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Adaptive learning: a cluster-based literature review (2011–2022)

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Abstract. Adaptive learning is a personalized instruction system that adjusts to the needs, preferences, and progress of learners. This paper reviews the current and future developments of adaptive learning in higher education, especially in relation to the digital education strategy of the European Union. It also uses a cluster analysis framework to explore the main themes and their relationships in the academic literature on adaptive learning. The paper highlights the potential of emerging technologies such as AI, eye-tracking, and physiological measurements to improve the personalization and effectiveness of adaptive learning systems. It presents various methods, algorithms, and prototypes that incorporate learning styles into adaptive learning. It also stresses the importance of continuous professional development in e-learning, media literacy, computer security, and andragogy for teachers who use adaptive learning systems. The paper concludes that adaptive learning can promote creativity, innovation, and lifelong learning in Ukrainian higher education, but it also acknowledges the challenges and suggests further research to assess its impact.

Keywords: adaptive learning, cluster-based literature review, adaptive systems, cluster analysis, artificial intelligence, learning styles, personalized learning, e-learning, learning experience

1. Introduction

Education is regarded as a fundamental pillar in Ukraine, encompassing intellectual, moral, physical, and cultural development, as well as fostering social integration, economic well-being, and national progress. The Law on Education underscores the goal of comprehensive human development, emphasizing the significance of responsible citizenship, enriched potential, and sustainable development aligned with Ukraine's European aspirations [191].

Within the realm of higher education, competent teaching staff plays a vital role. The Strategy for Higher Education Development in Ukraine emphasizes the enduring relevance of professions related to healthcare, education, creativity, and personalized services, as they remain irreplaceable by automated systems, even with the advent of artificial intelligence. [22].

The Strategy also sets objectives for higher education, including "ensuring high-quality education and scientific activity and offering competitive and accessible education for diverse segments of the population" [22]. To achieve these goals, it emphasizes equipping institutions

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with digital infrastructure, promoting innovative technologies, and employing modern teaching aids to enhance the educational process [22].

The attractiveness of Ukrainian higher education institutions on the international stage is crucial. Hence, another strategic goal is to enhance attractiveness by implementing student-centered learning and innovative technologies, which will contribute to academic careers and facilitate the pursuit of knowledge [22].

Law of Ukraine "On Higher Education" classifies teacher training and retraining institutions into four types: branch-oriented (pedagogical) universities, academies, institutes, and colleges [190]. However, the Concept of Development of Pedagogical Education highlights an existing imbalance between the demand for highly qualified teaching staff, the evolution of society, technological advancements, and the current pedagogical education system. Addressing this issue is imperative [128]. The Concept emphasizes the necessity to bridge the gap between the critical professional competencies of pedagogical graduates and the demands of the digital society. It proposes solutions such as continuous professional development in e-learning, media literacy, computer security, and andragogy. It also advocates for aligning pedagogical professionals' digital competence methods with applicable standards [128].

Considering Ukraine's integration into the European Union, it is essential to align with the EU's strategic direction for digitalization in higher education. The Digital Education Action Plan for 2021-2027 emphasizes digitally competent teachers and staff, high-quality learning content and platforms, digital literacy, and knowledge of data-intensive technologies, including artificial intelligence [43].

The recent challenges faced by Ukrainian educators during the COVID-19 pandemic and Russia's invasion of Ukraine have highlighted the urgency for digital competence and emergency distance education [94, 95]. The education community has shown resilience and adaptability, organizing itself to ensure continuous learning across all levels. This experience has sparked interest in flexible and innovative professional development models, where educators learn from one another.

Moreover, the emergence of technologies like AI, virtual and augmented reality, and social robotics poses new challenges and opportunities for educators [21, 52, 189]. They must take an active role in designing and implementing these tools to ensure their effectiveness, desirability, and inclusiveness [32].

Overall, there is a need for the development and testing of new pedagogies and techniques. Investigating the seamless integration of emerging technologies into existing teaching practices is crucial. Adaptive learning, facilitated by technology, represents a prominent application of AI in education, supporting personalized and effective learning experiences [86].

The following are some of the research gaps in adaptive learning in higher education from both international and national perspectives:

1. There is a need for *more understanding of the interaction between brain and technology, the improvement of the emotion domain model, the integration of education and technology, and the protection of data security and privacy* Li, He and Xue [102].
2. There is a scarcity of research on the *effectiveness of adaptive learning across different cultural contexts.* Most of the existing research on adaptive learning has been done in Western countries, and it is uncertain whether the same findings would apply to other

cultural settings. For instance, a study by Li, He and Xue [102] showed that adaptive learning was more effective for Chinese students than for American students. Another study by Muñoz et al. [132] showed that adaptive learning was more effective for Spanish students than for English students.

3. There is a lack of research on the *use of adaptive learning for different types of learners*. Adaptive learning systems are usually designed to suit the needs of a specific kind of learner, such as a novice or an expert learner. However, there is little research on the effectiveness of adaptive learning for different kinds of learners. For example, a study by Badhe, Banerjee and Dasgupta [13] showed that adaptive learning was more effective for self-regulated learners than for non-self-regulated learners.
4. There is a lack of research on the *long-term impact of adaptive learning*. Most of the research on adaptive learning has focused on short-term outcomes, such as student achievement. However, there is limited research on the long-term impact of adaptive learning, such as its impact on student retention or graduation rates.
5. There is a lack of research on the *cost-effectiveness of adaptive learning*. Adaptive learning systems can be expensive to develop and implement. It is important to understand the cost-effectiveness of adaptive learning before it can be widely adopted.
6. There is a lack of research on the *ethical implications of adaptive learning*. Adaptive learning systems collect a lot of data about students, and it is important to understand the ethical implications of this data collection.

These studies are similar to ours in that they all focus on the research of adaptive learning in higher education. However, they differ in their specific focus. For example, the study by Kabudi, Pappas and Olsen [86] focuses on AI-enabled adaptive learning systems, while the study by Alajlani, Crabb and Murray [4] focuses on the role of stakeholders in developing adaptive learning systems.

Our review stands out due to its utilization of unique sources that have not been previously discussed. These include numerous technical reports and theses from the National Repository of Academic Texts (Ukraine, URL: https://nrat.ukrintei.ua/en/), which were first made available to the world in 2022.

Our review follows a cluster-based literature approach, and thus, our primary research question is: "What are the key thematic clusters and trends in the literature on adaptive learning in higher education based on keyword analysis, and how do these clusters relate to each other?"

After this introduction, we will proceed with the bibliometric review (section 2), where we will explore the main research concepts divided into five clusters. Following this, in section 3, we will elaborate on our research findings, supplemented by an extensive discussion. Finally, we will wrap up with a summary of our significant insights and implications.

2. Bibliometric review

To systematize available scientific knowledge, a bibliographic analysis was conducted using the VOSviewer [23]. In order to carry out the analysis, a selection of sources from the scientometric database Scopus was made upon request:

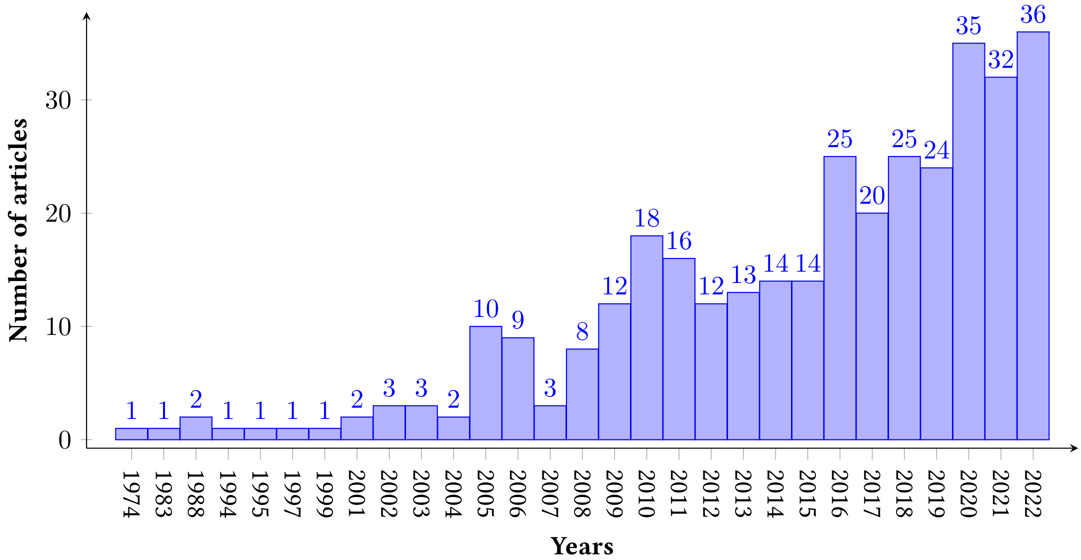

Figure 1: Distribution of articles from Scopus database by years.

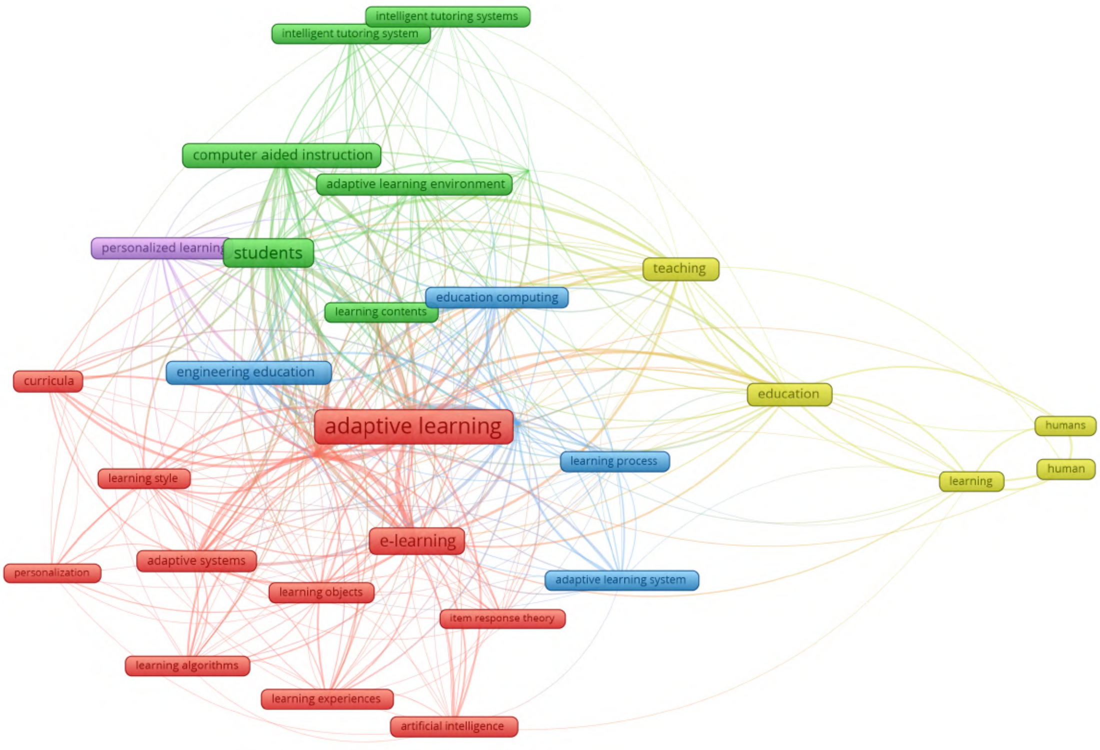

Figure 2: Network visualization.

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TITLE ( "adaptive learning" ) AND ( LIMIT-TO ( SUBJAREA, "SOCI" ) )
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According to the request, the term "adaptive learning" appeared in the titles of articles, chapters, or books belonging to the subject area "social sciences". As a result, 344 documents were received, and the distribution of works by year is presented in figure 1.

Table 1
Distribution of keywords by clusters.

Keyword	Cluster	$\text{Weight}_{\text{Links}}$	$\text{Weight}_{\text{Total link strength}}$	$\text{Weight}_{\text{Occurrences}}$	$\text{Score}_{\text{Avg. pub. year}}$	$\text{Score}_{\text{Avg. citations}}$	$\text{Score}_{\text{Avg. norm. citations}}$
adaptive learning	1	29	425	158	2016.0443	10.6076	0.966
learning systems	1	27	445	118	2014.6356	10.6949	0.8159
e-learning	1	27	280	70	2015.4571	6.6857	0.7592
adaptive systems	1	25	126	28	2013.6429	28.3929	1.1589
learning objects	1	22	46	12	2012	24.8333	1.6496
learning style	1	21	72	17	2013.4706	32.4118	1.5342
learning algorithms	1	20	53	13	2015.4615	34	1.6297
learning experiences	1	19	56	11	2015.4545	9.2727	1.1661
artificial intelligence	1	18	41	14	2016.6429	7.8571	0.8118
item response theory	1	18	33	10	2017.3	17.1	1.8503
curricula	1	17	78	21	2014.7143	7.9048	0.8894
personalization	1	14	27	10	2013.9	70.8	3.1478
students	2	26	338	75	2015.68	11.72	1.0332
computer aided instruction	2	25	209	40	2014.975	13.975	1.0588
adaptive learning environment	2	23	82	19	2014.4211	14.5263	1.4182
learning contents	2	20	49	11	2013.6364	11.6364	0.9208
learning performance	2	19	48	11	2014.1818	11.3636	0.8037
intelligent tutoring system	2	17	49	11	2014.5455	22.0909	1.4888
intelligent tutoring systems	2	15	34	12	2017.9167	15.6667	1.9702
adaptive learning systems	3	27	269	66	2015.1667	7.9697	0.8392
education computing	3	25	135	25	2015.96	4	0.5437
engineering education	3	23	121	29	2013.7931	6.8966	0.7189
learning process	3	20	48	12	2016.5833	4	0.5026
adaptive learning system	3	19	58	15	2016.4667	9.8667	0.8269
education	4	25	144	35	2011.8286	11.8286	0.7189
teaching	4	25	133	29	2015.7931	8.1379	0.6896
learning	4	12	38	17	2015.0588	5.9412	0.5421
human	4	5	29	11	2013	12.0909	0.8125
humans	4	5	27	10	2015.5	10.3	0.8126
personalized learning	5	20	79	21	2017.7619	14.5714	1.3967

Cluster analysis by keyword co-occurrence was conducted: from 1836, keywords were selected, that appeared at least 10 times (table 1).

The results of the cluster analysis are presented in figure 2.

According to table 1 and figure 2, keywords were divided into five clusters. Let's analyze them in more detail.

The first cluster includes 12 keywords (figure 3), 5 of which are primarily related to the theory of adaptive learning: *adaptive learning*, *adaptive systems*, *curricula*, *learning style*, *learning experiences*, *learning algorithms*, *personalization*. Other concepts are related to adaptive testing (*item response theory*), which is implemented in *e-learning* systems – a type of *learning system* that operate with *learning objects* and can be automated by means of *artificial intelligence*.

The second cluster contains 7 keywords (figure 4) related to the practice of *computer aided instruction* of *students* (in particular, assessment of *learning performance*, and evaluation of *learning contents*) at *adaptive learning environment* (in particular, *intelligent tutoring systems*).

The third cluster contains 5 keywords (figure 5) that describe the implementation of *learning*

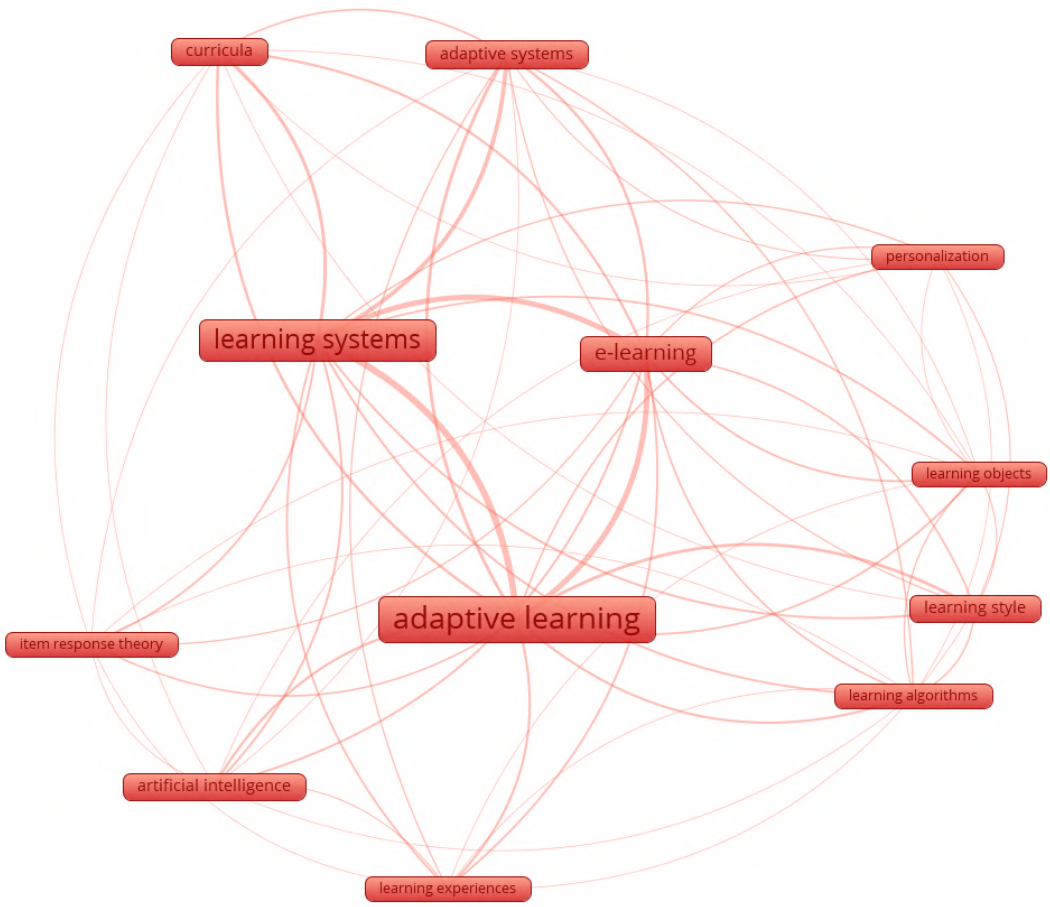

Figure 3: A cluster of general concepts of adaptive learning in e-learning systems.

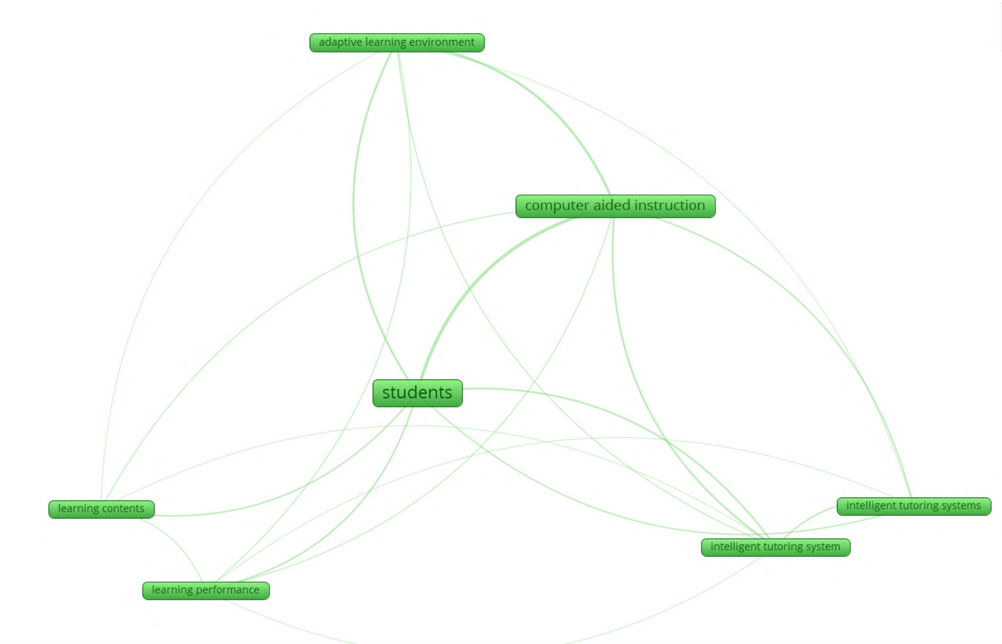

Figure 4: A cluster of educational technology.

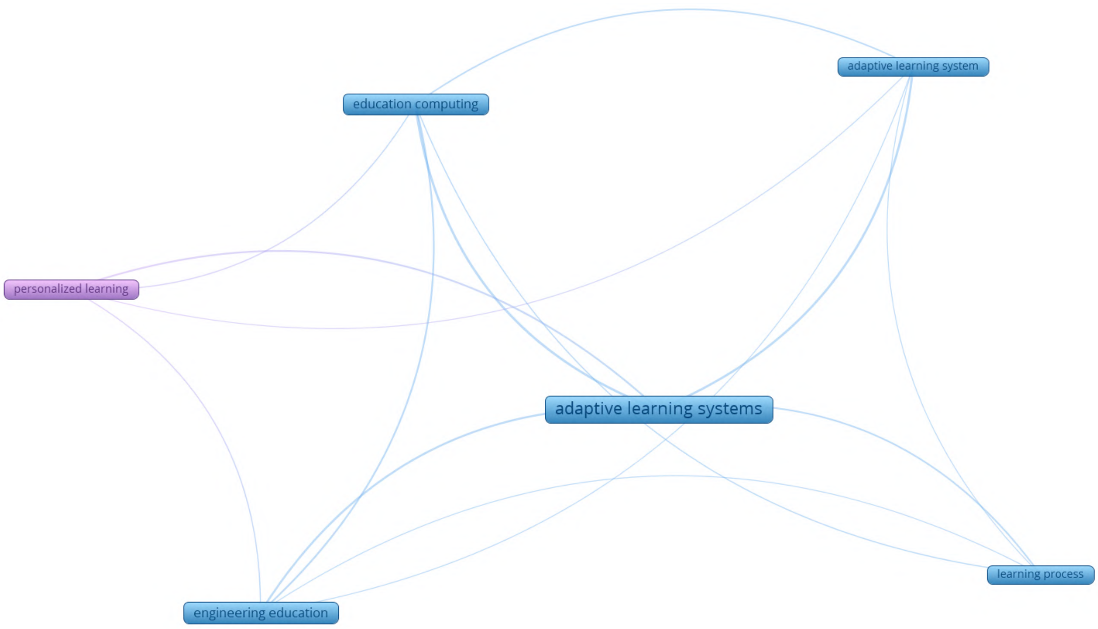

Figure 5: A cluster of adaptive learning systems and education computing.

process within *engineering education* by means of *education computing*, e.g. *adaptive learning systems*.

The fourth cluster also includes 5 keywords (figure 6) that describe the didactic fundamentals: *human(s)*, *education*, *teaching*, and *learning*.

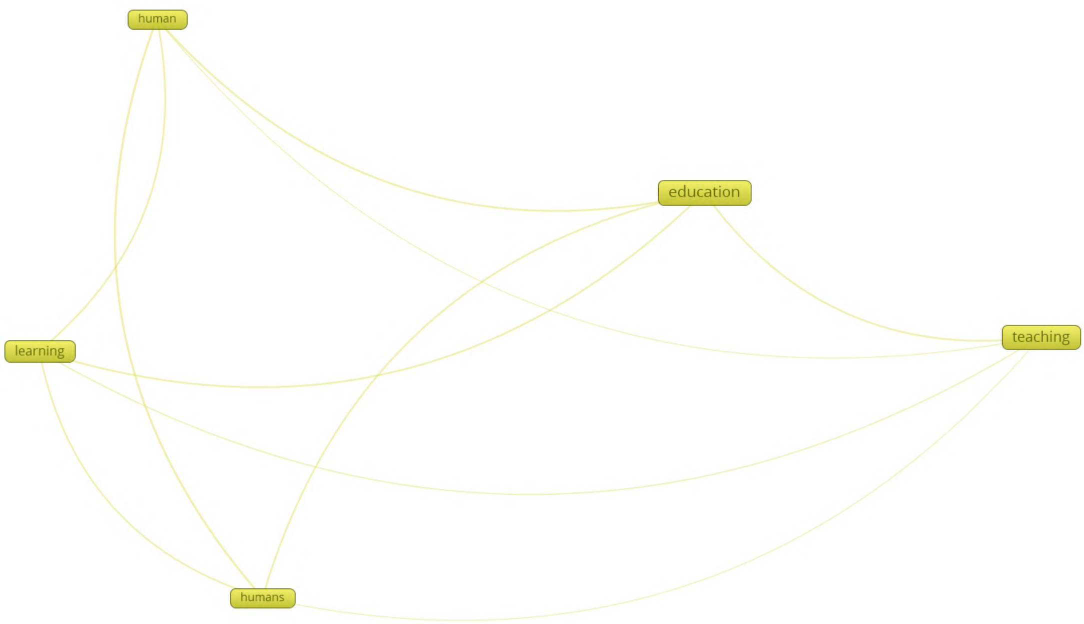

Figure 6: A cluster of learning and education research.

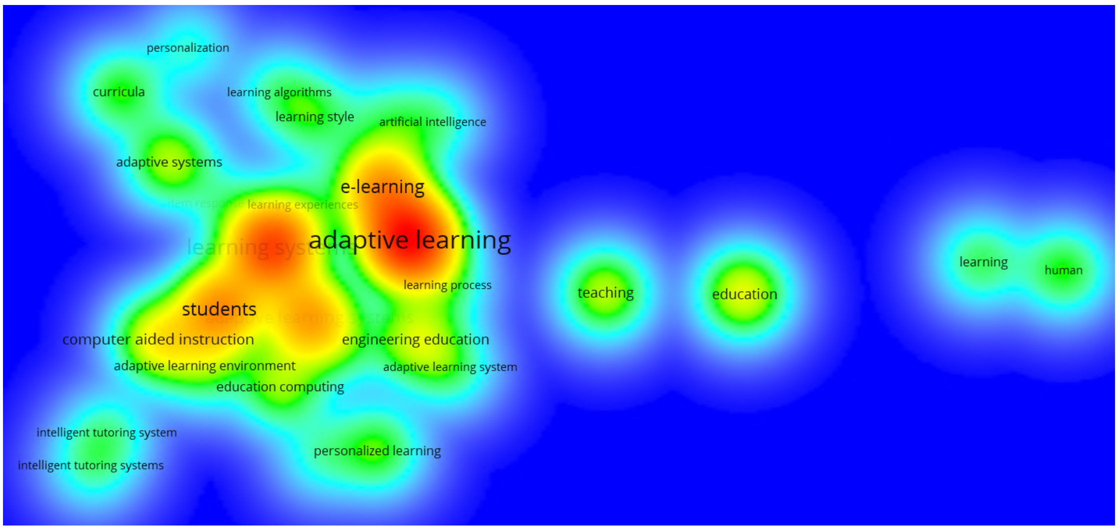

Figure 7: Item density visualization.

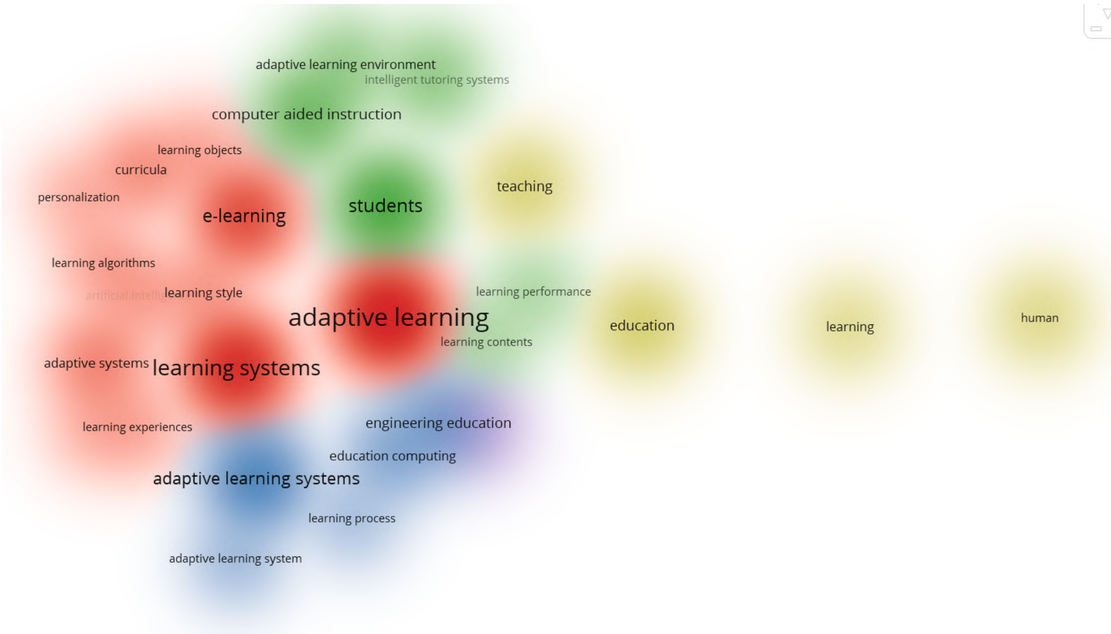

Figure 8: Cluster density visualization.

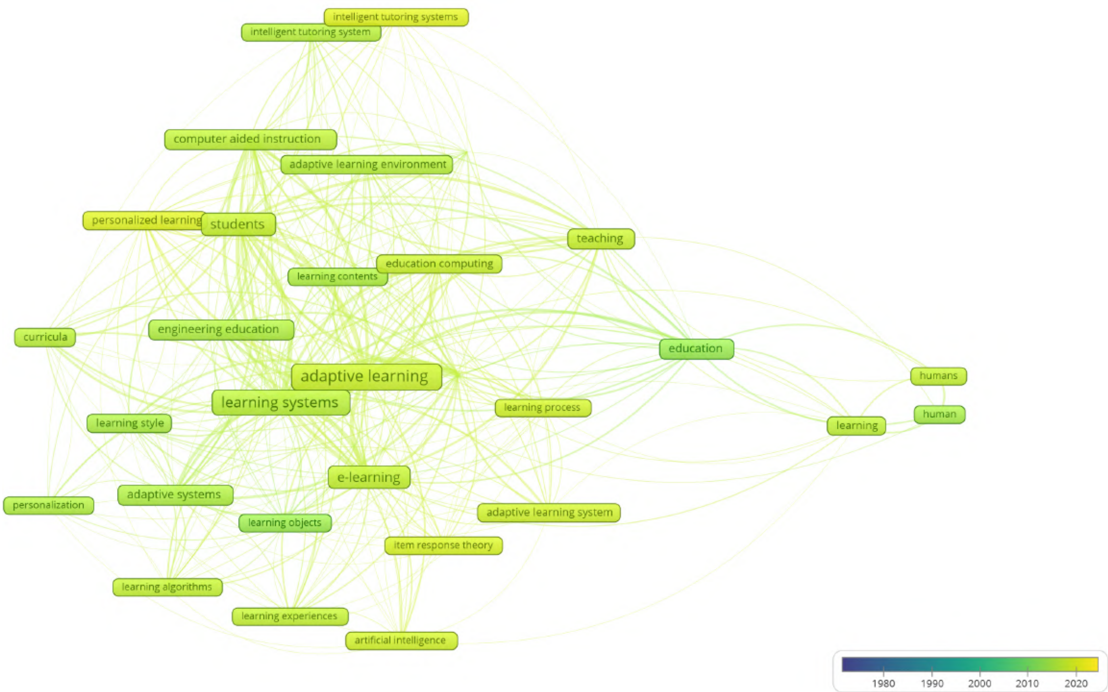

Figure 9: Extension of terms from 1974 to 2022.

The smallest cluster consists of only 1 keyword (figure 5) – *personalized learning*.

Another important criterion for source analysis is density. First, was analyzing the item's density (figure 7). From this visualization, the keywords "adaptive learning" ($\text{Weigth}_{\text{Total link strength}}$ = 425), "learning system" ($\text{Weigth}_{\text{Total link strength}}$ = 445), "students" ($\text{Weigth}_{\text{Total link strength}}$ = 338), and "e-learning" ($\text{Weigth}_{\text{Total link strength}}$ = 280) have the highest density. This means that these items are the most interconnected (maximum value of total link strength).

In order to determine primary concepts (earliest keywords by time scale), let's show overlay data visualization by years. As is shown in figure 9, there are no fundamentally new concepts, their emergence and spread occurred at least since 2020. There are also no concepts that were widespread before 2000. This visualization gives us grounds for limiting the analysis years.

So, let's try to analyze these concepts from 2000 to 2020 (figure 10). Within these limits, we can see that such concepts as *"human(s)"*, *"education"*, and *"learning objects"* begin to stand out as those that were formed earlier. At the same time, such concepts as *"personalized learning"* and *"intelligent tutoring systems"* are distinguished as those highlighted later. And since most of the concepts were disseminated after 2000, to see their distribution more accurately, we will raise the lower limit from 2000 to 2010 (figure 11).

When comparing figure 11 with figure 10, we observe that most of the concepts have changed color, but it is still unclear which concepts were discussed by researchers in the different years.

So, let's try to change both the upper and lower limits for 1 year, i.e. from 2011 to 2019 (figure 12). Now we can observe a more transparent distribution of concepts by time scale. From this figure, we can see that adaptive learning and artificial intelligence became disseminated

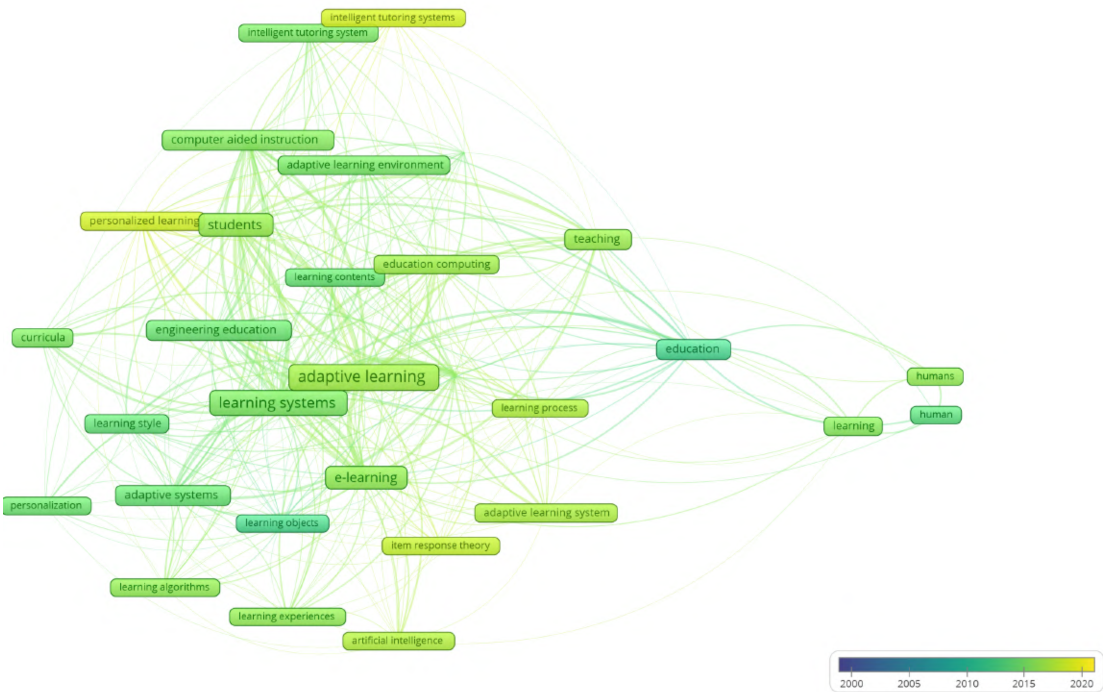

Figure 10: Extension of terms from 2000 to 2020.

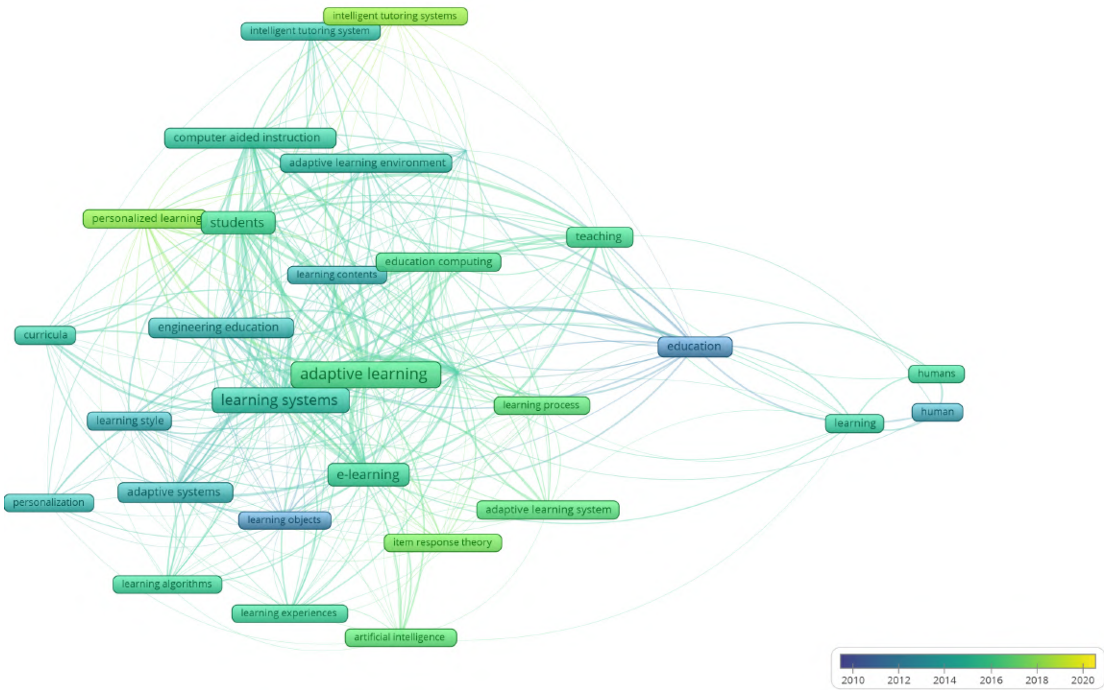

Figure 11: Extension of terms from 2010 to 2020.

later than those related to the use of ICT in education.

As a result of the bibliometric review, the following conclusions were obtained:

1. The years of literature analysis from 2011 to 2019 are limited since it is during this period that there is an increasing interest in adaptive learning.
2. With the help of cluster analysis, the problem field of the research was determined.
3. The key concepts are defined: adaptive learning, learning systems, e-learning, adaptive systems, learning objects, learning style, learning algorithms, students, computer aided instruction, adaptive learning environment, learning contents, adaptive learning systems, education computing, engineering education, learning process, education, teaching, personalized learning.

3. Cluster-based literature review

The analysis allows focus on the detailed study of 163 papers from 2011 to 2019 [1, 3, 5–8, 10, 12, 14–17, 20, 24–31, 33–42, 44–47, 49–51, 56, 58–60, 62–81, 83–85, 87–93, 98–101, 103–113, 115–120, 122, 124–127, 129–131, 133–146, 149, 150, 152, 153, 155, 157–160, 162, 163, 165–168, 170, 172–182, 184–188, 192, 195–204, 206–210]. Additionally, 29 Ph.D. theses and technical reports related to adaptive learning systems were reviewed: [2, 9, 11, 18, 19, 48, 54, 55, 57, 61, 82, 96, 97, 114, 121, 123, 147, 148, 151, 154, 156, 161, 164, 169, 171, 183, 193, 194, 205].

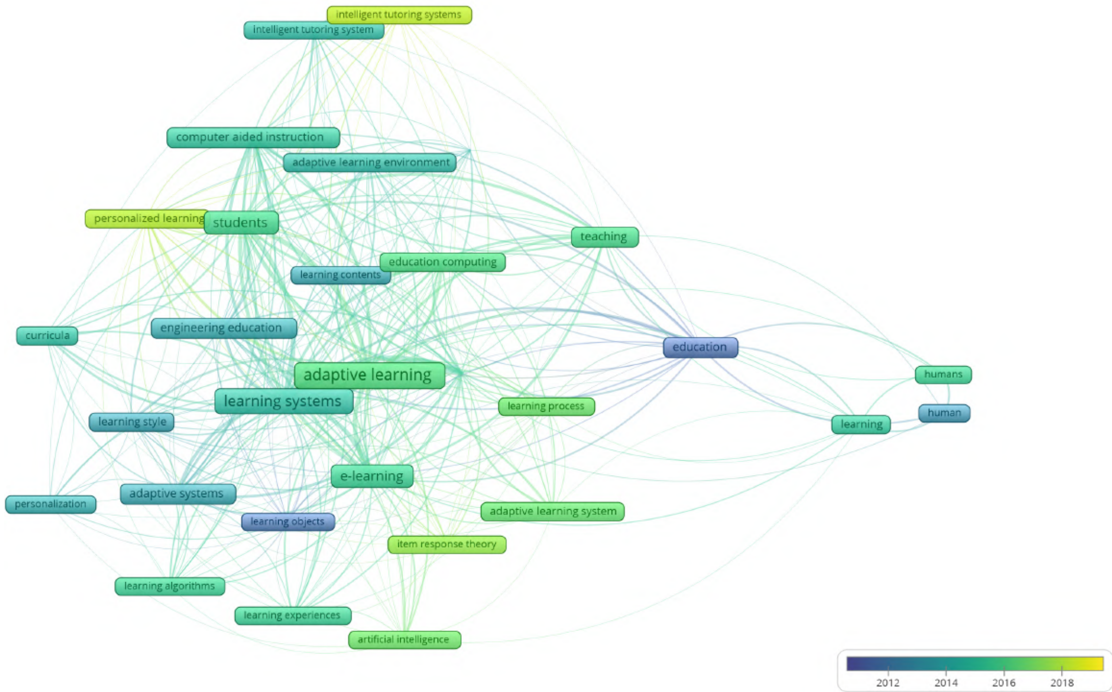

Figure 12: Extension of terms from 2011 to 2019.

3.1. A cluster of general concepts of adaptive learning in e-learning systems

A cluster of general concepts of adaptive learning in e-learning systems (in red color) represented by 67 papers.

8 papers are related to the *theory of adaptive learning* – a kind of personalized instruction, where the learning system dynamically adjusts the learning experience to the individual learner's needs, preferences, and progress. Natriello [135] reviews historical and contemporary work on creating adaptive learning opportunities, identifies active lines of relevant research and development activities, and concludes by identifying issues for further development of adaptive learning applications. Skuballa et al. [172] discusses the advantages of adaptive educational systems and the relevance of eye-movement measurements for learning with multiple representations. It also presents initial results on the usefulness of eye-movement assessment in adaptive systems. Aleven et al. [6] discusses the need for adaptive instruction to not only adapt to learner differences but also to learner similarities and suggests using a deep understanding of the demands of a task domain to adapt system design. Chauhan, Taneja and Goel [27] highlighted the need for Massive Open Online Courses (MOOCs) to embrace advanced learning techniques such as Augmented Reality, Adaptive Learning, and Gamification to provide a more engaging experience to learners. Bayounes et al. [16] proposes a faceted framework to understand and classify issues in learning process construction for adaptive learning systems, identifying four different viewpoints and associated facets to capture the diversity of these aspects. Hardy et al. [64] presents an intervention study on an adaptive form of instruction in elementary school

science education. Lishon-Savarino [110] analyzes distance education topics related to the instructional design of developmental mathematics courses at post-secondary institutions that utilize adaptive learning technologies and provides recommendations to improve existing course designs. Hertel, Warwas and Klieme [68] discusses the theoretical definition and empirical investigation of dealing with heterogeneity in educational settings. These papers discuss various aspects of adaptive learning theory, including the history and contemporary work on creating adaptive learning opportunities, the need for adapting to learner differences and similarities, the use of eye-movement measurements in adaptive systems, the construction and classification of issues in learning process, the effectiveness of adaptive instruction in elementary school science education, and the instructional design of developmental mathematics courses that utilize adaptive learning technologies.

12 papers are devoted to personalized course content delivery based on students' learning styles, context awareness, individual characteristics, physiological responses, and other components of the *learner's model*, and provide different approaches and frameworks to improve the quality of learning. Bai et al. [14] establishes an adaptive learning support system for air traffic control, which can determine learning strategies based on learners' styles and significantly improves study efficiency. Ako-Nai et al. [3] presents an adaptive learning content generation platform for mobile learning that is context-sensitive and utilizes the 5R adaptation framework to provide the right content to the right learner at the right time and location. Lestari, Nurjanah and Selviandro [100] proposes learning recommendations and adaptive learning based on detecting the learning style and working memory capacity of students to improve the quality of learning itself. Tortorella and Graf [185] proposes a mobile adaptive learning approach for providing personalized course content to students based on their learning style while incorporating adaptive context awareness. An evaluation with 45 students shows that the approach improved comprehension of subject matter by 23% and was popular with students. Pelánek [152] proposed a classification of student performance into several categories based on response times and wrong answers to guide the adaptation of personalized educational systems. Nakic, Granic and Glavinic [133] reviews the use of user individual characteristics as sources of adaptation in recent adaptive learning systems and contributes to the body of knowledge on individual differences in student modeling. Midgley [126] examines the relation between achievement goals, the learning context, and students' and teachers' patterns of cognition, affect, and behavior, using goal theory as the lens. It provides an overview of the research conducted in this field and suggests future research directions. Hardy et al. [65] investigated the relationship between physiological responses and affective experiences of learners during a programming training session. The study explored skin conductance responses as a physiological measure to design augmented adaptive systems that respond to the learner's cognitive and affective states. Slater et al. [173] surveys math identity measures and correlates them with behavior and performance in an online math learning system. Shikano and Kittel [170] compares two behavioral models of electoral turnout and presents experimental evidence supporting the model that generates more habitual voting behavior. Ueno et al. [187] verifies the effectiveness of a model that measures learners' understanding through item response theory in a flipped classroom using an adaptive learning system, through case studies in programming and algorithm classes. Ueno et al. [188] proposes a flipped classroom model using an adaptive learning system for C programming classes, which measures the degree of understanding through item response theory. The papers

cover topics such as an adaptive learning support system for air traffic control, an adaptive learning content generation platform for mobile learning, learning recommendations based on detecting students' learning style and working memory capacity, mobile adaptive learning approaches, classification of student performance, the use of user individual characteristics as sources of adaptation, the relationship between physiological responses and affective experiences of learners, surveys of math identity measures, and comparisons of behavioral models of electoral turnout.

7 papers and 1 Ph.D. thesis are devoted to the *development of the adaptive e-learning system.* Kaw et al. [91] describes the development and implementation of an adaptive learning platform for a Numerical Methods course, including analytic data and student focus group feedback. Panicker et al. [150] discusses the development and testing of an adaptive learning system using rule-based logic for undergraduate courses, with analytics serving as feedback to instructors. Werlen and Bergamin [200] conducted a preliminary study on self-evaluation as a source of learning data for sensors of an intended adaptive learning system, which showed moderate correlation with external evaluation and provided insights into designing corresponding sensors. Heiyanthuduwage, Schwitter and Orgun [67] introduced an adaptive learning system that relies on a domain-specific ontology to overcome terminological and structural differences among different educational institutions. The system's plug-and-play architecture and reasoning services were demonstrated in the study. Matthews et al. [117] discusses the development and implementation of an adaptive learning and grading system to improve feedback quality for computer skills. Matar [116] proposes a structure for an Adaptive Learning Object Repository to provide adaptability in unified e-learning environments. Oliveira et al. [146] suggests a conceptual framework for integrating adaptive hypermedia into learning management systems from a cognitive-semantic perspective. Vu Minh [193] proposes a set of criteria for certain aspects of constructivism and uses it both as guidelines for designing learning systems and for evaluating the conformity of learning systems with constructivist principles. On the basis of the criteria for cognitive flexibility, the author proposes an operational instructional design process and introduces an adaptive e-Learning platform that may be used for designing adaptive learning systems supporting cognitive flexibility in various domains.

10 papers are primarily focused on the *use of AI in the development and improvement of adaptive learning systems.* Su [177] proposes an adaptive learning path recommendation system for e-learning that outperforms other approaches, using a novel hybrid approach based on fuzzy Delphi method, fuzzy ISM, and Kelly Repertory Grid Technology. Zhou et al. [208] provides a new insight into the non-convergence issue of Adam, an adaptive learning rate method, proposing a novel method called AdaShift that decorrelates gradient and second-moment terms to address the non-convergence problem while maintaining competitive performance. Huang, Yang and Lawrence [74] proposes a classification-based approach to improve the accuracy and reduce the computational complexity of data mining-based concept map generation in adaptive learning systems. Hämäläinen, Kumpulainen and Mozgovoy [77] discusses the clustering of student data, which is a central task in educational data mining and the design of intelligent learning tools. The authors evaluate the main clustering methods and suggest the most promising methods for different situations. Kardan, Imani and Ebrahim [90] proposed a novel two-stage adaptive learning path algorithm, called ACO-Map, that discovers groups of learners based on their knowledge patterns and applies ant colony optimization to find a learning path based

on Ausubel Meaningful Learning Theory. Schaul and LeCun [163] proposes an algorithm for stochastic gradient descent that automatically adjusts learning rates without the need for manual tuning, addressing issues of minibatch parallelization, sparse or orthogonal gradients, and non-smooth loss functions. Nguyen [138] proposes a new approach to manage learner modeling in an adaptive learning system using a Bayesian network and overlay model. Nurjanah [141] discussed the design of a learner model ontology for lifelong learning to support adaptive learning systems, which classified learners' attributes into static and dynamic attributes. Oke et al. [145] discusses how machine learning, adaptive learning, and data analysis can be used to cater to each student's individual needs based on their psychological concepts like brain dominance and multiple intelligences. Cho, Raiko and Ilin [28] presents an enhanced gradient and a way to automatically adjust the learning rate to improve the training of restricted Boltzmann machines. The listed works discuss various approaches and algorithms, such as fuzzy Delphi method, AdaShift, classification-based approach, clustering methods, ant colony optimization, stochastic gradient descent, Bayesian network and overlay model, learner model ontology, machine learning, and data analysis, to improve the performance, accuracy, and complexity of adaptive learning systems, addressing issues such as non-convergence, sparsity, non-smooth loss functions, and learner modeling, while catering to individual student needs based on their psychological concepts like brain dominance and multiple intelligences.

10 papers and 3 Ph.D. theses describe *algorithms and approaches in adaptive learning systems*, including an improved ant colony algorithm for online learning, a bio-inspired system for reduced energy consumption, a technique for recommending learning materials, and a negotiation-based approach for combining adaptivity and adaptability. Li [104] proposes an adaptive online learning system that uses an improved ant colony algorithm to cater to learners' preferences, tastes, and knowledge levels. Martinez et al. [113] focused on designing and implementing a bio-inspired adaptive learning system using cerebellar model articulation controller principles, which showed reduced energy consumption with improved throughput and convergence. Vo and Dutkiewicz [192] presents an algorithm for data segmentation in arrhythmia detection, utilizing an adaptive learning scheme to improve classification performance. Nurjanah [140] proposed a new technique for recommending learning materials in adaptive learning systems that combines content-based filtering and collaborative filtering based on the similarity between learners' and learners' competence. Rimbaud et al. [158] investigates the use of the Content and Language Integrated Learning (CLIL) approach and mixed methods to develop algorithms for adaptive learning to meet the needs of learners in an additional language. Anderman and Midgley [10] provides an overview of the methods used in a large-scale longitudinal study examining the emotional, social, and academic well-being of young adolescents using goal orientation theory. Chaoui and Laskri [25] proposed the "Fusion of Web Resources" approach to create an adaptive learning domain in an e-learning platform. The approach enables the extraction of relevant educational web resources, filtering them and structuring them into courses, and adapting the courses to learners' profiles. Lai, Chou and Lan [98] proposes a negotiation-based approach to combine adaptivity and adaptability in adaptive learning systems, where the system suggests adaptations and the student negotiates if their preference differs. Miyagi [131] proposes an algorithm based on smooth fictitious play and regret matching models to establish behavioral rules of route choice under incomplete information in traffic environments. Wang and Liao [198] proposes a five-step algorithm based on four

learner characteristics to develop an adaptive learning sequence system for English as a Second Language (ESL) instruction. Borsuk [19] proposes the structure of a functional simulator with adaptive algorithms as a software tool for the organization of training and knowledge control of the aviation specialist industry. The author has developed adaptive algorithms for each of the subsystems of the simulator, which allow influencing such parameters of the training process as the proportion of time intended for work in different systems of the simulator. Pogrebniuk [156] presents the model of adaptive learning scenario development for distance learning with the use of Petri nets, depending on certain characteristics of the student's model (academic background, test results, maps of the gaps in knowledge, curve of forgetting). The IRT-based model for developing adaptive testing scenarios offered by the author allows the test length and testing time to be reduced. Fasihuddin [54] proposes using knowledge maps and adaptivity to individual learning styles using adaptive navigational support technology for enhancing open learning environments.

6 papers on the *implementation and effectiveness of adaptive learning systems in education*. Mirata and Bergamin [130] discusses the challenges preventing higher education institutions from adopting adaptive learning technologies and proposes an implementation framework based on empirical data from two universities. Lin and Wu [107] explored the effectiveness of an adaptive learning platform with flipped classroom instruction on elementary school students' learning performance and self-learning approach. Rosen et al. [160] reports on an experimental implementation of adaptive learning in a self-paced Microsoft MOOC on edX, which showed that adaptivity in assessment, with emphasis on remediation, led to a substantial increase in learning gains. Basitere and Ivala [15] evaluates the effectiveness of an adaptive learning platform in improving learners' performance in a first-year introductory engineering physics course. Results show a positive relationship between proficiency scores and enhanced performance in the paper-based midterm test. Dziuban et al. [47] presents the results of a pilot study on the use of an adaptive learning platform for an online General Psychology course, indicating students found it easy to use, and successful, but an early prediction of at-risk students is possible using learning outcome metrics. Jonsdottir, Jakobsdottir and Stefansson [85] describes a system for computer-assisted education that offers interactive drills to increase learning and investigates what affects students' decision to stop working. These studies provide insights into the challenges of adopting adaptive learning technologies in higher education institutions, the effectiveness of such systems in improving students' learning performance in different subject areas and grade levels, and the ease of use of adaptive learning platforms. Additionally, the studies highlight the potential for early prediction of at-risk students using learning outcome metrics. Overall, these findings provide valuable information for educators and administrators interested in implementing adaptive learning systems to improve student learning outcomes.

3 papers on the *evaluation of adaptive learning systems in education*. *Evaluating adaptive learning model* [50] describes adaptive learning as a trend in modern education and discusses user modeling as the heart of adaptive learning systems. The paper proposes evaluation criteria for adaptive learning systems and gives an evaluation scenario as an example. Nussbaumer et al. [142] presents an evaluation service that supports the evaluation of adaptive learning systems, using a layered evaluation approach to define qualities that are evaluated individually. The evaluation service supports the whole evaluation process, including modeling, data collection, and automatic reports based on data analysis. Albert and Steiner [5] aims to advance the

maturity of evaluation approaches for adaptive learning technologies by stimulating discussion and dialogue on future research directions.

11 papers and 1 Ph.D. thesis provide examples of various *adaptive learning platforms* that have shown their effectiveness in improving student performance and providing positive learning experiences, ranging from platforms that use crowdsourcing to improve learning outcomes, to systems that manipulate student characteristics to provide personalized learning, to serious game adaptive learning systems. Grother [63] highlights the benefits of crowdsourcing questions for revision and consolidation of knowledge, specifically through the use of the free platform PeerWise, which has been shown to improve performance in summative assessments. Sfenrianto et al. [166] proposed an adaptive learning system-knowledge level (ALS-KL) to personalize materials according to the proficiency level of English language learners, which was able to improve learners' proficiency and reduce the number of learners with elementary level. Li et al. [103] presents the YiXue adaptive learning platform, which was more efficient than two comparison platforms in an after-school English language arts course in China. Linden et al. [109] presents an adaptive online neurophysiology lesson using the Smart Sparrow platform that shows significant promise in enhancing student learning in a difficult first-year subject. Lin, Wu and Cheng [108] reports on the Adaptive E-learning for Science Project (AESP) in Taiwan, which aims to develop an adaptive science learning system for primary science teachers and examines its effectiveness using adaptive dynamic assessment in adaptive learning. Allison and Extavour [8] evaluates the experiences of first-year pharmacy students in Trinidad and Tobago using adaptive learning technology in the form of a SmartBook for an Anatomy and Physiology course. The study finds that the SmartBook supported learning and provided positive learning experiences. De Santana et al. [40] examined the "Mars and Venus Effect" by investigating the use of an adaptive learning technology called MeuTutor on 191 students from public schools in Brazil. Results showed that the technology improved both male and female students' performance in Mathematics and Portuguese, with male students showing more significant improvement in Mathematics. Heffernan et al. [66] explored the potential of crowdsourcing contributions from teachers and students to perpetually improve adaptive learning technologies, using online platform ASSISTments as an example. Nguyen [137] proposes a novel user modeling system named Zebra, which manipulates students' characteristics effectively to provide personalized learning. Zebra has a powerful inference mechanism for explaining new information about students to support adaptive learning. Obikwelu and Read [144] reviewed the literature on the different adaptation logics embodied in existing serious game Adaptive Learning Systems (ALS). The study investigated various ALS, including NUCLEO, S.M.I.L.E, Framework for Adaptive Game Presenters with Emotions and Social Comments, Fine-Tuning System (FTS), and ALIGN. De-La-Fuente-Valentín, Pardo and Kloos [38] proposes an extension to the IMS Learning Design specification to allow bidirectional communication between the course engine and third-party tools, enabling the customization of learning experiences. Aguar [2] develops an adaptive learning framework for STEM education. This research takes an approach by adapting content and practice problems based on a student's interests. This work presents the design and pilot of the system for adaptive interest-based Learning designed to help alleviate many of the concerns in STEM education by providing a competent and compelling curriculum delivering individualized instruction to help increase motivation, and performance and fill the gaps in STEM education.

3.2. A cluster of educational technology

A cluster of educational technology (in green color) represented by 50 papers.

9 papers are focused on the *use of AI-related technologies and methods in the development of adaptive learning systems*. Palomino, Silveira and Nakayama [149] describes an intelligent or adaptive learning management system based on multiagent systems that use software agents to personalize and adapt the learning experience according to each user's personal way of learning. Chaplot, Rhim and Kim [26] proposes a new adaptive learning system architecture that uses Artificial Neural Networks to construct the Learner Model and select items of optimal difficulty personalized to the student's skill level and learning rate. Zhang [206] proposes a multi-agent system for adaptive learning environments that offer flexibility in presentation of material and a greater ability to respond to idiosyncratic student needs. Mavroudi, Giannakos and Krogstie [119] conducted a systematic review of twenty-one peer-reviewed studies and identified the interplay between learning analytics and adaptive learning, as well as the need for further research on the topic. Afini Normadhi et al. [1] conducted a systematic literature review to identify the most commonly used personal traits in modelling the learner and the existing techniques for identifying personal traits in an adaptive learning environment. Most previous works used a learning style from the cognition learning domain category to model individual personal traits, while the computer-based detection technique was commonly applied to identify a learner's personal traits. Wang et al. [197] used K-means clustering to identify three clusters of middle school students based on prior achievement, and found that the Yixue intelligent learning system was able to help students from different achievement levels learn equally well in mathematics. How and Hung [70] proposes an approach for educational stakeholders to employ Bayesian networks to simulate predictive hypothetical scenarios with controllable parameters to evaluate an AI-ALS for its suitability in enhancing students' problem-solving abilities. Sosnovsky and Chacon [175] proposes a mechanism for detecting metadata gaps in collections of learning content by converting learning objects metadata into an OWL2 ontology, detecting logical conflicts, and generating human-readable explanations. Tsai and Huang [186] investigated the factors impacting high school students' adaptive learning, using machine learning approaches such as neural networks and decision tree analysis. The authors found that the school teaching environment was the main factor impacting students' adaptive learning. These studies describe different aspects and approaches of adaptive learning design, including the use of multiagent systems, artificial neural networks, machine learning algorithms, and ontology-based mechanisms. Additionally, the studies also discuss various factors impacting adaptive learning, such as individual personality traits, prior achievement levels, and the school teaching environment. Overall, the studies are highlights the growing interest in developing adaptive learning systems that can personalize the learning experience and enhance students' problem-solving abilities, which is an important goal of AI in education.

2 papers are related to *the use of IRT to adapt learning*. Huang and Shiu [73] discusses the challenges of finding suitable learning paths and content on e-learning 2.0 platforms and proposes a user-centric adaptive learning system (UALS) that uses sequential pattern mining and Item Response Theory (IRT) to construct adaptive learning paths and estimate learners' abilities for recommending adaptive materials. The experimental results show that the effectiveness of UALS is comparable to expert-designed learning, and guidelines for designing e-learning

2.0 platforms are proposed. Pliakos et al. [155] propose a system that combines item response theory (IRT) with machine learning to predict the proficiency of new learners entering an adaptive learning environment, addressing the cold-start problem. The hybrid model combining IRT with Random Forests provided the best results.

9 papers provide a broad overview of the current research and developments in the field of *adaptive learning environments*. Gasparinatou and Grigoriadou [59] describes the development of an adaptive learning environment for computer science students called ALMA, which uses Kintsch's Construction-Integration model for text comprehension and various activities to assess and support learner comprehension. De Marsico, Sterbini and Temperini [39] proposes an integration of two web-based e-learning systems, LECOMPS and SOCIALX, to provide personalized and collaborative learning in line with Vygotsky's social-cultural theory. Graf et al. [62] provides an overview of adaptive and intelligent learning systems and how they can be integrated into various learning environments to improve the learning experience for learners and teachers. Massey et al. [115] introduced perceptual learning modules (PLMs) in middle and high school mathematics, showing that appropriately designed PL technology can produce rapid and enduring advances in learning. Daniello et al. [36] proposes a flexible seamless learning environment that identifies a learner's context and applies adaptation by respecting their learning goals using situation awareness, adaptive learning, and semantic technologies. Mavroudi et al. [120] presents a participatory design process for an adaptive learning environment and suggests a methodology of framing key requirements into a set of critical success factors for meeting the end-users' expectations. Isaksson, Naeve and Lefrère [81] explores the reconceptualization of learning environments as performance augmentation through ubiquitous and adaptive learning and work environments. Yuan et al. [204] investigates the utility of gesture-based interaction in adaptive learning environments based on theories of embodied cognition. It applies gesture-based technologies within an adaptive learning system and found that the learners in the gesture-based group significantly outperformed the learners in the mouse-based group. Szijarto and Cousins [180] studied developmental evaluation (DE) and how mediators influence the relationships between components of a social learning system in adaptive learning. They found that evaluators making space for the interrogation of ideas and choices employed strategies such as turning down the heat, seeking balance, normalizing evaluation practice, and legitimizing DE. The study has implications for evaluation capacity building in adaptive learning contexts.

13 studies and 1 technical report are related to *adaptive learning systems design and development*. Rodrigues Pereira et al. [159] discusses the development of the OAEditor framework, which allows teachers to create educational hyper documents that adapt to students' performance and includes self-evaluative questionnaires for monitoring progress. Fidalgo-Blanco et al. [56] suggests breaking the organizational structure of learning content management systems to manage the learning process individually and adapt resources to the profile and needs of each student. The system presents an emergent window to the student with the most useful resources available. Clougherty and Popova [31] argues that adaptive learning design should be developed prior to tool implementation and is not limited to course-based adaptation. The Seven Model Approach illustrates the range and degree of adaptivity that can be modified based on the granularity of the learning elements. Essa [49] discusses the possible future of designing next-generation adaptive learning systems based on new developments

in learning science and data science. Minkovska, Ivanova and Yordanova [129] discusses the design principles of interactive eLearning and presents a prototype of an adaptive eLearning system that improves students' understanding and assists educators in teaching and assessment. Chou et al. [30] presents a negotiation-based adaptive learning system that regulates the help-seeking behavior of students. Gavrilović et al. [60] presents an algorithm for creating an adaptive learning process to improve learners' knowledge and skills in Java programming language. Sun, Norman and Abdourazakou [178] examines the perceived value of LearnSmart, an interactive digital textbook, and its implications on adaptive learning and student learning effectiveness. LearnSmart was found to improve students' perceived competency and satisfaction, thus increasing their perceived value of using it, with varying perceived value across different course delivery formats and devices. Shelle et al. [168] discusses the use of adaptive learning tools in Extension programming and found that it aided learners in mastering content. Nye et al. [143] investigated the learning outcomes and user perceptions of a hybrid intelligent tutoring system created by combining the AutoTutor conversational tutoring system with the ALEKS adaptive learning system for mathematics. Qu, Cai and Haj-Hussein [157] describes a project that integrated adaptive learning software, Amazon's Web Services, and discussion board assignments to create an Online Learning Environment suited to Bachelor of Science of Computer Science and Information Technology degree programs. Surahman et al. [179] aimed to develop online learning services that can adapt to learners' characteristics and learning styles, resulting in effective learning outcomes that exceeded targets. Chou et al. [29] proposes a negotiation-based approach for combining system-controlled and user-controlled adaptation in adaptive learning systems. The system suggests adaptations, but the student also submits their adaptation preference, and if they disagree with the system, they negotiate an agreement. This approach improves metacognitions and performance in students. Shyshkina [171] developed methods of using the adaptive cloud-based system of training and professional development of teachers of general secondary education institutions.

These studies explore different approaches, frameworks, algorithms, and prototypes used in adaptive learning systems, including negotiation-based approaches, interactive eLearning, hybrid intelligent tutoring systems, and online learning services that can adapt to learners' characteristics and learning styles. These studies also highlight the importance of developing adaptive learning design prior to tool implementation and breaking the organizational structure of learning content management systems to manage the learning process individually and adapt resources to the profile and needs of each student.

6 papers are related to the *personalization of education with adaptive learning systems.* In Yang, Hwang and Yang [201], an adaptive learning system was developed based on personalized presentation modules for computer science students, resulting in significantly better learning achievements than the control group. Walkington [196] showed that an interest-based personalization intervention within an intelligent tutoring system for secondary mathematics improved learning outcomes for struggling students. Indrayadi and Nurjanah [80] discusses approaches to improving adaptation and personalization in adaptive educational hypermedia. It presents a knowledge map that combines individual learner progress and preference with peer experiences to improve adaptation and implements an open learner model to nurture self-progress awareness. Natriello and Chae [136] discusses the growth of adaptive learning technologies that claim to support personalized learning experiences. Miller, Asarta and Schmidt [127] examines

the effects of different deadline strategies on student participation and performance in adaptive learning assignments in a face-to-face macroeconomics course. The study found that rigid deadlines negatively impacted participation, but the assignments still positively contributed to exam and homework performance. Extavour, Ocho and Allison [51] evaluated students' perceptions and attitudes towards an adaptive learning technology used in a nursing pharmacology course and found that the technology was positively received by students and resulted in higher course marks than the traditional class. These papers discuss the development and evaluation of personalized presentation modules, interest-based personalization interventions, approaches to improving adaptation and personalization, and the effects of different strategies on student participation and performance.

3 papers and 1 Ph.D. thesis are related to *adaptive learning gamification*: Durieu, Solal and Tercieux [45] discusses a study on perturbed joint and independent fictitious play processes in n-person games and how they relate to the selection of strategies in the long run, Del Blanco et al. [41] discussed the integration of digital games in virtual learning environments, using a middleware architecture to integrate video games in VLEs, and Johnson and Zaiane [83] proposes an online Intelligent Tutoring System gamified to teach medical imaging. Ghaban [61] proposes a model of adapting the gamification elements, that can predict the best combination of gamification elements for a learner's personality profile.

4 papers are primarily focused on *teaching methodology and the use of adaptive learning systems to enhance learning outcomes*. Yang et al. [202] investigates the effectiveness of critical thinking infused adaptive English literacy instruction using a Moodle system. Results demonstrate that CT-enhanced adaptive English literacy instruction simultaneously improves students' CTS and English literacy, and students' online discussions develop towards higher levels of interaction. The study illustrates an effective blended learning model for adaptive instruction and offers recommendations for designing CT-infused language learning activities. Kakosimos [89] presents a teaching methodology for providing students with feedback before lecture and adapting course content accordingly. This methodology was tested and demonstrated with a Chemical Engineering Fluid Operations course and showed improvements in students' engagement and motivation. Kerr [93] is part of a series that aims to discuss and demystify technology-related themes and topics for English language teachers. Johnson [84] highlights the challenge for teacher educators to prepare teachers for the increasingly diverse and complex contexts of learning shaped by globalization, technology, and other factors.

4 papers explore the effectiveness of adaptive learning systems in improving learning outcomes and the *role of learning styles* and other factors in their design and implementation. Hwang et al. [76] investigated whether students were able to choose the best-fit e-learning systems for themselves, concluding that developing adaptive learning systems based on learning styles is essential. Chang et al. [24] describes the development of an adaptive learning management system that assesses students' learning styles and uses Mashup technology to provide supplementary learning materials. An experiment showed that the system improved learning outcomes and was well-received by participants. Dziuban et al. [46] examines an adaptive learning partnership between universities and Realizeit, finding that the adaptive modality stabilizes learning organization in multiple disciplines. Serrao-Neumann, Cox and Low Choy [165] proposed a conceptual model to identify components of adaptive learning for natural resource management and validated it through on-ground experience, offering insights

to enable bridging between adaptive learning and NRM outcomes.

3.3. A cluster of adaptive learning systems and education computing

A cluster of adaptive learning systems and education computing (in blue color) represented by 18 papers.

5 papers relate to the integration of learning styles, developing computer-based science learning media, proposing adaptive learning frameworks, exploring adult constructive-developmental theory, and recommending learning paths based on learners' knowledge and course topics. Aljojo et al. [7] presents an approach to integrating learning styles into an adaptive e-learning hypermedia system and evaluates the impact of such a system on students' learning. Zulfiani, Suwarna and Miranto [210] developed a computer-based science learning media that accommodated students' learning styles, producing a system that was declared valid and effective for different types of learners. Ibrahim and Hamada [78] proposes an adaptive learning framework that classifies learners based on individual preferences in terms of understanding and processing information, generating a learning style and suggesting learning content accordingly. Stewart and Wolodko [176] explores Robert Kegan's adult constructive-developmental theory and proposes that university teaching practitioners at different meaning-making levels may benefit from adaptive approaches to the application of interactive pedagogies and digital technologies. Fiqri and Nurjanah [58] discusses a modified Dijkstra algorithm that recommends learning paths based on learners' knowledge, the weight of topics in a course, and the influence scores of each topic, considering the possibility of success in learning a topic.

6 papers and 2 Ph.D. theses relate to intelligent tutoring systems and adaptive learning approaches (primarily in mathematics education), discussing their effectiveness, benefits, and the design of personalized learning experiences using different methods. Walkington and Sherman [195] investigates the effectiveness of context personalization within an intelligent tutoring system for Algebra I students and how it facilitates algebraic symbolization. Li et al. [106] discusses the advantages of adaptive learning, which can provide personalized learning experiences for students. It describes a model that simplifies the concept map and presents the learner's cognition abilities with a belief vector. Bian et al. [17] proposes an approach for generating adaptive learning paths by creating a learner-centered concept map and using an immune algorithm to select learning objects for the optimal path. Smith [174] investigated preservice teachers' perceptions of adaptive learning programs for K-8 mathematics classrooms, finding that such programs were seen as beneficial, but required careful consideration when integrating them into teaching practice. Idrobo and Davidson-Hunt [79] examines the adoption of a technology to appropriate an ecologically constrained resource within the context of a restructuring fisheries sector using the conceptual lenses of adaptive learning and practice. Hou and Fidopiastis [69] reviews the evolution of learning theories and provides guidance for designers of intelligent adaptive learning systems for individualized learning, illustrated by a customised intelligent tutoring system for improvised explosive device disposal operator training. Pedan [151] proposed a method for developing adaptive tutoring software in the frame of competence-based learning principles. Vyshnevska [194] proposes a computer-based system of adaptive learning developed on the principles of fuzzy logic. The teacher-like system is based on the model of the student which consists of two parts, a stable (student's psychological

features measured before training) and a variable (student's development during training). The correction of the learning curve is based on both the model of student and management goals.

7 papers, 1 D.Sc. thesis, 8 Ph.D. theses and 3 technical reports related to the application of adaptive learning and analytics in various educational settings and systems, including MOOCs, school education, and technology-enhanced learning projects. Li, Zhao and Gan [105] focuses on the application of adaptive learning in MOOCs and proposes a customized MOOC learning model that includes a personalized course map and an adaptive MOOC learning system to improve pedagogical effectiveness and reduce the high attrition rate of students in MOOCs. Mavroudi, Giannakos and Krogstie [118] reviews recent publications on learning analytics applications in adaptive learning and identifies a lack of studies on school education and non-STEM topics, as well as a trend of considering more complex student behaviors. Welsh and Uys [199] discussed the reconfiguration of institutional learning analytics at Charles Sturt University to create an Adaptive Learning and Teaching program that integrates analytics and feedback to personalize online learning. Angelaccio and Buttarazzi [12] presents EduSHARE, a P2P distributed learning system based on a group-based file sharing extended with dynamic test modules aimed to be integrated into a course to improve interactivity between several actors playing in a common lesson scenario. Di Mascio et al. [42] describes the user-centered design approach used to design and develop TERENCE, a technology-enhanced learning project aimed at stimulating inference-making about stories for poor comprehenders aged 7-11. Hu and Huang [71] presents an approach for designing a test bank using the grasp degree towards concepts mechanism to record students' learning performance and provide adaptive guides for learners. Cui et al. [34] described the use of item response theory to measure student ability and item difficulty, using real data to evaluate the Squirrel AI Learning System. Fedoruk [55] proposed a set of models, e.g. model of a student, the model of class, the models of adaptive knowledge control (algorithmic and fuzzy), and a model of individual adaptive learning trajectory technology. For the first time, proposed models have been used for the development of the adaptive system of distance learning. Yurchenko [205] proposes the structural and logical charts of learning and knowledge control based on semantic connections between the educational material blocks and test questions. A method author for determining the priority of blocks of educational material and a method for determining the adequacy of the complexity level of knowledge control questions, taking into account the final specialist's assessment, as well as adaptive models for adjustment of the complexity in real-time. Martynova [114] developed methods that use semantic functional networks for the representation of knowledge on the tasks of the learning and control process, as well as the situational method of learning and control of knowledge acquisition for control tasks, and methods of classification of situations, criteria for managing the learning process and testing in the elimination of critical situations. For the formalized description of the tasks of adaptive management the models of knowledge about the process of determining the trainees' category, as well as about the events of management were developed. Tonkonohyy [183] develops decision-making information technology using a quantitative assessment of the level of assimilation of students' knowledge as complex objects. A method for the identifying and collection of SCORM-based educational content for the preparation of an electronic course in the system of adaptive learning is proposed by Kyrychenko [97]. Mazurets [121] proposes a method for automated structuring of learning materials and a method for generating test questions automatically from the learning materials that can be used for adaptive knowledge

control. Osadchyy [147, 148] introduce an immersive techniques into adaptive system of blended learning [147]. As result, the adaptive information system for individual professional training in the conditions of blended learning was developed [148]. Ananta [9] proposes an adaptive hypermedia learning system that initially limits the choices students can make until they have mastered key concepts. The system analyses learner responses and once key concepts have been mastered, learners are allowed increased access to a greater range of learning materials and options. Jiang [82] has focused on applying the techniques of adaptive testing to the learning environment. The researcher proposes a new online learning system that features a Bayesian algorithm that computes item and person parameters on the fly. Fielder [57] proves that a computer adaptive test as compared to using the entire test is more effective. The major finding of this study indicates that with a well-targeted audience, there are significant correlations between the two test versions and that the computer adaptive test is significantly quicker to take than the computer-administered full test. Mehigan [123] investigates how biometric technologies, in particular accelerometer and eye-tracking technologies, could effectively be employed within the development of mobile learning systems to facilitate the needs of individual learners. The author provides recommendations for developers in the creation of adaptive mobile learning systems through the employment of biometric technology as a user interaction tool within mobile learning applications. Rudnitska [161] proposes a conceptual model of an adaptive system of continuing education for smart industries and a method for building an individual learning trajectory that allows student-based management of learning taking into account their competencies, evaluation of the effectiveness of the planned activities, and modernization of training content by EdTech providers.

The papers from the cluster of adaptive learning systems and education computing are related to three main topics:

1) *integrating learning styles into adaptive e-learning hypermedia systems*: developing computer-based science learning media, proposing adaptive learning frameworks, exploring adult constructive-developmental theory, and recommending learning paths based on learners' knowledge and course topics;
2) *intelligent tutoring systems and adaptive learning approaches in mathematics education*: highlighting their effectiveness, benefits, and the design of personalized learning experiences using different methods.
3) *application of adaptive learning and analytics in various educational settings and systems*, including MOOCs, school education, and technology-enhanced learning projects: related papers demonstrate the potential of adaptive learning to personalize learning experiences, improve pedagogical effectiveness, and reduce attrition rates.

Overall, the papers reflect the growing interest in the use of adaptive learning and analytics in education and the need for further research in this area.

3.4. A cluster of learning and education research

A cluster of learning and education research (in yellow color) represented by 23 papers.

15 papers, 1 Ph.D. thesis and 1 technical report covers a range of topics related to learning and education, including topics such as teacher-centered instruction, logistical support for learners,

learning styles, flipped learning, personalized-adaptive learning environments, etc. Ziimpe [209] discusses the introduction of adaptive learning into the new canonical macroeconomic model, and how it affects the stability of monetary policy rules. Mccaslin and Burross [122] presents research on teacher-centered instruction and individual differences among students within a sociocultural perspective. Nasr-Eddine, Zaidi and Eddine [134] proposes an approach to improve logistical support in the learning process for learners of all ages. Huang et al. [72] explores the use of mobile agents to assist students in virtual learning environments, with a focus on reducing the burden on teachers. Covington [33] discusses the current understanding of the cognitive, motivational, and situational determinants of school achievement and identifies gaps in knowledge. Sandman [162] reports on a study that examined the learning styles of business students and found that their styles may depend more on the course than their major. Nurjanah [139] proposes a collaborative authoring approach for creating adaptive learning systems and presents the results of qualitative and quantitative experiments validating the approach. Levy [101] describes a book that presents the principles of classical and instrumental conditioning and their applications in understanding the human condition. Daniel, Cano and Gisbert Cervera [35] discusses the challenges facing MOOCs and proposes five dimensions for understanding their future. Dong and Sharma [44] explores the combination of the flipped classroom model and adaptive learning in medical education. Yetişir and Ceylan [203] adapted a scale to measure students' attitudes toward science learning into Turkish and found it to be a valid and reliable measure. Tashiro et al. [182] explores the development and evaluation of a personalized-adaptive learning environment for computer information technology education. Torrano and González-Torres [184] reports on the initial validation study of motivational scales for secondary education students in Spain. Mei, Guo and Li [124] describes the design of a multimedia-based English pronunciation learning system with a self-adaptive learning mode. Laitinen, Piazza and Stenvall [99] presented the qualitative study that explores learning processes in smart city organizations in Helsinki and Catania. Elbrekht [48] highlights the transformation of the management culture of school principals. According to Elbrekht [48], the technology of adaptable management is a transformational cycle of planning (aims, goals, and tasks), modeling (algorithms, criteria of efficiency, prediction), management (communication and collaboration), monitoring (measurement, assessment, evaluation), correction (reflexly and self-reflexly, SWOT analyses, etc.). Bobrova [18] proposes a set of models, e.g., the general model of adaptive management of the professional development of scientific and pedagogical workers, and the model of adaptive management of the student's independent work.

5 papers discusses several studies related to adaptive learning in medical education. Menon et al. [125] identified factors associated with persistent use of the Osmosis platform by US medical students. Huffman et al. [75] investigated the use of data from Human Dx to assess diagnostic reasoning skills and deliver tailored content. Bouzenada, Boissier and Zarour [20] proposed a multi-agent system for adaptive learning based on learning styles and domain knowledge. Tackett et al. [181] examined the use of crowdsourcing for multiple-choice questions in medical education. Finally, Sharma and Jordan [167] discussed the potential of adaptive learning in medical education in the UK.

3 papers, 1 Ph.D. thesis, and 1 technical report related to the implementation and effectiveness of adaptive learning technology. Kakish and Pollacia [87] discusses the use of adaptive learning technology in an Information Technology course to improve student scores, pass rate, and

retention levels. Kakish, Robertson and Jonassen [88] presents a study on student and instructor perceptions of adaptive learning technology in a computing course, finding that it was viewed as a beneficial addition to the course. Kellman and Krasne [92] discusses the use of adaptive learning technology in combination with perceptual learning interventions to improve medical learning and performance. Seriakov and Shcheholkova [164] propose an automated method of determining the structure of a student's cognitive model. Pikulyak [154] proposes a method of assessment of results of knowledge test control based on multiset theory and information quantification.

After reviewing the selected articles from the cluster of learning and education research, it is clear that adaptive learning technology is becoming increasingly popular in the education sector, particularly in the fields of macroeconomics, information technology, and medical education. The articles discussed various approaches to implementing adaptive learning, including personalised-adaptive learning environments, collaborative authoring, and the use of mobile agents. The potential benefits of using adaptive learning technology include improving student scores, pass rates, and retention levels, as well as reducing the burden on teachers.

The studies also highlighted the importance of considering individual differences among students, including their learning styles and attitudes towards learning, when implementing adaptive learning systems. Moreover, several studies emphasized the need for further research to identify the cognitive, motivational, and situational determinants of school achievement, as well as to validate motivational scales for different educational contexts.

Finally, the studies discussed the challenges facing adaptive learning technology, such as the need to ensure the validity and reliability of measures and to address ethical and privacy concerns. Despite these challenges, the potential of adaptive learning technology to improve educational outcomes and enhance the learning experience for students and teachers alike is promising.

3.5. A cluster of personalized learning

A cluster of personalized learning (in violet color) presented by 5 papers and 3 Ph.D. theses discusses various aspects of adaptive learning as a highly intelligent learning resource service model that provides personalized learning paths and resources to learners. Peng, Ma and Spector [153] introduces personalized adaptive learning, a new teaching method enabled by a smart learning environment that promotes the development of personalized and adaptive learning. Liu et al. [111] emphasizes the need for evidence-based research to understand how user behavior patterns can be used to design effective adaptive learning systems. Zhao and Wang [207] focuses on the three core modules of the adaptive learning system, including the knowledge network model, cognitive level model, and adaptive recommendation model, which improve learning by integrating user-specific behavioral characteristics such as learning habits and knowledge capacity. Davis et al. [37] shares experiences in exploring and implementing adaptive learning for first-year pharmacy students. Finally, Liu et al. [112] investigates the impact of an adaptive learning intervention to provide remedial instruction in various content areas to first-year students entering a pharmacy professional degree program. The study findings highlight the importance of design in adaptive learning and emphasize the need to consider affective factors such as motivation in adaptive learning. Kuzikov [96] develops the model of the adaptive construction of an individual learning trajectory and a criterion for evaluating the effectiveness of the distance learning system. Andrukhiv [11] develops an adaptive method of forming a list of recommended literature for academic disciplines, which includes an assessment of the relevance of the list items. Shemshack [169] investigated personalized adaptive learning, teacher education, and self-efficacy to determine if personalized adaptive teacher education can increase self-efficacy. The researcher suggested that teachers with higher self-efficacy tend to stay in the teaching profession longer. As a result, it was found that teachers' self-efficacy increases with more training, support, and resources. Components of personalized adaptive learning to provide support/help at the right time for teachers to increase their self-efficacy were introduced in the teacher's training curriculum.

All reviewed works from the cluster of personalized learning are:

- focus on the benefits and challenges of adaptive learning, which is a form of personalized learning that uses technology to provide learners with customized learning experiences based on their individual needs and abilities;
- explore various aspects of adaptive learning, such as the design and implementation of adaptive learning systems, the role of user behavior patterns in designing effective adaptive learning systems, and the impact of adaptive learning interventions on student learning outcomes;
- highlight the importance of evidence-based research and design in the development and implementation of adaptive learning systems.

4. Conclusion

With the help of a bibliometric review, the main directions of research in the field of adaptive learning were determined. A cluster analysis was conducted, in which 5 clusters were distinguished: a cluster of general concepts of adaptive learning in e-learning systems, a cluster of educational technology, a cluster of adaptive learning systems and education computing, a cluster of learning and education research, and a cluster of personalized learning. This made it possible to group the reviewed scientific papers and Ph.D. theses in a literature review to highlight the main themes related to adaptive learning.

The primary limitations of the research stem from the exclusive use of the Scopus database and specifically, the social sciences section of this database, rather than its full range. This is particularly noteworthy given the potential relevance of this topic to other fields such as engineering. To determine whether this first limitation is critical, we conducted a similar search in the Web of Science database. This search yielded 290 documents, and their distribution by years (figure 13) mirrors the distribution of documents from the Scopus database (figure 1). Although not all documents listed in Web of Science are included in Scopus and vice versa, they exhibit a similar distribution of keywords by clusters.

There are some restrictions with the VOSViewer tool: a clustering algorithm was applied with the default settings, and the low limit for keyword occurrence was set at 10. The number of clusters can be decreased or increased depending on the clustering settings. Additionally, the third cluster can be combined with the fifth one because the fifth cluster only has one keyword (personalized learning).

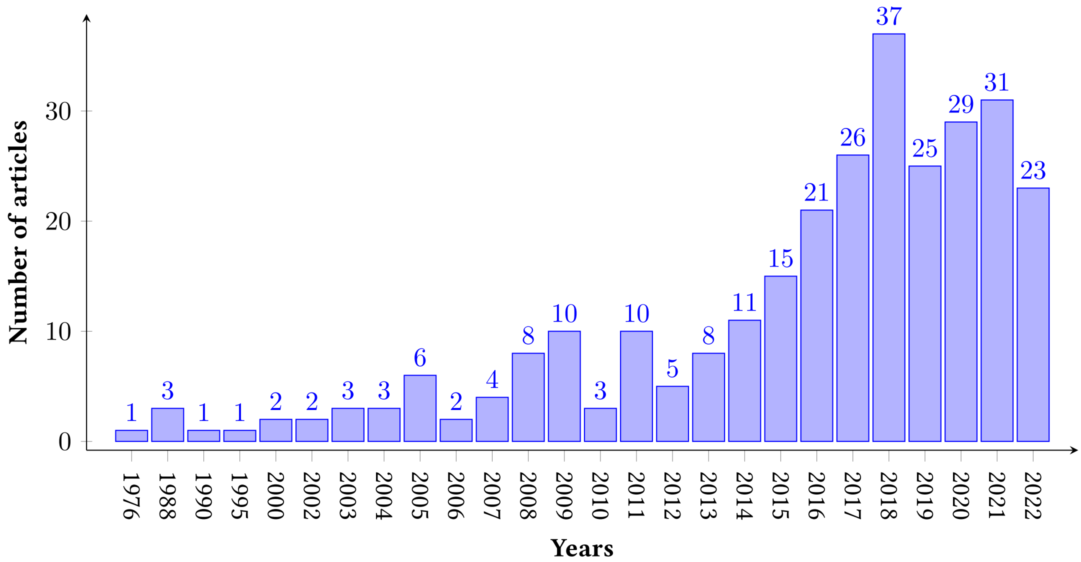

Figure 13: Distribution of articles from Web of Science database by years.

Additionally, sources like technical reports and Ph.D. theses that are not indexed by Scopus were used for this research. Prior to 2022, most of these sources from the National Repository of Academic Texts (Ukraine) were not indexed by web search engines.

Using only one term, such as "adaptive learning", for a cluster-based literature review in a specialized field like adaptive learning in higher education can be effective in capturing the majority of relevant studies due to a consensus around this term that is widely accepted and used across the literature. Also, using a single keyword like "adaptive learning" can help to reduce the number of false positives in the search results that might be retrieved when using multiple terms.

As a result of the conducted research, it was determined that

- All articles reveal certain aspects of adaptive or personalized learning.
- An attempt to divide the clusters into subclusters revealed that the clusters are closely connected.
- Outlined topics that are most closely related to adaptive learning: AI technologies in the development of adaptive learning systems, personalized education, learning styles, approaches in adaptive learning systems, development and use of adaptive learning systems, implementation and effectiveness of adaptive learning technologies, including eye-tracking, and physiological measurements to enhance the personalization and effectiveness of learning.

Furthermore, the bibliometric review highlighted the dynamic and interconnected nature of research in the field of adaptive learning. The analysis revealed that the clusters identified are not isolated entities but rather interconnected domains, indicating the multidimensional nature of adaptive learning research. This suggests that advancements in one cluster can have implications and contribute to developments in other clusters, fostering a holistic understanding of adaptive learning.

The findings of the cluster-based literature review underscored the importance of AI technologies in the development of adaptive learning systems, as well as the significance of personalized education and catering to individual learning styles. The identified topics emphasized various approaches within adaptive learning systems, including their development, implementation, and effectiveness. As Ukraine progresses in its pursuit of educational excellence, embracing adaptive learning systems and personalized approaches will play a pivotal role in fostering a highly effective and dynamic education system for the future.

Building on this analysis, several areas of future research can be explored to advance our understanding of adaptive learning and its applications in education:

1. *AI-driven adaptive learning*: investigate the role of artificial intelligence in the development of adaptive learning systems and explore the use of advanced AI algorithms and approaches to enhance the adaptivity and personalization of learning experiences.
2. *Evaluation and effectiveness*: examine the implementation and effectiveness of adaptive learning systems in educational settings and conduct empirical studies to assess the impact of adaptive learning on student performance, engagement, and satisfaction.
3. *Adaptive learning environments*: explore the design and development of adaptive learning environments that cater to individual learners' needs and preferences and investigate how adaptive systems can be integrated into existing educational platforms to create personalized learning experiences.
4. *Gamification and adaptive learning*: investigate the potential of gamification techniques in adaptive learning systems and explore how gamified elements can enhance student motivation, engagement, and learning outcomes.
5. *Learning styles and personalization*: study the role of learning styles in adaptive learning systems and investigate how learning styles can be effectively integrated into adaptive learning platforms to cater to diverse learner preferences.
6. *Analytics and adaptive learning*: explore the use of learning analytics in adaptive learning systems and investigate how data-driven insights can be utilized to personalize learning pathways and support educators in making informed decisions.
7. *Application in different educational settings*: investigate the implementation of adaptive learning and analytics in various educational settings, including K-12 schools, higher education institutions, corporate training, and online learning platforms.
8. *Ethical and privacy considerations*: examine the ethical and privacy implications of using adaptive learning systems, especially when leveraging AI and data-driven approaches and address concerns related to data security, bias, and transparency.

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