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DEVELOPMENT AND EVALUATION OF STEM PROJECTS BASED ON THE INTEGRATION OF MACHINE LEARNING AND THE INTERNET OF THINGS (IOT).

Abstract. The paper considers theoretical and practical underpinnings of integrating machine learning and Internet of Things (IoT) technologies into the educational process of STEM (Science, Technology, Engineering, and Mathematics). The research shows that when IoT devices are included in STEM projects, the ability of learners to process, analyze and automate processes significantly increases. Besides, the paper gives assessment standards of how to design and evaluate STEM projects. A sample study with 44 students resulted in a STEM project that combines the use of IoT hardware and machine learning algorithms. The main goal of the project is the development of fire safety and evacuation management system. The study provides suggestions towards the successful implementation of the modern technologies in STEM education and also seeks to streamline the methodological approach to evaluating STEM projects. Moreover, project-based work-related activities enable learners with analytical thinking abilities and develop their ability to solve real-world problems.

Keywords: STEM education; project-based learning; machine learning; Internet of Things; assessment.

Introduction

In the modern educational context, STEM-based approaches to instruction provide students with both scientific and technological literacy and help them to adjust to the fast-changing technological settings. Combining machine learning as one of the subfields of artificial intelligence with Internet of Things (IoT) technologies enhances the functional potential of STEM projects and proactively promotes the skills of creative and logical thinking, data processing, predictive modeling, and automated decision-making in learners (Abichandani et al., 2022; Zhai et al., 2021).

At the same time, rapid technological transformation has created an increasing need of qualified STEM professionals. Kazakhstan is one of the developing countries in Central Asia that showed the understanding of the significance of STEM education. In this regard, colleges in the country have collaborated with the European Erasmus+ programme to develop a new program based on STEM teacher training. This program is being carried out as part of a two-year long program, «7M01525 - STEM Education» , whose purpose is to develop the professional knowledge of future STEM educators (Serik et al., 2022).

The curricula of the 7M01525 - STEM Education - course have several subject areas, such as robotics in education, circuit design, the Internet of Things, and STEM project management, among others (L. N. Gumilyov Eurasian National University, n.d.). These sciences help in formation of the STEM education system and improvement of the professional competencies of future specialists. In the international practice, it is always proven that STEM projects development promotes the development of practical skills in learners and makes them oriented towards scientific inquiry. The current paper not only discusses the theoretical foundations of applying machine learning and IoT in STEM projects but also the assessive standards that can be applied to project preparation in practice.

Research objective: to carry out a theoretical study of the methodological strategies of the integration of machine learning into different IoT technologies, and to create the practical assessment criteria of the design of STEM projects.

By using IoT-based devices, learners can acquire skills in programming, sensor management, and data processing, and implementing machine learning algorithms can broaden intellectual capabilities of projects and allow them to make decisions automatically. This approach is consistent with modular IoT-based

STE(A)M learning practices that support hands-on sensing, data collection, and analysis (Cappelle et al., 2022).

There are multiple academic papers devoted to the exploration of applying machine learning and IoT to STEM projects. The work of Thakur et al. (2024), focusing on the implementation of the IoT and machine learning approaches in robotics education can be listed among the most striking ones. The study is based on the improvement of robotic systems with the help of real-time analysis of sensor data and reports that an RNN model reached the predictive accuracy of 96.7 in the student behaviour modelling. A study by Sahu et al. (2024) on the possible uses of IoT and machine learning in energy management and precision agriculture has shown how these technologies can enhance operational efficiency, but has not dealt directly with the design and evaluation of STEM projects. Ali and Rani (2024) explore the role of machine learning in guaranteeing the safety of the IoT, detect weak points, and suggest the protective against cyber-attacks, which is a major contribution to information security development in STEM projects. Akintayo et al. (2024) examined how machine learning and IoT integration impact the data analysis and decision-making processes.

Methodology

The experimental and practical work was conducted at L.N. Gumilyov Eurasian National University and at East Kazakhstan University named after S. Amanzholov in the city of Ust-Kamenogorsk. Study participants comprised a total of 44 Master's students enrolled in the «7M01525 - STEM Education» programme. Each participant held a Bachelor's degree in one of the following disciplines: Computer Science, Engineering Informatics, Physics, or Mathematics. The practical work was carried out in accordance with the following three principal phases (Figure 2).

During the preparatory phase, introductory sessions were delivered to familiarise learners with the fundamentals of IoT technologies and machine learning. This phase extended over a period of five weeks, with each practical session lasting three hours.

During the design phase, learners selected and implemented project topics addressing real-world social challenges. Project development was grounded in the stages of the system life cycle methodology, and each student received a STEM project preparation guide. By fulfilling the requirements of each phase as set out in the guide, students ultimately submitted written reports documenting the progress of their project work.

During the evaluation phase, the submitted project reports were assessed against the established evaluation criteria (Table 1). In addition, students received feedback on their work through formal project defence presentations.

Table 1.

STEM Project Evaluation Criteria

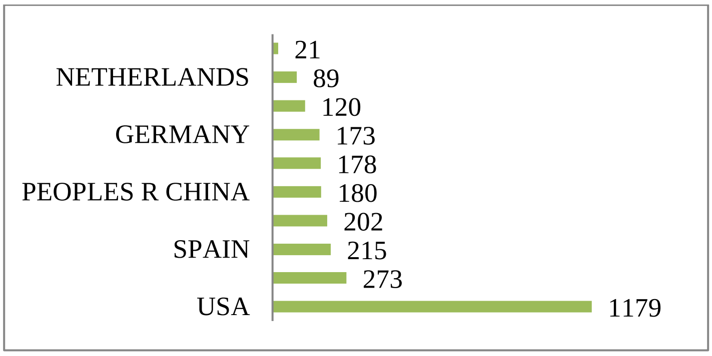
STEM Project Evaluation Criteria (Technical / Content)				
	(1-2 points) Unsatisfactory	(3-5 points) Satisfactory	(6-7 points) Good	(8-10 points) Very good
Analysis	Organisation description and methods used in the selected project area.	Evidence from attempts to interview the client, some of which are described.	Ensure good client engagement and record the interview(s). Most of the required items are covered, with a thorough analysis of alternative approaches.	There is evidence of high client engagement with comprehensive requirements documentation. Alternative approaches have been identified and a systematic analysis has been conducted.
Design	It is accompanied by some unclear information about what the new system does, along with a brief schematic diagram.	The new system has objectives. The data structures (block diagram, diagram) have been defined, but there are sections that do not meet the requirements.	The complete technical requirements for the assigned tasks have been included, although there may be logical inconsistencies. Each of the implemented design requirements has concrete evidence.	The project's technical content is fully covered and its technical requirements are logically structured. A complete description of each process is clearly provided.

Implementation, programming	Software and description of IoT devices. The proposed algorithm does not conform to the design specifications.	The software code for the input and output algorithms is shown. The proposed algorithm has logical flaws.	The input and output algorithms, together with the codes for establishing connections with the data structure, largely conform to the design specifications of the proposed solution.	The communication for IoT devices and data processing is properly configured. It demonstrates strong technical proficiency in programming. The annotated code explains the logic.
Testing	Test results may be without a test plan or vice versa.	There is minimal evidence of testing, and no link between development and testing.	There must be printed copies of the results of at least eight different tests.	A complete implementation plan, including system migration, training and testing phases, with evidence provided.
Documentation	Incomplete guide; not all steps are described.	All options, except for one or two, are fully described.	A fully recommended user manual with an index and glossary.	A comprehensive, well-organised user manual with an index and glossary.
Assessment	Discussing the success of the work without referring to the design objectives.	Discussing some of the design objectives with insufficient explanations.	A comprehensive discussion, beginning with the design section, for each objective, presenting supporting evidence from the project or explaining the reasons for objectives that were not met.	A fully user-friendly system has been released. The user indicates that the system's section design fully complies with the specification.

The search of the Web of Science Core Collection database, with the restrictions of the period 2020-2025 and open-access articles, and the type of article searched among the categories Education, it became evident that the topic of study has been discussed by many scholars over a variety of countries. A prolonged search also helped to determine the quantity of publications produced in Kazakhstan (Figure 1).

Figure 1.

Geographic distribution analysis of sources in Web of Science



In the United States, the application of IoT technologies in educational settings has emerged as a significant priority for the improvement of the instructional process. In this context, particular attention has been drawn to the following works. Bondaryk et al. (2021) demonstrated that IoT-based sensor systems enable students at secondary educational institutions to observe scientific phenomena in concrete terms. Their proposed IoT Dataflow system features a software interface that ensures transparency in data collection and processing, thereby fostering learners' computational and scientific research competencies. Similarly, Ahmed et al. (2022) describe the experience of integrating IoT technologies into a computer science curriculum, whereby new instructional modules were introduced to develop the practical skills necessary for designing intelligent IoT systems. This approach was found to increase students' interest in the IoT domain and to strengthen their professional competencies in this field.

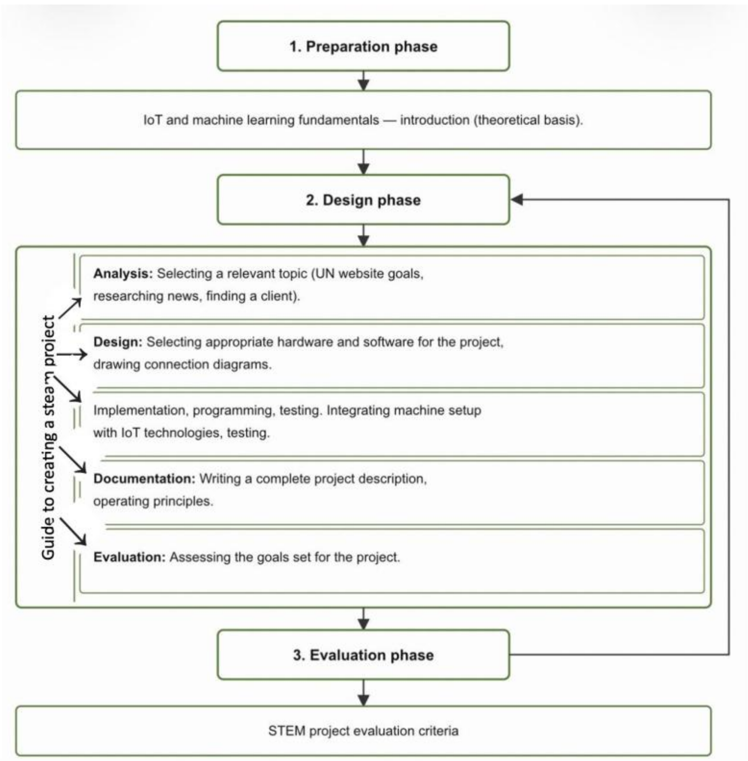
Research from the United Kingdom demonstrates the impact of artificial intelligence and machine learning on the educational system, revealing their potential for enhancing both academic and technical knowledge, and highlights the importance of policy measures aimed at encouraging enrolment in STEM-related engineering disciplines. More specifically, the study conducted by Kara et al. (2021) assessed the effect of class size on students' academic achievement across STEM and non-STEM disciplines in UK universities. The findings indicate that students in larger classes tend to achieve lower grades, underscoring the importance of accounting for the impact of policies aimed at increasing student participation in STEM fields on overall educational quality.

The works of Kazakhstani researchers attest to the significance of integrating IoT technologies into the educational process. Notably, Tutkyshbayeva and Zakirova (2024) analysed the effectiveness of IoT-based digital educational materials in developing students' digital competencies. Through a comparison of experimental and control groups, the study demonstrated that IoT-integrated instructional methods yield superior outcomes compared to traditional approaches. Research into the factors influencing academic achievement in STEM and non-STEM disciplines is equally important. Sultanova and Shora (2024) analysed the influence of non-cognitive skills—such as perseverance and information-processing ability—on achievement in mathematics, physics, language, and history within Kazakhstan's secondary education system. Their findings indicate that information-processing ability and perseverance play a particularly significant role in STEM subjects, whereas responsibility and collaborative skills are more prominent in the humanities. Furthermore, STEM teacher preparation has a direct bearing on the quality of education. Zhumabay et al. (2024) investigated the effects of STEM courses on teachers' sense of self-efficacy and instructional practice, concluding that such courses play a crucial role in teachers' professional development.

Accordingly, the body of research reviewed above indicates that the application of IoT technologies, the role of non-cognitive skills, and the preparation of STEM educators constitute key factors in improving educational quality. On this basis, the present study is directed towards investigating the effectiveness of instructional methods that combine IoT technologies with machine learning algorithms.

Figure 2.

Phases of the experimental and practical work



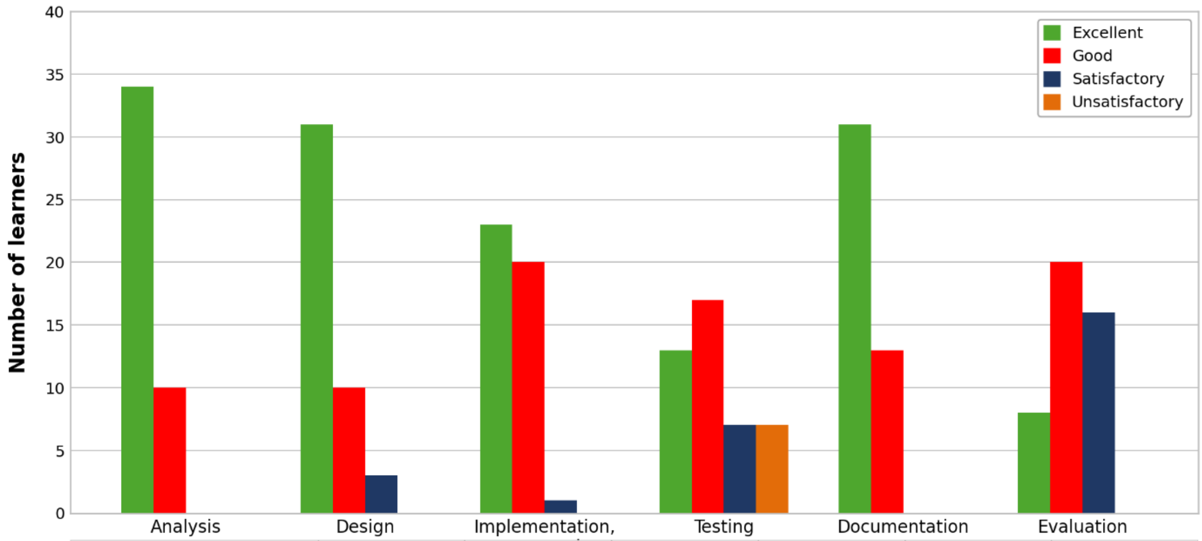
As an experimental work, the additional modules about the integration of the IoT technologies with machine learning were included into the course of the programme 7M01525 - STEM Education at the L. N. Gumilyov Eurasian National University, as well as into the course of the programme Robot Programming at the East Kazakhstan University named after S. Amanzholov.

Results and Discussion

The study has led to a thorough exploration of ways of combining machine learning and IoT technologies, which have led to the creation of STEM projects. Students were able to integrate hardware-software technology within their projects and had to make progress reports. These reports were organized in the following ways: analysis, design, implementation, programming, testing, documentation, and evaluation. The results were measured at four levels (unsatisfactory, satisfactory, good, and excellent) based on the evaluation criteria that had been set

Figure 3.

Evaluation results based on the phases of the system life cycle



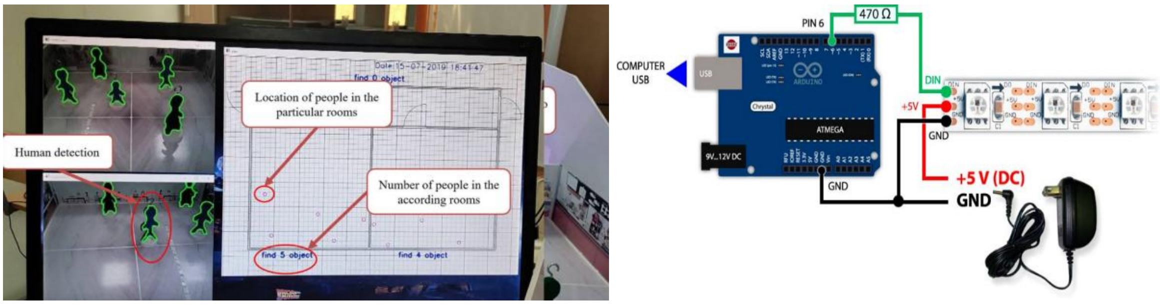
	Analysis	Design	Impl., prog.	Testing	Docum.	Evaluation
Excellent	34	31	23	13	31	8
Good	10	10	20	17	13	20
Satisfactory	0	3	1	7	0	16
Unsatisfactory	0	0	0	7	0	0

In the course of the project work, students demonstrated the highest results in the analysis (93%) and documentation (91%) stages. During the design phase, they presented the external structure of their STEM projects and achieved 89%. However, in the implementation stage, the performance decreased to 82%, as some of the developed functions did not fully correspond to the initial project plan. The lowest average score (80%) was observed in the evaluation stage, which can be explained by difficulties in completing self-assessment and collecting client feedback. These results indicate that future iterations of the course should place greater emphasis on developing students' skills in independent evaluation and client-oriented analysis.\

Sample Student STEM Project

Students of the STEM Education programme at L.N. Gumilyov Eurasian National University developed a project aimed at solving two important modern challenges: fire prevention and rapid evacuation of large supermarkets in case of fire. The project was implemented using an Android-based microcontroller as an IoT device, combined with machine learning algorithms.

Figure 4.
STEM project developed through the integration of IoT technology and machine learning



The figure shows a high-occupancy building fire safety and evacuation management system, which is built by the students using the combination of the IoT technology and machine learning algorithms. To detect fire, the flame recognition algorithm developed by Garrido et al. (2020), namely OpenCV and texture feature analysis was used. Their model provided experimental results which showed that it performed at a 95% accuracy in real-world conditions. Adaptive LED signage systems were deployed to realise evacuation optimisation. A study conducted by Kim et al. (2022) revealed that smart LED systems can be relied upon to visibly influence the evacuation speed, and the ability to decrease evacuation time by up to 40 percent. IoT sensors were incorporated with cloud technologies to monitor the system. As the results of Patel and Singh (2020) reveal, the implementation of IoT devices into the fire safety systems can make the response time of fire detection three times shorter. Their experiment revealed the use of IoT sensors to transfer data on temperature, smoke concentration, and carbon monoxide levels to cloud services, which could be analyzed later. In the case of fire prediction, machine learning was utilized. Wei et al. (2023) came up with a prediction algorithm of fires in multi-storey buildings using neural networks. Their model examines past fire records and determines possible risks that can be pre-emptively used to employ safety nets; experimental findings indicated that they can predict with a 92% accuracy.

Conclusion

The findings of the study demonstrate that the proposed methodology effectively develops learners' creative and analytical thinking skills through the integration of Internet of Things (IoT) technologies and machine learning into STEM education. The results confirm that incorporating IoT devices into STEM projects enables students to work with real-time data while simultaneously enhancing their engineering and problem-solving competencies. Furthermore, the application of machine learning techniques provides students with practical experience in processing, analyzing, and predicting large datasets, thereby preparing future specialists to work confidently with advanced digital technologies.

The research also revealed several important educational benefits of combining IoT and machine learning within STEM projects. Practical interaction with real hardware significantly strengthens students' theoretical understanding and facilitates the acquisition of applied skills. The integration of machine learning algorithms with IoT sensor data promotes the development of data processing and analytical competencies, while the design and optimization of intelligent systems foster algorithmic thinking and automation skills. In addition, the use of interactive, project-based learning approaches increases students' motivation to study STEM disciplines, encourages active engagement in the learning process, and stimulates interest in future scientific and engineering careers.

As part of the study, a set of evaluation criteria for assessing STEM projects was developed and successfully validated, demonstrating the effectiveness of the proposed educational approach. However, the sustainable implementation of such practices requires further modernization of pedagogical methods, continuous professional development of teachers, and the systematic integration of emerging digital technologies into the educational process.

Overall, the integration of machine learning and Internet of Things technologies into STEM education contributes to improving the quality of professional training, fostering digital, engineering, and analytical competencies among future specialists, and supporting the broader digital transformation of the education system in Kazakhstan.

Conflict of Interest Statement

The authors declare no potential conflicts of interest regarding the research, authorship, or publication of this article.

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Author Contributions

Meruert Serik, Kymbat Tleuzhanova, and Celal Karaca contributed equally to the conception and design of the study, methodology development, project implementation, data collection and analysis, interpretation of results, and preparation of the manuscript. All authors participated in writing, reviewing, and editing the article and approved the final version for publication.

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