation: An Overview

A Survey of Adaptive PCG Techniques and Applications in Educational Environments

Marijn Timmerije[1]
Responsible Professor: Rafael Bidarra[1]
[1]EEMCS, Delft University of Technology, The Netherlands

A Thesis Submitted to EEMCS Faculty Delft University of Technology,
In Partial Fulfilment of the Requirements
For the Bachelor of Computer Science and Engineering
June 23, 2024

Name of the student: Marijn Timmerije
Final project course: CSE3000 Research Project
Thesis committee: Rafael Bidarra, Sicco Verwer

Abstract

This paper investigates the use of Adaptive Procedural Content Generation (APCG), a form of procedural content generation that is adjusted to a player model, to tailor educational content based on individual learner profiles, thereby improving engagement and consequent learning outcomes. Key research questions include how to measure the success of APCG, its impact on academic performance, and the comparative advantages over traditional PCG methods. Through a literature review, this study identifies current trends, methodologies, and challenges in the application of APCG in educational settings. A list of existing papers has been synthesized on the knowledge body that exists on APCG implementations. We present these findings together with their most relevant methods, domains, target demographics and conclusions to gain an insight in which research currently exists on it. The findings aim to provide insights for educators, game developers, and researchers on effective implementations of APCG, paving the way for more personalized and impactful educational technologies.

1 Introduction

Procedural Content Generation (PCG) is a method used in game development and various digital media to create game content algorithmically rather than manually. By using algorithms, PCG can generate vast amounts of game assets, such as levels, maps, characters, and items, dynamically and efficiently. This approach not only enhances replayability and variety but also reduces development time and costs.

Within the field of educational and serious games, the integration of Procedural Content Generation (PCG) exists as a growing field of exploration and innovation. As technology continues to advance, the potential for PCG to improve learning experiences has become increasingly apparent. Existing research highlights the benefits of PCG in creating dynamic and engaging learning environments, such as increased student motivation and personalized learning experiences.

Despite these advances, there remains a need for a deeper understanding of how PCG can be effectively utilized in educational games, as generating content with an inappropriate difficult does not lead to improved learning outcomes [5]. Adaptive Procedural Content Generation (APCG), which tailors content based on player models, promises to further enhance learning by catering to individual learning styles and providing interactive methods for skill development. Understanding which educational games effectively employ PCG, and how APCG enhances this process, holds significant implications for instructional design and educational technology development.

This research addresses several key questions within the realm of PCG use in educational games. Specifically, we explore:

- How can we measure successful PCG use?
- What is the impact of PCG on users' academic performance?
- Are there similarities between the games in which PCG finds success?
- What are the benefits of APCG over traditional PCG?
- Where does APCG excel?

Through a comprehensive literature review, we aim to synthesize existing knowledge and identify patterns and trends within the realm of educational gaming. By examining a diverse array of sources, we seek to gain insights into the effectiveness of PCG and the potential benefits of APCG in enhancing learning outcomes.

There are existing literature reviews on PCG itself, such as [4], but these are primarily focused on the use on PCG itself, without a focus on education or adaptive methods.

The conclusions drawn from this research will contribute to a better understanding of the role of PCG in educational gaming and provide valuable insights for educators, game developers, and researchers alike. By elucidating the successes and challenges of PCG implementation, we aim to inform future efforts in the design and development of educational games that effectively leverage procedural content generation to create engaging and impactful learning experiences.

2 Methodology

To conduct this research, we employ a literature review. This method is chosen because it allows us to systematically analyze and synthesize the existing body of work on PCG in education, providing a thorough understanding of the current state of the field.

2.1 Search and Selection

The literature review process begins with a systematic search for relevant studies. We use databases such as Google Scholar and IEEE Xplore and other sources offered by TU Delft's library to gather literature. Keywords used in the search include "Procedural Content Generation in education," "APCG," "serious games," "educational technology," and "game-based learning."

To ensure the relevance and quality of the literature, we apply the following inclusion criteria:

- Studies published in peer-reviewed journals or conferences.
- Studies focusing on the application of PCG in educational or serious games.
- Research discussing APCG and its impact on learning outcomes.

Papers that focus on APCG speciifcally were of special interest.
We also employ some exclusion criteria such as:

- Studies not written in English.
- Papers that are low quality or are not good fits for our area of interest.

2.2 Analysis and Synthesis

Once the relevant literature is gathered, the next step is to critically analyze and evaluate the findings. This involves summarizing key themes, methodologies, and results from the selected studies. We compare different perspectives, methodologies, and findings to identify patterns, strengths, and weaknesses in the existing body of work.

3 Background

In recent years, the integration of technology into educational practices has revolutionized the way students learn and educators teach. Among these technological innovations, Adaptive Procedural Content Generation (APCG) has emerged as a promising approach to enhancing personalized learning experiences in educational games.

3.1 Educational Games and Personalized Learning

Educational games, also known as serious games, have gained popularity as effective tools for engaging students and facilitating active learning. These games leverage game mechanics and interactive simulations to deliver educational content in a dynamic and engaging manner. By incorporating elements of challenge, exploration, and discovery, educational games provide students with opportunities to apply and reinforce their knowledge in authentic contexts.

3.2 The Role of Procedural Content Generation

Procedural Content Generation (PCG) techniques are widely used in game development to create dynamic and diverse game environments. By algorithmically generating game content such as levels, characters, and challenges, PCG enables developers to create infinitely replayable and adaptive experiences. In the context of educational games, PCG offers the potential to tailor learning content to the individual needs and preferences of each student, thereby promoting personalized learning outcomes.

3.3 Adaptive Procedural Content Generation

Adaptive Procedural Content Generation (APCG) builds upon the foundation of PCG by incorporating adaptive learning techniques to dynamically adjust the generated content based on the learner's performance and preferences. By continuously monitoring the learner's interactions and progress, APCG systems can adapt the difficulty, complexity, and pacing of the game content to match the learner's skill level and learning trajectory. This personalized approach to content generation ensures that each student receives a tailored learning experience that maximizes engagement and learning outcomes.

3.4 Theoretical Frameworks and Methodologies

In our analysis, we draw upon established theoretical frameworks and methodologies in the fields of adaptive learning systems and intelligent tutoring systems to inform our understanding of APCG in educational contexts. These frameworks provide valuable insights into the design, implementation, and evaluation of adaptive learning technologies, guiding our exploration of the role of APCG in personalized learning environments.

3.5 Objectives of the Study

In this paper, we aim to provide a structured and comprehensive overview of the existing literature of APCG in educational games. By analyzing the methodologies, educational contexts, types of APCG techniques, and evaluation metrics employed in existing studies, we seek to identify trends, challenges, and opportunities in the application of APCG for personalized learning. Our systematic approach ensures that our findings are grounded in

rigorous analysis, providing valuable insights for educators, game developers, and researchers seeking to leverage APCG to enhance learning experiences.

4 Responsible Research

In conducting this literature review, it is important to adhere to principles of responsible research and ethics. This ensures the integrity of our findings and respects the intellectual contributions of previous researchers.

Respecting intellectual property rights is fundamental to our research ethics. All sources are appropriately cited, and the contributions of original authors are duly acknowledged. We have taken care to accurately present the context and content of cited works without distortion or misrepresentation. Proper citation practices not only give credit to original authors but also allow readers to trace the origins of ideas and findings, fostering a transparent scholarly dialogue.

Another ethical obligation we adhered to is to maintain honesty and transparency throughout the review process. This involves accurately representing the findings, methodologies, and conclusions of the studies reviewed.

While our review does not involve the direct collection or processing of data, we critically evaluate the ethical standards of the studies we review.

By adhering to these ethical principles, we strive to conduct a literature review that is rigorous, respectful, and responsible, contributing valuable insights to the field of APCG in education.

5 Literature Review

In this section, we provide an overview of the existing literature on APCG in educational and serious games. The literature review aims to organize the existing body of research and implementations of APCG.

The focus here lies primarily on more modern implementations of APCG, so entries from previous work such as listed in [2] will not be mentioned.

5.1 List of Implementations

Technology	Education Domain	Target Audience	Relevant papers
APCG	Social Skills	Children	SIREN [12]
	Mathematics	Children	Refraction [10]
	Emergency Scenarios	Firefighters	FCVTE [3]
APCG and DCGAN	Logic Puzzles	Children	ENGAGE [7].
APCG and NSFI-2Pop	Planning/sequencing	Children	Knight Tour [9]

Table 1: Implementations of Adaptive Procedural Content Generation

5.2 Closer look at APCG Implementations

In this section, we take a closer look at the games from Table 1 that employed APCG to enhance the educational experience. We will discuss the specific adaptive techniques used, the types of educational content generated, target audience and the observed outcomes from these implementations.

5.2.1 Refraction

An educational puzzle game that has the player split laser beams to power spaceships, thereby teaching them concepts of fractions, division, and spatial reasoning [10]. It dynamically adjusts the difficulty of puzzles based on the player's progress and understanding. An interesting element that was mentioned was that it independently seems to tweak the difficulty of the puzzle itself and the underlying mathematical statements. It has been mentioned in multiple studies such as [1]

5.2.2 Siren

This is an educational game focused on teaching children and young people learn and practice social skills, particularly those related to conflict resolution [12]. It employs APCG to create scenarios that are tailored to the player's interactions and choices.

The study found that SIREN was effective in helping children develop conflict resolution skills, with adaptive PCG playing a significant role in maintaining engagement and providing a personalized experience.

5.2.3 ENGAGE

ENGAGE is an educational game designed to teach block-based programming concepts to students. This game uses multistep deep convolutional Generative Adversarial Networks (GANs) to create an adaptive experience [7]. ENGAGE dynamically generates and adjusts programming challenges based on the individual student's performance and learning pace. [6]

The primary focus of ENGAGE is to make students solve block-based programming challenges. These challenges are presented in a visual, drag-and-drop interface, making programming more accessible and less intimidating for beginners. The adaptive nature of the game ensures that each student encounters tasks that are neither too easy nor too difficult, promoting an optimal learning experience. This game uses multistep deep convolutional GAN's to create an adaptive experience [7]. It primarily focuses on making the student solve block-based programming challenges.

5.2.4 Knight Tour

This is a small game in which the player is taked with planning/sequencing tasks by solving problems through the knight's movements on the chessboard [9]. It is primarily aimed at younger learners and uses a constrained multi-objective algorithm (NSFI-2Pop) to generate puzzles in an adaptive way, based on the player's performance.

5.2.5 Firefighter Command Virtual Training Environment

This explores the development of adaptive learning environments tailored to emergency scenarios [3]. Through dynamic scenario adjustment and personalized learning paths, the framework enhances emergency response skills and situational awareness.

6 Discussion

In this paper, we have gone over various different implementations and methods of APCG. It has been shown that there exists a variety of fields where the methods find success when applied.

As highlighted in [8], tailoring the difficulty level to the learner enhances knowledge acquisition, and adaptive methods can similarly be employed to optimize the intake of information through procedurally generated content.

Several interesting elements and contributions have shown themselves during this study. One of these interesting elements, is that certain games, such as Refraction (5.2.1) and ENGAGE (5.2.3) show up in multiple papers as well as that there are distinct patterns in which areas are most likely to see APCG (and PCG in general) use.

6.1 Measuring Successful APCG Use

One method of measuring successful APCG use involves evaluating learner engagement and satisfaction levels. By assessing factors such as retention rates, completion rates, and user feedback, researchers can gauge the effectiveness of APCG implementations in educational settings.

6.2 Impact on Academic Performance

Research indicates that APCG has the potential to positively impact users' academic performance by providing tailored learning experiences. Early studies have shown correlations between adaptive learning environments and improved student outcomes, suggesting that APCG could similarly enhance academic achievement.

6.3 Similarities Between Successful APCG Games

When comparing the different games in the existing literature body it can be observed that there are some similarities between games where PCG and APCG are applied. The greatest commonality between the application targets of APCG seems to be that most of them are used for STEM (mathematics in particular) education historically. There is a possibility that this area in particular sees a lot of successful and widely adopted implementations because mathematics and other STEM subjects often have problems that are more easily procedurally generated because of a lack of need to perform natural language processing and there being clear correct and incorrect answers, making adapting to learner development more easily quantifiable.

However, in recent times succesful implementations such as Siren (covered in 5.2.2) have explored fields such as communication that were traditionally not covered. Despite these innovations, it does seem that till this day APCG finds most application in the STEM subjects, especially in areas where repetition and problems with clear answers. This is

seems even more obvious when we consider succesful implementations that are not part of the literature or that are older, such as ALEKS [11]

6.4 Benefits of Adaptive PCG Over Traditional PCG

Compared to traditional PCG methods, APCG offers several advantages, including increased learner engagement, improved learning outcomes, and enhanced retention rates. By dynamically adjusting content in real-time, APCG can address individual learner needs more effectively, leading to greater educational efficacy.

6.5 Areas Where APCG Excels

APCG excels in creating personalized learning experiences that adapt to individual learner characteristics and preferences. By leveraging adaptive algorithms and real-time feedback mechanisms, APCG can tailor educational content to match the skill levels and learning trajectories of users, thereby maximizing engagement and facilitating deeper learning as well as preventing users from getting stuck or bored.

7 Conclusion

Although the research is ongoing, preliminary insights suggest that Adaptive Procedural Content Generation has potential for enhancing learner engagement and improving educational outcomes. By dynamically adjusting content to meet the needs of individual learners, APCG can create more effective and personalized learning environments.

Future research should explore the long-term impact of APCG on academic performance and learner retention as some of the papers seem fairly inconclusive in that area. Investigating the integration of APCG with emerging technologies such as artificial intelligence and machine learning could also offer new avenues for innovation. By addressing these challenges and exploring new questions, we can further enhance the capabilities of APCG and its application in education.

References

[1] E. Andersen. Optimizing adaptivity in educational games. pages 279–281, 2012.

[2] P. Brusilovsky and C. Peylo. Adaptive and intelligent web-based educational systems. *International Journal of Artificial Intelligence in Education*, 13(2-4):159–172, 2003.

[3] Nicola Capuano and Richard King. Adaptive Serious Games for Emergency Evacuation Training. In *2015 International Conference on Intelligent Networking and Collaborative Systems*, pages 308–313, September 2015.

[4] Mark Hendrikx, Sebastiaan Meijer, Joeri Van Der Velden, and Alexandru Iosup. Procedural content generation for games: A survey. *ACM Transactions on Multimedia Computing, Communications, and Applications*, 9(1):1:1–1:22, 2013.

[5] Benny Hansen Lifindra, Darlis Herumurti, and Imam Kuswardayan. The Effects of Mathematics Game-based Learning with Random Maze Generation. In *2023 International Seminar on Application for Technology of Information and Communication (iSemantic)*, pages 69–74, September 2023.

[6] K. Park, B. Mott, W. Min, E. Wiebe, K.E. Boyer, and J. Lester. Generating Game Levels to Develop Computer Science Competencies in Game-Based Learning Environments. *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, 12164 LNAI:240–245, 2020. ISBN: 9783030522391.

[7] Kyungjin Park, Bradford W. Mott, Wookhee Min, Kristy Elizabeth Boyer, Eric N. Wiebe, and James C. Lester. Generating Educational Game Levels with Multistep Deep Convolutional Generative Adversarial Networks. In *2019 IEEE Conference on Games (CoG)*, pages 1–8, August 2019. ISSN: 2325-4289.

[8] J.L Plass, B.D. Homer, S. Pawar, C. Brenner, and A.P. MacNamara. The effect of adaptive difficulty adjustment on the effectiveness of a game to develop executive function skills for learners of different ages. *Cognitive Development*, 49:56–67, January 2019.

[9] Marco Scirea. Adaptive Puzzle Generation for Computational Thinking. In Xiaowen Fang, editor, *HCI in Games*, volume 12211, pages 471–485. Springer International Publishing, Cham, 2020. Series Title: Lecture Notes in Computer Science.

[10] Adam M. Smith, Erik Andersen, Michael Mateas, and Zoran Popović. A case study of expressively constrainable level design automation tools for a puzzle game. In *Proceedings of the International Conference on the Foundations of Digital Games*, pages 156–163, Raleigh North Carolina, May 2012. ACM.

[11] Holly Stillson and John K. Alsup. Smart aleks ... or not? teaching basic algebra using an online interactive learning system. *Mathematics and Computer Education*, 37:329, 2003.

[12] Georgios Yannakakis, Julian Togelius, Rilla Khaled, Arnav Jhala, Kostas Karpouzis, Ana Paiva, and Asimina Vasalou. Siren: Towards Adaptive Serious Games for Teaching Conflict Resolution. *4th European Conference on Games Based Learning 2010, ECGBL 2010*, December 2010.