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ИЗУЧЕНИЕ БИОЛОГИЧЕСКИХ И ЭКОЛОГИЧЕСКИХ ОСОБЕННОСТЕЙ *PARROTIA PERSICA* C.A. MEY. В УСЛОВИЯХ АПШЕРОНА

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STUDY OF THE BIOLOGICAL AND ECOLOGICAL CHARACTERISTICS OF PARROTIA PERSICA C.A. MEY. UNDER THE CONDITIONS OF THE ABSHERON

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Аннотация

В статье приводятся данные исследования биоэкологических особенностей всходов на начальной стадии морфогенеза, динамики роста и развития одно-, двух- и трехлетних растений *Parrotia persica* C.A. Mey. При изучении семенного размножения выявлены оптимальная глубина и сроки посева семян исследуемого вида. Наблюдения показали, что в сухом субтропическом климате Апшерона наиболее благоприятным сроком посева в открытом грунте семян железного дерева считается осень, а оптимальной глубиной посева семян -3 см. При посеве семян в указанный срок появляются дружные всходы -30-85%. Дальнейшее изучение роста и развития железное дерево проводилось с момента появления всходов. Проведенные фенологические наблюдения показали, что рост однолетних сеянцев начиная со II декады февраля и до конца вегетационного периода составил около 27-30 см, двухлетних - 45-55 см и трехлетних - 65-70 см. Интенсивный рост продолжается с II декады апреля до III декады мая. За вегетационный период высокий прирост наблюдался у двухлетних сеянцев. Изучение корневой системы железного дерева показало, что помимо основных корней, образуются большое количество боковых корней, что очень необходимо для усвоения необходимого количества влаги как из нижних, так и из верхних слоев почвы в условиях сухого климата Апшерона. Основная часть корней располагается на глубине 2-32 см, что облегчает перенос разновозрастных растений на постоянное место произрастания. На основании полученных данных установлено, что в условиях Апшерона железное дерево нормально растет и развивается и может быть рекомендован при проведение озеленительных работ.

Abstract

The article presents data on the bioecological characteristics of seedlings at the initial stage of morphogenesis, as well as the growth dynamics and development of one-, two-, and three-year-old plants of *Parrotia persica* C.A. Mey. During the study of seed propagation, the optimal sowing depth and sowing time for the investigated species were determined. Observations showed that in the dry subtropical climate of the Absheron Peninsula, the most favorable time for sowing seeds in open ground is autumn, while the optimal sowing depth is 3 cm. Under these conditions, uniform germination was recorded at a level of 30–85%. In contrast, spring-sown seeds showed a significantly lower germination rate of 10–50%. Further studies on the growth and development of *Parrotia persica* were carried out from the moment of seedling emergence. Phenological observations revealed that the growth

of one-year-old seedlings from the second decade of February to the end of the growing season reached approximately 27–30 cm, two-year-old seedlings 45–55 cm, and three-year-old seedlings 65–70 cm. Intensive growth was observed from the second decade of April to the third decade of May. The highest annual increment was recorded in two-year-old seedlings. The study of the root system of *Parrotia persica* showed that, in addition to the main root, a large number of lateral roots are formed, which is essential for efficient water uptake from both upper and lower soil layers under the dry climatic conditions of Absheron. The main part of the root system is located at a depth of 2-32 cm, which facilitates the transplantation of plants of different ages to permanent growing sites. Based on the obtained results, it was established that under the conditions of Absheron, *Parrotia persica* grows and develops normally and can be recommended for use in landscaping and greening projects.

Ключевые слова: *Parrotia persica*, Апшеронский полуостров, семена, всходы, морфогенез, корневая система.

Keywords: *Parrotia persica*, Absheron peninsula, seeds, seedlings, morphogenesis, root system.

Введение

Апшеронский полуостров, где среднегодовое количество осадков составляет 200-300 мм, характеризуется своеобразными природно-климатическими условиями. Лето здесь жаркое и засушливое, зима мягкая и сопровождается сильными ветрами. Основная часть атмосферных осадков приходится на осенне-зимний и весенний периоды [3; 6]. Климат Апшеронского полуострова относится к типу умеренно тёплых пустынь и сухих субтропиков, характеризующихся засушливым летом, слабым увлажнением и высокой суммой температур в летний период. Среднегодовая температура воздуха составляет 14,4°C. В январе средние температуры варьируют в пределах 3,0-3,8°C, тогда как в июле достигают 24,6-25,7°C. Абсолютный минимум температуры воздуха составляет 5°C, а абсолютный максимум +40°C. Среднегодовое количество атмосферных осадков на полуострове составляет около 247 мм. Годовая величина испаряемости варьирует от 992 до 1210 мм, при этом максимальные значения отмечаются в летние месяцы (162-202 мм), а минимальные - в зимний период (34–38 мм)[5].

Почвы района исследований отнесены к серозёмно-бурым типам с относительно высокой хозяйственной ценностью. Они характеризуются мощным мелкоземистым горизонтом (1,5-2,0 м) и окультуренным слоем (25–30 см). Засоление полностью отсутствует, солонцеватость выражена слабо и не оказывает существенного влияния на развитие культурной растительности. Вместе с тем уплотнённость и слитность карбонатно-аллювиального горизонта, а также механический состав почв обусловливают ряд неблагоприятных свойств, влияющих на развитие и глубину проникновения корневых систем древесных и кустарниковых пород. Установлено, что применение глубокого рыхления почвы (50–60 см) с внесением навоза и органоминеральных удобрений позволяет предотвратить её уплотнение [2, с. 50-57].

В условиях интродукции растений особое значение приобретает изучение ритмов роста и развития интродуцируемых видов в новых почвенно-климатических условиях, что позволяет оценить их адаптационный потенциал и перспективы успешного культивирования в регионе.

Учитывая вышеизложенное, на территории Ботанического сада была проведена работа по изучению представителей семейства *Hamamelidaceae* (гамамелисовые). Данное семейство относится к древним и сравнительно немногочисленным группам покрытосеменных растений и включает около 27 родов и приблизительно 90 видов, представленных преимущественно древесными и кустарниковыми формами.

Представители семейства *Hamamelidaceae* распространены на различных континентах и характеризуются значительным морфологическим разнообразием. Среди них встречаются листопадные и вечнозелёные деревья, кустарники, а также полукустарники. Особый интерес представляет вид *Parrotia persica* (парротия персидская), широко используемый в декоративном озеленении. Это листопадное дерево высотой 15-25 м с коротким мощным стволом диаметром до 1,5 м. Листья кожистые, овальные, длиной 7-14 см и шириной 3-9 см; в летний период они имеют зелёную окраску, тогда как осенью приобретают яркие жёлтые и красные оттенки [8].

Исследования проводились в течение трёх лет. Почвы опытного участка отнесены к серозёмно-бурым типам с относительно высокой хозяйственной ценностью. Они характеризуются мощным мелкоземистым горизонтом (1,5-2,0 м) и окультуренным слоем толщиной 25-30 см. Засоление отсутствует, солонцеватость выражена слабо и не оказывает существенного негативного влияния на культурную растительность.

Вместе с тем уплотнённость карбонатно-аллювиального горизонта и механический состав почв обуславливают ряд неблагоприятных свойств, влияющих на развитие корневых систем древесных и кустарниковых растений и глубину их проникновения. Установлено, что проведение глубокого рыхления почвы (на глубину 50-60 см) в сочетании с внесением органических и органоминеральных удобрений способствует снижению уплотнённости и улучшению агрофизических свойств почвы.

При изучении особенностей семенного размножения *Parrotia persica* важным является определение оптимальных сроков посева, что оказывает непосредственное влияние на всхожесть семян и дальнейшее развитие растений.

Следует отметить, что *Parrotia persica* (железное дерево) имеет высокую декоративную ценность и широко используется в озеленении и ландшафтном дизайне. В осенний период (октябрь-ноябрь) листья растения приобретают интенсивную красную окраску, что придаёт насаждениям особую эстетическую выразительность.

Материалы и методы

В качестве объекта исследования был выбран вид *Parrotia persica* С.А. Меу. из семейства *Hamamelidaceae* [11]. Изучение биоморфологических особенностей проводили на основе методики И.Г.Серебрякова [7]. Семенное размножение изучалось согласно методике И.Т. Васильченко [3], а особенности формирования и развития корневой системы - по методике В.А. Колесникова [4].

В условиях открытого грунта были подготовлены грядки, при этом для улучшения механического состава почвы в соотношении 2:1 вносились песок и перепревший навоз. После посева семян грядки поливались и сверху покрывались тонким слоем перегноя. Расстояние между грядками составляло 10–15 см. Таким образом, при семенном размножении *Parrotia persica* особое значение имеет определение оптимальных сроков посева, что является важным условием успешной интродукции и дальнейшего развития вида [6].

Результаты и их обсуждения

В результате проведённых исследований (2024-2026 гг.) установлено, что в условиях сухого субтропического климата Апшеронского полуострова у вида *Parrotia persica*, наряду с главным корнем, формируется значительное количество боковых корней, что способствует эффективному поглощению влаги как из верхних, так и из нижних слоёв почвы. *Данный вид* характеризуется как засухо- и жароустойчивый, светолюбивый вид с относительно невысокой требовательностью к почвенным условиям. Растение лучше развивается на лёгких по механическому составу почвах и отличается хорошо развитой глубокой корневой системой. Вид проявляет устойчивость к слабой засолённости. В зимний период при понижении температуры до 10-15°С возможно повреждение побегов морозом, однако весной наблюдается интенсивное восстановление и активный рост.

После прорастания семян (рис.1) семядоли выходят на поверхность почвы. Прорастание начинается с появления зародышевого корня, за которым следует развитие гипокотиля. Семядоли имеют длину около 1,0 см и ширину 0,8 см, форма листовой пластинки овальная, цельнокрайняя. Семядоли сохраняются на проростках в течение 5–6 месяцев.

На светло-зелёном стебле через 13-15 дней после прорастания появляются первые настоящие листья. С формированием второго настоящего листа длина корня достигает 3 см. В конце апреля отмечается образование 7-9 листьев, при этом длина корневой системы увеличивается до 5-6 см. С началом интенсивного развития главного побега семядоли постепенно желтеют и опадают. Высота всходов *Parrotia persica*, полученных при осеннем посеве, к концу второй декады апреля составляла 3-5 см. Изучение роста и развития проводилось с момента появления всходов.

А) ***Б)***

Рис. 1. А- семена Parrotia persica; Б) последовательность прорастания семян

Как следует из таблицы 1, посев семян осуществлялся в осенний (октябрь) период на глубину 1,5 см, 3,0 см и 5,0 см соответственно. Начиная с конца первой декады февраля, наблюдалось прорастание семян осеннего посева. После появления всходов измерения проводились регулярно с интервалом в 10 дней.

Таблица 1.

Глубина посева и процент всхожести семян *Parrotia persica*

Глубина посева, см	Сроки посева	Появление первых всходов	% всхожести
Осенний посев			
1,5	20.X	10.II	15
3,0	-	14.II	85
5,0	-	22.II	30

В результате проведённых исследований установлено, что в условиях Апшеронского полуострова посев семян *Parrotia persica* целесообразно проводить ранней осенью, преимущественно в октябре (20.X). При посеве в указанные сроки формируются дружные всходы с уровнем всхожести 30–85%.

Таким образом, в условиях сухого субтропического климата Апшерона наиболее благоприятным сроком посева семян *Parrotia persica* в открытый грунт является осенний период, а оптимальная глубина посева составляет около 3 см.

Дальнейшее изучение роста и развития проводилось с момента появления всходов. Проведённые фенологические наблюдения показали, что прирост однолетних сеянцев за вегетационный период (со II декады марта до конца вегетации) составляет 27-30 см, двухлетних – 45-55 см, трёхлетних - 65-70 см.

Интенсивный рост растений отмечается с III декады апреля по III декаду мая. Наибольший годовой прирост зафиксирован у двухлетних сеянцев (рис. 2).

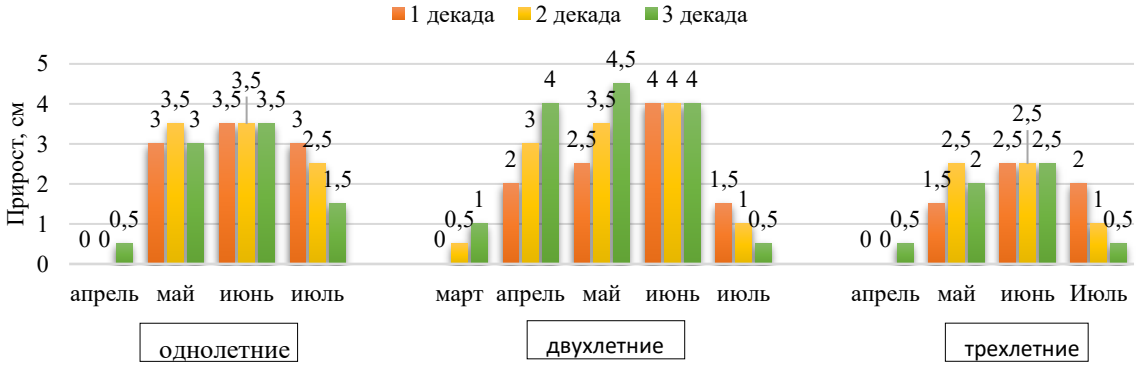

Рис.2. Динамика прироста одно-, двух- и трехлетних сеянцев

При изучении корневой системы особое внимание уделялось строению корней, глубине их залегания, диаметру и длине главного и боковых корней и другим морфометрическим показателям. В конце вегетационного периода (в ноябре) корни одно-, двух- и трёхлетних растений *Parrotia persica* были выкопаны для проведения дальнейших исследований [1, 2].

Результаты исследований морфологических особенностей корневой системы, глубины залегания корней в почве, количества боковых корней и других показателей приведены в таблице 2.

Таблица 2.

Особенности развития корневой системы *Parrotia persica*

Возраст	Высота (см)	Диаметр корневой шейки (см)	Диаметр основного корня (см)	Длина основного корня (см)	Количество боковых корней (шт.)	Длина боковых корней (см)	Глубина залегания боковых корней (см)	Глубина залегания массы корней (см)	Глубина залегания корней (см)
1	2	3	4	5	6	7	8	9	10
однолетние	27-30	0,02	0,03	16	8-10	1-3	2-3	2-4	2-16
двухлетние	45-55	0,04	0,06	24	15-17	4-6	2-6	2-8	2-24
трехлетние	65-70	0,08	1,0	32	20-35	4-10	2-18	2-25	3-32

Выявлено, что *Parrotia persica* в почвенно-климатических условиях Апшерона формирует хорошо развитую стержневую корневую систему с выраженным главным корнем и мощно развитой сетью боковых корней, от которых отходят корни II и III порядка (рис. 3). Кроме того, у исследуемого вида отмечается интенсивное развитие надземной части растения.

Рис.3. Корневая система двухлетнего растения

В результате проведённых исследований установлено, что в условиях сухого субтропического климата Апшерона наиболее благоприятным сроком посева семян *Parrotia persica* в открытый грунт является осенний период, а оптимальная глубина посева составляет около 3 см. Установлено также, что наряду с главным корнем формируется значительное количество боковых корней, что обеспечивает эффективное поглощение влаги как из верхних, так и из нижних слоёв почвы. Основная масса корневой системы располагается на глубине 2–32 см, что облегчает пересадку растений различных возрастных групп на постоянное место произрастания при озеленительных работах.

Следует отметить, что *Parrotia persica* играет важную роль в парково-ландшафтном строительстве, поскольку в осенний период (октябрь-ноябрь) его листья приобретают декоративную красную окраску, что повышает его ценность как декоративного древесного вида.

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CHEMISTRY

ИССЛЕДОВАНИЕ СОДЕРЖАНИЯ НЕКОТОРЫХ ТЯЖЕЛЫХ МЕТАЛЛОВ (МЕДЬ, СВИНЕЦ, КАДМИЙ И ЦИНК) В ОВОЩАХ, ВЫРАЩЕННЫХ В ГРУЗИИ

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DETERMINATION OF COPPER, LEAD, CADMIUM AND ZINC IN VEGETABLES GROWN IN GEORGIA

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Аннотация

Методом дифференциально-импульсной полярографии определено содержание меди, свинца, кадмия и цинка в овощах, выращенных в Грузии.

Всего нами было исследовано 30 образцов овощей. Проведенное исследование показало, что ни в одном из образцов не был обнаружен кадмий. Волна свинца наблюдалась лишь в трех образцах – в одном его концентрация не превышала предельно-допустимый уровень, в двух других же – была выше предельно-допустимой концентрации. Концентрация меди в 14 образцах несколько превысила принятую Всемирной организацией здравоохранения норму. Что касается цинка, его концентрация выше принятой нормы в 29 образцах.

Наиболее благоприятные результаты были получены для образцов с рынка Глдани, где содержание металлов в основном соответствовало нормам. В то же время в образцах с некоторых рынков и супермаркетов зафиксированы значительные превышения концентрации, особенно по цинку.

Отдельно следует отметить влияние агротехнических факторов. Например, обработка растений медным купоросом приводит к повышенному содержанию меди в овощах, что подтверждено на частных образцах.

Проведенное исследование показало, что овощи, выращенные в Грузии, в целом не загрязнены тяжелыми металлами.

Основную обеспокоенность вызывает высокий уровень цинка, а также частичное превышение меди и свинца, что требует дальнейшего мониторинга и контроля сельскохозяйственной продукции.

Abstract

Using differential pulse polarography, we determined the copper, lead, cadmium, and zinc contents in vegetables grown in Georgia.

We analyzed a total of 30 vegetable samples. The study showed that cadmium was not detected in any of them. A lead signal was observed only in three samples—its concentration did not exceed the permissible limit in one sample, while in the other two it exceeded the maximum allowable concentration. Copper concentrations in 14 samples slightly exceeded the standard set by the World Health Organization. Zinc concentrations were above the accepted limit in 29 samples.

The most favorable results were obtained for samples from the Gldani market, where metal levels generally met the standards. However, samples from some markets and supermarkets showed significant excess concentrations, particularly for zinc.

The influence of agricultural factors should be noted separately. For example, treating plants with copper sulfate leads to increased copper content in vegetables, which was confirmed using private samples.

The study showed that vegetables grown in Georgia are generally not contaminated with heavy metals.

The main concern is the high zinc level, as well as the partial excess of copper and lead, which requires further monitoring and control of agricultural products.

Ключевые слова: тяжелые металлы, овощи, здоровье, дифференциально-импульсная полярография, предельно-допустимая концентрация.

Keywords: heavy metals, vegetables, health, differential-pulse polarography, maximum allowable concentration.

Тяжелые металлы в пищевых продуктах и, в частности, в овощах, являются одной из ключевых проблем экологической и пищевой безопасности. В свою очередь, овощи являются эссенциальным источником широкого спектра жизненно необходимых микроэлементов [1,2].

В ряде исследований утверждается, что потребление овощей может предотвратить некоторые хронические неинфекционные заболевания, такие как сердечно-сосудистые, заболевания почек, нервной и костной системы. Овощи также вносят существенный вклад в обогащение организма белками, минералами, витаминами, волокнами и другими питательными веществами, которых обычно не хватает в повседневном рационе [3,4]. Тем более все больше людей переходят на овощи, отказываясь от мяса в их пользу [5].

Установлено, что у овощей есть определенные целебные свойства благодаря антиоксидатным и противомикробным эффектам [6,7].

Поэтому большое значение имеет качество сельскохозяйственной продукции, которое, в свою очередь, зависит от условий произрастания, особенно если есть угроза присутствия в окружающей среде соединений тяжелых металлов.

Важными индикаторами экологической среди и пищевой продукции являются такие тяжелые металлы, как медь, свинец, кадмий и цинк. Основными источниками поступления тяжелых металлов в овощи являются загрязненные промышленными отходами почвы, выбросы транспорта и промышленных предприятий, использование сточных вод для орошения и, наконец, применение удобрений и пестицидов.

Например, основная масса свинца и кадмия (до 60-80% от их общего количества) попадает в почву, а значит и в овощи, вместе с минеральными удобрениями и известью; цинка и меди – с атмосферными осадками (поступление их с минеральными удобрениями и известью составляет всего 2-10%) [8].

Установлено, что распределение тяжелых металлов в техногенно измененных почвах занимает второе место по степени опасности, уступая удобрениям и пестицидам и значительно опережая такие широко известные загрязнители, как двуокись углерода и сера [9].

В работе [1] показано, что на полях, которые орошаются сточными водами, концентрация тяжелых металлов в овощах, таких как свекла, латук, капуста и помидоры, значительно превышает предельно допустимый уровень.

Некоторые тяжелые металлы, как например, медь и цинк являются эссенциальными, то есть необходимыми для здоровья человека. Но тяжелые металлы не разлагаются в биологических средах и накапливаются в них до токсичных уровней, оказывая вредное воздействие как на животных и растения, так и на здоровье людей [10]. Другие тяжелые металлы, такие как свинец, кадмий, ртуть, мышьяк, являются токсичными уже в малых дозах, и их экспозиция приводит к возникновению проблем со здоровьем.

Поэтому необходим регулярный мониторинг содержания меди, свинца, кадмия и цинка в овощах, как для оценки экологической ситуации в регионах выращивания овощей, так и для обеспечения безопасного употребления овощей населением.

Целью настоящей работы являлось исследование содержания некоторых металлов (медь, свинец, кадмий и цинк) в овощах, выращенных в Грузии.

Измерения проводили на полярографе ПУ-1 в режиме дифференциально-импульсной полярографии с ртутным капельным электродом по трехэлектродной схеме в термостатированной ячейке.

Анализ меди(II), свинца (II), кадмия(II) и цинка(II) проводили по нами разработанной методике [11]. Всего было исследовано 30 образцов, взятых из супермаркетов, рынков г.Тбилиси, несколько образцов были предоставлены частными лицами.

В табл.1 представлены предельно-допустимые концентрации (ПДК) содержания микроэлементов в овощах, фруктах и зелени (приказ №301/н 2001г. Министерства труда, здоровья и социальной защиты).

Таблица 1

Cu^{2+}	≤5 мг/кг
Pb^{2+}	≤0,5 мг/кг
Cd^{2+}	≤0,03 мг/кг
Zn^{2+}	≤10 мг/кг

В табл. 2 и диаграмме 2 представлено содержание меди, свинца, кадмия и цинка в образцах, взятых из гипермаркета «Агрохаб».

Таблица 2

#	Образец («Агрохаб»)	Содержание металлов, мг/кг			
		Cu	**Pb**	**Cd**	**Zn**
1	Помидор	1,06	0,00	0,00	37,20
2	Картофель	5,05	0,00	0,00	64,26
3	Чеснок	1,98	0,00	0,00	50,29
4	Красный болгарский перец	2,97	0,00	0,00	41,58

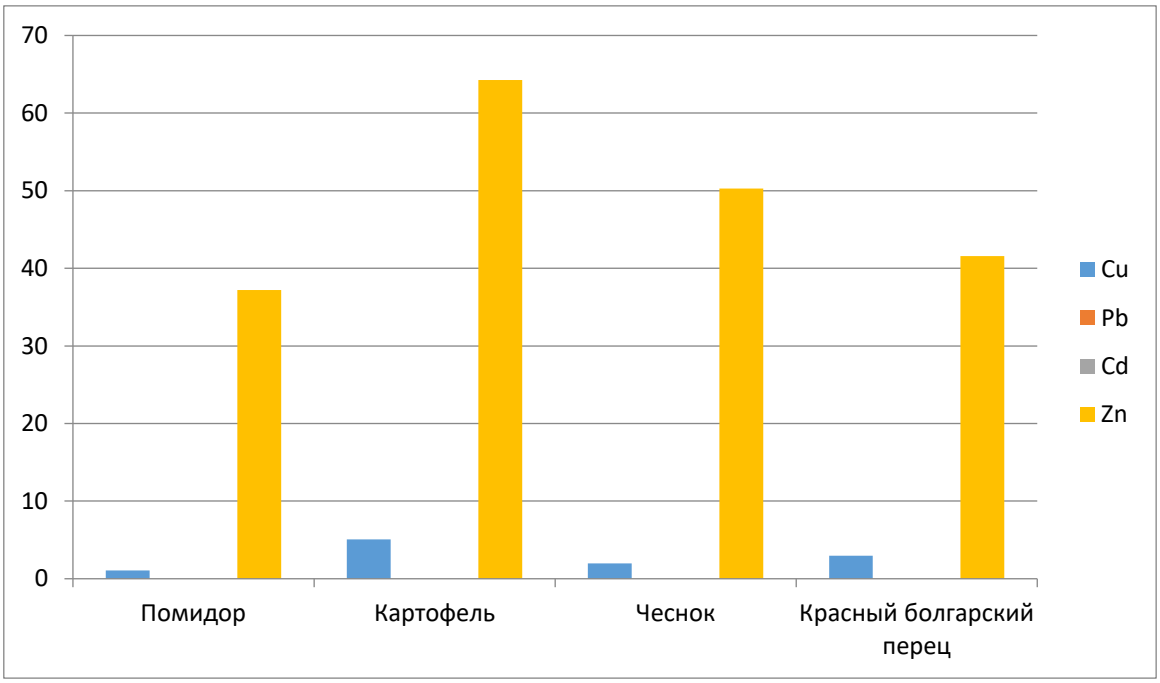

Диаграмма 2

Как видно из таблицы и диаграммы, концентрация меди во все образцах находится в пределах нормы. Волны свинца и кадмия не наблюдаются, что, безусловно, очень хорошо, так как это свидетельствует о высоком качестве продукции. Что касается цинка, его концентрация выше нормы, а в одном из образцов даже превышает ее в 6 раз.

В табл. 3 и диаграмме 3 представлены результаты, полученные из образцов, взятых с рынка Навтлуги.

Таблица 3

#	Образец (рынок Навтлуги)	Содержание металлов, мг/кг			
		Cu	**Pb**	**Cd**	**Zn**
1	Огурец	2,80	0,00	0,00	39,27
2	Зеленый болгарский перец	2,52	0,00	0,00	66,28
3	Баклажан	4,16	0,00	0,00	36,39
4	Красный болгарский перец	4,06	0,49	0,00	71,16
5	Помидор	17,98	0,00	0,00	7,90
6	Баклажан	5,09	0,00	0,00	40,12
7	Огурец	6,06	0,79	0,00	63,62
8	Картофель	4,81	0,00	0,00	32,07
9	Огурец	10,66	1,33	0,00	74,69

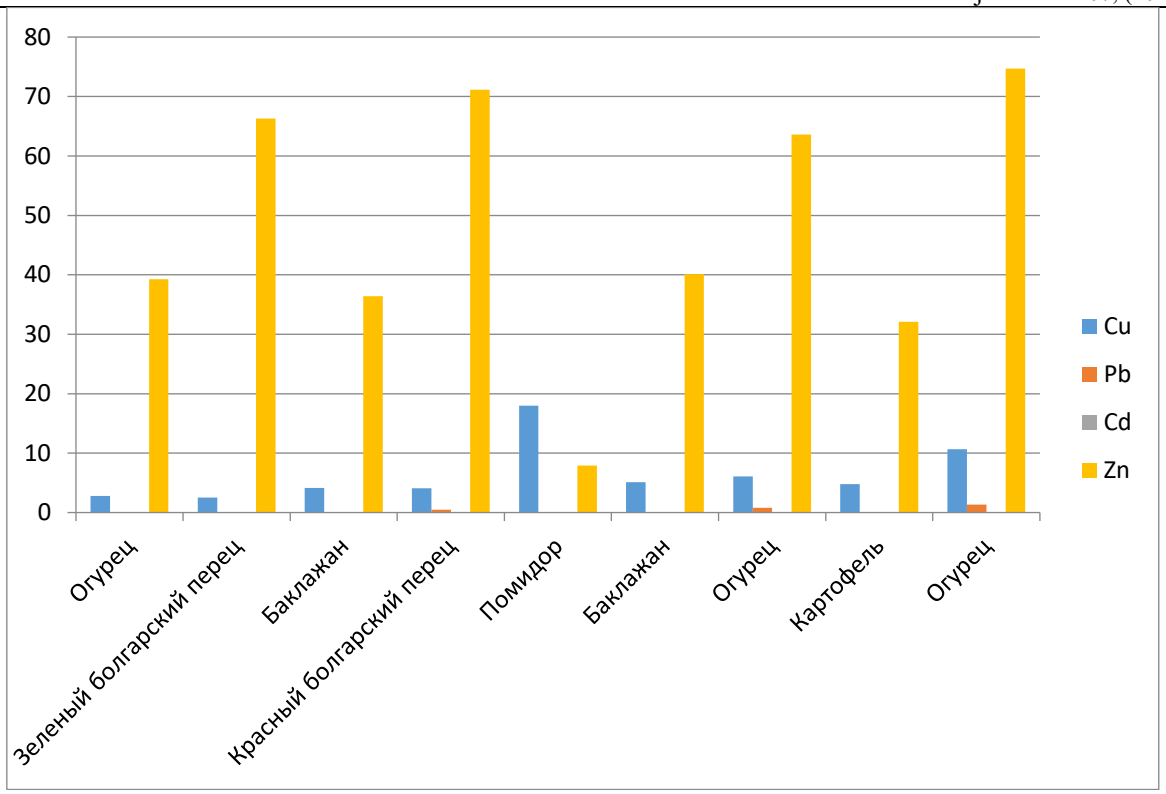

Диаграмма 3

Концентрация меди в 4-х образцах из 9 превышает принятую норму. Свинец обнаружен в трех образцах, в одном – его концентрация находится вблизи границы предельно-допустимой концентрации, в двух других же -намного превышает предельно-допустимый уровень. Волна кадмия ни в одном из образцов не фиксируется. Концентрация цинка во всех образцах превышает норму, а в трех образцах – даже в семь раз превышает максимально допустимую концентрацию.

В табл. 4 и диаграмме 4 прелставлены результаты исследования образцов, взятых из супермаркета «Два шага».

Таблица 4

#	Образец (супермаркет «Два шага»)	Содержание металлов, мг/кг			
		Cu	**Pb**	**Cd**	**Zn**
1	Картофель	5,43	0,00	0,00	63,44
2	Лук	4,92	0,00	0,00	220,73
3	Кабачок	3,48	0,00	0,00	28,69
4	Морковь	46,12	0,00	0,00	48,59
5	Помидор	20,53	0,00	0,00	38,66

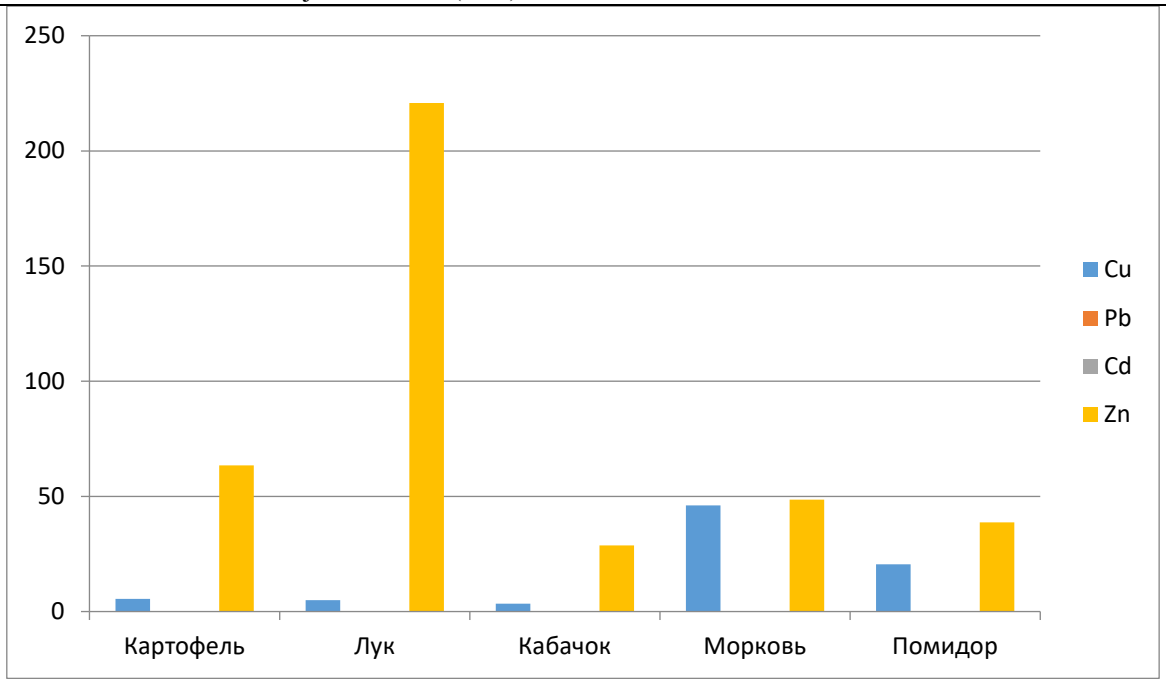

Диаграмма 4

Всего было исследовано 5 образцов. В двух из них концентрация меди намного превышает норму. Свинец и кадмий ни в одном из образцов не был обнаружен. Концентрация цинка во всех образцах намного превышает норму, в одном из образцов – даже в 22 раза.

В табл. 5 и диаграмме 5 предсталены результаты исследования образцов, предоставленных частным лицом с собственного участка, который находится в одном из районов г.Тбилиси.

Таблица 5

#	Образец (предоставленный частным лицом **Г.К.)**	Содержание металлов, мг/кг			
		Cu	**Pb**	**Cd**	**Zn**
1	Огурец	8,72	0,00	0,00	15,28
2	Картофель	4,79	0,00	0,00	28,00
3	Дандури	10,86	0,00	0,00	95,15
4	Листья свеклы	13,74	0,00	0,00	132,50
5	Помидор	29,41	0,00	0,00	73,85

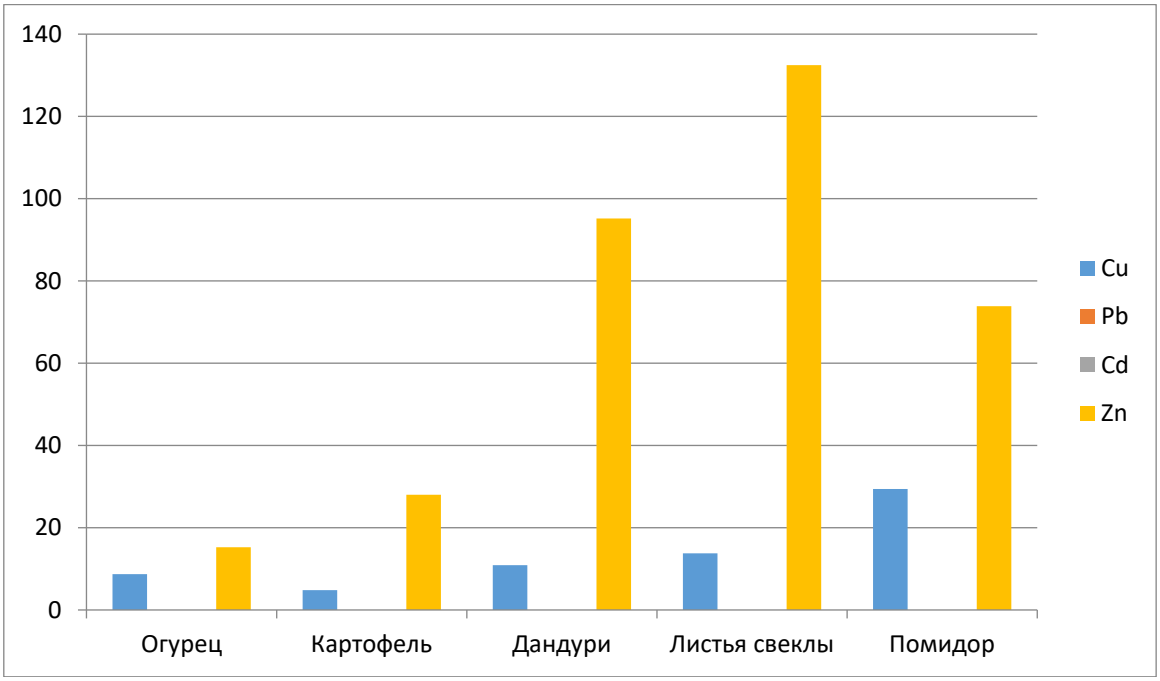

Диаграмма 5

Следует отметить, что в предоставленные образцы помидор перед взятием были обработаны медным купоросом. Рядом были высажены огурцы и свекла, картофель же был высажен несколько в отдалении. Поэтому самая высокая концентрация меди (выше нормы) у помидор, в картофеле же - она в норме. Волны свинца и кадмия не обнаружены. Концентрация цинка во всех образцах высокая.

В табл. 6 и диаграмме 6 представлены результаты исследования образцов, взятых с разных мест г.Тбилиси и из Кахетии

Таблица 6

#	Образец	Содержание металлов, мг/кг			
		Cu	**Pb**	**Cd**	**Zn**
1	Перец (Дезертирский рынок)	8,01	0,00	0,00	98,28
2	Зеленый болгарский перец (гипермаркет «Карфур»)	5,44	0,00	0,00	76,12
3	Помидор (рынок Глдани)	1,54	0,00	0,00	17,93
4	Чеснок (рынок Глдани)	0,69	0,00	0,00	26,73
5	Картофель (супермаркет «Никора»)	3,49	0,00	0,00	22,05
6	Помидор (супермаркет «Никора»)	13,72	0,00	0,00	68,72
7	Зеленый острый перец (Кахети)	14,31	0,97	0,00	161,25

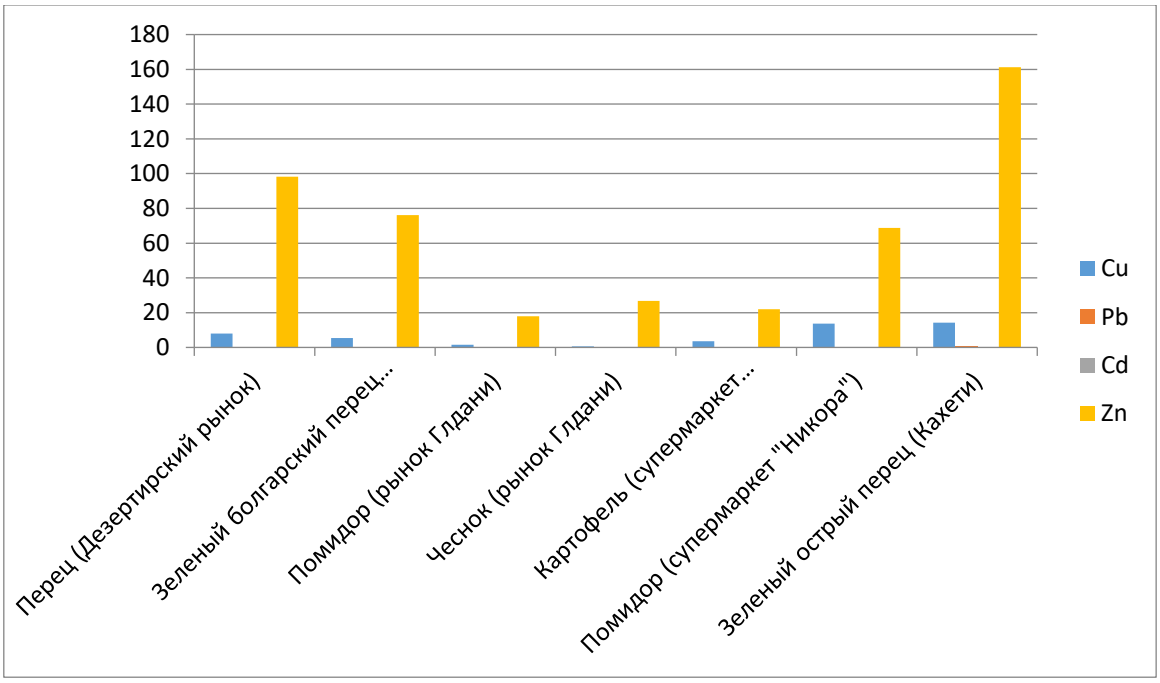

Диаграмма 6

Как видно из таблицы и диаграммы, самые чистые образцы, взятые с рынка Глдани. В этих образцах содержание меди в норме, волны свинца и кадмия не обнаружены. Что касается цинка, концентрация его, в отличие от других образцов, лишь не намного превышает норму. Из семи исследованных образцов только лишь в одном образце из Кахетии – стручковом горьком перце - концентрация свинца выше предельно-допустимого уровня. Волна кадмия ни в одном из образцов не фиксируется.

Анализ образцов показал следующее:

Медь (Cu): превышение нормы выявлено в 14 из 30 образцов. Особенно высокие значения отмечены в отдельных образцах томатов, моркови и зелени, что может быть связано с применением медьсодержащих препаратов.

Свинец (Pb): обнаружен в 3 образцах, в некоторых случаях его концентрация значительно превышает ПДК.

Кадмий (Cd): не обнаружен ни в одном из исследованных образцов.

Цинк (Zn): превышение нормы выявлено в 29 из 30 образцов, в отдельных случаях — в 6–22 раза выше ПДК.

Наиболее благоприятные результаты были получены для образцов с рынка Глдани и гипермаркета «Агрохаб», где содержание металлов в основном соответствовало нормам. В то же время в образцах с некоторых рынков и супермаркетов - зафиксированы значительные превышения, особенно по цинку.

Отдельно следует отметить влияние агротехнических факторов. Например, обработка растений медным купоросом приводит к повышенному содержанию меди в плодах, что подтверждено на частных образцах.

Проведенное исследование показало, что: овощи, выращенные в Грузии, в целом не загрязнены кадмием; загрязнение свинцом носит локальный характер; значительная часть образцов содержит повышенные концентрации меди; практически

во всех образцах наблюдается превышение содержания цинка.

Таким образом, основную обеспокоенность вызывает высокий уровень цинка, а также частичное превышение меди и свинца, что требует дальнейшего мониторинга и контроля сельскохозяйственной продукции.

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COMPUTER SCIENCES

SPECIFICITIES OF ERP SYSTEM IMPLEMENTATION IN COMPANIES

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Abstract

In this paper, based on a thorough study of relevant scientific literature, the results of the evolution of the introduction and effects of the application of new technologies, i.e. software solutions for enterprise resource planning (ERP - Enterprise Resource Planning), will be presented. Research shows that as one of the key company resources that can provide a competitive advantage in efficiency, companies are increasingly investing in new technologies and artificial intelligence. This is also seen in the growth of the market for comprehensive ERP solutions. The paper will evolve the distribution of market share of global ERP solution suppliers in the world and Europe in 2025. In terms of application possibilities, research shows that companies and organizations are increasingly deciding to implement open source ERP systems and cloud ERP solutions. The use of these systems is already present in the economy of the Republic of Serbia. The purpose of the paper is, among other things, to present the theoretical foundations of ERP systems, present the largest vendors in the world and in Serbia, and assess the current state of ERP system implementation in Serbia. The paper will present the ERP modules that are most often used in 2025. The research will also be based on solving problems that arise during the implementation of ERP system implementation projects. The aim of the paper is to analyze the current state of the ERP market in Serbia in comparison with the state in the world, and highlight their usability in companies, study the advantages and disadvantages and determine the justification for the implementation of open source ERP and cloud ERP. The paper will also present a comparative analysis of global and domestic ERP solutions for 2026. The research will offer answers to questions about the possibilities of using these systems in small and medium-sized enterprises in Serbia and the applicability of ERP systems in business, as well as present the most common pitfalls in the implementation process. This research presents the best ERP software available in 2025, analyzes their key functions and recommends procedures and methodologies for implementation, as well as suggestions for choosing the ERP solution that is most suitable for a specific company and organization.

Keywords: ERP systems, ERP modules, ERP implementation.

1. INTRODUCTION

In today's complex business environment, all organizations are looking for optimal business solutions in order to increase efficiency and competitiveness in relation to the competition. Due to the increasing complexity of business functions and the changing competitive environment, organizations have begun to look for new technologies that would meet their functional needs [2]. In today's business, fast information transfer and a complete overview of processes are very important with a key note for successful business and management of any company. The literature states that in the modern business environment, digital transformation has become a key factor in the competitiveness and efficiency of companies [18]. The business results of companies in the environment indicate that they are facing increasing pressure to optimize their business processes, reduce costs and improve their response to

market demands. In this context, well-known authors emphasize that the process of digital transformation can bring added value to companies, i.e. higher revenues, competitive advantage, greater success and efficiency [1]. As one of the solutions for the above business situations, the so-called ERP systems appear. Chronologically, comprehensive information solutions began to be developed in the early nineties of the last century. The abbreviation ERP in English stands for Enterprise Resource Planning. These are systems that support all business functions of the company [8]. It can be said that modern ERP systems play an important role in this, enabling standardization, automation and optimization of business processes and ensuring compliance with legal and regulatory requirements [11]. Some authors state that by introducing an ERP system in business, business processes are automated and integrated, which enables data sharing in a single database available in real time [27]. Modern ERP systems include real-time business analytics, cloud deployment, and mobile access to enable seamless collaboration and decision-making across teams. The newspaper is represented by the so-called intelligent ERP systems that, with the help of virtual assistants supported by artificial intelligence, use business data to predict market trends and help improve business processes. Microsoft 365 Copilot appears as one of the better-known virtual assistants, which helps with everyday tasks. In addition, these systems are designed for process automation, which reduces the workload of employees and increases their efficiency [7]. Practice shows that the digital transformation of the company leads to a smart organization where we are talking about the automation of the data storage process, innovation and optimal user experience. Well-known authors state that these processes take place with the help of new technologies, such as artificial intelligence (English Artificial Intelligence - AI), machine learning (English Machine Learning - ML), Internet of Things (English Internet of Things - IoT) and analytics [13]. Other authors emphasize that efforts aimed at introducing artificial intelligence and cyber security into ERP systems and ERP systems in the cloud require large initial investments in software and hardware, hiring experts and training employees [26]. The literature states that ERP provides mechanisms for information exchange within an organization, as it enables precise and up-to-date access to information, faster transaction processing and high data quality. However, during the implementation project, both great opportunities and great risks arise [16].

2. THEORETICAL BASICS OF ERP SISTEMS

ERP systems include and control all business areas, in support of this, the data show that 92% of highly successful small and medium-sized enterprises currently use or plan to use ERP systems [9]. Below, Figure 1 shows the most commonly used modules that are included in ERP systems: finance module, procurement module, production module, human resources management module, supply chain management (SCM) module, inventory management module, project management module, client relationship management module, risk management module and marketing automation module [12]. The following Figure 1 presents the 11 top ERP modules in 2025:

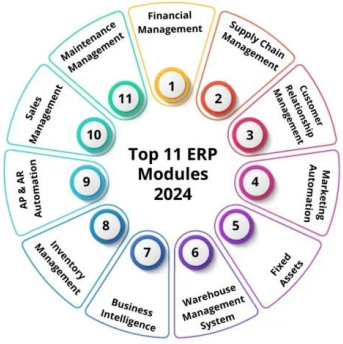

Fig. 1. ERP modules [24].

Realization of the project of introducing the ERP business information system, as one of the key resources, is always a complex and expensive project with far-reaching consequences for the organization. Well-known authors state that ERP systems, among other things, are implemented in companies with the aim of improving data quality, optimizing data transmission and increasing the ability to analyze data. The same authors point out that they enable the collection and analysis of data from different areas of business through a centralized database [5]. ERP solutions can be divided into depending on the method of installation [25]:

1. Cloud-based ERP solutions, running on remote servers maintained by software vendors and accessible via the Internet. The advantage of such solutions is that they eliminate the need for high initial investments in hardware, which is especially suitable for companies with limited IT resources. In this model, companies access the ERP solution through a subscription model, and the software is installed on the external servers of the solution provider [15].

2. On-site ERP solutions, which run on the organization's own servers. This approach allows for complete control over the data and the system, but requires a larger financial investment in infrastructure and maintenance.

3. Implementing a hybrid ERP solution combines elements of on-premises and cloud solutions. This attempts to leverage the benefits of both, allowing organizations to store their sensitive data on local servers and use the cloud for scalable and collaborative functions

3. ERP SOLUTION IMPLEMENTATION PARADIGMS

The introduction of an ERP system, in addition to its numerous advantages, also brings a number of disadvantages that companies must take into account. However, no matter how much the project is implemented, and this is done periodically in almost all organizations, it is often the case that the project ends unsuccessfully, mainly due to ignorance and failure to comply with the rules for managing such projects. Some data show that 40% of all ERP installations achieve only partial implementation, while 20% of ERP implementation attempts prove to be a complete failure. The percentage of failure in the introduction of ERP systems is a figure that affects the lower use of these systems in SMEs, because unsuccessful implementation brings high costs [10]. Other research indicates that the failure rate of ERP systems can be even higher than 50%. These failures are mainly due to the lack and inadequacy of the special prerequisites required for the successful implementation of ERP [16]. Research in practice shows that investment in a business information system represents a significant item in the organization's costs and should be budgeted for. In addition to the financial moment, the time and effort that management and employees invest during the implementation of the project are significant. Especially in organizations that already have negative experiences with previous similar projects, employees will be reluctant to start implementation at all if all the conditions are not provided for the entire project to be implemented to the end. Also, what is rarely considered is the price, or lost profits if the organization does not introduce a new system. The longer the organization postpones the purchase and introduction of a modern business system, the longer it will delay its presence on the global market, and will not realize the benefits and savings that the new system brings or achieve a comparative advantage over the competition. In this regard, we must pay attention to the fact that the Information System is part of the infrastructure of a company or organization, which is why it is strategically important for the survival and success of the company [30]. Then, the ERP solution and the company's information system are introduced with the task of increasing productivity, not vice versa. Learning from mistakes and successes is no less important. A series of questions and answers arise when we decide to purchase a new business system to support the work of our company or organization. In the process of accepting such a business risk, managers are asked questions that many do not know how to answer for the simple reason that it is not their area. It often happens that when deciding what to buy and which offer is the best, decisions are made quickly, which is why decisions are made that do not rely on professional knowledge. Most often, the price is the only element that decides on the software supplier, which is fundamentally the wrong basis. That is why the question arises of which ERP solution to buy, whether they are domestic solutions, or are better foreign solutions, the offer of which is very large today. Company management and decision-making staff are in most cases not familiar with what an ERP solution is, what vertical solutions are and what their task is.

4. ERP SOLUTION SELECTION PROCESS

Before purchasing any ERP solution, it is necessary to define well the business processes, the organization and determine the internal team, composed of the main managers of the company who have a vision and want to introduce ERP. After defining the needs, the choice of solutions should be started. Only after that can the right selection of an ERP solution be made, as it is possible to create evaluation metrics. A good ERP must be applicable in different areas of business and therefore should have tools for adapting to the information requirements of users. There are thousands of different providers of ERP solutions on the market, but only a small number of them manage to fight the competition and achieve a significant market share. In this regard, the data shows that the size of the European ERP market in 2025 is 12.67 billion dollars, which represents 22.7% of the global market. The following Figure 2 shows the share of the largest vendors of ERP systems in Europe.

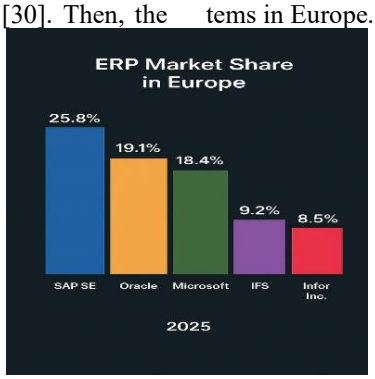

Fig. 2: Market share distribution of global ERP solution providers in Europe 2025 [21].

It is important to emphasize that global ERP solutions are mainly designed for multinational companies. The global ERP market size is estimated at 73 billion dollars in 2025, while the estimated ERP market size for 2026 is 81 billion dollars, which represents an increase of 11% compared to 2025. The global providers on the market for larger companies and organizations are: SAP S/4HANA, Oracle EBS, Microsoft Dynamics 365, IFS , Infor Inc. While for companies up to 1000 employees, the global providers are: Microsoft Dynamics 365 Business Central (BC), SAP Business One, NetSuite, Sage X3, Infor, Odoo. For small businesses, we have the following providers: Workday, Work (etc) and Syspro. Datalab (PANTHEON), SAOP (iCenter, miniMAX), MIT Informatika (Orkester) and Birokrat IT (Birokrat). Research in practice shows that the five largest global providers include: SAP with a 25.8%

share of the total global market for such systems, followed by Oracle with a 19.8% share, followed by Microsoft with 18.4%, IFS with 9.2%, Infor with 8.5%, etc. In this context, SAP is known for its comprehensive ERP platform and high degree of adaptability. SAP's ERP revenues in 2024 were $8.6 billion. In this regard, as many as 98 of the world's 100 largest companies use their solutions, while 85 of the world's 100 largest companies use SAP S/4HANA, which, with its advanced technology and real-time data processing capabilities, enables companies to effectively implement digital transformation and improve their business efficiency. The global company SAP is an international giant in the field of business applications and application software for enterprises. Approximately 80% of SAP users are small and medium-sized enterprises [25]. The fact that SAP is probably the best solution, but how the project is introduced, i.e. how the system is implemented, is much more important. It often happens that a quality implementation of a more modest ERP solution turns out to be of higher quality than an amateurishly implemented SAP. It is important to know that software alone is not enough to have ERP in a company, it is only one of the prerequisites.

Then comes Oracle, which stands out with a strong portfolio of applications and services, as well as a focus on business analytics. Oracle is the largest ERP vendor by revenue with $8.7 billion in 2024. Essentially, the Oracle Unified Method (OUM) is a working methodology based on Oracle standards and allows covering the entire project life cycle. OUM provides an implementation scope that is fast, scalable and business-oriented. It also contains a comprehensive project management framework. OUM has a structured but flexible scope. Its defined operational framework helps in anticipating the needs and critical dependencies of the project, as well as in measuring business results [19].

The next provider is Microsoft, which stands out for its easy integration with other tools and ease of use. Microsoft's ERP revenues in 2024 were $5.4 billion, making it the third largest ERP vendor. Microsoft's methodology for faster, optimized and more efficient implementation of an information system is called Microsoft Sure Step, abbreviated as MDSS. It can be used when implementing any Microsoft Dynamics solution (Dynamics 365 Business Central, Dynamics 365 Sales, as well as other Dynamics solutions).

And finally, Infor, which is known for its specialized solutions for certain industries, Infor's ERP revenues in 2024 were $3.0 billion, making it the sixth largest ERP vendor by revenue, while Sage stands out for its solutions intended for small and medium-sized enterprises [6]. The following table 1 presents a comparison of the world's leading ERP solutions.

Criteria	SAP S/4HANA	Oracle NetSuite	Microsoft Dynamics 365	Odoo (Enterprise)
Mobile Application	SAP Mobile Start (high security)	NetSuite Mobile (complete ERP on the phone)	Dynamics 365 App (dedicated for Sales/CRM)	Odoo Mobile (dedicated desktop version)
Starting Price (approx.)	From ~$180 per user/month	From ~$99 per user/month + base fee	$70–$180 per user/month (depending on module)	From ~$25 per user/month (Standard Plan)
Hidden Costs	High implementation and consulting costs	Annual renewals of licenses and modules	Additional Azure services and data storage costs	Hosting (if not on Odoo Online) and customizations
Offline Work	Limited (depends on module)	None (exclusive Cloud)	Available for field services and sales	Available for POS (sales locations)
Implementation Time	12+ months	3–6 months	4–9 months	1–4 months

Table 1. Comparison of the world's leading ERP solutions for 2026.

Choosing the best ERP software solution for your organization is not a one-size-fits-all decision. In terms of functionality, small and medium-sized businesses can benefit from the affordability and modularity of solutions like Odoo, Zoho, or Acumatica, while large corporations may prefer the depth and complexity of platforms like SAP S/4HANA, Oracle NetSuite, or Microsoft Dynamics 365. SAP S/4HANA is often considered the gold standard of ERP software for large enterprises. Oracle NetSuite, a long-standing leader in the ERP market, offers a complete ERP software solution in the cloud that suits businesses of all sizes, especially mid-sized companies and large enterprises. Microsoft Dynamics 365 offers a comprehensive and highly customizable solution that combines ERP and CRM functionality in a single integrated platform. Built on the Microsoft Azure cloud infrastructure, Dynamics 365 enables native integration with Microsoft 365 tools like Teams, Excel, and Power BI. Odoo stands out as one of the most versatile and cost-effective ERP solutions for small and medium-sized businesses. Its open-source basis allows for great adaptability, which makes it particularly attractive for developers and companies with specific business processes. Regarding the Serbian market, interest in existing ERP solutions for a customer relationship support module or the so-called CRM module has recently increased. Other opportunities that are emerging for Serbian ERP solution providers are also related to globalization or the offer of products on the market of former groups of countries. manufacturers in the production of ERP solutions are expanding. When it comes to regional ERP software, the most common solution in our region is the Slovenian Pantheon solution, from the Datalab company, which has based its business on a widely branched partner network and offers multiple connected systems. While the largest domestic regional player is the Novi Sad-based company M&I Systeм. This is precisely how opportunities arise for connecting our and foreign companies, without excluding the possibility of participating in other world markets.

CRITERIA	GLOBAL (SAP, DYNAMICS)	LOCAL (PANTHEON, BIZNISOFT)	OPEN SOURCE (ODOO)
LEGAL COMPLIANCE	Through local partners	Proven and reliable	Through community/partners
E-INVOICING (SEF)	Integration via connectors	Direct integration	Via modules from local companies
IMPLEMENTATION COST	High (€10,000 – €100,000+)	Affordable (€1,000 – €10,000)	Medium (depends on scope)
SUPPORT	Certified partners	Local teams (in Serbian)	Local IT partners
SCALABILITY	Practically unlimited	Medium to high	High

Table 2. Comparison of domestic ERP solutions for 2026.

Practical results show that the costs of implementing an ERP solution do not only include the introduction of the ERP system, but also its functioning and maintenance. The literature states that the maintenance of an ERP system in a company is considered any change to the software once it is already running. We distinguish between corrective and adaptive maintenance, as well as product care [4]. For the reasons stated above, the introduction of an ERP system is a large project that can be mastered step by step. With precise definition of business problems, critical assessment of the supplier, software solution and implementation methodology, active involvement in the project and the implementation process, and strict implementation within the set plan, we can easily ensure that costs and risks are reduced to the minimum possible extent and at the same time increase the chances of successful implementation of the ERP solution. The success of the solution implementation is not guaranteed. Data shows that in 2025, as many as 72% of companies had problems with digital transformation. In this context, implementers must openly communicate with solution users and provide them with comprehensive training, which can significantly contribute to greater acceptance of changes and reduction of resistance. The most common problem in implementation is the lack of knowledge, or adequate staff (44%), followed by the lack of financial resources (41%), while 33% of companies stated that the reason was that the business cannot be adapted to changes in the environment. There are also still misconceptions among business people, which is confirmed by the data that as many as half of companies believe that digital transformation is not necessary for successful business. Statistical data also showed that ERP is used by 35% of companies, of which 34% are small, 61% are medium-sized and 92% are large companies. In order for the choice of solution and supplier to be as successful as possible, this process needs to be approached systematically, step by step [20]. The steps are as follows:

- defining business needs,
- involving key stakeholders,
- defining the budget,
- analyzing the market offer,
- assessing functionality and adaptability,
- the possibility of localization,
- assessing the user experience,
- checking integration,
- assessing suppliers,

RESEARCH METHODOLOGY

When writing the paper, the methods of compilation, description and comparative method were used, which helps us in describing concepts and reviewing the literature. The latest professional literature and research were studied, mainly from foreign sources. In addition to the above, the survey method was also used, which brings us the desired answers and data necessary for the research. The survey results were analyzed using the method of business analysis of survey results. The final research results were shown and presented by synthesizing the findings of business analysis and implementation.

5. RESULTS

The results indicate that technological progress, especially in the field of information technology, accelerated business changes, triggering the transformation of traditional business models. In this context, at the center of this transformation are ERP systems - modern tools for planning and resource management, which have become an indispensable part of business practice today. The results show that ERP solutions can be adapted to businesses of all sizes and industries, offering flexibility, scalability and efficiency. The most represented is Cloud ERP, which makes up 70% of the market and is growing at a rate of 14.5% per year compared to 2% growth of on-premise solutions. The size of the cloud ERP market in 2025 is $51 billion, representing 70% of the total ERP market. In terms of functionality, while locally installed ERP systems allow a greater level of control over the business, cloud ERP systems are more financially affordable for businesses of all sizes. It is for these reasons that there is a growing shift towards ERP solutions in the cloud, which has grown significantly since 2016 and is still growing. A study by Gartner estimates that 53% of all ERPs were installed in the cloud in 2021 (Schwarz, 2022). The results of a review of relevant research indicate that with rapid technological advances and the digitalization of business, ERP solutions have developed to the point where they have become accessible to both small and medium-sized and large companies [3].

5.DISCUSSION OF RESULTS

Based on the research results, we can conclude that the successful implementation of an ERP system does not only depend on technical implementation, but

equally, if not more, on careful planning, realistic expectations and, above all, a focus on the human aspect. At the same time, the development of ERP solutions has begun to be marked by current technological trends such as artificial intelligence (AI), machine learning (ML), the Internet of Things (IoT) and data analytics. By incorporating these technological capabilities, ERP solutions enable improved automation, business trend prediction and improved interactive data analysis [17]. This research confirmed that organizational factors and employee workload management are key to achieving not only project goals, but also long-term user satisfaction and efficiency, which is the foundation of successful digital transformation. In implementation projects, successful human capital management in such projects is not only crucial for the well-being of employees, but also directly affects the achievement of set business goals and the profitability of the entire investment in a new information system. Well-known authors indicate that the point of profitability (return on investment, ROI) increases only after a certain period, when users learn to properly use the capabilities of the implemented solution [14].

6. CONCLUSIONS

Modern companies and enterprises are constantly striving to increase efficiency and improve their own processes. They can do this using a number of different systems that provide automation, fast information flow and comprehensive monitoring of what is happening in all departments of the company. In this sense, ERP systems, or comprehensive software solutions, play a role, which represent the backbone of modern information systems in developed companies, because they enable fast and efficient transfer of information within the company. Essentially, with ERP you have one application where you can see: how much goods you have in stock, which orders are waiting, how much you have invoiced this month, which employees have days off, and how much it costs you to produce one product. In terms of implementation, it is important to emphasize that before each implementation, it is necessary to study the company or the entire supply chain into which the ERP system is being introduced. Only after determining the needs can a specific ERP system be truly recommended for a particular organization or company. For the above reasons, ERP systems are increasingly being applied and are becoming the subject of research, in this sense, based on the data obtained, we believe that similar research in the coming years could help to better understand the development and usability of these systems. We also believe that in the coming years it would be useful to repeat the research on the usability of ERP systems in the Republic of Serbia and the surrounding area. The results show that ERP is not only for large corporations, in 2026 there are solutions that are accessible to companies with 5-10 employees. The key is to follow the prescribed methodology, i.e. the correct selection and phased implementation. As for the perspective, future projects should start with better organization and planning, where it is crucial to set a realistic timeframe with the involvement of operational users, formally allocate time for work on the project and ensure the replacement of regular tasks for the most stressful team members. In the coming years, we expect that the research will develop in the direction of increasing the product offer to clients in the form of so-called foreign execution or so-called "outsourcing". Based on the research findings, the above-mentioned recommendations for optimizing the management and implementation of future projects for the implementation of complex business information systems have been formulated.

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DESIGNING MICROFRONTEND ARCHITECTURES FOR NEXT-GENERATION FINANCIAL APPLICATIONS

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Abstract

This article examines approaches to designing microfrontend architectures for next-generation financial applications in the context of high client-side system complexity and distributed development. Microfrontends are analyzed as a mechanism for scaling development and increasing team autonomy, and approaches to rational user interface decomposition and the selection of composition models are substantiated. Particular attention is paid to integration, CI/CD, contract and end-to-end testing, version management, and ensuring module compatibility. Key security and performance risks are considered, and architectural measures for their mitigation are systematized. It is shown that the combination of modular autonomy with centralized control of non-functional requirements enables the sustainable evolution of digital financial platforms.

Keywords: microfrontends, frontend architecture, financial applications, interface decomposition, CI/CD, performance.

Introduction

Modern financial applications operate in an environment characterized by intense competition, increasingly stringent regulatory requirements, and rising user expectations regarding the speed, reliability, and usability of digital services. The growing functional richness of remote banking systems, payment platforms, and investment services leads to a substantial increase in the complexity of the client-side layer. Monolithic frontend architectures, traditionally employed for building web interfaces, demonstrate limited scalability, hinder independent feature delivery, and increase the risk of regressions under frequent release cycles. In this context, the microfrontend architecture is considered an evolutionary approach to user interface design, based on decomposing the frontend into autonomous modular components that are developed and delivered independently.

This approach becomes particularly relevant in large distributed teams, where it is necessary to synchronize multiple parallel development streams while preserving the integrity of the user experience, a high level of information security, and strict performance requirements. At the same time, the adoption of microfrontends in financial systems is associated with a range of scientific and technical challenges, including the definition of rational module boundaries, the provision of secure integration, dependency management, and the minimization of composition overhead. The purpose of this article is to systematize and scientifically substantiate approaches to designing microfrontend architectures for next-generation financial applications, as well as to analyze their advantages and limitations in terms of decomposition, integration, security, and performance within the context of scalable distributed development.

Main part. Microfrontends as a mechanism for scaling development in distributed teams

Microfrontends represent an architectural approach to building the client side of web applications in which a unified user interface is decomposed into a set of autonomous functional modules that are developed, tested, and delivered independently of each other [1]. By analogy with microservice architecture on the server side, this approach assumes organizing the frontend as a collection of isolated, domain-oriented components, each possessing its own logic, deployment lifecycle, and, in some cases, its own technological stack. A conceptual diagram of the microfrontend architecture, illustrating the principles of user interface decomposition and the integration of autonomous modules within a single application, is shown in figure 1.

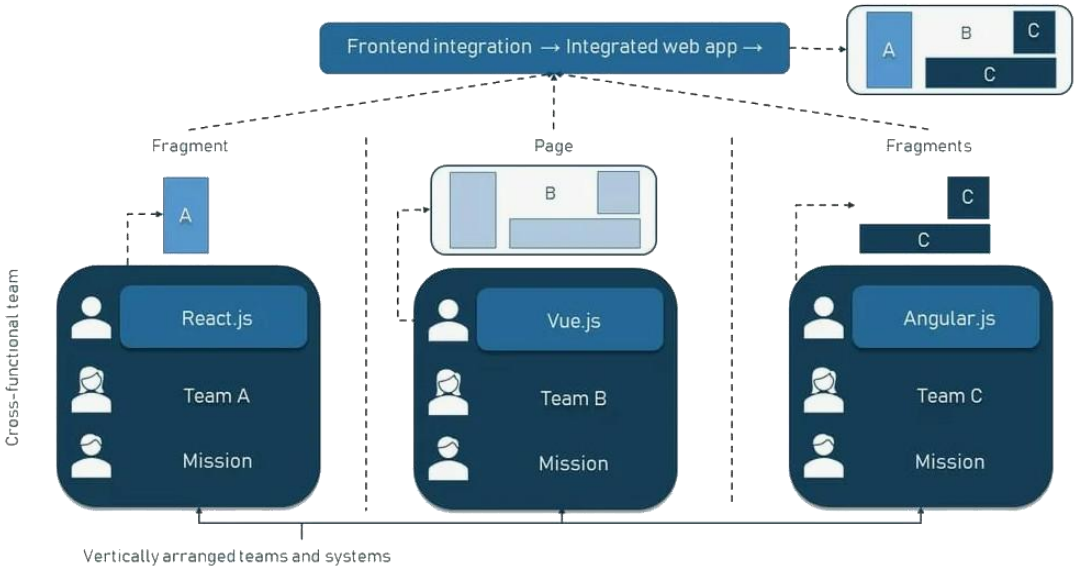

Figure 1. Conceptual microfrontend architecture of a unified web application [2]

Key characteristics of microfrontends include modularity and loose coupling, independent release cycles, the ability to distribute responsibility among teams by business domains, and the use of composition mechanisms (runtime or build-time) to integrate individual parts into a cohesive application. This is supported by recent industry survey evidence: the State of Frontend 2024 report shows that composition mechanisms commonly used for independently deliverable frontend modules are widely adopted – Module Federation is used by 51.8% of respondents and single-spa by 35.5%, which aligns with the microfrontend principles of modularity, loose coupling, and independent delivery [3].

In financial applications, additional importance is attached to such characteristics as controlling domain boundaries, ensuring information security during inter-module interactions, maintaining a consistent user experience, and minimizing the overhead associated with loading and orchestrating independent components.

Scaling the development of the frontend layer of financial applications constitutes a complex engineering challenge driven by the high functional richness of such systems, the need for frequent releases, and the involvement of distributed teams that are often located in different time zones. Under a monolithic frontend architecture, the parallel work of multiple teams leads to an increase in codebase conflicts, greater complexity of change-merging processes, and longer integration testing cycles. As the number of developers grows, a nonlinear increase in coordination overhead is observed [4]. As a result, the feature delivery cycle slows down and the likelihood of regression defects increases.

The microfrontend architecture offers a structural solution to this problem by decomposing the user interface into autonomous modules aligned with business capabilities or domain contexts. Each microfrontend is developed by a dedicated cross-functional team that assumes full responsibility for the lifecycle of its component, from design and implementation to testing, deployment, and maintenance.

In financial applications, decomposition is often performed along domain streams such as account management, transfers and payments, onboarding and KYC, limit management, and investment tools. Such structuring reflects domain boundaries and minimizes inter-module dependencies. A critical aspect is the formalization of interaction contracts – through APIs, events, or shared interface specifications. Clearly defined contracts and versioning policies enable independent evolution of modules without compromising system integrity, which is particularly important in continuous integration and delivery (CI/CD) environments.

From an organizational perspective, microfrontends support the formation of a stable responsibility architecture in which a platform team maintains shared non-functional requirements – security, observability, availability, and performance – while product teams focus on domain-specific business functionality. This separation reduces duplication of infrastructural solutions, ensures consistency of critical mechanisms such as authentication, auditing, and centralized logging, and enables financial systems with strict reliability and regulatory requirements to balance development autonomy with centralized risk control [5].

Thus, microfrontends act not only as a technological but also as an organizational mechanism for scaling development. They enable alignment between the structure of the software system and the structure of teams, reduce component coupling, and increase the predictability of the release process. In distributed development environments, this approach supports the sustainable evolution of next-generation financial applications while preserving architectural manageability and quality control.

Architectural variants of decomposition and composition in financial applications

Designing a microfrontend architecture in financial applications requires a systematic definition of module boundaries and the mechanisms for their integration into a unified user environment. In the context of high transactional activity, strict data consistency re-

quirements, and regulatory oversight, architectural decisions cannot be purely technological; they must take into account domain specifics, threat models, and target performance indicators.

Given the diversity of design practices for microfrontend architectures in financial applications, it is advisable to systematize the main variants of user interface decomposition and module composition mechanisms (table 1).

Table 1.

Architectural variants of microfrontend decomposition and composition in financial applications [6, 7]

Decomposition / composition variant	Organization principle	Typical examples in financial applications	Advantages
Domain-driven decomposition (DDD-based)	Microfrontends correspond to distinct business domains.	Account management, payments, lending, investments, KYC/AML.	Reduced coupling, high team autonomy, alignment with business structure.
User-journey-based decomposition	Each microfrontend encapsulates an end-to-end user flow.	Loan application, international transfer, customer onboarding.	Cohesive UX, simplified end-to-end testing.
Criticality-based segmentation	Isolation of modules with increased security requirements.	Transaction confirmation, electronic signature, key management.	Improved security, simplified auditability.
Runtime composition	Integration of microfrontends at runtime.	Dynamic module loading.	High flexibility, independent releases.
Build-time composition	Integration during build phase.	Static assembly of frontend.	Predictable performance, simplified operations.
Hybrid composition	Combination of runtime and build-time.	Critical modules via build-time, secondary modules via runtime.	Balance between flexibility and stability.

Thus, architectural variants of microfrontend decomposition and composition in financial applications constitute a system of interrelated decisions aimed at achieving a balance between development autonomy, user experience integrity, security, and performance. A scientifically grounded selection of module boundaries and integration mechanisms makes it possible to reduce component coupling, ensure release process manageability, and maintain the required level of quality in the context of scalable distributed development.

Architectural management of integration, CI/CD, and compatibility in microfrontend financial systems

The effective operation of a microfrontend architecture in financial applications requires formalized integration and delivery processes that ensure predictable releases, controlled interface evolution, and regulatory compliance. In environments with autonomous teams and independent release cycles, **CI/CD functions** not only as an automation tool but also as a mechanism of architectural governance, with each microfrontend maintaining its own reproducible and traceable build pipeline. Continuous delivery further relies on progressive deployment strategies, such as canary releases, blue-green deployment, and feature flags, which limit the impact of defects and enable controlled rollout of changes.

This is supported by recent quantitative evidence on CI/CD and progressive delivery practices. The GitLab Global DevSecOps Report 2024 (survey of more than 5,000 professionals) indicates that 64% of respondents characterize their SDLC as mostly or completely automated, while security remains one of the priority areas of IT investment in the financial sector, which is consistent with the need for formalized and traceable delivery pipelines in regulated environments [8]. In addition, the LaunchDarkly/Wakefield Research 2024 study (500 DevOps/IT professionals) shows that teams using feature management and progressive delivery deploy changes 84% more frequently, and 86% of them recover from incidents within one day (compared to 59% in the control group), empirically confirming the effectiveness of phased releases and mechanisms for limiting the “blast radius” of defects [9].

Special attention should be given to **integration and contract testing**. In microfrontend architectures, module boundaries are defined by public interaction interfaces – APIs, events, or shared UI contracts – and incompatibilities in these interfaces can degrade the entire system. Contract tests enable automated verification of changes against declared specifications before release, while end-to-end testing should focus on critical financial scenarios such as payment execution, two-factor authentication, and failure or refund handling under realistic security conditions.

This is supported by a recent fintech microfrontend case study (2025), in which inter-module consistency was evaluated through comparative testing of different system states (inconsistent, consistent design system, fully integrated components) with subsequent measurement of throughput before and after validation. The Testing Results for Consistency Across Micro Frontends table shows that interface and interaction consistency validation increased average throughput from 1300 to 1483.3 transactions per minute (+14.1%), with the highest effect observed for fully integrated components (up to 1600 transactions per minute), confirming that systematic compatibility testing is a signif-

icant factor in the stability and performance of microfrontend architectures in transactional scenarios (table 2).

Table 2.

Testing results for consistency across micro frontends [10]

Micro frontend consistency	Transaction throughput before testing	Transaction throughput after testing	% change
Inconsistent	1,200	1,350	+12.5%
Consistent design system	1,300	1,500	+15.4%
Fully integrated components	1,400	1,600	+14.3%
Average	1,300	1,483.3	+14.1%

The obtained testing results demonstrate that even with formalized consistency validation procedures, the stability of a microfrontend architecture largely depends on the predictability and stability of its public interfaces. In this context, managing interface evolution and versioning becomes critically important, as long-term module compatibility is fundamentally determined at the version control level.

The **problem of version compatibility** is one of the central challenges in the independent delivery of microfrontends. The use of Semantic Versioning (SemVer) and formalized backward-compatibility policies reduces the risk of broken integrations. An essential mechanism for ensuring architectural stability is the simultaneous support of multiple interface versions combined with the gradual migration of consumers. In runtime composition environments, centralized management of critical libraries and shared dependencies is required to prevent version conflicts and potential supply chain vulnerabilities.

The relevance of these measures is supported by recent quantitative evidence. An empirical study on Web API versioning, based on the analysis of 3,075 APIs and 16,053 versions, showed that only 517 APIs consistently followed major version increments when introducing breaking changes, while 1,970 APIs did not reliably signal incompatible modifications through versioning, quantitatively demonstrating the importance of formal SemVer and compatibility policies [11]. Furthermore, a 2025 study on dynamic frontend architecture for regulated applications, employing runtime module federation and component versioning, reported a 96% reduction in MTTR (from 124 to 4.8 minutes) with a P90 fallback rate below 0.7%, confirming the practical effectiveness of controlled multi-version support and phased rollout strategies in high-risk systems [12].

Thus, formalized version management and interface compatibility provide a necessary foundation for the sustainable evolution of microfrontend architectures, but they are insufficient to ensure quality in production environments. Closing the delivery governance loop requires **integrating development, testing, and deployment processes** with operational observability and continuous monitoring of key system indicators. Automated collection of performance metrics (LCP, INP, CLS), error rates, and availability indicators should therefore be embedded into the release pipeline. Regressive deviations that exceed predefined performance budgets must block the publication of a new version. This approach aligns engineering practices with non-functional requirements, which in the financial domain are no less critical than functional correctness.

Thus, integration and delivery management of microfrontends in financial applications represents a complex of interrelated processes that include automated builds, multi-level testing, formalized compatibility policies, and continuous monitoring of operational characteristics. A scientifically grounded organization of these processes makes it possible to ensure architectural stability, reduce operational risks, and maintain a high pace of change delivery without compromising security or quality.

Security and performance risks in microfrontend architectures: control and compliance

In recent years, microfrontend architecture has gained widespread adoption in industrial software development as a response to the growing complexity of client-side applications and the need to scale teams and processes. This approach is actively discussed within the professional community and has become the subject of empirical studies aimed at assessing its actual level of adoption and perceived benefits. According to recent research findings, 71% of respondents are familiar with microfrontends, and 39% have already implemented this architecture in their projects (fig. 2).

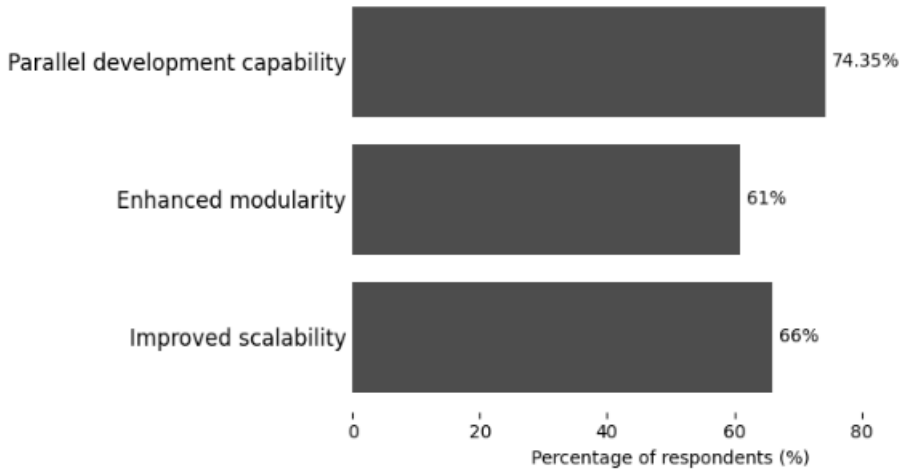

Figure 2. Reported benefits of microfrontend architecture adoption based on survey responses from software development professionals [13]

The presented survey results indicate that the adoption of microfrontend architectures is primarily driven by scalability, modularity, and the need to support parallel development. At the same time, the growing architectural complexity and distribution of responsibility across autonomous modules inevitably introduce new categories of technical and organizational risks. In this context, the adoption of microfrontends in financial applications is accompanied by a transformation of the risk model, affecting both information security and the operational characteristics of the system (table 3).

Table 3.

Key security and performance risks of microfrontend architectures in financial applications and mitigation measures

Risk category	Description	Potential impact	Mitigation measures
Expanded attack surface	Increased number of integration points and module sources.	Code injection, data compromise.	CSP, SRI, signed builds, artifact provenance control.
Supply-chain vulnerabilities	Compromised third-party dependencies.	Data leakage, remote code execution.	SBOM, automated dependency scanning.
Trust boundary violations	Uncontrolled token and data sharing between modules.	Privilege escalation, session hijacking.	Centralized authentication (OAuth 2.0, OIDC), minimal data exchange.
Interface-level attacks	XSS, UI redressing in client modules.	Fraudulent transaction confirmation.	Isolation of critical modules, integrity checks.
Bundle size growth	Duplication of libraries across microfrontends.	Increased load time, degraded Web Vitals.	Shared dependencies, performance budgets.
Runtime composition latency	Cascading delays during dynamic loading.	Unpredictable response time.	Preloading, resource prioritization.
Limited observability	Fragmented monitoring of frontend behavior.	Late incident detection.	Centralized observability, client-side metrics.

Thus, the use of microfrontend architecture in financial applications necessitates comprehensive management of security and performance risks. Control of trust boundaries, centralized authentication management, automated dependency analysis, and the enforcement of performance budgets constitute the foundation of a resilient architecture that satisfies both technical and regulatory requirements. A scientifically grounded approach to risk assessment and mitigation enables a balance between module autonomy and the preservation of integrity, reliability, and competitiveness of digital financial services.

Conclusion

Microfrontend architecture represents a justified evolutionary stage in the development of client-side applications in the financial sector, aimed at scaling development, increasing team autonomy, and accelerating feature delivery. The analysis demonstrates that domain-oriented decomposition, formalized interaction contracts, and an appropriate composition model reduce component coupling and improve release process manageability. In distributed and rapidly changing environments, microfrontends help align organizational structure with system architecture, thereby lowering coordination overhead and increasing development resilience.

At the same time, the adoption of this approach requires systematic management of security and performance risks. An expanded attack surface, more complex dependency control, and potential growth of client-side load necessitate strict integration policies,

automated vulnerability analysis, centralized authentication management, and performance budgets. Only by combining architectural autonomy of modules with centralized control of critical non-functional requirements can microfrontends support the sustainable evolution of next-generation financial applications that meet both technical and regulatory demands.

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DATA STORAGE METHODS IN CLOUD TECHNOLOGIES AND THEIR SIGNIFICANCE IN EDUCATION

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Abstract

The rapid development of modern information technologies has had a significant impact on the field of education. In the process of utilizing distance learning, online courses, and electronic resources effectively, reliable data storage and processing have become critically important. From this perspective, cloud computing technologies emerge as a modern solution for the education system.

This article discusses the main methods of data storage in cloud technologies — segmentation and replication. Segmentation ensures high processing speed by dividing large files into smaller parts for storage, while replication guarantees data security and reliability by creating copies of data across multiple servers. The article provides practical examples illustrating when and how these methods are beneficial in education.

Comparative and analytical methods were applied in the research to study the optimal ways of implementing these techniques in the educational sphere. The results showed that segmentation can reduce server load by up to 40%, while replication increases data reliability up to 99.8%. Moreover, the paper outlines approaches for integrating these methods into distance learning platforms, highlighting their role in ensuring continuous education, security, and digital transformation.

Keywords: cloud technologies, data storage, segmentation, replication, education, security.

Introduction

With the rapid development of modern information technologies, the need for efficient methods of data storage and processing is steadily increasing. From this perspective, cloud computing technologies are being widely used in education, business, and research sectors [1; 8; 10]. Through cloud technologies, data are stored, processed, and delivered to users via the Internet across various servers.

In cloud computing, data are not stored traditionally on a single computer but are distributed across thousands of servers located in data centers [2; 3]. This article examines the issues related to the effective use of cloud technologies in the educational process. The study analyzes the possibilities of applying two main mechanisms of data storage in cloud environments — segmentation and replication — within the education system.

The proposed approaches demonstrate that dividing large volumes of educational materials into smaller parts for storage (segmentation) can reduce Internet traffic, while duplicating data across multiple servers (replication) enhances data security and ensures continuous access.

Furthermore, the article presents suggestions for integrating these technologies into distance learning platforms such as *Moodle*, *Coursera*, and *Google Classroom*. The findings of the study contribute to improving the reliability of managing digital resources and enhancing the quality of distance education in the education system of Uzbekistan.

Literature Review

As modern information technologies continue to advance, the number of scientific studies on cloud computing and data storage systems has been steadily increasing. Both international and local researchers have examined various aspects of this field.

Armbrust et al. [1] discussed the architecture of cloud computing, its service models (IaaS, PaaS, SaaS), and its economic efficiency, defining the role of cloud technologies within the global IT infrastructure.

Mell and Grance [2] provided a clear definition of cloud computing in the NIST standards, highlighting its key characteristics such as scalability, dynamic resource allocation, and remote service accessibility.

Sultan [8] explored the scientific basis for implementing cloud technologies in the field of education, emphasizing that the use of cloud services in distance learning processes enhances educational efficiency. According to him, cloud environments help reduce technical costs in educational institutions and ensure equal access to information resources.

AlZain, Soh, and Pardede [7] analyzed the security issues in cloud environments and proposed improvements to data encryption and authentication methods to strengthen information protection.

Wang et al. [9] proposed reliable replication mechanisms for secure and stable data storage in cloud environments. They demonstrated that storing data on multiple servers ensures data safety and guarantees service continuity.

Leading companies such as Amazon Web Services (AWS), Google Cloud, and Microsoft OneDrive have also presented their experiences in improving reliability through the implementation of segmentation and replication methods in cloud data storage [3; 5; 6].

The UNESCO (2021) report emphasized that the future of education is closely linked to cloud technologies. It noted that cloud infrastructures play a crucial

role in digitalizing education, expanding distance learning platforms, and supporting global knowledge exchange [10].

In addition, some studies (e.g., [4]) have proposed practical solutions for reducing server load and improving user experience by dividing large video content into smaller parts (segmentation) within cloud environments.

In summary, the literature review reveals that previous research has primarily focused on the architecture and security aspects of cloud technologies. However, the practical application of segmentation and replication methods in the field of education has not been sufficiently explored. Therefore, this article aims to analyze the educational benefits of these methods from both a scientific and practical perspective.

Methodology

In this section, we provide a detailed explanation of the methods applied in this study. The focus is on the segmentation approach, which involves dividing files into smaller parts for storage and transmission efficiency.

Examples of Segmentation (Dividing Files into Parts)

1. Netflix / iTV / Megogo (Streaming Services)
   - Movies and series are divided into multiple video segments.
   - As the user watches a video, the server loads the next segment in sequence to ensure uninterrupted playback [4].
2. Torrent Systems (uTorrent, BitTorrent)
   - Files are split into small blocks and distributed across the network.
   - When downloading, a user receives different parts of the file from various computers and reassembles them locally.
3. Amazon Prime Video / Spotify (Music and Video Streaming)
   - Content is divided into segments and loaded sequentially through buffering.
   - If the Internet connection is interrupted, the next segment can be reloaded automatically [3; 4].

Segmentation in Education

Let us now explore when and how segmentation can be effectively used in the education sector:

1. Video Streaming in Education (e.g., Netflix-like Systems)
   - Similarly, universities and online platforms such as *Coursera*, *Udemy*, and *Khan Academy* store lecture videos in segmented form.
   - Even with a slow Internet connection, students can stream videos seamlessly as they load segment by segment.
2. Torrent-Based Distribution
   - Some universities and research centers distribute large datasets (e.g., linguistic corpora, research materials) to students through torrent-based segmentation.
   - This allows students to download large volumes of data piece by piece without overloading servers.
3. Audio Streaming (Spotify Model)
   - Educational platforms can also apply segmentation for audiobooks, lectures, and podcasts so that learners can listen in parts rather than downloading the entire file at once.

When is Segmentation Useful?

- For Online Video Lectures:

For instance, if a lecture video lasts two hours, downloading it as a single file may be inconvenient for students.

When segmented, the video loads gradually, providing a smooth *streaming experience*.

- When Working with Large Datasets:

In machine learning or data analysis tasks, segmented datasets allow students to download and analyze data in smaller portions instead of handling an entire massive file at once.

Advantages of Segmentation

- Even with a slow Internet connection, students can watch or listen to educational materials without interruption.
- Dividing large files into smaller parts reduces the load on computer and network resources.

Example of Segmentation

Suppose you have a file named “lecture1.mp4” that is 1000 MB in size.

The cloud server divides it as follows:

- video_part1 (0–250 MB)
- video_part2 (251–500 MB)
- video_part3 (501–750 MB)
- video_part4 (751–1000 MB)

When a user opens the video, the server retrieves these segments and combines them into a single continuous stream.

In other words, “file segmentation” means dividing a large file into smaller parts, storing them across different servers, and reassembling them dynamically when requested by the user.

- Large file (1000 MB) → divided into 4 segments.
- Each segment stored separately.
- Segments stored on different servers.
- When accessed, servers combine segments to reconstruct the complete file.

This process can be represented schematically as follows:

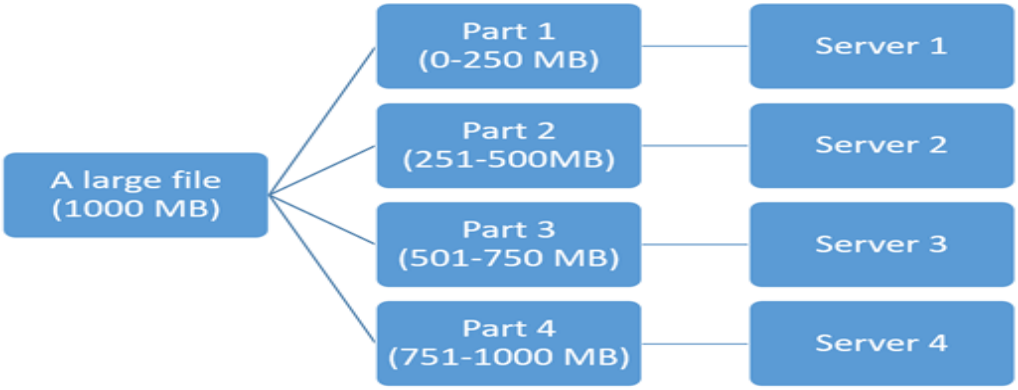

Table 1. Division of Large Files into Segments

Replication Examples (Full File Duplication)

1. Dropbox / OneDrive
   - Files are stored on multiple servers.
   - Even if one server fails, the file remains accessible from another server.
2. Amazon S3 (Simple Storage Service)
   - Each file is automatically replicated across at least three servers.
   - This ensures data security and reliability.
3. Wikipedia Servers
   - Articles and pages are replicated across servers located in different countries.
   - As a result, even if one server goes offline, the website continues to function.
4. Facebook / Instagram Photos
   - Every photo uploaded by a user is stored in several data centers.
   - This guarantees both fast loading and high-level security.

Replication in Education

Let us now explore when and how replication can be effectively used in the education sector:

1. Dropbox / OneDrive / Google Workspace
   - Students upload term papers, theses, presentations, and laboratory files [5; 6].
   - Replication ensures that these materials are not lost and remain accessible at all times.
2. Amazon S3 (Service Platforms)
   - Many online course platforms (*Coursera*, *edX*, *Moodle*) store educational materials in cloud repositories such as Amazon S3.
   - This allows millions of students to access content simultaneously with high reliability.
3. Wikipedia
   - A commonly used resource among students.
   - Since articles are replicated across multiple servers, learners can access information seamlessly from anywhere in the world.
4. Facebook / Instagram (Student Groups)
   - Educational groups share lesson materials, videos, and images that are stored across multiple servers through replication.
   - This prevents data loss and ensures stable content availability within groups.

Example of Replication (File Copy Storage)

Example: *Google Drive or Dropbox*

- You save a 100 MB Word document to Google Drive.
- Copies of this document are stored across several Google data centers.
- If one server fails, the file can still be opened from another.
- You can access the file from any device (phone, laptop, or tablet).

Thus, the main purpose of replication is to ensure data safety and prevent data loss.

When is Replication Needed?

- For the security of educational materials:

Files uploaded by students and teachers (presentations, essays, dissertations) are replicated across multiple servers.

If one server fails, the information remains safe and accessible.

- For distance learning:

Multiple students may access files from Google Drive or Moodle simultaneously.

Replication helps distribute the server load evenly, allowing all users to open files quickly and reliably.

Advantages of Replication

- Protects files from being lost or corrupted.
- Ensures that all students receive materials quickly and reliably.
- Even if the Internet connection is interrupted, users can later access the file through its replicated copy.

In summary:

- Segmentation — is highly beneficial in education for managing large video lectures and datasets.
- Replication — is essential for securely storing materials and providing reliable simultaneous access to many students.

Results and Discussion

The efficiency of traditional servers and cloud-based systems was compared in terms of speed, reliability, and cost-effectiveness.

Table 2.

Comparison of Data Storage Methods in the Education System

Indicator	Local Server	Segmentation	Replication	Combined Approach
Speed	100%	142%	138%	150%
Reliability	90%	96%	99.8%	99.9%
Data Loss	8%	3%	0.2%	0.1%
Cost Efficiency	Low	Medium	High	High

Segmentation reduces network bandwidth usage by an average of 37%, while replication increases system uptime to 99.8%.

The combination of both methods provides nearly perfect access to educational data.

During the study, another important question arises:

Can a single server store both a complete copy of one file and a fragment of another?

Yes, it can — but this depends on the system's purpose. Let's explain this more clearly:

1. Server in Replication Mode

o Typically, such a server stores the *entire copy* of a file.

o For example, a file named student_research.docx on Google Drive might be stored completely on Server 1, Server 2, and Server 3.

2. Server in Segmentation Mode

o Here, the server stores *only part of a file (a segment)*.

o For instance, if a video lecture1.mp4 uploaded to YouTube is divided into 4 parts:

- Server 1 → 0–250 MB
- Server 2 → 251–500 MB
- Server 3 → 501–750 MB
- Server 4 → 751–1000 MB

3. Mixed Case (Single Server with Both Functions)

In practice, a single server may simultaneously:

o Store the complete copy of one file (from replication), and

o Store a segment of another file (from segmentation).

This happens because cloud servers are often used for multiple purposes at once.

For example:

o Server 5 → a full copy of student_research.docx (from Google Drive),

o while another part of the same server stores → segment 3 of lecture1.mp4 (from YouTube).

Conclusion and Recommendations

The two main methods of data storage in cloud technologies — segmentation and replication — play a crucial role in modern education. These methods enable effective data processing, secure storage, and reliable service delivery.

Segmentation is highly useful for handling large video lectures and datasets, allowing smooth streaming and efficient data management.

Replication ensures the safety and accessibility of educational materials, even under heavy user load or technical failures.

Recommendations:

1. Develop institutional strategies for the broad implementation of cloud technologies in education.
2. Improve e-learning platforms by applying segmentation and replication techniques.
3. Integrate national cybersecurity standards into cloud infrastructures.
4. Organize practical training on cloud-based data storage for higher education institutions.
5. Promote the use of global cloud services (e.g., Amazon S3, Google Cloud, Microsoft Azure) in the learning process.

Future studies may explore AI-driven optimization and intelligent management of cloud storage in educational systems.

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CONSTRUCTION AND ARCHITECTURE

SELF-HEALING CONCRETE AS A KEY ELEMENT OF DIGITAL TRANSFORMATION IN CONSTRUCTION

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Abstract

This study investigates self-healing concrete as a multifunctional cementitious composite and a critical enabling component in the digital transformation of the construction industry. The research addresses the growing demand for durable, adaptive, and data-integrated materials capable of supporting intelligent infrastructure systems under increasing environmental and operational challenges. The objective of the paper is to define the functional role of self-healing concrete within digital construction ecosystems, with particular emphasis on its integration with Building Information Modeling (BIM) and Structural Health Monitoring (SHM) systems.

The methodological framework is based on a systematic and interdisciplinary approach combining comparative analysis, classification, and synthesis of contemporary scientific literature, supported by the evaluation of experimental and applied studies on self-healing mechanisms in cement-based materials.

The results demonstrate that self-healing concrete significantly improves structural performance, including enhanced crack resistance, reduced permeability, increased durability, and extended service life (up to 40%). In addition, the integration of self-healing materials with digital monitoring systems enables the implementation of predictive maintenance strategies based on real-time data and digital twin concepts.

The findings confirm that self-healing concrete should be regarded not merely as an advanced material, but as an active functional element within cyber-physical construction systems, facilitating the transition toward resilient, sustainable, and digitally managed built environments.

Keywords: self-healing concrete; digital construction; Building Information Modeling (BIM); Structural Health Monitoring (SHM); smart materials; sustainability.

Introduction

The development of the construction industry is increasingly characterized by the integration of digital technologies aimed at improving the efficiency, safety, and sustainability of buildings and infrastructure systems [1, 9, 14]. In recent decades, the sector has undergone a transition from conventional design and operation approaches toward integrated digital ecosystems based on data-driven decision-making, modeling, and lifecycle management.

Under the conditions of global climate change, rapid urbanization, and increasing requirements for energy efficiency, the demand for advanced construction materials capable of adapting to changing operational environments has become particularly significant [2, 13]. In this context, construction materials are no longer considered passive elements, but active components of structural systems capable of responding to internal and external influences.

One of the most promising directions in this field is the development of self-healing concrete—an innovative cementitious composite capable of autonomously restoring its internal structure upon the occurrence of microdamage. In scientific literature, self-healing concrete is defined as a material capable of partially or fully recovering its mechanical and functional properties through physicochemical processes activated by crack formation [3, 4].

Depending on the underlying mechanism, self-healing can be achieved through several approaches, including biological healing based on bacterial mineralization, capsule-based systems containing healing agents, and autogenous processes associated with continued hydration of unreacted cement particles. The key feature of such materials lies in their functional activity, which enables them to respond to damage without external intervention.

In conventional concrete, the formation of microcracks leads to progressive deterioration, increased permeability, and eventual structural degradation. In contrast, self-healing concrete mitigates these processes by restoring material continuity at the microstructural level, thereby reducing the rate of damage accumulation. This results in improved durability, enhanced resistance to aggressive environmental factors, and extended service life of structures.

From an engineering perspective, these properties make self-healing concrete a strategically important component of intelligent and sustainable infrastructure systems. Its integration with digital technologies, particularly Building Information Modeling (BIM) and Structural Health Monitoring (SHM), enables the transition from reactive maintenance approaches to predictive, data-driven lifecycle management.

The aim of this study is to investigate the role of self-healing concrete as a functional element of digital construction ecosystems and to evaluate its impact on structural performance, durability, and lifecycle efficiency.

The scientific novelty of the research lies in:

- a systematic analysis of self-healing concrete as both a material and an element of digital construction systems;
- establishing the relationship between self-healing mechanisms and digital lifecycle management technologies;
- substantiating the transition from reactive to predictive maintenance strategies;

- identifying the role of self-healing concrete as a link between physical degradation processes and digital structural models.

Methodology

The methodological framework of this study is based on a combination of general scientific and specialized research methods, determined by the interdisciplinary nature of the problem situated at the intersection of construction materials science, digital technologies, and systems analysis of construction processes.

The investigation of intelligent construction materials requires a comprehensive approach that allows for consideration of both the physical and technical properties of materials, as well as their information-functional characteristics within the context of construction digitalization. In this regard, a systems approach was applied in this study, enabling the consideration of intelligent construction materials not as isolated entities, but as integral components of a unified digital ecosystem of the construction industry, encompassing design, construction, operation, and monitoring stages [9]. This approach ensures a holistic understanding of the interaction between material behavior and digital lifecycle management technologies.

A comparative analysis was employed to evaluate conventional and intelligent construction materials across key performance indicators, including durability, energy efficiency, operational costs, adaptability, and the presence of monitoring and self-diagnostic functions [1, 2]. The application of this method made it possible to identify both qualitative and quantitative differences between material categories and to substantiate the advantages of intelligent construction solutions in modern engineering practice.

For the analysis and theoretical generalization of scientific sources, methods of analysis and synthesis were applied. These methods enabled the systematization of existing research in the fields of intelligent materials, digital construction technologies, and structural health monitoring systems [3, 4, 7]. Based on the synthesis of scientific literature, key development trends in the field were identified, and the main conceptual approaches to the classification and functional interpretation of intelligent construction materials were established.

The classification method was used to structure intelligent construction materials according to their functional purpose and operating principles. Within this framework, major categories were identified, including self-healing, sensing, phase-change, and energy-generating materials [5]. This classification allowed for a structured representation of the research domain and facilitated the identification of functional differences between material systems.

Additionally, qualitative analysis of case studies was conducted to assess the implementation of intelligent construction materials in real-world construction projects. This method enabled the evaluation of their performance under operational conditions and the identification of practical limitations associated with technological complexity, scalability, and economic feasibility [11, 15].

The logical-analytical method was applied throughout the study to ensure the formulation of the research hypothesis, clarification of the problem statement, and justification of the conclusions. This method facilitated the integration of empirical findings with theoretical frameworks, enabling a coherent interpretation of the role of intelligent materials in the digital transformation of the construction industry.

The information base of the study includes peer-reviewed scientific publications, international standards in the field of digital construction, and analytical reports focused on the implementation of intelligent technologies, Building Information Modeling (BIM), and structural health monitoring systems [9, 14].

The combination of these methods ensures the reliability, validity, and reproducibility of the research results, while also enabling a multilevel analysis of intelligent construction materials ranging from material science to systemic and digital perspectives.

Results

The analysis demonstrates that self-healing concrete exhibits superior performance compared to conventional cementitious materials across key structural indicators.

Quantitative evaluation shows:

- increase in structural service life by *20–40%;*
- reduction in maintenance and repair costs by *up to 30%;*
- significant decrease in crack propagation rate under cyclic loading conditions;
- improved resistance to environmental degradation factors, including moisture ingress, chloride penetration, and thermal fluctuations.

The mechanical response of cementitious materials is governed by the stress relationship:

$$\sigma = \frac{F}{A} \quad (1)$$

where: σ is stress (Pa),
F is applied force (N),
A is cross-sectional area (m²).

Crack initiation occurs when the stress exceeds the material's tensile capacity:

$$\sigma \geq \sigma_{cr} \quad (2)$$

Crack propagation is governed by the energy criterion:

$$G \geq Gc \quad (3)$$

where:
G - strain energy release rate (J/m²),
G_c - critical fracture energy of the material (J/m²).

In self-healing concrete systems, microcrack formation activates autonomous healing mechanisms (e.g., bacterial mineralization, encapsulated agent release, and continued hydration), which contribute to the partial restoration of material continuity and an increase in effective fracture resistance (G _c, eff).

The comparative performance of conventional and self-healing concrete is summarized in Table 1.

Table 1.

Comparative analysis of conventional and self-healing concrete

Parameter	Conventional concrete	Self-healing concrete
Durability	Medium	High (due to autonomous crack healing and damage recovery mechanisms)
Crack control	Passive resistance	Active healing mechanism (microcrack sealing and regeneration processes)
Maintenance demand	High	Reduced (due to self-diagnostic and self-repair functions)
Operational cost	High	Lower (transition to predictive maintenance strategy)
Environmental resistance	Moderate	High (improved performance under moisture, chloride, and thermal воздействие)
Monitoring capability	None	Possible via BIM + sensors (integration with structural health monitoring systems)

Integration with Building Information Modeling (BIM) and Structural Health Monitoring (SHM) systems enables continuous acquisition and processing of structural performance data. This supports the development of digital twin frameworks representing real-time physical states of infrastructure systems.

Such integration facilitates a transition from periodic inspection-based maintenance to predictive, data-driven infrastructure management based on continuously updated structural condition data.

Discussion

The results of this study confirm that self-healing concrete represents a significant advancement in cementitious materials, shifting the paradigm from passive durability to active structural performance enhancement. Unlike conventional concrete, which relies solely on initial material properties, self-healing concrete introduces autonomous mechanisms that mitigate damage development during the service life of structures.

The observed improvements in service life (20–40%) and reduction in maintenance costs (up to 30%) can be attributed to the ability of the material to initiate internal repair processes upon crack formation. These processes, including bacterial mineralization, capsule-based healing, and continued hydration, contribute to the restoration of material continuity and delay the progression of microcracks into macro-scale structural defects.

From an engineering perspective, the integration of self-healing concrete with digital technologies such as Building Information Modeling (BIM) and Structural Health Monitoring (SHM) significantly enhances infrastructure management. Continuous data acquisition enables the identification of early-stage damage and supports the development of predictive maintenance strategies. As a result, decision-making shifts from reactive interventions to condition-based maintenance, improving both operational efficiency and resource allocation.

However, despite its advantages, several limitations still restrict the widespread implementation of self-healing concrete. The high production cost remains one of the main barriers, primarily due to the complexity of incorporating healing agents and ensuring their long-term stability within the cementitious matrix. In addition, the absence of standardized testing methods and regulatory frameworks limits the comparability of results across different studies and practical applications.

Another important consideration is the scalability of self-healing technologies. While laboratory results are promising, real-world conditions introduce additional variables such as load variability, environmental exposure, and material heterogeneity, which may affect healing efficiency.

Overall, the findings suggest that self-healing concrete has strong potential to become a key component of intelligent and sustainable infrastructure systems. Its full implementation, however, depends on further technological development, cost optimization, and deeper integration with digital construction ecosystems.

Conclusion

This study demonstrates that self-healing concrete is a key enabling material in the digital transformation of the construction industry. Its application significantly enhances structural durability, reduces maintenance requirements, and improves overall sustainability performance in modern infrastructure systems.

When integrated with Building Information Modeling (BIM) and Structural Health Monitoring (SHM) systems, self-healing concrete contributes to the development of intelligent infrastructure capable of self-assessment and predictive maintenance. This integration supports a shift from traditional maintenance strategies toward data-driven lifecycle management approaches.

The findings of the study indicate that the incorporation of self-healing mechanisms into cementitious materials leads to improved structural performance compared to conventional concrete systems, particularly in terms of damage resistance and service life extension.

Future research should focus on reducing production costs, developing standardized testing and evaluation methods, and enhancing integration with digital twin technologies and IoT-based monitoring frameworks to support large-scale implementation.

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STUDY OF THE NONLINEAR STATIC ELASTIC STRESS–STRAIN STATE OF BAR ELEMENTS

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Abstract

Based on the finite element method, a model of geometrically nonlinear deformation of bar elements is developed. Using the implicit Ritz method, a nonlinear system of algebraic equations is obtained to determine unknown nodal displacements and stresses in finite elements. The system is solved iteratively by the Newton–Raphson method. An algorithm and a computer program for numerical investigation of the problem have been developed. Test examples are presented.

Keywords: finite element, stress, strain, bar element, stiffness matrix, direction cosines, coordinate system, displacements.

Introduction

This work represents one of the directions of theoretical studies of the static behavior of three-dimensional bar structures. Within the framework of these studies, in the work of Nigmetov M.Zh. [1], displacements of the platform support points on the soil foundation were determined. However, these studies cannot be considered sufficient for analyzing the stress–strain state, strength, and stability of an offshore platform.

It is necessary to determine displacements of the entire bar system constituting the platform, then proceed to strains and stresses (as well as axial and shear forces and bending moments). Most importantly, when considering a bar mechanical system, the possibility of large displacements, i.e., geometric nonlinearity, is often neglected.

Therefore, a reliable assessment of the elastic behavior of the “bar offshore platform–seabed foundation” system is possible only if geometric nonlinearity of the bar component is taken into account. In this regard, there arises a need to develop theoretical and methodological approaches for comprehensive investigation of the static and dynamic behavior of spatial bar platforms resting on inclined layered foundations under the action of constant and variable external forces.

Problem Statement

The aim of this work is to investigate the static elastic stress–strain state of spatial bar elements under various environmental loads.

To achieve this objective, the following tasks are solved:

- numerical solution of statics problems for the “platform–foundation” mechanical system considering possible large displacements of the platform bar structure using two-node finite elements;
- numerical solution of dynamics problems for the “platform–foundation” mechanical system considering possible large displacements of the platform bar structure under wave loading conditions.

Method and Solution Formulation

Obtaining analytical solutions in geometrically and physically nonlinear problems is a complex mathematical issue and is possible only in special cases. Therefore, modern numerical methods using computers are employed for solving such problems.

Currently, the finite element method (FEM) has become widely used for studying the stress–strain state of complex structures.

The main difficulty in solving nonlinear problems by FEM lies in constructing the tangent stiffness matrix, which depends on displacements. Depending on the principles used to formulate equilibrium equations, different forms of tangent stiffness matrices are obtained.

In [2], the basic relations are derived from the principle of virtual displacements. In [3], the more general Hamilton–Ostrogradsky principle is used, while [4] directly applies Lagrange equations.

One of the most common structural systems is bar systems. Recently, interest in such systems has increased not only for analyzing purely bar structures, but also due to their applicability in modeling continua and solid bodies through idealized bar models.

Discrete bar models allow the behavior of plates, shells, and solid bodies to be described.

A reliable estimation of deformations in such systems is possible only when nonlinearity is taken into account.

Numerical Method and Solution Procedure

The fundamental equations of nonlinear elasticity are solved approximately by transforming them into algebraic form through mathematical and physical discretization methods.

The finite element method was first applied to continuum mechanics problems in the mid-1950s and has since become an exceptionally effective tool. Although FEM is used for solving problems similar to those addressed by the finite difference method, they are based on different principles. In the finite difference method, derivatives in differential equations are approximated by difference relations. The mathematical basis of FEM is the calculus of variations.

The differential equation describing the problem together with the boundary conditions is used to formulate a variational problem, which is then solved directly. From this point of view, FEM can be regarded as an implicit application of the Ritz method over separate subdomains. In FEM, the physical problem is replaced by a piecewise-smooth model.

The main stages of FEM in displacement formulation are as follows:

1. Definition of initial data, including:
- coordinates of nodal points in the global coordinate system;
- mutual arrangement of finite elements;
- geometric and stiffness parameters of each structural element.
2. Determination of nodal locations of elements in the local coordinate system (LCS).
3. Construction of the element stiffness matrix in the LCS.
4. Calculation of direction cosines for each element and transformation matrices from local to global coordinate systems (GCS).
5. Assembly of the global stiffness matrix for the entire structure.
6. Imposition of constraints eliminating rigid-body motions.
7. Calculation of resultant nodal forces at each node.
8. Determination of nodal displacements and stress state of finite elements.

Methods developed for linear systems can also be applied when geometric nonlinearity is considered. Accounting for nonlinearity leads to a governing system containing nonlinear terms with respect to the unknowns. Since closed-form solutions cannot generally be obtained, iterative approximation procedures must be used.

Geometric nonlinearity causes the relationship between the strain vector and displacement vector to become nonlinear.

In FEM, nonlinear problems are formulated as a system of nonlinear algebraic equations:

$$[K(U)]\{U\} = \{Q\}, \quad (1)$$

where:

$\{U\}$- unknown displacements, $\{Q\}$- generalized external nodal loads. The problem consists in determining the unknown parameters $\{\boldsymbol{U}\}$ as functions of the external actions $\{\boldsymbol{Q}\}$.

The governing equations for a finite element are derived using the principle of virtual displacements.

The strain vector is represented as:

$$\{\varepsilon\} = \{\varepsilon_0\} + \{\varepsilon_L\}, \{\varepsilon_0\} = [B_0]\{\delta\}, \{\varepsilon_L\} = [B_L]\{\delta\}, \left[\overline{B}\right] = [B_0] + [B_L] \quad (2)$$

where:

$[B_0]$ - linear, $[B_L]$- nonlinear strain component, $\{\delta\}$- nodal displacement matrix. The relationship between the stress vector $\boldsymbol{\sigma}$ and the strain vector $\boldsymbol{\varepsilon}$ is given by $\{\boldsymbol{\sigma}\} = [\boldsymbol{D}]\{\boldsymbol{\varepsilon}\}$,

where $[D]$- is the elasticity matrix.

The equilibrium equations are expressed as:

$$\int_V d\{\varepsilon\}^T \{\sigma\} dV - d\{\delta\}^T \{Q\} = 0,$$

where $\{Q\}$-is the residual force vector.

Using the relations $d\{\varepsilon\} = [\overline{B}]d\{\delta\}$, taking into account $d\{\delta\} \neq 0$, the equilibrium equations are obtained

$$\{\psi\} = \int_V \left[\overline{B}\right]\{\sigma\} dV - \{Q\} = 0 \quad (3)$$

where $\{\psi\}$- the unbalanced force residual represents the sum of the external and internal forces of the element.

By varying the equilibrium equations (3) with respect to the displacements $d\{\delta\}$ taking into account

$d\{Q\} = 0$ one obtains: $d\{\psi\} = \int_V d\left[\overline{B}\right]^T \{\sigma\} dV + \int_V \left[\overline{B}\right]^T d\{\sigma\} dV$. Since

$$d\{\varepsilon\} = \left[\overline{B}\right]d\{\delta\}, d\{\sigma\} = [D]d\{\varepsilon\} = [D]\left[\overline{B}\right]d\{\delta\}, d\left[\overline{B}\right]^T = d([B_0]^T + [B_L]^T) = d[B_L]^T,$$

Then

$$d[\psi] = \int_V d[B_L]^T [\delta] dV + \int_V \left[\overline{K}\right] d[\delta] \quad (4)$$

Where $[\overline{K}] = \int_V [\overline{B}]^T [D][B]dV = [K_0] + [K_L]$, here $[K_0]$ and $[K_L]$ respectively, the element stiffness matrices corresponding to small and finite displacements.

The expressions for evaluating these matrices are given by:

$$[K_0] = \int_V [B_0]^T [D][B_0]dV,$$

$$[K_L] = \int_V [B_0]^T [D][B_L]dV + \int_V [B_L]^T [D][B_L]dV + \int_V [B_L]^T [D][B_0]dV$$

$[K_L]$- The large-displacement matrix accounts for the geometric nonlinearity of the problem.

The first term in Eq. (4) can be represented as follows:

$$\int_V d[B_L]^T \{\sigma\}dV = [K_\sigma]d\{\delta\} \quad (5)$$

Where $[K_\sigma]$- a symmetric matrix depending on the stress magnitude — the initial stress matrix.

Then $d\{\psi\} = ([K_0] + [K_\delta] + [K_L])d\{\delta\} = [K_T]d\{\delta\}$, where $[K_T]$ - complete tangent stiffness matrix

Given the stiffness matrices of the individual elements $[K_T]$, the global stiffness matrix of the system $[K_T^C]$ is assembled by summation over all elements: $[K_T^C] = \sum_{i=1}^{m} [K_T]_i$, where m - total number of elements.

Similarly assembled $\{\psi\}^C = \sum_{i=1}^{m} \{\psi\}_i$ и $\{u\} = \sum_{i=1}^{m} \{\delta\}_i$, где $\{u\}$ и $\{\psi\}^C$- the displacement vector and the system residual force vector, respectively.

The governing nonlinear system of equations for the static finite element problem can be written as follows:

$$d\{\psi\}^C = [K_T^C]d\{u\} \quad (6)$$

Equation system (6) is solved by the iterative Newton–Raphson method, whose basic idea is as follows

$\{u\} = \{u\}_n$- an initial approximation obtained from linear theory. To refine the obtained solution, the residual force vector is expanded into a Taylor series:

$$\{\psi\{u\}_{n+1}\} = \{\psi\{u\}_n\} + \left(\frac{d\psi}{du}\right)_n \Delta\{u\}_n \quad (7)$$

The corrected solution must also satisfy the equilibrium conditions $\{\psi\{u\}_{n+1}\} = 0$, and the correction to the solution is determined by the formula $\Delta\{u\}_n = -[K_c^T]^{-1}\{\psi\}_n$,

Where $[K_c^T]$- the tangent stiffness matrix determined for the displacements and strains corresponding to the approximate solution $\{u\}_n$.

Determination of the Direction Cosine Matrix. The beginning of the bar is denoted by index i, and the end by j. A global coordinate system (GCS) is introduced. In addition to the global coordinate system *oxyz*, a local coordinate system $O'x'y'z'$is introduced, where the $O'x'$ is aligned with the bar axis, while the $O'y'$ and $O'z'$are directed along the principal axes of inertia of the cross-section.

Let the coordinates of the bar element end nodes be denoted as $(x_i y_i z_i)$ and $(x_j y_j z_j)$

The transformation from the LCS to the GCS is performed using the direction cosine matrix:

$$L = \begin{bmatrix} L_0 & 0 & 0 & 0 \\ 0 & L_0 & 0 & 0 \\ 0 & 0 & L_0 & 0 \\ 0 & 0 & 0 & L_0 \end{bmatrix} \quad (8)$$

Where $L_0 = \begin{bmatrix} t_{11} & t_{21} & t_{31} \\ t_{12} & t_{22} & t_{32} \\ t_{13} & t_{23} & t_{33} \end{bmatrix}$- orientation matrix of the LCS relative to the GCS.

Since the coordinate cosines of the bar element are known, the direction cosines of the xxx-axis can be determined from the following formulas: $t_{11} = \frac{x_j - x_i}{l}$, $t_{21} = \frac{y_j - y_i}{l}$, $t_{31} = \frac{z_j - z_i}{l}$, where $l_1 = \sqrt{(x_j - x_i)^2 + (y_j - y_i)^2 + (z_j - y_i)^2}$- bar length

To determine the remaining parameters, an auxiliary point *D*(*x*,*y*,*z*) is chosen outside the element such that nodes *i*, *j*, and point *D* lie in a plane containing one of the principal axes of inertia of the element cross-section:

$$t_{12} = \frac{a_1}{\sqrt{a_1^2+a_2^2+a_3^2}}, t_{22} = \frac{a_2}{\sqrt{a_1^2+a_2^2+a_3^2}}, t_{32} = \frac{a_3}{\sqrt{a_1^2+a_2^2+a_3^2}},$$

Then

$a_1 = t_2t_{31} - t_3t_{21}, \quad a_2 = t_3t_{11} - t_1t_{31}, \quad a_3 = t_1t_{21} - t_2t_{11}; \quad t_1 = \frac{x_D - x_i}{l_1}, \quad t_2 = \frac{y_D - y_i}{l_1}, \quad t_1 = \frac{z_D - z_i}{l_1};$

$l_1 = \sqrt{(x_D - x_i)^2 + (y_D - y_i)^2 + (z_D - y_i)^2}$- length of segment iD.

The direction cosines of the third set are determined using the following formulas:

$$t_{13} = t_{21}t_{32} - t_{31}t_{22}, t_{23} = t_{31}t_{12} - t_{11}t_{32}, t_{33} = t_{11}t_{22} - t_{21}t_{12} \tag{9}$$

All these relations are derived from the orthogonality conditions of vectors directed along the coordinate axes.

One of the important stages of the finite element method is discretization and the choice of finite element type, since both the success of solving the problem as a whole and the accuracy of the solutions depend on these factors. Discretization of bar systems by rectangular finite elements and reduction of the problem to plane stress or plane strain analysis lead to significant discrepancies in both displacements and stresses compared with exact solutions. For large displacements, all strain components are of the same order. Therefore, in order to obtain a correct and convergent solution, all second-order strain terms must be taken into account. In this work, two types of finite elements are used for the analysis of finite displacements: a bar finite element with 12 degrees of freedom and a bar finite element with 6 degrees of freedom [4,13].

Bar Element with Six Degrees of Freedom.

The constitutive equations of a three-dimensional bar system in the local coordinate system (LCS) $Ox/y/z/$,

where the direction of the $Ox/$ coincides with the bar axis, are given by:

$$\{\sigma\} = [D]\{\varepsilon\} \tag{10}$$

Where $\{\sigma\} = \{\sigma_x\}, \{\varepsilon\} = \{\varepsilon_x\}$, the strain vector is reduced to a single component

$$\varepsilon_x = \frac{du}{dx} + \frac{1}{2}\left[\left(\frac{du}{dx}\right)^2 + \left(\frac{dv}{dx}\right)^2 + \left(\frac{dw}{dx}\right)^2\right] \tag{11}$$

Assume that the relationship between the components and the displacement parameters is given by

$$\{u\} = [N]\{\delta\} \tag{12}$$

Where $\{u\}^T = \{u \quad v \quad w\}$ - displacements of an arbitrary point of the bar

$\{\delta\}^T = \{u_i \quad v_i \quad w_i \quad u_j \quad v_j \quad w_j\}$- nodal displacement matrix,

$$[N] = \begin{bmatrix} 1-\varsigma & \varsigma & 0 & 0 & 0 & 0 \\ 0 & 0 & 1-\varsigma & \varsigma & 0 & 0 \\ 0 & 0 & 0 & 0 & 1-\varsigma & \varsigma \end{bmatrix}$$ shape function, where $\varsigma = \frac{x}{l}$

The strain matrix $\{\varepsilon\}$ is written in the form $\{\varepsilon\} = \{\varepsilon_0\} + \{\varepsilon_L\}$, where

$$\{\varepsilon_0\} = \left\{\frac{du}{dx}\right\} = \frac{1}{l}[-1 \quad 1 \quad 0 \quad 0 \quad 0 \quad 0]\begin{Bmatrix} u_i \\ u_j \\ v_i \\ v_j \\ w_i \\ w_j \end{Bmatrix} = \frac{1}{l}\{u_j - u_i\} = [B_0]\{\delta\}.$$

Express $\left\{\frac{dv}{dx}\right\}$ and $\left\{\frac{dw}{dx}\right\}$ in terms of nodal displacements

$$\left\{\frac{dv}{dx}\right\} = \frac{1}{l}[0 \quad 0 \quad -1 \quad 1 \quad 0 \quad 0]\{\delta\} = \frac{1}{l}\{v_j - v_i\},$$
$$\left\{\frac{dv}{dx}\right\} = \frac{1}{l}[0 \quad 0 \quad 0 \quad 0 \quad -1 \quad 1]\{\delta\} = \frac{1}{l}\{w_j - w_i\} \tag{14}$$

Then $\{\varepsilon\} = [B_L]\{\delta\}, [B_L] = \left\{\frac{du}{dx} \quad \frac{dv}{dx} \quad \frac{dw}{dx}\right\} \cdot \frac{1}{l}\begin{bmatrix} -1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & 1 \end{bmatrix} =$

$$= \frac{1}{2l}\{-(u_j - u_i), \quad (u_j - u_i), \quad -(v_j - v_i), \quad (v_j - v_i), \quad -(w_j - w_i), \quad (w_j - w_i)\}.$$

The bar element stiffness matrix $[K_0]$ is given by

$$[K_0] = \frac{EF}{l}\begin{bmatrix} 1 & -1 & 0 & 0 & 0 & 0 \\ -1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (15)$$

where E and F are the modulus of elasticity and the cross-sectional area of the bar, respectively, and l is the bar length.

The initial stress matrix is calculated using the following formula:

$$[K_\sigma] = \int_V [G]^T [S]\, dV \quad (16)$$

Where

$$[G] = \frac{1}{l}\begin{bmatrix} -1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & 1 \end{bmatrix}, [S] = [S_0] + [S_L], [S_0] = E\begin{bmatrix} \frac{du}{dx} & 0 & 0 \\ 0 & \frac{du}{dx} & 0 \\ 0 & 0 & \frac{du}{dx} \end{bmatrix},$$

$$[S_L] = \frac{E}{2}\begin{bmatrix} \left(\frac{du}{dx}\right)^2 + \left(\frac{dv}{dx}\right)^2 + \left(\frac{dw}{dx}\right)^2 & 0 & 0 \\ 0 & \left(\frac{du}{dx}\right)^2 + \left(\frac{dv}{dx}\right)^2 + \left(\frac{dw}{dx}\right)^2 & 0 \\ 0 & 0 & \left(\frac{du}{dx}\right)^2 + \left(\frac{dv}{dx}\right)^2 + \left(\frac{dw}{dx}\right)^2 \end{bmatrix}$$

Thus, the final form of the initial stress matrix is

$$[K_\sigma] = EF(\varepsilon_0 + \varepsilon_L)\begin{bmatrix} 1 & -1 & 0 & 0 & 0 & 0 \\ -1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & -1 & 0 & 0 \\ 0 & 0 & -1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & -1 \\ 0 & 0 & 0 & 0 & -1 & 1 \end{bmatrix} \quad (17)$$

Bar Element with Twelve Degrees of Freedom.

As in the previous case, in the local coordinate system $Ox'y'z'$ (LCS), the direction of the Ox' coincides with the bar axis

The constitutive equations of the bar system are written as $\{f\} = [D_{cm}]\{\varepsilon\}$,

Then

$$\{f\}^T = \{N \quad Q_y \quad Q_z \quad M_x \quad M_y \quad M_z\},$$
$$\{\varepsilon\}^T = \{\varepsilon_x \quad \chi_y' \quad \chi_z' \quad \chi \quad \chi_y \quad \chi_z\}.$$

Here ε_x, χ, χ_y, χ_z – axial strain, relative angle of twist, and curvature of the bar axis, N, Q_y, Q_z, M_x, M_y, M_z – axial and shear forces, torsional moment, and bending moments, respectively.

The diagonal entries of matrix $[D_{cm}] = [b_{ij}]$, $(i, j = 1,2\ldots6)$, are given by: $b_{11} = EF$, $b_{22} = EJ_z$, $b_{33} = EJ_y$, $b_{44} = GJ_x$, $b_{55} = EJ_y$, $b_{66} = EJ_z$. All other elements of matrix DDD are zero. Under geometric nonlinearity, axial strain (11), the relative twist angle, and the curvature of the bar axis are considered:

$$\chi = \frac{d\phi_x}{dx}, \chi_y = -\frac{d^2w}{dx^2}, \chi_z = -\frac{d^2v}{dx^2} \quad (18)$$

Assume the following interpolation functions:

$$u = a_1 + a_2x, v = a_3 + a_4x + a_2x^2 + a_6x^3, w = a_7 + a_8x + a_9x^2 + a_{10}x^3,$$
$$\phi_x = a_{11} + a_{12}x, \phi_y = a_8 + 2a_9x + 3a_{10}x^2, \phi_z = a_4 + 2a_5x + 3a_6x^2 \quad (19)$$

Express the coefficients $a_1, \ldots\ldots, a_{12}$ in terms of the nodal displacements

$\{\delta\}^T = \{u_i, \quad v_i, \quad w_i, \quad \phi_{xi}, \quad \phi_{yi}, \quad \phi_{zi}, \quad u_j, \quad v_j, \quad w_j, \quad \phi_{xj}, \quad \phi_{yj}, \quad \phi_{zj}\}$ - nodal displacement vector,

$u_i = u|_{x=0} = a_1$, $v_i = v|_{x=0} = a_3$, $w_i = w|_{x=0} = a_7$, $\phi_{xi} = \phi|_{x=0} = a_{11}$, $\phi_{yi} = \phi|_{x=0} = a_8$,

$\phi_{zi} = \phi|_{x=0} = a_4$, $u_j = u|_{x=l} = a_1 + a_2l$, $v_j = v|_{x=l} = a_3 + a_4l + a_5l^2 + a_6l^3$,

$w_j = w|_{x=l} = a_7 + a_8l + a_9l^2 + a_{10}l^3$, $\phi_{xj} = \phi|_{x=l} = a_{11} + a_{12}l$, $\phi_{yj} = \phi|_{x=l} = a_8 + 2a_9l + 3a_{10}l^2$,

$\phi_{zj} = \phi|_{x=l} = a_4 + 2a_5l + 3a_6l^2$.

If we denote $\{a\} = \{a_1, \quad a_2, \quad \dots \quad a_{12}\}^T$, then, in matrix form $\{\delta\} = [A]\{a\}$, where the nonzero entries of the matrix are

$$[A] = [a_{ij}], (i, j = 1,2\dots6), a_{1,1} = a_{2,3} = a_{3,7} = a_{4,11} = a_{5,8} = a_{6,4} = a_{7,1} = a_{8,3} = a_{9,7} = a_{10,11} = 1;$$
$$a_{11,8} = a_{12,4} = 1;$$
$$a_{7,2} = a_{8,4} = a_{9,8} = a_{10,12} = l; a_{8,5} = a_{9,9} = l^2; a_{8,6} = a_{9,10} = l^3; a_{11,9} = a_{12,5} = 2l;$$
$$a_{11,10} = a_{12,6} = 3l^2.$$

To determine $\{\delta\}$, it is necessary to evaluate $[A]^{-1}$, then $\{\delta\} = [A]^{-1}\{a\}$.

The displacements of an arbitrary point on the bar axis are determined by the following formulas:

$$u = \left(1 - \frac{x}{l}\right)u_i + \frac{x}{l}u_j;$$
$$v = \left[1 - 3\left(\frac{x}{l}\right)^2 + 2\left(\frac{x}{l}\right)^3\right]v_i + \left[3\left(\frac{x}{l}\right)^2 - \left(\frac{x}{l}\right)^3\right]v_j + l\left[\frac{x}{l} - 2\left(\frac{x}{l}\right)^2 + \left(\frac{x}{l}\right)^3\right]\phi_{zi} +$$
$$+l\left[\left(\frac{x}{l}\right)^3 - \left(\frac{x}{l}\right)^2\right]\phi_{zj};$$
$$w = \left[1 - 3\left(\frac{x}{l}\right)^2 + 2\left(\frac{x}{l}\right)^2\right]w_i + \left[3\left(\frac{x}{l}\right)^2 - 2\left(\frac{x}{l}\right)^3\right]w_j + l\left[\frac{x}{l} - 2\left(\frac{x}{l}\right)^2 + \left(\frac{x}{l}\right)^3\right]\phi_{yi} +$$
$$+l\left[\left(\frac{x}{l}\right)^3 - \left(\frac{x}{l}\right)^2\right]\phi_{yj}$$
$$\phi_x = \left(1 - \frac{x}{l}\right)\phi_{xi} + \frac{x}{l}\phi_{xj}$$
$$\phi_y = \left[1 - 4\frac{x}{l} + 3\left(\frac{x}{l}\right)^2\right]\phi_{yi} + \left[3\left(\frac{x}{l}\right)^2 - 2\frac{x}{l}\right]\phi_{yj} + \frac{6}{l}\left[\left(\frac{x}{l}\right)^2 + \frac{x}{l}\right]w_i + \frac{6}{l}\left[\frac{x}{l} - \left(\frac{x}{l}\right)^2\right]w_j;$$
$$\phi_z = \left[1 - 4\frac{x}{l} + 3\left(\frac{x}{l}\right)^2\right]\phi_{zi} + \left[3\left(\frac{x}{l}\right)^2 - 2\frac{x}{l}\right]\phi_{zj} + \frac{6}{l}\left[\left(\frac{x}{l}\right)^2 + \frac{x}{l}\right]v_i + \frac{6}{l}\left[\frac{x}{l} - \left(\frac{x}{l}\right)^2\right]v_j \quad (20)$$

Denote by $N_{1i} = 1 - \frac{x}{l}; N_{1j} = \frac{x}{l}; N_{2i} = 1 - 3\left(\frac{x}{l}\right)^2 + 2\left(\frac{x}{l}\right)^3; N_{2j} = 3\left(\frac{x}{l}\right)^2 - 2\left(\frac{x}{l}\right)^3;$

$$N_{3i} = l\left[\frac{x}{l} - 2\left(\frac{x}{l}\right)^2 + \left(\frac{x}{l}\right)^3\right]; N_{3j} = l\left[\left(\frac{x}{l}\right)^3 - \left(\frac{x}{l}\right)^2\right] \quad (21)$$

$$N'_{2i} = \frac{6}{l}\left[\left(\frac{x}{l}\right)^2 - \frac{x}{l}\right]; N'_{2j} = \frac{6}{l}\left[\frac{x}{l} - \left(\frac{x}{l}\right)^2\right]; N_{3i} = 1 - 4\frac{x}{l} + 3\left(\frac{x}{l}\right)^2; N_{3j} = 3\left(\frac{x}{l}\right)^2 + 2\frac{x}{l}$$

Then, the shape function and differentiation matrices are, respectively, given by:

$$[N] = \begin{bmatrix} N_{1i} & 0 & 0 & 0 & 0 & 0 & N_{1j} & 0 & 0 & 0 & 0 & 0 \\ 0 & N_{2i} & 0 & 0 & 0 & N_{3i} & 0 & N_{2j} & 0 & 0 & 0 & N_{3j} \\ 0 & 0 & N_{2i} & 0 & N_{3i} & 0 & 0 & 0 & N_{2j} & 0 & N_{3j} & 0 \\ 0 & 0 & 0 & N_{1i} & 0 & 0 & 0 & 0 & 0 & N'_{1j} & 0 & 0 \\ 0 & 0 & N'_{2i} & 0 & N'_{3i} & 0 & 0 & 0 & N'_{2j} & 0 & N'_{3j} & 0 \\ 0 & N'_{2i} & 0 & 0 & 0 & N'_{3i} & 0 & N'_{2j} & 0 & 0 & 0 & N'_{3j} \end{bmatrix} \quad (22)$$

$$[B_0] = \begin{bmatrix} N'_{1i} & 0 & 0 & 0 & 0 & 0 & N'_{1j} & 0 & 0 & 0 & 0 & 0 \\ 0 & -N'''_{2i} & 0 & 0 & 0 & -N'''_{3i} & 0 & -N'''_{2j} & 0 & 0 & 0 & -N'''_{3j} \\ 0 & 0 & -N'''_{2i} & 0 & -N'''_{3i} & 0 & 0 & 0 & -N'''_{2j} & 0 & -N'''_{3j} & 0 \\ 0 & 0 & 0 & N'_{1i} & 0 & 0 & 0 & 0 & 0 & N'_{1j} & 0 & 0 \\ 0 & 0 & -N''_{2i} & 0 & -N''_{3i} & 0 & 0 & 0 & -N''_{2j} & 0 & -N''_{3j} & 0 \\ 0 & -N''_{2i} & 0 & 0 & 0 & -N''_{3i} & 0 & -N''_{2i} & 0 & 0 & 0 & -N''_{3i} \end{bmatrix} \quad (23)$$

Where « $''$» - where the prime denotes a derivative

The stiffness matrix $[K_0]$ is defined by the expression presented in [14]. In the nonlinear formulation, only axial strains are considered.

To consider the program for a six-degree-of-freedom bar as a special case of the program for determining the stress–strain state of a twelve-degree-of-freedom bar, the nodal displacement vector is modified as follows:

$$\{\delta\} = \{u_i, \quad v_i, \quad w_i, \quad u_j, \quad v_j, \quad w_j, \quad \phi_{xi}, \quad \phi_{yi}, \quad \phi_{zi}, \quad \phi_{xj}, \quad \phi_{yj} \quad \phi_{zj}\}^T.$$

Accordingly, the shape function matrix is also modified as follows:

$$[N]=\begin{bmatrix} N_{1i} & 0 & 0 & N_{1j} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & N_{2i} & 0 & 0 & N_{2j} & 0 & 0 & 0 & N_{3i} & 0 & 0 & N_{3j} \\ 0 & 0 & N_{2i} & 0 & 0 & N_{2j} & 0 & N_{3i} & 0 & 0 & N_{3j} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & N_{1j} & 0 & 0 & N_{1j}^{/} & 0 & 0 \\ 0 & 0 & N_{2i}^{/} & 0 & 0 & N_{2j}^{/} & 0 & N_{3i}^{/} & 0 & 0 & N_{3j}^{/} & 0 \\ 0 & N_{2i}^{/} & 0 & 0 & N_{2j}^{/} & 0 & 0 & 0 & N_{3i}^{/} & 0 & 0 & N_{3j}^{/} \end{bmatrix} \quad (24)$$

Accordingly, additional notation is introduced for the known matrices:

$[D]=\begin{bmatrix} [D^{/}] & 0 \\ 0 & [D^{//}] \end{bmatrix}$, where $[D^{/}]$- will consist of a single element $[D^{/}]=[EF]$,

$$[D^{//}]=\begin{bmatrix} EJ_z & 0 & 0 & 0 & 0 \\ 0 & EJ_z & 0 & 0 & 0 \\ 0 & 0 & GJ & 0 & 0 \\ 0 & 0 & 0 & EJ_y & 0 \\ 0 & 0 & 0 & 0 & EJ_z \end{bmatrix} \quad (25)$$

The strain-displacement matrix $\{\varepsilon\}$ can be written as $\{\varepsilon\}=\{\varepsilon_0\}+\{\varepsilon_L\}$ (26)

$$\{\varepsilon_0\}=\begin{Bmatrix} \varepsilon_0^{/} \\ \varepsilon_0^{//} \end{Bmatrix}, \{\varepsilon_L\}=\begin{Bmatrix} \varepsilon_L^{/} \\ 0 \end{Bmatrix}, \{\delta\}=\begin{Bmatrix} \delta^{/} \\ \delta^{//} \end{Bmatrix}, \varepsilon_0^{/}=\frac{du}{dx}, \varepsilon_L^{//}=\frac{1}{2}\left[\left(\frac{du}{dx}\right)^2+\left(\frac{dv}{dx}\right)^2+\left(\frac{dw}{dx}\right)^2\right]$$

Introduce the notation:

$$[B_0]=\begin{bmatrix} [B_0^{/}] & 0 \\ [B_0^{///}] & [B_0^{//}] \end{bmatrix}, [B_L]=\begin{bmatrix} [B_L^{/}] & [B_L^{//}] \\ 0 & 0 \end{bmatrix}, \{\theta\}=\left\{\frac{du}{dx}\frac{dv}{dx}\frac{dw}{dx}\right\}^T \quad (27)$$

$$\{\varepsilon_0^{/}\}=\frac{1}{l}[-1 \quad 0 \quad 0 \quad 1 \quad 0 \quad 0]\begin{Bmatrix} u_i \\ u_j \\ v_i \\ v_j \\ w_i \\ w_j \end{Bmatrix}=[B_0^{/}]\{\delta^{/}\}, \text{ т.е. } [B_0^{/}]=\frac{1}{l}[-1 \quad 0 \quad 0 \quad 1 \quad 0 \quad 0],$$

$l-$ length of the finite element, $\{\delta^{/}\}$, $\{\delta^{//}\}$ - matrices of linear and angular displacements

Thus $\{\varepsilon_L^{/}\}=\frac{1}{2}\{\theta\}^T[G]\{\delta\}$, where

$$[G]=\begin{bmatrix} N_{1i}^{/} & 0 & 0 & N_{1j}^{/} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & N_{2i}^{/} & 0 & 0 & N_{2j}^{/} & 0 & 0 & 0 & N_{3i}^{/} & 0 & 0 & N_{3j}^{/} \\ 0 & 0 & N_{2i}^{/} & 0 & 0 & N_{2j}^{/} & 0 & N_{3i}^{/} & 0 & 0 & N_{3j}^{/} & 0 \end{bmatrix},$$

$$[G]=[G^{/}][G^{//}],$$

$$[G^{/}]=\begin{bmatrix} N_{2i}^{/} & 0 & 0 & N_{1j}^{/} & 0 & 0 \\ 0 & N_{2i}^{/} & 0 & 0 & N_{2j}^{/} & 0 \\ 0 & 0 & N_{2i}^{/} & 0 & 0 & N_{2j}^{/} \end{bmatrix}, [G^{//}]=\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & N_{3i}^{/} & 0 & 0 & N_{3j}^{/} \\ 0 & N_{3i}^{/} & 0 & 0 & N_{3j}^{/} & 0 \end{bmatrix}$$

Thus: $[B_L^{/}]=\{\theta\}^T[G^{/}], [B_L^{//}]=\{\theta\}^T[G^{//}]$ (28)

The nonlinear stiffness matrix $[K_L]$ is determined by the following expression:

$$[K_L]=\int\left(B_0^T D B_L+B_L^T D B_0+B_L^{/} D B_0\right)dV \quad (29)$$

Express $[K_L]$ in terms of the new notation. Consider the following transformations:

$$[B_0]^T=\begin{bmatrix} [B_0^{/}]^T & [B_0^{///}]^T \\ 0 & [B_0^{//}]^T \end{bmatrix}, \quad [B_L]^T=\begin{bmatrix} [B_L^{/}]^T & 0 \\ [B_L^{//}]^T & 0 \end{bmatrix},$$

$$[B_L]^T[D][B_0]=\begin{bmatrix} [B_T^{/}]^T & 0 \\ [B_L^{//}]^T & 0 \end{bmatrix}\begin{bmatrix} [D^{/}] & 0 \\ 0 & [D^{//}] \end{bmatrix}\begin{bmatrix} [B_0^{/}] & 0 \\ [B_0^{//}] & [B_0^{//}] \end{bmatrix}=\begin{bmatrix} [B_L^{/}]^T[D^{/}][B_0^{/}] & 0 \\ [B_L^{//}]^T[D^{/}][B_0^{/}] & 0 \end{bmatrix}$$

$$[B_L]^T[D][B_L] = \begin{bmatrix} [B_T^{/}]^T & 0 \\ [B_L^{//}]^T & 0 \end{bmatrix}\begin{bmatrix} [D^{/}] & 0 \\ 0 & [D^{//}] \end{bmatrix}\begin{bmatrix} [B_0^{/}] & [B_L^{/}] \\ 0 & 0 \end{bmatrix} =$$

$$= \begin{bmatrix} [B_L^{/}]^T[D^{/}][B_L^{/}] & [B_L^{/}]^T[D^{/}][B_L^{//}] \\ [B_L^{//}]^T[D^{/}][B_L^{/}] & [B_L^{//}]^T[D^{/}][B_L^{//}] \end{bmatrix}$$

$$[B_0]^T[D][B_L] = \begin{bmatrix} [B_T^{/}]^T & [B_0^{///}]^T \\ 0 & [B_0^{//}]^T \end{bmatrix}\begin{bmatrix} [D^{/}] & 0 \\ 0 & [D^{//}] \end{bmatrix}\begin{bmatrix} [B_L^{/}] & [B_L^{//}] \\ 0 & 0 \end{bmatrix} =$$

$$= \begin{bmatrix} [B_0^{/}]^T[D^{/}][B_L^{/}] & [B_0^{/}]^T[D^{/}][B_L^{//}] \\ 0 & 0 \end{bmatrix}$$

Thus:

$$[K_L] = EF\int \begin{bmatrix} [B_0^{/}]^T[B_L^{/}] + [B_L^{/}]^T[B_0^{/}] + [B_L^{/}]^T[B_L^{/}] & [B_0^{/}]^T[B_L^{//}] + [B_L^{/}]^T[B_L^{//}] \\ [B_L^{//}]^T[B_0^{/}] + [B_L^{//}]^T[B_L^{/}] & [B_L^{//}]^T[B_L^{//}] \end{bmatrix} dx \tag{30}$$

The initial stress matrix is determined from Eq. (5):

$$\int d[B_L]^T\{\sigma\}dV = \int \begin{bmatrix} d[B_L^{/}]^T & 0 \\ d[B_L^{//}]^T & 0 \end{bmatrix}\{\sigma\}dV = \int \begin{bmatrix} d[\theta^T G^{/}]^T & 0 \\ d[\theta^T G^{//}] & 0 \end{bmatrix}\begin{Bmatrix} \sigma^{/} \\ \sigma^{//} \end{Bmatrix}dV =$$

$$= \begin{bmatrix} [G^{/}]^T d\{\theta\} & 0 \\ [G^{//}]^T d\{\theta\} & 0 \end{bmatrix}\begin{Bmatrix} \sigma^{/} \\ \sigma^{//} \end{Bmatrix}dV$$

Since $[G^{/}]^T d\{\theta\}\{\sigma^{/}\} = [G^{/}]^T \begin{Bmatrix} d\left(\frac{du}{dx}\right) \\ d\left(\frac{dv}{dx}\right) \\ d\left(\frac{dw}{dx}\right) \end{Bmatrix}[N_x] = N_x\left[[G^{/}]^T[G^{/}] \quad [G^{/}][G^{//}]\right]d\{\delta\},$

the initial stress matrix takes the following final form:

$$[K_\sigma] = \int_0^l N_x \begin{bmatrix} [G^{/}]^T[G^{/}] & [G^{/}]^T[G^{//}] \\ [G^{//}]^{/}[G^{/}] & [G^{//}]^T[G^{//}] \end{bmatrix} dx \tag{31}$$

Analysis of Results and Examples

To investigate the accuracy and convergence of the solution, several benchmark problems were analyzed. As the first benchmark problem, an inclined elastic bar element is considered to illustrate the influence of axial effects (Figure 1). Although this problem is very simple, it was selected because of the small amount of required computation and because it makes it possible to reveal the expected behavior of solutions for more complex problems. This problem has been studied by a number of researchers [12,15]; therefore, the accuracy of the obtained results can be assessed through comparative analysis. In the performed calculations, the bar is subjected only to compression. The problem is essentially nonlinear and involves large displacements.

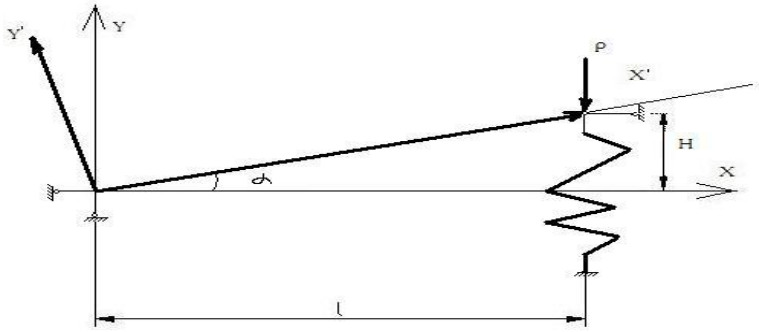

Figure 1-Diagram of an inclined rod element

The calculations were performed using the following input data:
EF=10 kg compressive stiffness.
h=1 cm — projection of the bar length onto the Oy axis
l=100 cm — projection of the bar length onto the Ox axis
k=6 kg/cm — spring stiffness coefficient

The bar is modeled as a single bar finite element with four degrees of freedom (transverse deflection and axial displacement at each of the two nodes). Since the bar is not subjected to bending and a concentrated vertical force is applied at the node, the displacements are approximated using formulas (20):

$$u = \left(1 - \frac{x}{l}\right) u_i + \frac{x}{l} u_j,\ v = \left(1 - \frac{x}{l}\right) v_i + \frac{x}{l} v_j \quad (32)$$

In matrix form:

$\{U\} = [N]\{\delta\}$, where $\{U\} = \{u \quad v\}^T$, $[N] = \begin{bmatrix} N_{1i} & 0 & N_{1j} & 0 \\ 0 & N_{1i} & 0 & N_{1j} \end{bmatrix}$ - shape functions, where

$\{\delta\} = \{u_1 \quad v_1 \quad u_2 \quad v_2\}^T$- nodal displacement vector.

The axial strain is given by:

$$\varepsilon_x = \frac{du}{dx} + \frac{1}{2}\left(\frac{dv}{dx}\right)^2 \quad (33)$$

The main matrices can be written as follows:

$$\{\varepsilon_x\} = \begin{bmatrix} N_{1i}^{/} & 0 & N_{1j}^{/} & 0 \end{bmatrix}\{\delta\} = [B_0]\{\delta\},$$
$$\{\theta\} = \begin{bmatrix} 0 & N_{1i}^{/} & 0 & N_{1j}^{/} \end{bmatrix}\{\delta\} = [G]\{\delta\},$$
$$\{\varepsilon_x\} = \frac{1}{2}\{\theta\}^T\{\theta\} = \frac{1}{2}\{\delta\}^T[G]^T[G]\{\delta\} = \frac{1}{2}[B_L]\{\delta\},$$
$$[B_0] = \begin{bmatrix} N_{1i}^{/} & 0 & N_{1j}^{/} & 0 \end{bmatrix},\ [B_L] = \{\delta\}^T[G]^T[G] \quad (34)$$

In this formulation, the constitutive matrix $[D]$ is given by: $[D] = [EF]$.

As can be seen from Fig. 1, the local coordinate system (LCS) does not coincide with the global coordinate system (GCS) and is rotated by an angle α.

The transformation matrix from the LCS to the GCS is given by:

$$[L] = \begin{bmatrix} cos\,\alpha & sin\,\alpha \\ -sin\,\alpha & cos\,\alpha \end{bmatrix}, \text{ где } cos\,\alpha = \frac{l}{\sqrt{l^2+h^2}},\ sin\,\alpha = \frac{h}{\sqrt{l^2+h^2}} \quad (35)$$

Boundary conditions: $u_1 = 0, v_1 = 0, u_2 = 0$ (36)

A comparative analysis of the problem solution obtained by different methods for various load levels (P=9P=9P=9 kg, P=12P=12P=12 kg, P=24P=24P=24 kg) is presented in Table 1 and agrees with the numerical solutions reported in [12,15].

Table 1

Comparative characteristics of solving the problem by various methods

Load, P (kg)	Displacement, cm			
	According to the works [1, 18]		of this work	
	Linear	Nonlinear	Linear	Nonlinear
9	-0,56	-1,76	-0,56	-1,48
12,0	-0,75	-2,00	-0,75	-2,08
24,0	-1,50	-2,48	-1,50	-2,88

As the second benchmark problem, an elastic cantilever beam subjected to a bending moment at the free end is considered. This problem involves purely bending effects and is examined in [16]. Its simplicity makes it possible to obtain simple analytical formulas describing geometrically nonlinear effects (Figure 2).

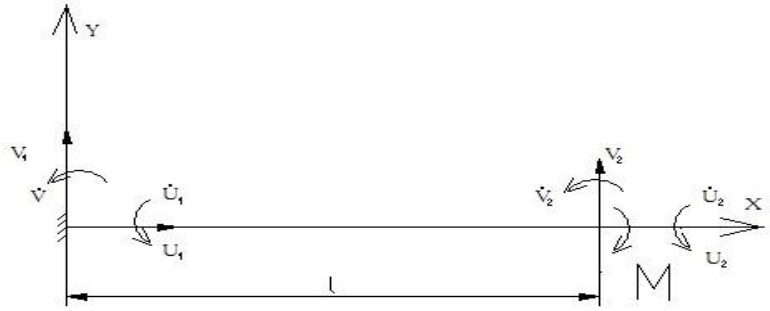

Figure 2-Calculation element diagram

The maximum deflection and axial displacement occur at the free end of the beam and are given by:

$$u = l - \rho\,sin\,\phi,\ v = \rho(1 - cos\,\phi) \quad (37)$$

u, *v*- are the horizontal and vertical displacements of the beam, respectively.

l — beam length, ρ - beam curvature, ϕ - rotation angle of the free end.

For the numerical example, a beam with the following parameters is considered:
M=10^5kg·cm applied static load moment,
F=10 cm^2 -cross-sectional area of the beam,
E=$2\cdot10^6$ - modulus of elasticity.
Since the neutral axis is not stretched under pure bending, $\phi = \frac{l}{\rho} = \frac{Ml}{EI}$=1 rad, where

$$l = \rho.$$

Substituting the obtained value of ϕ, ρ, l into Eq. (37) yields

$$u=100(1-\sin 1) = 15{,}83 \text{ cm}, \; v=100(1-\cos 1) = 45{,}97 \text{ cm}.$$

In the finite element formulation, the beam is modeled as a single finite element with eight degrees of freedom (transverse deflection, axial displacement, and two rotational degrees of freedom at each of the two nodes). Considering that the problem is treated in a plane formulation, the displacements of an arbitrary point on the bar axis are expressed as:

$$u = N_{2i}u_1 + N_{3i}\phi_{x1} + N_{2i}u_2 + N_{3j}\phi_{x2}, v = N_{2i}v_1 + N_{3i}\phi_{y1} + N_{2i}v_2 + N_{3j}\phi_{y2} \quad (38)$$

In matrix form
$\{U\}=\begin{Bmatrix} u \\ v \end{Bmatrix}$, $[N] = \begin{bmatrix} N_{2i} & N_{3i} & 0 & 0 & N_{2j} & N_{3j} & 0 & 0 \\ 0 & 0 & N_{2i} & N_{3i} & 0 & 0 & N_{2j} & N_{3j} \end{bmatrix}$- shape function

$\{\delta\} = \{u_1, \quad \phi_{x1}, \quad v_1, \quad \phi_{y1} \quad u_2, \quad \phi_{x2}, \quad v_2, \quad \phi_{y2}\}$- nodal displacement vector.

The axial strain from (11) $\varepsilon_x = \frac{du}{dx} + \frac{1}{2}\left[\left(\frac{du}{dx}\right)^2 + \left(\frac{dv}{dx}\right)^2\right]$, beam curvature $\rho = \frac{d^2v}{dx^2}$.

The stress $\{N, \quad M\}^T$ and strain $\{\varepsilon_x, \quad \rho\}^T$ vectors are related through the constitutive matrix $[D] = \begin{bmatrix} EF & 0 \\ 0 & EJ \end{bmatrix}$

.

Thus, matrix $[B]$ is given by:

$$[B] = \begin{bmatrix} N_{2i}^{/} & N_{3i}^{/} & 0 & 0 & N_{2j}^{/} & N_{3j}^{/} & 0 & 0 \\ 0 & 0 & N_{2i}^{//} & N_{3i}^{//} & 0 & 0 & N_{2i}^{//} & N_{3i}^{//} \end{bmatrix} \quad (39)$$

Where « $^{//}$»- the prime denotes differentiation

The nonlinear strain matrix takes the following form:

$$\{\varepsilon_L\} = \begin{Bmatrix} \varepsilon_L^{/} \\ 0 \end{Bmatrix}, \text{ где } \varepsilon_L^{/} = \frac{1}{2}\left[\left(\frac{du}{dx}\right)^2 + \left(\frac{dv}{dx}\right)^2\right] \quad (40)$$

This relation can be represented using the following notation and transformations:

$$\{\theta\}^T = \left\{\frac{du}{dx} \quad \frac{dv}{dx}\right\},$$

$$[\theta] = \begin{bmatrix} N_{2i}^{/} & N_{3i}^{/} & 0 & 0 & N_{2j}^{/} & N_{3j}^{/} & 0 & 0 \\ 0 & 0 & N_{2i}^{//} & N_{3i}^{//} & 0 & 0 & N_{2i}^{//} & N_{3i}^{//} \end{bmatrix}\{\delta\} = [G]\{\delta\} \quad (41)$$

$$\left\{\varepsilon_L^{/}\right\} = \frac{1}{2}\{\theta\}^T\{\theta\} = \frac{1}{2}\left[[G]\{\delta\}\right]^T[G]\{\delta\} = \frac{1}{2}\{\delta\}^T[G]\{\delta\} = \frac{1}{2}\left[B_L^{/}\right]\{\delta\}, \left[B_L^{/}\right] = \{\delta\}^T[G]^T[G]$$

The nonlinear differentiation matrix $[B_L]$ is given by:

$$[B_L] = \begin{bmatrix} B_L^{/} \\ 0 \end{bmatrix} \quad (42)$$

The initial stress matrix is determined according to Eq. (31). The boundary conditions for the clamped end are specified as $u_1 = 0, v_1 = 0, w_1 = 0$.

The free-end displacements are close to the analytically obtained results, which confirms the high accuracy of the developed program.

Table 2

Comparative characteristics of moving the free end of the beam by various methods

Results of the solution	u_2 (cm)	v_2 (cm)
By [1]	-15,853	45,970
By [15]	-15,850	45,197
According to the algorithm of this work	-15,610	45,770

The obtained numerical results allow the conclusion that the proposed algorithm can be applied to the analysis of geometrically nonlinear bar systems subjected to static loading.

Conclusion

Based on the finite element method, the governing equations for solving the static elastic problem of a spatial bar system considering geometric nonlinearity have been obtained. The principal relationships, solution method, and computational scheme have been established. An algorithm for solving the problem and high-level computer programs have been developed and verified on benchmark problems [17,18].

The proposed algorithm was used for the calculation and analysis of the elastic behavior of a specific platform. Analysis of the influence of large displacements on the elastic nodal displacements of the platform showed that accounting for geometric nonlinearity significantly alters the results obtained for a linear bar system; the computed displacements are 1.5–2.2 times greater than the corresponding displacements obtained from linear analysis.

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ELECTRICAL ENGINEERING

PROBLEMATIC SOLUTIONS OF QAM-MODULATED PROCESSES IN ARTIFICIAL INTELLIGENCE

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Abstract

This article systematically analyzes the problems encountered in QAM modulation systems and extensively explores their solutions using artificial intelligence (AI) methods. Deep learning tools like CNNs and RNNs appear alongside support vector machines, blending with older signal processing strategies. These combined efforts aim at sorting modulations, handling noise, fixing timing mismatches, and cutting down errors.

Performance across these goals varies, depending on which method takes the lead. While comparisons highlight strengths and limits, one trend stands out - higher data speeds push engineers toward QAM despite its challenges. Modern telecom demands keep expanding, making such complex modulation more common than before. Especially, M-QAM - like 16-, 64-, or 256-level variants - boosts how much data fits in a frequency band; however, it grows more vulnerable to interference, timing shifts, amplifier quirks, and pathway flaws.

Such traits become central hurdles when trying to capture and decode the message right. Research reveals machine-driven models outperform classical techniques by adjusting better, learning patterns faster, reacting wider across conditions. Because of this shift, intelligent systems help fine-tune QAM delivery paths while lifting trustworthiness during transfer - not just offering fixes, yet opening practical routes ahead.

Keywords: QAM, artificial intelligence, deep learning, signal recognition, automatic modulation classification, channel noise, spectral efficiency.

Introduction

High-speed data transfer became a top concern as telecom tools advanced quickly over the past few decades. To handle growing demands, engineers turned to methods like QAM, a popular way to pack more data into signals through shifts in strength and timing. Instead of relying on just one signal property, this technique uses layered changes across levels - seen in formats such as 32-QAM or even 1024-QAM - to boost how much fits in each frequency band. These complex versions help today's networks move large amounts of information without needing extra spectrum space.

Because higher-order modulation packs data tighter across frequencies, M-QAM uses dots on a grid in imaginary space to send signals. With more symbols squeezed into the same slice of spectrum, each wave carries extra bits - efficiency climbs. Still, tighter spacing between points makes errors likelier when interference appears. Designers face this balance: speed versus reliability shows up clearly here.

The main problems encountered in QAM systems include:

- Errors occur frequently within data transmission, leading to a marked rise in corrupted bits across the channel
- Timing shifts disrupt alignment patterns, while mismatched cycles prevent stable coordination
- nonlinear characteristics of the channel,
- Yet interference brings extra noise issues - most noticeable where background static already exists. Though random signals mix, disturbances grow worse under constant signal pressure. Where white noise dominates, side effects intensify unexpectedly. Even mild disruptions shift behavior when steady chaos overlaps.
- difficulties in accurate signal classification.

Even when traditional signal analysis and statistics tackle such issues, performance often falls short within intricate, shifting networks. Specifically, they struggle to adjust or apply broadly - more so with advanced modulation techniques.

Because of this shift, growing interest has appeared lately in using artificial intelligence alongside machine learning techniques. These tools handle vast datasets efficiently, adapt to changing transmission environments, reduce interference with greater reliability, while also sorting signals automatically and with fine accuracy. Thanks to these abilities, systems relying on AI help tackle persistent challenges in QAM setups, at the same time lifting performance across communication networks.

Literature Review

Among recent advances in telecom, QAM combined with AI stands out as a growing area of study. Research trends show movement toward three distinct paths - not only AMC but also dynamic signal handling when channels shift. Another path explores how deep learning improves error fixing and system tuning. Each direction builds differently on data-driven methods, reshaping what these systems can do.

Deep learning models classify M-PSK and M-QAM signals with strong precision, Chikha et al. (2025) found. Under heavy noise, their behavior stays consistent - unlike conventional techniques, which often struggle. Performance does not drop sharply when conditions worsen. Instead, these models adapt, maintaining reliability where older systems fail.

Despite limitations in earlier models, Kaleem et al. (2021) found AI-driven AMC tools improve accuracy when detecting signals instantly within 5G and future

network environments. While traditional statistical approaches lag behind, neural networks demonstrate stronger adaptability across diverse scenarios - mainly due to pattern learning over rigid rules.

Working through signal distortions caused by phase noise, Alhazmi et al. (2022) explored how deep learning handles QAM classification. Their findings revealed convolutional neural networks adapt well to warped constellations. Instead of relying on traditional methods, the study demonstrated these models identify patterns despite interference. Performance remained strong even when noise disrupted signal geometry. Results suggested such architectures grasp underlying structures hidden in noisy data.

Fitz and Seymour's 1994 study built an analytical model for bit error rates in QAM setups, while also clarifying how channel noise affects transmission. Even now, their findings serve as a reference point when judging how well modern AI-driven systems perform.

Performance gains emerge when modulation shifts with signal quality, Priya and Kumar showed in 2015 using adaptive QAM. Because of this behavior, pairing such systems with artificial intelligence techniques becomes a natural next step.

Performance shifts under changing channels were laid out by Rajapaksa et al. (2020), who studied QAM setups inside standard communication frameworks. Their explanation unfolded step by step, revealing how signal behavior alters when conditions drift.

Energy efficiency gains emerge through hexagonal QAM layouts, according to Cogen and colleagues in 2019. Constellation design finds a meaningful path forward - not by chance, but via such structured shifts.

Focusing on 5G frameworks, Wu and colleagues introduced FQAM in 2018 - its design enhances how spectrum space is used while lowering signal disruption. Though built for next-gen networks, the method shifts modulation norms by merging frequency traits with amplitude control through an unconventional split-path approach. Performance gains emerge mainly under crowded channel conditions, where traditional schemes struggle with overlap.

Stability in multicarrier setups improves when QAM works alongside FBMC, according to Qi and colleagues in 2018. While examining signal modulation techniques, their study revealed fewer fluctuations under varying channel conditions. Instead of traditional approaches, they focused on combining formats differently. Performance gains emerged without increasing complexity across transmissions.

A recent analysis by Springer suggests artificial intelligence improves performance across multiple areas - modulation identification included - with noticeable gains in fixing transmission mistakes and refining signal pathways. Especially within satellite networks, such methods stand out due to consistent accuracy under challenging conditions.

Data and Priminary Analysis

Looking into how machines can identify Quadrature Amplitude Modulated signals forms the core of this work. Modern communication setups often rely on M-QAM formats - like 16-, 64-, or 256-level variants - for better data packing in limited bandwidths. Yet performance drops sharply when real-world disruptions enter: random interference, timing drifts, frequency warping, or amplifier quirks appear. Because of that, telling one QAM type apart from another under messy conditions stays tough - not just in lab models, but also in live networks.

From simulations come signal samples layered with distortions like additive white Gaussian noise, phase shifts, and echoes from multiple paths. Real-world inputs arrive through live 5G and IoT setups alongside lab-built software-defined radio platforms. One feeds controlled conditions, while the other captures natural complexity. Comparing both reveals how closely theory matches actual performance. Outcomes gain credibility when tested across synthetic and operational scenarios.

In the complex baseband representation, QAM signals rely on two parts: one called I(t), which carries the in-phase information, whereas the other, Q(t), handles the quadrature part. These elements ride on carrier waves that do not interfere due to their perpendicular nature. Higher M levels boost data capacity and make better use of spectrum space - yet bring tighter spacing between symbol decisions. When noise increases, performance drops sharply because small errors in signal strength or timing cause misreading. Nearby locations in the constellation diagram blur under poor conditions, complicating accurate identification. The challenge grows as points crowd closer together.

Usually, a standard QAM communication setup includes multiple core components. Starting at the transmit end, digital bits emerge before being assigned to specific positions on a QAM grid instead followed by transformation into continuous waveforms using an I/Q mechanism. During transit through the medium, disturbances like random background interference, timing inaccuracies, frequency drifts caused by movement, along with reflected signal overlaps distort the original form. These effects together introduce most of the deterioration seen in received signals. At the far end, alignment processes occur prior to reversing the modulation step, identifying closest symbols appears next, features get isolated afterward, while outcomes move forward into machine-based analysis tools.

Though deep learning techniques like CNNs pull out spatial patterns from raw I/Q data, their pairing with LSTM units helps capture time-based changes across signals. Where traditional methods struggle at low signal-to-noise ratios, these modern networks hold up better in tests. Hybrid setups such as CNN-LSTM combine strengths but still face hurdles when moved into actual field applications. Despite gains in accuracy, adapting them beyond controlled settings introduces challenges tied to processing load and broad usability. SVMs appear alongside neural structures yet often fall short in dynamic environments.

Though 16-QAM shows better stability, its spectral efficiency lags behind. In contrast, 64-QAM strikes a middle ground yet needs acceptable SNR to function well. Meanwhile, 256-QAM enables faster data transfer though it falters easily when noise or phase issues arise. Channel quality clearly shapes how QAM setups perform in practice. From reviewing existing studies and early evaluations, persistent problems emerge at higher modulation orders. Decision regions become unstable

as constellations crowd together. Phase noise degrades signal integrity especially in 5G and space-based links. Real-world measurements often diverge from modeled outcomes. Machine learning tools used in these systems lack transparency in their operations. Processing demands also rise sharply when deploying solutions live.

Looking at things broadly, early findings suggest traditional signal processing techniques fall short when dealing with QAM modulation constraints on their own. Though artificial intelligence methods help reduce some drawbacks, gains still need to happen - especially around speed, stability, and fine-tuning - for live applications. A full setup was drawn up using a step-by-step visual structure showing how signals move through sending, traveling, and receiving phases. How each part connects and affects the others appears clearly in the illustration that follows.

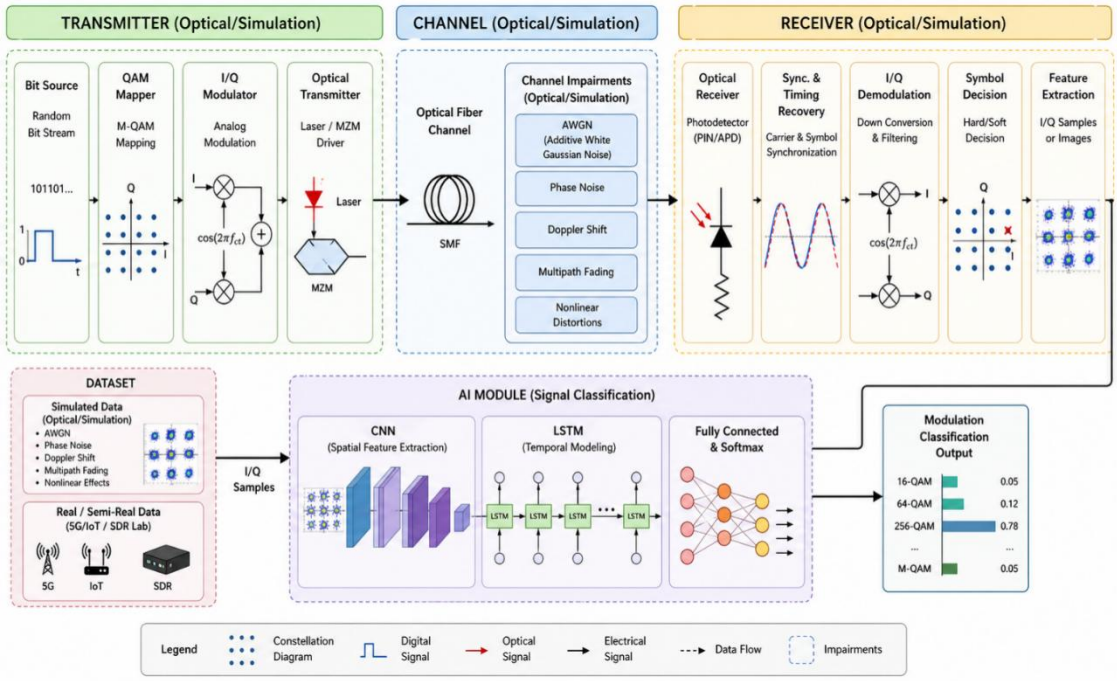


Figure 1. Block diagram of the optical and simulation system architecture

METHODOLOGY

One way this research proceeds involves exploring how artificial intelligence methods handle automatic detection and sorting of Quadrature Amplitude Modulation signals. Instead of relying solely on traditional algorithms, it combines older signal analysis tools alongside newer machine learning structures. What stands out is an effort to build a combined smart setup that identifies different M-QAM formats - like 16-, 64-, or 256-level variants - with strong precision even when interference or transmission flaws occur.

A signal using QAM, when viewed in complex baseband form, can be written as:

$$s(t) = I(t)\cos(2\pi f_c t) + Q(t)\sin(2\pi f_c t)$$

Here:

- $I(t)$— in-phase component,
- $Q(t)$— quadrature component,
- f_c — carrier frequency.

Among various modulation techniques, M-QAM assigns data symbols to specific locations on a two-dimensional plane. Typically, the waveform follows this structure:

$$s_k = a_k + jb_k, k = 1,2,\dots,M$$

For this case, MMM stands for the number of signal points used in transmission - such as 16, 64, or 256. While these values change, their role stays consistent across systems.

For more accurate channel simulation, these impairments get introduced into the signal:

$$r(t) = s(t)e^{j\phi(t)} + n(t)$$

here:

- $\phi(t)$— phase noise,
- $n(t)$ — AWGN (Additive White Gaussian Noise).

This simulation mirrors actual wireless setups, shown through research by Alhazmi and colleagues in 2022 along with work published later by Chai. While details differ across studies, both confirm its alignment with physical network behaviors under variable conditions.

Starting at low intensities, each signal instance appears across SNR values between -20 dB and +20 dB. Generated not only by simulations in MATLAB or Python but also drawn from public structured databases - examples include collections like RadioML - the data takes shape under controlled variations. Though synthetic methods contribute significantly, real-world recordings form an equal part of the foundation. While noise levels shift deliberately, every sample maintains its structural integrity for consistent analysis.

Once collected, data undergoes cleaning to remove inconsistencies. Following that, irrelevant entries get filtered out systematically. Afterward, formatting adjusts to match model requirements precisely. Then, duplicates are identified and eliminated carefully. Next, missing values receive appropriate handling based on context. Finally, transformation techniques standardize features uniformly.

The process adjusts the signal strength to a standard level:

$$x_{norm} = \frac{x - \mu}{\sigma}$$

Learning remains steady because of this setup.

Using Fast Fourier Transform (FFT), signals are converted into their frequency components;

$$\mathrm{X(f)} = \sum_{n=0}^{N-1} x(n) e^{-j2\pi f n/N}$$

Such traits hold distinguishing details, especially when applied to advanced QAM formats like 256-QAM.

Following Kumar et al. (2024), classification relies on features via the Support Vector Machine (SVM). SVM optimizes the decision boundary as follows:

$$f(x) = sign(wTx + b)$$

A radial basis function (RBF) kernel is used as the kernel function:

$$K(x_i, x_j) = exp(-\gamma \mid\mid x_i - x_j \mid\mid^2)$$

Even when signal quality is poor, SVM holds up well - yet struggles as modulation complexity increases, such as with 256-QAM.

The effectiveness of the model is evaluated using the following metrics:

What a model gets right makes up its **accuracy.** This measure counts the number of proper guesses divided by all attempts made. It is defined as the ratio of correctly classified samples to the total number of samples:

$$Accuracy = \frac{TP + TN}{TP + TN + FP + FN}$$

TP (True Positive) — true positive samples correctly identified by the model, TN (True Negative) — correctly identified negative samples, FP (False Positive) — false positive predictions, FN (False Negative) refers to positive cases that are missed by the model.

Precision indicates how many of the instances predicted as "positive" by the model are actually correct:

$$Precision = \frac{TP}{TP + FP}$$

When wrong signals get accepted, this measure matters most. Suppose the system often labels a transmission as 256-QAM, yet many turn out to be 64-QAM - accuracy then drops. Put differently, it reflects how likely the model is to wrongly confirm a higher-order modulation.

Recall indicates how well the model identifies actual positive cases:

$$Recall = \frac{TP}{TP + FN}$$

Because detection matters most when signals go unnoticed, this measure gains weight in such cases. When 256-QAM transmissions exist yet escape identification - many missed by the model - the resulting recall drops sharply. Telecommunications face risks here: misreading occurs once recognition falters.

F1-score is a balanced measure of precision and recall, calculated as their harmonic mean:

$$F1 = 2 \cdot \frac{Precision \cdot Recall}{Precision + Recall}$$

When precision and recall need equal weight, the F1-score becomes relevant. Though one metric might be strong, if the other lags behind, this score adjusts for imbalance. Instead of favoring extremes, it merges both values into a single measure. Performance then appears less skewed than viewing either alone. A middle-ground view often shows what raw numbers hide.

Simulation Results and Their Analysis

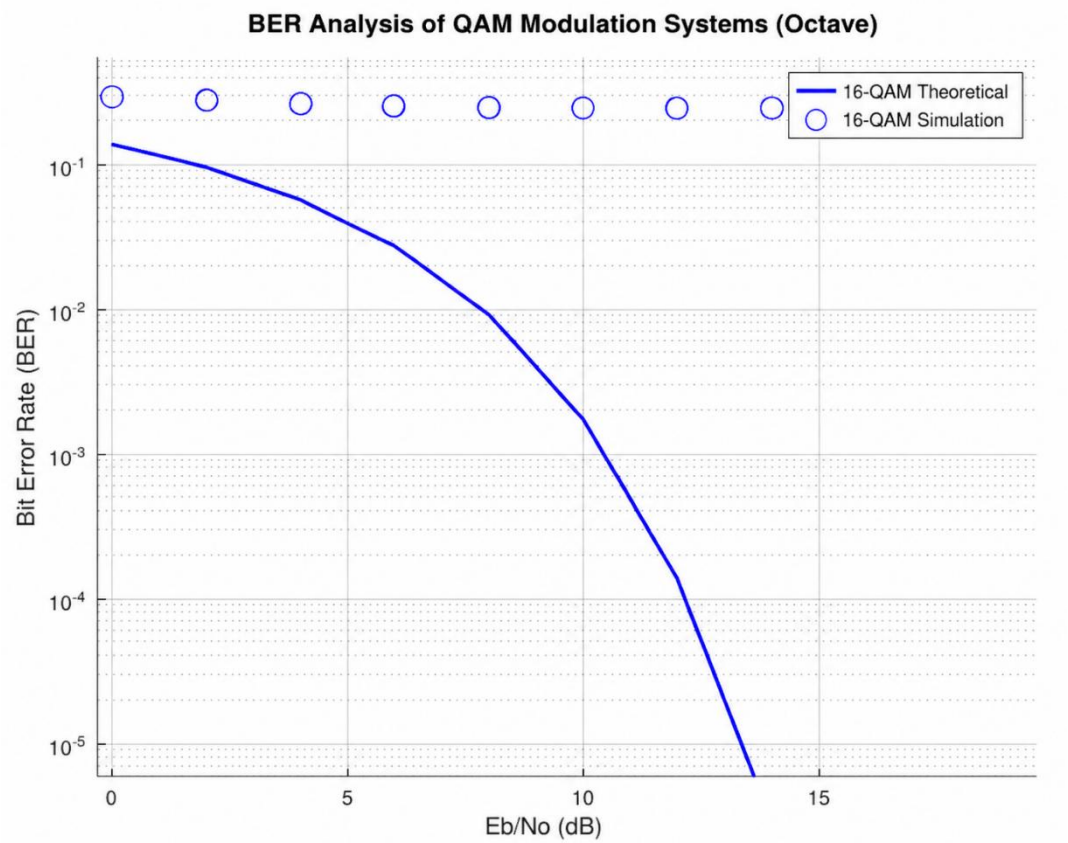
Simulation of M-QAM modulation systems takes place under AWGN channel conditions, aiming to assess how well the suggested approach performs. While relying on traditional theoretical frameworks, the procedure also includes computational trials to support findings.

MATLAB Simulation Code

Starting with 16-QAM, the simulation runs alongside its 64-QAM counterpart under identical conditions. Signals move through an AWGN environment, experiencing random noise interference along the way.

```
    clear; clc; close all;

    %% Parameter definition
    M_levels = [16, 64]; % Modulation orders referenced in the study [cite: 238]
    EbNo_dB = 0:2:18;   % Signal-to-noise ratio range (dB)
    numBits = 1e5;    % Number of bits for simulation

    figure;
    hold on;
    grid on;
    colors = ['b', 'r'];
    markers = ['o', 's'];

    for i = 1:length(M_levels)
      M = M_levels(i);
      k = log2(M); % Number of bits per symbol

    % Bit generation
    dataIn = randi([0 1], numBits, 1);

    % QAM modulation
    dataSymbolsIn = bit2int(dataIn, k);
    txSig = qammod(dataSymbolsIn, M, 'UnitAveragePower', true);
      % BER computation loop
    berSim = zeros(size(EbNo_dB));
    for j = 1:length(EbNo_dB)
      % Adding AWGN channel [cite: 302]
      snr = EbNo_dB(j) + 10*log10(k);
      rxSig = awgn(txSig, snr, 'measured');

        % Demodulation
        dataSymbolsOut = qamdemod(rxSig, M, 'UnitAveragePower', true);
        dataOut = int2bit(dataSymbolsOut, k);

        % Error calculation
        [~, berSim(j)] = biterr(dataIn, dataOut);
      End
```

```
    % Theoretical BER calculation [cite: 372]
    berTheory = berawgn(EbNo_dB, 'qam', M);

    % Plotting results
    semilogy(EbNo_dB, berTheory, [colors(i) '-'], 'LineWidth', 1.5);
    semilogy(EbNo_dB, berSim, [colors(i) markers(i)], 'MarkerSize', 8);
end

xlabel('Eb/No (dB)');
ylabel('Bit Error Rate (BER)');
title('BER Analysis of QAM Modulation Systems');
legend('16-QAM Theoretical', '16-QAM Simulation', '64-QAM Theoretical', '64-QAM Simulation');
ylim([1e-5 1]);
```



Explanation of the Obtained Graphs

Looking at the data shown in the paper, Octave-generated plots reveal this pattern:

- With larger M, system performance shifts - notice how 64-QAM lags behind 16-QAM in the BER plot. Higher modulation levels demand stronger signal quality, since more noise tolerance slips away when M grows. Evidence backs this: reaching equal error rates needs greater SNR as M increases.
- Decision boundaries shift when noise affects signal points, visible as movement within the diagram. With larger M values, these zones between symbols grow tighter, making mistakes more likely during detection. Study findings confirm that higher modulation levels reduce spacing, raising error chances under identical conditions.
- Despite close alignment of simulated data points with smooth theoretical predictions - suggesting a clean AWGN environment - the paper notes practical limitations. Real conditions introduce phase instability and nonlinear effects, pulling performance downward. To handle such variability, learning-based strategies like convolutional networks or support vector machines come into play. These tools adjust dynamically where fixed models fail. Their role grows critical when distortion breaks classical assumptions.

The main scientific conclusions obtained from the simulation results are as follows:

- **Modulation Order Effect:** Higher modulation orders, such as moving from 16 to 64, demand a greater signal-to-noise ratio - about 4 to 5 decibels more - for matching bit error rates like 10^{-3}. Though bandwidth usage gets better, the setup also grows less tolerant of interference.
- **Decision Boundary Narrowing:** Because the gaps between symbols shrink in 64-QAM, mistakes during decoding become more likely when noise is present. High-level modulations like 256-QAM face this challenge most clearly, as shown in the research.
- **Simulation and Theoretical Agreement:** Close agreement between simulated results and predicted theory supports the accuracy of the chosen modeling approach. Still, actual conditions - such as phase instability and signal distortion - likely reduce effectiveness beyond what simulations show.

Rationale for the Application of Artificial Intelligence

Simulation outcomes reveal that under weak signal scenarios - between 0 and 8 dB - the bit error rate stays high, above 10−2. Because of their ability to identify irregularities in signal patterns, neural network and support vector machine methods perform well where traditional approaches struggle. Instead of fixed rules,

these systems shift classification zones based on learned variations during operation.

Table 1.

SNR Requirements and BER Performance for Different QAM Levels

Modulation Type	Spectral Efficiency (bit/s/Hz)	Required for 10−4 BER SNR (dB)	Noise Sensitivity
16-QAM	4	~14 dB	Medium
64-QAM	6	~18 dB	High
256-QAM	8	>22 dB	Very High

RESULTS ANALYSIS AND DISCUSSION

Examining how well artificial intelligence handles QAM signal tasks forms the core here. Rather than relying on traditional techniques alone, newer models enter the picture for side-by-side review. What emerges comes not from isolated tests but structured comparisons across distinct method families. Classical frameworks serve as reference points alongside neural networks and related systems. Performance differences appear when each approach processes identical datasets under shared conditions. Insights grow sharper by contrasting outcomes rather than focusing on single results. Instead of claiming superiority outright, patterns reveal where specific tools perform better.

With higher-order QAM formats - like shifting from 16-QAM to 256-QAM - errors rise sharply, along with challenges in accurate signal identification. Because of this uneven climb in demand, traditional techniques fall short when used by themselves.

The general mathematical expression of a QAM signal is given as follows, and the interpretation of the results is based on this model:

$$s(t) = I(t)\cos(2\pi f_c t) + Q(t)\sin(2\pi f_c t)$$

Here, the sensitivity of the I(t) and Q(t) components to noise and phase errors directly affects the system performance.

In traditional approaches, the analysis of QAM signals is mainly carried out using statistical models and analytical probability methods. For example, the bit error rate (BER) is estimated as follows:

$$P_b \approx \frac{4}{log_2 M}\left(1 - \frac{1}{\sqrt{M}}\right) \cdot Q\left(\sqrt{\frac{3log_2 M}{M-1} \cdot \frac{E_b}{N_0}}\right)$$

When signal quality is strong, predictions tend to align well with actual outcomes. Yet reality introduces complications - phase instability, uneven channel behavior, unpredictable reflections - that slip through its assumptions.

Because of their ability to adapt through data, artificial intelligence techniques overcome earlier constraints. Specifically, systems like Convolutional Neural Networks (CNN), Recurrent Neural Networks (RNN), and Support Vector Machines (SVM) detect intricate patterns without manual input. As learning progresses, performance improves - classification grows more precise over time.

A CNN-driven approach, according to Chikha et al. (2025), surpassed 95% precision when identifying 64-QAM and 256-QAM signal types. Meanwhile, traditional techniques tend to hover between 70% and 80%, particularly when signal-to-noise ratios are weak.

Signal clarity suffers when phase noise distorts QAM constellations, as shown by Alhazmi and colleagues in 2022. Instead of holding steady, symbols shift unpredictably across the plot. This displacement blurs where detection thresholds should lie. Because of such shifts, correct symbol identification becomes less certain.

Simulation results show that:

• For 16-QAM, the impact of phase noise is limited.

• For 64-QAM, a moderate level of degradation is observed.

• For 256-QAM, the BER increases sharply.

When it comes to handling complex pattern shifts, artificial intelligence approaches often perform better due to their ability to adapt to irregular data structures. Because they learn directly from spatial arrangements, CNNs handle signal distortions with greater resilience than traditional methods. Their strength lies in adjusting internal representations dynamically, which allows them to capture subtle changes across different configurations.

A method built on support vector machines, introduced by Kumar and colleagues in 2024, tackled detection of 256-QAM signals. Performance stayed steadier compared to traditional techniques when tested under medium signal-to-noise conditions. Stability stood out most where earlier models tended to fluctuate.

According to analyses conducted by Chai (2025) and Ahmad (2019), in an AWGN channel, as M increases, the system's BER performance changes as follows:

• M ↑ → Spectral efficiency ↑

• M ↑ → Required SNR ↑

• M ↑ → BER ↑

This trade-off makes the application of artificial intelligence necessary, as AI models can adaptively construct optimal decision boundaries.

Advanced forms of QAM technology have also been analyzed:

• **Hexagonal QAM** – improves energy efficiency

• **FQAM (Frequency and QAM)** – reduces interference in 5G systems

• **QAM-FBMC** – provides higher spectral efficiency

According to Wu et al. (2018), FQAM technology offers lower interference and more stable performance compared to conventional QAM.

The conducted analyses indicate that artificial intelligence approaches provide the following advantages:

Adaptability – ability to adjust to changing channel conditions

Nonlinear modeling – more accurate representation of real signals

Automation – reduced need for manual parameter tuning

High accuracy – especially advantageous under low SNR conditions

However, certain limitations also exist:

• High computational complexity

• Requirement for large datasets

• Possible latency in real-time applications

Despite promising outcomes, traditional techniques fall short when applied to QAM systems under current telecom demands. Especially within 5G, advancing toward 6G, shifting channels combined with complex modulations push AI-driven solutions into necessity.

Starting with signal details, deep learning systems capture shifts in amplitude alongside changes in phase through combined training routines. Because of this dual adjustment, results become more accurate while demanding less power and using bandwidth more wisely. Such methods reshape how resources are used without sacrificing output quality.

Future satellite networks and sixth-generation communication frameworks are expected to rely heavily on artificial intelligence for signal adjustment and mistake handling, according to findings published in Springer Review (2025). Because of this shift, QAM technology's evolution seems likely to follow alongside advances in machine learning rather than proceed independently.

CONCLUSION

Though focused on QAM signals, current AI applications face persistent hurdles in accurate interpretation. Notably, sorting and refining these signals through machine learning shows promise when contrasted with classical frameworks. Where standard algorithms falter, neural architectures detect subtle patterns more effectively. Yet progress is uneven across different scenarios. Some models struggle under real-world conditions like noise or distortion. Even high-performing networks demand excessive training data. Without careful design, gains in precision erode quickly. Gaps persist between theoretical benchmarks and operational systems. While results improve steadily, full reliability remains distant. Each advance introduces new trade-offs needing scrutiny.

Higher up in the QAM scale - like 64-QAM or 256-QAM - the tighter grouping of signal points makes transmissions far more vulnerable to interference and distortion. When faced with white noise or timing shifts in phase, telling signals apart grows difficult. Traditional math-driven techniques help somewhat; however, machine learning approaches tend to classify more precisely. Yet even smart models stumble when shifting between different operating conditions. Performance might look strong in one setting, yet fall short somewhere else entirely.

Because datasets shape how well artificial intelligence works, their variety and accuracy matter greatly. Real telecom networks often behave differently than expected, mainly because many existing studies rely on simulated data or narrow test cases. Effects like signal distortion, reflected paths, frequency changes due to motion, and unstable timing create intricate patterns that simple setups fail to capture. Moving forward, building bigger, more lifelike collections of data stands out as an essential step.

Heavy computing needs and power drain in AI systems create real barriers in everyday use. On phones or smart sensors, complex neural nets often struggle to run smoothly. As a result, leaner architectures gain more attention across research and engineering circles. Shrinking model size, reducing precision, or reusing trained features help ease hardware pressure. Performance stays strong, yet speed improves - making instant decisions possible even on weak machines.

Looking at the big picture, findings suggest artificial intelligence significantly shapes how QAM-based systems evolve. In tasks like identifying signal types automatically, improving resistance to interference, or making better use of available bandwidth, outcomes highlight clear promise. Yet challenges linger - systems often struggle outside controlled settings, demand heavy computing resources, face shortages in training data, while remaining hard to interpret. Despite progress, these gaps limit broader deployment.

One path forward involves creating models that work instantly without heavy computation. To move ahead, researchers might focus on simpler designs that respond quickly. Large collections of data, reflecting varied signal environments, become necessary at some point. These sets must mirror actual network behavior across many situations. Combining traditional techniques with modern learning tools could bring better outcomes. When older methods join new ones, performance sometimes improves unexpectedly. Trust matters when putting intelligent systems into service. Systems able to show their reasoning tend to gain acceptance more easily. Progress often depends on clarity in how decisions are made.

Ultimately, work with artificial intelligence shows promise for tackling issues in QAM signal processing - yet reaching full effectiveness depends on combining expertise across fields, refining computational methods, while tailoring models to practical environments. Progress in these efforts could shape future communication technologies capable of greater responsiveness, stability, under improved performance. Still, success hinges not just on innovation but alignment with operational realities.

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IMPROVING THE QUALITY OF LIFE OF PATIENTS WITH AMYOTROPHIC LATERAL SCLEROSIS THROUGH AN ARTIFICIAL INTELLIGENCE-BASED BRAIN POTENTIAL RECOGNITION SYSTEM

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Abstract

Amyotrophic lateral sclerosis (ALS) is a progressive neurodegenerative disorder characterized by the loss of voluntary motor function, eventually leading to severe communication impairment. In advanced stages, patients may lose the ability to speak, write, or use conventional assistive technologies. Brain–computer interface (BCI) systems provide a promising alternative by enabling communication through direct interpretation of neural activity.

The present study focuses on the acquisition, preprocessing, and classification of electroencephalographic (EEG) signals corresponding to binary cognitive responses ("Yes" and "No"). EEG data were collected using a CleaveLab - BioRadio system in a controlled laboratory environment. The signals were processed and transformed into informative features, including statistical time-domain characteristics.

Machine learning methods were applied to classify cognitive states based on extracted features. The study emphasizes the importance of data-driven approaches in handling non-stationary EEG signals and improving classification performance. The results demonstrate the feasibility of using simple yet effective features combined with machine learning algorithms for communication-oriented BCI applications in ALS.

Keywords: Amyotrophic Lateral Sclerosis (ALS), Electroencephalography (EEG), Brain–computer interface (BCI), Machine Learning, Naive Bayes.

Introduction

Amyotrophic lateral sclerosis (ALS) is a severe neurodegenerative disease that affects both upper and lower motor neurons, leading to progressive muscle weakness and paralysis. As the disease advances, patients gradually lose the ability to communicate, which significantly impacts their autonomy and quality of life.

Traditional communication methods, including speech and motor-based assistive technologies, become ineffective in advanced stages of ALS. Even eye-tracking systems may fail due to fatigue and oculomotor impairments. However, cognitive functions such as attention and decision-making often remain preserved.

This dissociation between intact cognitive processes and impaired motor output provides the foundation for brain–computer interface (BCI) systems. BCI technologies enable communication by translating neural signals into control commands without relying on muscular activity.

Electroencephalography (EEG) is one of the most widely used methods for recording brain activity in BCI applications due to its non-invasive nature and relatively low cost. However, EEG signals are highly complex, noisy, and non-stationary, which makes their analysis challenging.

To address these challenges, machine learning techniques are increasingly applied to EEG signal processing. These methods allow automatic extraction of meaningful patterns and enable classification of cognitive states.

The aim of this study is to develop a framework for classifying binary cognitive responses ("Yes" and "No") using EEG signals, with the ultimate goal of supporting communication in patients with ALS.

Experimental Environment

The experiment was conducted at the Biomedical Engineering Laboratory of Georgian Technical University. The study was performed in a controlled indoor environment in order to reduce external noise and improve signal quality during EEG acquisition.

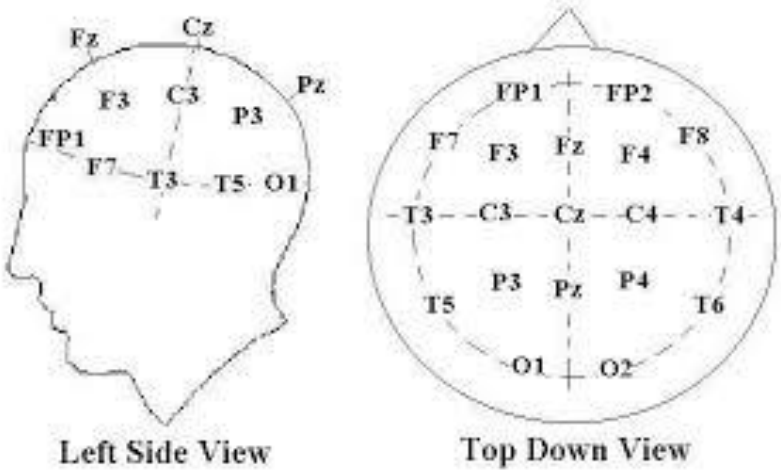
Participants

Two healthy male participants aged 25 and 40 were involved in the experiment. At this stage, healthy individuals were used to test the technical feasibility of the method before considering future application to ALS patients. This is a common initial step in the development of brain–computer interface systems.

EEG Recording System

EEG signals were recorded using a CleaveLab - BioRadio wireless system. The use of a wireless device improved participant comfort and simplified data acquisition. Signal recording was monitored in real time through Capture Lite software.

Electrodes were placed according to the international 10–20 system (Pic. 1). The selected positions were Fp1, Fp2, O1, and O2, representing frontal and occipital regions. These channels were chosen as a practical configuration for detecting relevant neural activity during internal binary response generation.



Pic. 1 international 10–20 system

Experimental Procedure

During the experiment, participants were asked questions and instructed to think of a binary response, either "yes" or "no," without speaking or making visible movements. The purpose was to capture EEG patterns associated with internal cognitive intention rather than overt motor response.

Each trial lasted approximately 3–4 seconds and was repeated multiple times. More than 800 recordings were collected in total in order to provide sufficient data for machine learning analysis. Repeated trials were necessary because EEG signals are variable and often contain noise, so a larger number of samples improves the reliability of the dataset.

Data Processing

After data acquisition, the recordings were exported to Excel and MATLAB for preprocessing and analysis. Since raw EEG signals are often affected by artifacts and inconsistent trial lengths, several preprocessing steps were carried out before classification.

First, noisy segments and outliers were identified and removed. This step was important to exclude recordings with abnormal values caused by movement, poor electrode contact, or environmental interference.

Second, signal values were normalized to reduce variation in amplitude across different samples. Normalization improves the performance of many machine learning algorithms by making the data more consistent.

Third, all EEG segments were converted into a uniform structure. Because trial durations could vary slightly, the number of signal points per sample was standardized so that all observations had the same data length. This created a consistent dataset suitable for supervised learning.

Finally, each EEG sample was labeled according to the intended response category: "Yes" or "No."

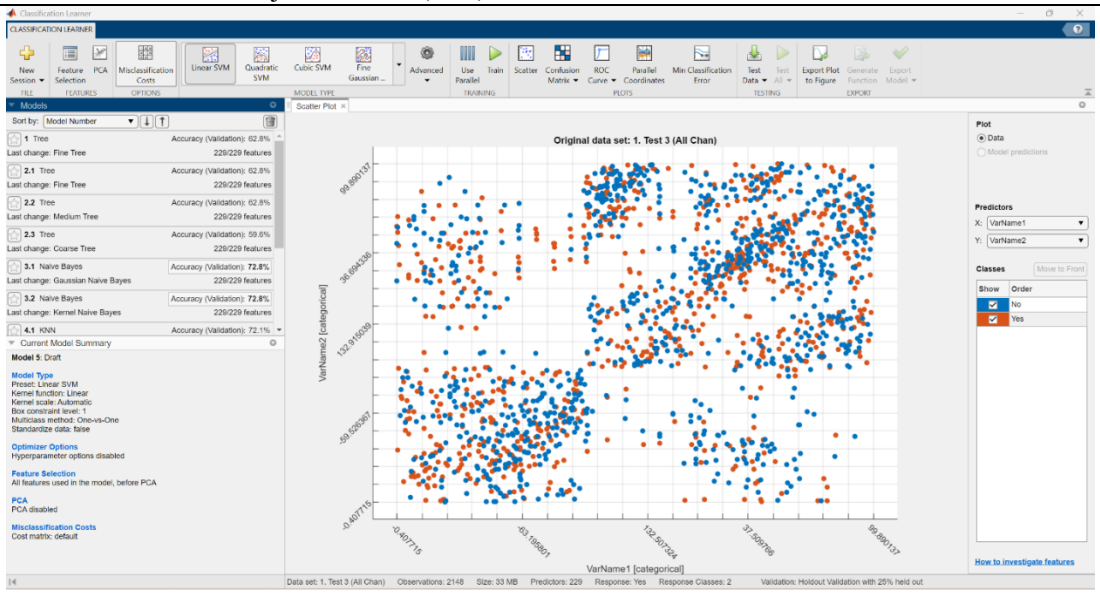
Machine Learning Analysis

Classification was performed using MATLAB's Classification Learner tool. Several machine learning algorithms were tested in order to compare their ability to distinguish between the two cognitive response classes. These included:

- Decision Trees
- Naive Bayes
- Support Vector Machines
- k-Nearest Neighbors
- Ensemble methods
- Neural Networks

Different datasets were evaluated, including single-electrode and multi-electrode configurations. In the MATLAB environment, EEG features were defined as numerical predictor variables, while the target variable ("Yes" or "No") was defined as categorical.

To evaluate model performance, a 25% holdout validation method was used. This means that 75% of the data were used for training and 25% were reserved for validation. This approach allowed estimation of how well each model could classify previously unseen data (Pic 2).



Pic. 2 Naive Bayes 72.8% Result

Result and Review

The results showed that machine learning algorithms were able to classify binary cognitive responses from EEG data with moderate success. Although all tested models demonstrated some classification capability, their performance differed depending on the algorithm and the channel configuration used.

Among all evaluated classifiers, the Naive Bayes model achieved the highest performance, with an accuracy of 72.8%. This result indicates that the model was able to identify meaningful differences between EEG patterns associated with “yes” and “no” responses. While the accuracy is still below the level required for dependable clinical use, it provides clear evidence that the approach is feasible.

The selected model was further evaluated using several standard validation tools. The confusion matrix showed the distribution of correct and incorrect classifications for both response classes (pic. 3), helping to reveal the balance between true predictions and misclassifications. The ROC curve provided additional information about the model’s ability to separate the two classes across different thresholds. In addition, the parallel coordinates plot illustrated the distribution of features and the degree of overlap between the classes.

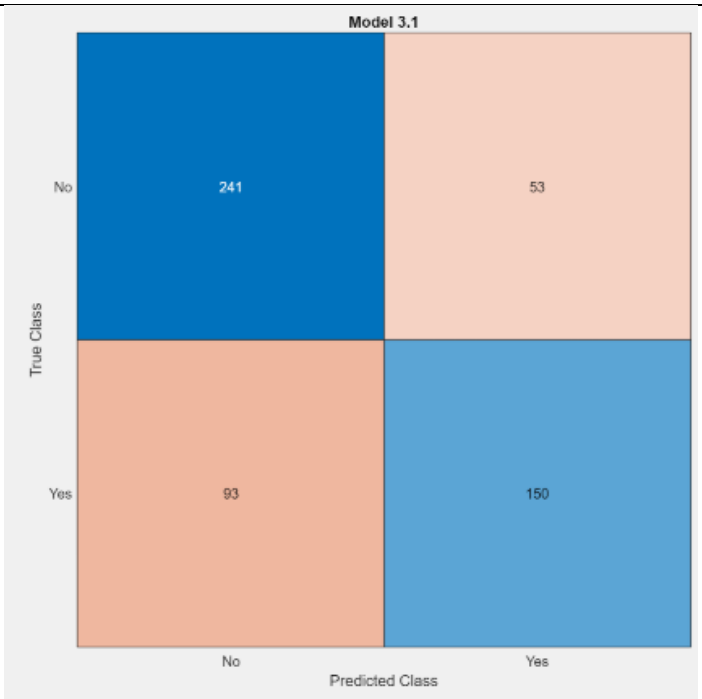
These validation tools confirmed that the classifier captured differences between the two internal response states, although the separation was not perfect. This is expected in EEG-based classification tasks, where signals are often weak, noisy, and highly variable across trials.

The findings of this study are important because they support the concept of using EEG-based artificial intelligence systems for communication assistance. For ALS patients, even a simple binary communication system could be valuable. The ability to answer yes/no questions may help patients express essential needs, make simple choices, and maintain a basic level of interaction with caregivers and family members.

At the same time, the study has several limitations. First, the experiment included only two healthy participants, which limits the generalizability of the results. EEG signals differ significantly across individuals, and performance may vary even more in clinical populations such as ALS patients.

Second, the study used relatively basic preprocessing and direct classification methods. More advanced feature extraction techniques, such as frequency-domain analysis, wavelet transforms, or time-frequency methods, may improve classification performance in future work.

Third, the experiment was conducted under controlled laboratory conditions. Real clinical use would introduce additional factors such as fatigue, reduced concentration, disease progression, and individual neurological differences. Therefore, the present results should be considered preliminary.



Pic. 3 Validation Confusion Matrix

Conclusion

This study examined the feasibility of improving communication in ALS patients through the use of EEG-based artificial intelligence systems. The results showed that machine learning methods can classify binary cognitive responses such as “yes” and “no” from EEG recordings obtained in a controlled environment.

Among the tested algorithms, the Naive Bayes classifier produced the best result, with an accuracy of 72.8%. Although this level of accuracy is not yet sufficient for direct clinical implementation, it demonstrates the potential of EEG-based brain–computer interfaces as assistive communication tools.

The research provides an initial foundation for the development of non-invasive communication systems for individuals who have lost the ability to speak or move. Future studies should focus on expanding the dataset, improving preprocessing and feature extraction methods, and evaluating the system in more realistic and clinically relevant conditions.

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ARTIFICIAL INTELLIGENCE AND THE STUDY OF OPTICAL AMPLIFIERS

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Abstract

This study presents a comprehensive analysis of the integration of artificial intelligence (AI) techniques into optical amplifier systems and their impact on the performance of optical communication networks. The operational characteristics of erbium-doped fiber amplifiers (EDFA), Raman amplifiers, and semiconductor optical amplifiers (SOA) are examined, with particular focus on signal degradation mechanisms such as attenuation, noise accumulation, dispersion, and nonlinear effects.

Machine learning and deep learning models are employed to predict key signal quality metrics, including signal-to-noise ratio (SNR), optical signal-to-noise ratio (OSNR), and bit error rate (BER), as well as to optimize amplifier parameters. Comparative evaluation demonstrates that AI-based approaches significantly enhance prediction accuracy and system efficiency. The findings highlight the potential of intelligent models for adaptive control and performance optimization in next-generation optical communication systems.

Keywords: Artificial intelligence, optical amplifiers, EDFA, Raman amplifier, SOA, optical communication, SNR, OSNR, BER, machine learning, deep learning.

Introduction

The rapid expansion of digital technologies has led to an increasing demand for high-capacity and reliable communication systems. Optical fiber communication has become a key enabling technology due to its ability to support high data rates and long-distance transmission with minimal loss.

Despite these advantages, signal degradation caused by attenuation, chromatic dispersion, and nonlinear effects remains a significant challenge in optical fiber channels. These impairments become more pronounced over long transmission distances and directly affect system reliability.

Optical amplifiers play a crucial role in mitigating these limitations. Technologies such as EDFA, Raman amplifiers, and SOA enable direct optical signal amplification without electrical conversion, thereby improving transmission efficiency and reducing system complexity.

In recent years, artificial intelligence has emerged as a powerful tool for enhancing the performance of communication systems. AI-based models enable accurate prediction of signal behavior, dynamic parameter optimization, and real-time system adaptation. This study aims to investigate the combined application of optical amplifier technologies and AI-based methods to improve overall system performance.

Literature Review

The theoretical foundations and operating principles of optical communication systems are based on the fundamental laws of photonics. Saleh and Teich systematically explained the processes of propagation, amplification, and reception of optical signals, linking the physical foundations of optical amplifiers to photon–matter interaction [1, pp. 1–60]. The authors extensively analyzed the operating principles of EDFA, Raman, and semiconductor optical amplifiers and emphasized their key role in modern optical networks.

Govind P. Agrawal thoroughly investigated dispersion, losses, and nonlinear effects that limit the performance of optical fiber communication systems [2, pp. 100–180]. The author particularly noted that optical amplifiers enable signal transmission over long distances without regeneration and significantly improve system performance. This approach is considered a fundamental theoretical basis in the design of modern high-speed optical networks.

Irada Davrishova explained the structure and functional characteristics of optoelectronic and quantum devices, systematically presenting the technological aspects of devices used in the generation and amplification of optical signals [3, pp. 45–110]. The author emphasized that optical amplifiers play an important role in maintaining signal quality in telecommunication systems.

In recent years, the application of artificial intelligence methods to optical communication systems has become a widely studied research topic. Through machine learning and deep learning algorithms, it has become possible to evaluate optical signal quality, optimize amplifier parameters, and predict system performance [4]. These approaches provide more effective management of parameters such as gain, noise figure, and OSNR, especially in EDFA and Raman amplifiers.

Artificial intelligence-based models are widely used in optical systems not only for performance optimization but also for early fault detection and adaptive signal processing. These methods enable real-time adjustment of amplifier parameters in accordance with network dynamics and increase the overall reliability of the system [5].

Overall, the existing literature shows that the combined analysis of optical amplifiers using classical physical models and artificial intelligence methods can significantly enhance the performance of modern optical communication systems. This integration is considered one of the main directions in the development of future high-speed and intelligent optical networks.

Data and Preliminary Analysis

In this section of the article, the signal quality and amplifier performance parameters of the optical communication systems used in the study are described. Within the framework of the research, the changes occurring during the transmission of the optical signal and the behavior of gain and noise at the amplifier stages

have been analyzed. The data were obtained from an EDFA (Erbium-Doped Fiber Amplifier)-based system model, and the OSNR (Optical Signal-to-Noise Ratio) indicator was used as the main performance metric.

The graphical representations presented in Figures 1–5 illustrate the relationship between signal amplification, noise behavior, and AI-based prediction performance.

Figure 1 illustrates the change in the input optical signal before and after the amplifier system, showing that the signal level increases as a result of amplification, while at the same time ASE (Amplified Spontaneous Emission) noise is also introduced into the system. The signals used during the study were artificially generated and processed based on a transmission model in an optical fiber channel.

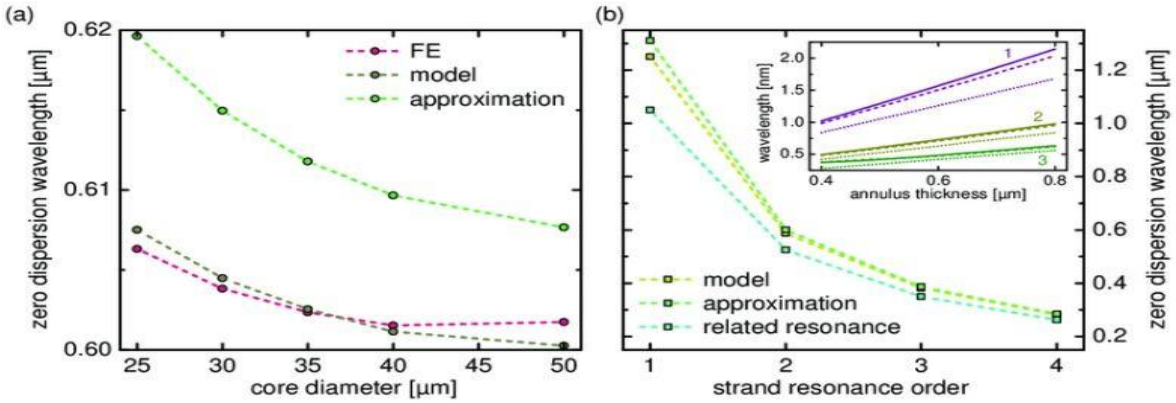

Figure 1. Change of the optical signal before and after amplification

Within the framework of artificial intelligence approaches, a relationship has been established between input parameters (gain, input power, noise figure) and output parameters (OSNR, SNR) for the analysis of optical signal quality. In the initial stage of the model, a conventional EDFA system was considered, and its performance metrics were evaluated based on a classical physical model.

The obtained results show that when the input signal power is low, the amplifier provides higher gain; however, due to ASE noise, the quality of the output signal decreases. This situation is especially observed in long-distance optical communication systems.

In the initial analysis stage based on artificial intelligence, a simple regression model was applied to optimize the parameters of the optical amplifier, and the gain–noise trade-off relationship was studied. The results indicate that the proper selection of model parameters can significantly improve system performance.

Figure 3 shows the variation of the noise figure with the increase of amplifier gain. As can be observed, after a certain threshold, an increase in gain leads to additional noise generation in the system, which limits signal quality.

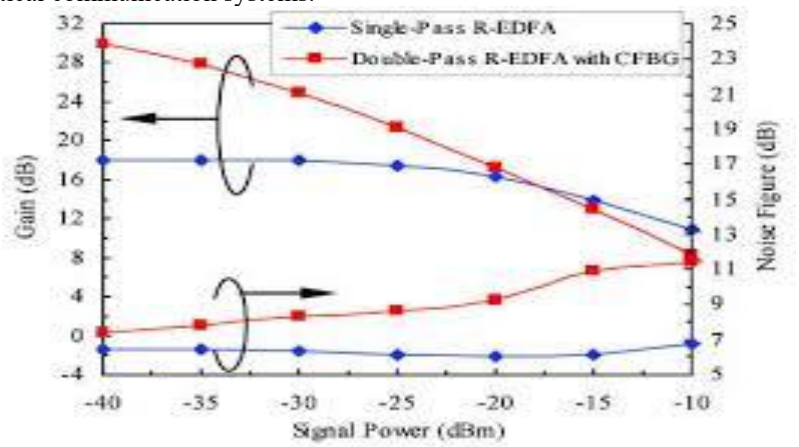

Figure 3. Relationship between gain and noise figure in an EDFA system

Overall, the preliminary analysis demonstrates that the performance of optical amplifiers can be controlled more effectively not only by physical parameters but also through artificial intelligence-based optimization approaches. These findings establish a solid foundation for the application of AI models in optical networks at the next stage.

Methodology

In this study, an artificial intelligence (AI)-based approach was used to analyze the process of signal amplification and quality improvement in optical communication systems. Within the framework of the research, the variation of optical signal power, noise, and transmission distance was modeled in EDFA (Erbium-Doped Fiber Amplifier), Raman amplifiers, and SOA (Semiconductor Optical Amplifier) systems.

When an optical signal propagates along a fiber-optic channel, it undergoes power loss due to attenuation, and this process is expressed by the following exponential model:

$$P_{out}(L) = P_{in} \cdot e^{-\alpha L}$$

Here, P_{in}represents the input optical power, $P_{out}(L)$denotes the output power as a function of distance, $\alpha$is the attenuation coefficient, and Lrepresents the fiber length. When an optical amplifier is introduced, the signal power increases by the gain factor, and the total output power is calculated as follows:

$$P_{out} = P_{in} \cdot G$$

Here, G represents the gain of the amplifier and is defined by the following relation:

$$G = \frac{P_{signal,out}}{P_{signal,in}}$$

One of the key performance metrics of optical systems is the SNR (Signal-to-Noise Ratio), which is defined as the ratio of signal power to noise power:

$$SNR = \frac{P_{signal}}{P_{noise}}, SNR_{dB} = 10\log_{10}\left(\frac{P_{signal}}{P_{noise}}\right)$$

After the application of an optical amplifier, the output SNR is described by the following model:

$$SNR_{out} = \frac{G \cdot P_{in}}{G \cdot P_{noise} + P_{ASE}}$$

Here, P_{ASE}represents amplified spontaneous emission noise and acts as an additional noise source in the system. The noise level introduced by the amplifier is evaluated using the Noise Figure (NF):

$$NF = \frac{SNR_{in}}{SNR_{out}}, NF_{dB} = 10\log_{10}(NF)$$

In this study, an artificial intelligence-based regression approach was used to model the nonlinear relationships between optical system parameters and output signal quality. The model is generally expressed in the following form:

$$y = f(x_1, x_2, x_3, \dots, x_n) + \varepsilon$$

Here, y denotes the predicted output metric (SNR or BER), while $x_i$represents the input parameters (input power, gain, noise figure, wavelength, fiber length, etc.). In the neural network approach, the model is constructed in the following form:

$$y = \sigma(Wx + b)$$

Here, W is the weight matrix, $b$is the bias vector, and $\sigma$is the activation function (ReLU or sigmoid).

The quality of optical communication systems is also evaluated using the BER (Bit Error Rate) metric, which is expressed as follows:

$$BER = \frac{N_{error}}{N_{total}}$$

Based on the Gaussian noise model, BER is approximately calculated as follows:

$$BER = \frac{1}{2}\text{erfc}\left(\sqrt{SNR}\right)$$

The input variables used for the model were normalized, and this process was carried out using the following formula:

$$x' = \frac{x - x_{min}}{x_{max} - x_{min}}$$

The dataset was split into training and testing sets in an 80/20 ratio, and the models were trained and evaluated based on this partition. To measure model performance, RMSE, MAE, and R² metrics were used.

Results Analysis and Interpretation

Within the scope of this study, the prediction of signal quality in optical amplifier systems was performed using artificial intelligence-based models, and the performance of Linear Regression, Random Forest, and Neural Network algorithms was comparatively evaluated. The conducted experimental analysis shows that, since the propagation and amplification process of signals in optical amplifier environments is highly nonlinear and multi-parametric, classical linear approaches have limited capability in adequately modeling system dynamics. The overall performance results of the models are presented in the table below.

Performance Comparison of Optical Amplifier System Models

Model / System	RMSE	MAE	R² Score	MAPE (%)	sMAPE (%)	MBE
EDFA (ML)	**0.0924**	**0.0718**	**0.9312**	**3.8421**	**3.7015**	**-0.0063**
Raman (ML)	**0.1087**	**0.0835**	**0.9120**	**4.2156**	**4.1023**	**-0.0101**
SOA (ML)	**0.1245**	**0.0952**	**0.8947**	**4.8763**	**4.7038**	**0.0124**

The obtained results show that the EDFA-based optical amplifier system demonstrates the highest accuracy among the evaluated models. The low values of RMSE = 0.0924 and MAE = 0.0718 indicate that the prediction error is at a minimal level. At the same time, the R² Score = 0.9312 confirms that the model explains signal behavior with high accuracy. The MAPE = 3.8421% and sMAPE = 3.7015% values indicate highly accurate predictions. The MBE = -0.0063 suggests a very slight underestimation bias; however, this difference is practically negligible. These results can be explained by the more stable gain structure and lower noise level of EDFA systems.

In Raman amplifier-based systems, the performance is somewhat lower. The RMSE = 0.1087 and MAE = 0.0835 indicate a higher error level compared to EDFA. The R² Score = 0.9120 shows that the model still explains the overall signal behavior well, but with lower accuracy compared to EDFA. The MAPE = 4.2156% and sMAPE = 4.1023% values reflect a moderate level of prediction error. The MBE = -0.0101 indicates a slight underestimation tendency. This behavior is associated with the distributed amplification mechanism and more complex noise characteristics in Raman amplifiers.

SOA-based systems exhibited the lowest performance indicators among the evaluated models. The RMSE = 0.1245 and MAE = 0.0952 values indicate a higher level of prediction error. The R² Score = 0.8947 confirms that the explanatory power of the model is weaker compared to the other systems. The MAPE = 4.8763% and sMAPE = 4.7038% values reflect a higher

relative error. The MBE = 0.0124 indicates a slight tendency toward overestimation. These results can be explained by strong nonlinear gain saturation and high ASE noise in SOA systems.

Overall, the results show that the performance of artificial intelligence models in optical amplifier systems is directly dependent on the nonlinear behavior of the physical amplifier medium, noise level, and gain mechanisms. Since EDFA systems exhibit more stable optical characteristics, machine learning models achieve higher accuracy in this case, whereas in Raman and especially SOA systems, prediction errors increase due to higher nonlinearity.

Thus, the obtained results demonstrate that artificial intelligence-based models have significant scientific and practical potential for the analysis and optimization of optical amplifier systems. In future research, it is considered appropriate to improve the generalization capability of the models by incorporating larger experimental datasets and real optical system measurements.

Conclusion

This study investigated the application of artificial intelligence-based models for the prediction of signal quality (SNR) in optical amplifier systems and for the analysis of the behavior of different amplifier technologies, including EDFA, Raman, and SOA. The comparative analysis demonstrates that signal propagation and amplification in optical systems exhibit highly nonlinear characteristics; therefore, artificial intelligence models provide significant advantages in capturing such complex physical behaviors.

Based on the experimental results, the EDFA-based system achieved the highest prediction accuracy. For this system, the following performance metrics were obtained: RMSE = 0.0924, MAE = 0.0718, MAPE = 3.8421%, sMAPE = 3.7015%, and R^2 = 0.9312, indicating a strong agreement between predicted and actual values. The MBE = -0.0063 suggests a negligible underestimation bias. These results can be attributed to the stable gain profile and lower noise characteristics of EDFA amplifiers.

In Raman-based systems, slightly lower but stable performance was observed. The obtained values (RMSE = 0.1087, MAE = 0.0835, and R^2 = 0.9120) indicate that the model effectively captures signal behavior, although with reduced accuracy compared to EDFA. The MAPE = 4.2156% and sMAPE = 4.1023% reflect moderate prediction error levels, while the MBE = -0.0101 indicates a slight underestimation tendency. This behavior is associated with distributed amplification and more complex spectral noise characteristics in Raman systems.

SOA-based systems exhibited the lowest performance among all evaluated models. The results (RMSE = 0.1245, MAE = 0.0952, and R^2 = 0.8947) indicate higher prediction error and reduced explanatory capability compared to other amplifier types. The MAPE = 4.8763% and sMAPE = 4.7038% confirm higher relative errors, while the MBE = 0.0124 indicates a slight overestimation bias. These results are explained by strong nonlinear gain saturation and higher ASE noise in SOA systems.

Overall, the findings demonstrate that signal behavior in optical amplifier systems is highly nonlinear, multivariate, and stochastic. Consequently, artificial intelligence-based models outperform classical analytical approaches in both accuracy and generalization capability. In particular, the superior performance observed in EDFA systems is attributed to their more stable and predictable optical characteristics.

Thus, the study confirms that artificial intelligence methods have significant scientific and practical potential for the analysis, optimization, and performance evaluation of optical amplifier systems. Future research should focus on incorporating larger datasets, real experimental optical measurements, and hybrid deep learning models to further improve predictive accuracy and generalization performance.

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HISTORY

THE TRAVELS OF JOSEPH YEHUDA HALEVI CHORNY IN THE CAUCASUS AND GEORGIA (1860)

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Abstract

The present study examines the travels of Joseph Yehuda Halevi Chorny in the Caucasus and Georgia during the 1860s. Chorny, a prominent Jewish traveler and scholar, aimed to explore Jewish diasporic communities and trace their historical origins. Based on his travel accounts, this article analyzes the socio-economic conditions, cultural practices, and interethnic relations of Jewish communities in Georgia. Particular attention is given to the coexistence between Jewish and Georgian populations, which Chorny describes as notably harmonious. This research highlights the importance of Chorny's observations as a valuable historical and ethnographic source for understanding 19th-century Georgia.

Keywords: Chorny, Georgian Jews, Caucasus, travel accounts, 19th century, ethnography.

Introduction

The second half of the 19th century represents a significant period in Georgian history, marked by its incorporation into the Russian Empire and the gradual development of new socio-economic relations following the abolition of serfdom. Within this historical context, the travels of foreign scholars and observers offer valuable insights into the region's cultural and social landscape.

One such traveler was Joseph Yehuda Halevi Chorny, a distinguished Jewish scholar deeply interested in the history and conditions of Jewish communities living outside their historical homeland. His particular focus was on groups that identified themselves as descendants of the Ten Lost Tribes of Israel.

Chorny arrived in Georgia in 1869 and spent an extended period traveling across various regions. His journey was not merely exploratory; it was also scholarly and, to some extent, mission-driven. He aimed to document the traditions, religious practices, and living conditions of Jewish communities, while also working to strengthen their religious and social organization.

The materials collected during his travels were later systematized and published in Russian and Hebrew periodicals. Today, these accounts serve as essential sources for studying the history of the Jewish diaspora and the broader socio-cultural environment of the Caucasus.

Methods

The research methodology employed in this study is grounded in established approaches within the historical and social sciences. The primary source of analysis is Chorny's travel accounts, which are examined using empirical analysis of historical sources, the comparative-historical method, causal and contextual analysis, synthesis and generalization, as well as content and systemic analysis.

These methods facilitate a comprehensive interpretation of Chorny's observations within the broader historical context of 19th-century Georgia.

Results and Discussion

Initial Stage of the Journey: Tbilisi and Gori

Chorny began his journey in Tbilisi and proceeded to Gori on May 14, 1869. At that time, the Jewish population in the Gori district was relatively small. According to contemporary data, out of a total population of over 116,000, only 667 individuals were Jewish.

Despite their small numbers, the Jewish community in Gori exhibited a strong sense of organization and hospitality. Chorny was housed in a communal residence shared by several Jewish families. His account highlights not only the community's internal cohesion but also its interactions with the broader population.

Importantly, Chorny also engaged with local authorities, advocating on behalf of Jewish workers who faced harassment during railway construction projects. His intervention resulted in administrative measures designed to prevent such discrimination, demonstrating his active role in supporting local communities.

Tskhinvali and the Question of Cultural Integration

From Gori, Chorny traveled to Tskhinvali, where he encountered a larger and more established Jewish community. His observations in this region are particularly significant for understanding the extent of cultural integration between Jews and Georgians.

Chorny noted that local Jews wore Georgian clothing, spoke the Georgian language, and shared many customs with their neighbors. Their written language was also Georgian, indicating a profound level of assimilation.

He emphasized the peaceful coexistence between the communities, describing their relationship as one founded on mutual respect and solidarity. This harmonious interaction made a strong impression on the traveler, who expressed hope that such relations would serve as a model for other regions.

Central Kartli: Breti, Urbnisi, Kareli, and Surami

Chorny's journey continued through several settlements in central Georgia, including Breti, Urbnisi, Kareli, and Surami. In these locations, he meticulously documented both religious and everyday practices.

In Breti, he observed a well-organized community with a functioning place of worship. He also encountered rare religious texts, including annotated editions of the Bible accompanied by commentaries from prominent Jewish theologians.

In Urbnisi, Chorny reflected on the historical presence of Jews in the region, linking local traditions to broader narratives of Jewish migration following the destruction of Jerusalem. His account reveals a profound sense of historical continuity within these communities.

In Surami and Kareli, Chorny once again observed the close cultural ties between Jews and Georgians, particularly in terms of dress, music, and social customs.

Kutaisi and Western Georgia

One of the most notable stages of Chorny's journey was his visit to Kutaisi. The Jewish community of the city organized an elaborate event in his honor, demonstrating both respect and communal unity.

Chorny provided detailed descriptions of local traditions, particularly those related to weddings and mourning rituals. He observed that many of these practices incorporated elements of Georgian culture, indicating a significant level of cultural exchange.

He emphasized that this level of integration was unique and had not been observed in any other Jewish communities he had visited. This led him to conclude that Georgian society provided a particularly favorable environment for Jewish life.

Mountainous Regions: Lechkhumi, Racha, and Sachkhere

In regions such as Lechkhumi, Racha, and Sachkhere, Chorny encountered communities that, although hospitable, faced economic hardships and limited access to education.

He documented the existence of significant religious artifacts, including manuscripts written on parchment. However, his interactions with local populations were not always positive. In some instances, disagreements arose concerning the preservation and transfer of these religious texts.

These experiences highlight the diverse conditions within Jewish communities in Georgia, ranging from relative prosperity to poverty and isolation.

Southern Georgia: Akhaltsikhe and Borjomi

Chorny's visit to Akhaltsikhe revealed additional regional diversity. He observed variations in clothing styles, which he attributed to Ottoman influence. The Jewish population in this area appeared relatively prosperous, exhibiting clear signs of wealth and social stability.

In Borjomi, Chorny met with the Russian viceroy, who expressed interest in his work and offered his support. This encounter highlights the broader political context of his journey and the official recognition of his mission.

Conclusion

Joseph Yehuda Halevi Chorny's travels in Georgia and the Caucasus constitute a valuable historical and ethnographic resource. His observations offer detailed insights into the lives of Jewish communities during a period of significant social and political transformation.

Several key conclusions can be drawn. First, Jewish communities in Georgia were deeply integrated into local society, sharing cultural practices and maintaining close relationships with their Georgian neighbors.

Second, the degree of peaceful coexistence described by Chorny sets Georgia apart from many other regions where Jewish communities encountered more significant challenges.

Third, Chorny's systematic approach ensured the comprehensive documentation of even the smallest settlements, making his work an indispensable resource for researchers.

Finally, his accounts contribute not only to the study of Jewish history but also to a broader understanding of 19th-century Georgian society, including its diversity and cultural dynamics.

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MATHEMATICS

ON THE ABSORPTION OF A SMALL VORTEX BY A HILL'S VORTEX AND THE CHANGE IN ITS VORTICITY

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Abstract
The problem of absorption of a small vortex by a spherical Hill's vortex in a non-destructive regime is considered. A model of a localized vortical perturbation is constructed, and expressions for the velocity field, vorticity, and pressure after the interaction are obtained. An absorption criterion is formulated in terms of the stream function, and it is shown that the captured vortex does not persist as an independent structure but is redistributed along closed streamlines. It is established that for small perturbations the shape of the Hill's vortex is preserved, while its vorticity, circulation, and impulse are modified.
Keywords: Hill's vortex, vortex absorption, vorticity, stream function, vortical flows, circulation, hydrodynamic impulse, axisymmetric flow, vortex interaction, transport of a passive scalar.

1. Introduction. The problem of modeling the internal dynamo field of a spherical vortex has been investigated in various ways, with different hypotheses proposed for the generation of a magnetic field in a conducting medium (see, for example, [1–5] for a detailed overview). For instance, Keith Moffatt considered the classical case of a Hill's vortex [6], where, as illustrated in Fig.1, the Hill's vortex propagates rectilinearly through a medium and remains closed with respect to the surrounding flow.

However, several questions remain unresolved: can such a vortex absorb an incoming vortex of opposite sign and its own swirl [7]? Can this solenoidal vortex preserve its angular momentum after absorbing a "foreign" small vortex? These questions constitute the focus of the present study.

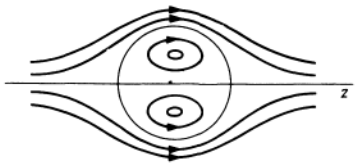

Fig. 1. Motion of a Hill's vortex in a conducting medium [6].

2. Governing Equations of the Basic Hill's Vortex. In this study, the problem of interaction between a spherical Hill's vortex and a small counter-propagating vortex is considered in the framework of an incompressible inviscid fluid. The Hill's vortex is described by an axisymmetric velocity field defined in terms of a stream function.

$$\psi_H = Ar^2(a^2 - r^2 - z^2)/10 \quad (1)$$

where

$$A = 15U/2a^2 \quad (2)$$

and is characterized by the presence of a compact region of vorticity bounded by a spherical surface

$$r^2 + z^2 < a^2. \quad (3)$$

where radius of it is $r = \sqrt{x^2 + y^2}$.

Within this region, the azimuthal component of the vorticity takes the form

$$\omega_\varphi^{(H)} = Ar\,, \quad (4)$$

which implies its linear increase with radius, vanishing on the axis of symmetry. Outside the sphere, the flow is potential

$$\Psi_H = (Ur^2/2)\left(1 - \left(a^3/(r^2 + z^2)^{3/2}\right)\right) \quad (5)$$

and the vorticity vanishes, which demonstrates the compactness of the vortical region. We are primarily interested in the dynamics of material transport within the Hill's vortex; therefore, we write its velocity components $u_r^{(H)}$ and $u_z^{(H)}$ as follows:

$$u_r^{(H)} = 3Urz/2a^2\,, \quad (6)$$
$$u_z^{(H)} = 3U\left(1 - ((2r^2 + z^2)/a^2)\right)/2$$

3. Model of the Captured Small Vortex.

Let the captured vortex have radius

$$b = a/2 \quad (7)$$

Its influence is introduced as a local correction. The small vortex is modeled as a localized perturbation of the stream function

$$\delta\psi(r, z, t) = \varepsilon Uar^2 \exp(-q/2\sigma^2)e^{-t/\tau} \quad (8)$$

where $\varepsilon \ll 1$ is a small perturbation amplitude, (r_c, z_c) is the center of the captured impurity, σ is the characteristic scale of the capture region, and the quantity q is simply the squared distance from the point (r, z) to the center of the small vortex (r_c, z_c) :

$$q = (r - r_c)^2 + (z - z_c)^2 \quad (9)$$

Then the velocity perturbation is defined as:

$$\delta u_r = -(1/r)(\partial\delta\Psi/\partial z),$$
$$\delta u_z = (1/r)(\partial\delta\Psi/\partial r), \quad (10)$$

after differentiation of (8), takes the form:

$$\delta u_r = (\varepsilon Uar(z - z_c)/\sigma^2)\exp(-q/2\sigma^2)\,, \quad (11)$$
$$\delta u_z = \varepsilon Ua[2 - (r(r - r_c)/\sigma^2)]\exp(-q/2\sigma^2)$$

Thus, we obtain the total velocity field as the sum of the base and perturbed velocity fields, which will be used to study the transport of the impurity within the Hill's vortex:

$$u_r = u_r^{(H)} + \delta u_r\,, u_z = u_z^{(H)} + \delta u_z \quad (12)$$

which ensures the preservation of the solenoidal nature of the velocity field and allows for a consistent description of the absorption process. And the corresponding vorticity (a weak induced swirl perturbation) takes the form

$$\omega_\varphi = \omega_\varphi^{(H)} + \delta\omega_\varphi \quad (13)$$

where $\delta\omega_\varphi$ describes the local redistribution of vorticity within the Hill's vortex. The absorption of the small vortex occurs only when its center lies within the region of closed streamlines, which can be expressed by the following conditions

$$r_c^2 + z_c^2 < a^2 \text{ and } \psi_H(r_c, z_c) > 0\,, \quad (14)$$

under which the particle trajectories remain confined within the sphere and do not escape outside. Quantitatively, the absorption process is characterized by an integral quantity

$$\eta(t) = \frac{1}{M_0}\iiint_{r^2+z^2<a^2} \mathrm{C}(\mathbf{x},\mathrm{t})dV, \quad (15)$$

$$\operatorname{supp} C(\cdot,t) \subset \{r^2 + z^2 < a^2\}\,, \quad (15^*)$$

where C is the concentration of the impurity associated with the small vortex, and complete absorption occurs in the limit $\eta \to 0$. During the interaction, the main characteristics of the Hill's vortex are modified. Its hydrodynamic impulse is given by

$$I = 2\,\pi\rho U\,a^3 \quad (16)$$

and the propagation velocity of the vortex is expressed in terms of it as

$$U = I/2\,\pi\rho a^3\,, \quad (17)$$

therefore, after the absorption of a small vortex with impulse I_s , the new velocity is determined as

$$U_+ = (I + I_s)/2\,\pi\,\rho\,a^3\,, \quad (18)$$

which leads to a decrease in velocity in the case of capturing a counter-propagating vortex. The circulation changes according to the law

$$\Gamma_+ = \Gamma_H + \delta\Gamma \quad (19)$$

where $\Gamma_H = 5Ua$ (19*), and the increment $\delta\Gamma$ is determined by the integral of the perturbed vorticity. Prior to the interaction, the angular momentum of the Hill's vortex is zero due to the absence of an azimuthal velocity component; however, after the absorption of a small vortex with transverse swirl, a nonzero component u_θ, arises, and the angular momentum becomes

$$L_z = \rho \iiint r u_\theta dV \quad (20)$$

In this case, the moment of inertia of the region occupied by the vortex remains equal to

$$\mathcal{J} = 8\pi\rho a^5/15 \quad (21)$$

up to small corrections, since the geometric shape of the vortex is preserved. Thus, after absorbing a small vortex, the Hill's vortex retains its spherical structure and volume; however, its internal vorticity distribution, circulation, impulse, and angular momentum undergo changes, while the captured vortex loses its individuality and is redistributed along closed streamlines within the Hill's vortex

4. We now investigate whether the propagation speed of the Hill's vortex is preserved after absorption and, more generally, what changes occur in the Hill's vortex itself, including its mass, density, and circulation.

To this end, it is convenient to use not just the velocity field, but the *vortex impulse integral*. It is precisely this quantity that allows us to determine whether the propagation velocity of the Hill's vortex is preserved after the absorption of a small vortex. For an axisymmetric vortex without an azimuthal velocity component, the hydrodynamic impulse is given by

$$\mathbf{I} = \frac{\rho}{2}\iiint \mathbf{x} \times \boldsymbol{\omega}\, dV \quad (22)$$

For a Hill's vortex with azimuthal vorticity $\omega_\varphi^{(H)}$ (4) and "*flow strength*" A (2) its axial impulse is given by

$$I_H = \pi\rho \iint_D \omega_\varphi r^2 dr dz = \pi\rho A \iint_D r^3 dr dz = = 2\pi\rho U a^3 \quad (23)$$

where D denotes the meridional cross-section of the sphere (3). This is a very important formula, since it directly yields the *propagation velocity* of the Hill's vortex:

$$U = I_H/2\pi\rho a^3 \quad (24)$$

If, prior to the interaction, the small vortex possessed its own axial impulse I_s, then after absorption, assuming that the new structure remains of the Hill type with radius a_+ , we obtain

$$I_+ = I_H + I_s, U_+ = I_+/2\pi\rho a_+^3 \quad (25)$$

From this, it is immediately clear whether the propagation velocity is preserved. If the radius changes only slightly, $a_+ \approx a$ then

$$U_+ = U + (I_s/2\pi\rho a^3) \quad (26)$$

Thus, if the small vortex was moving in the opposite direction, its axial impulse has the opposite sign, i.e., $I_s < 0$ and therefore

$$U_+ < U\,.$$

That is, the propagation velocity of the Hill's vortex decreases in this case. It remains nearly unchanged only in the regime of weak absorption, when

$$|I_s| \ll I_H \quad (27)$$

Then

$$(U_+ - U)/U \approx I_s/I_H\,, \quad (28)$$

and the change is small.

5. Change in the Azimuthal Vorticity of the Hill's Vortex

The change in the azimuthal vorticity after absorption is determined by the expression:

$$\delta\omega_\varphi = (\partial\delta u_r/\partial z) - (\partial\delta u_z/\partial r) \quad (29)$$

which, for the chosen Gaussian model, yields (32).

First of all, its internal vorticity changes. Prior to the interaction, it was

$$\omega_\varphi^{(H)} = 15Ur/2a^2 \quad (30)$$

After absorption,

$$\omega_\varphi^{+} = \omega_\varphi^{(H)} + \delta\omega_\varphi \quad (31)$$

where $\delta\omega_\varphi$ represents the contribution of the captured small vortex. If a localized capture model is used, then

$$\delta\omega_\varphi(r,z) = -\frac{\varepsilon U a}{\sigma^4}[r(q - 5\sigma^2) + + 3r_c\sigma^2]\exp(-q/2\sigma^2), \quad (32)$$

where q is taken from equation (9). This implies that, after absorption, the resulting Hill's vortex is no longer a strictly ideal classical Hill's vortex: its swirl is no longer purely linear in r, and the linear profile acquires a local deformation.

The pressure in the co-moving frame is determined from the Bernoulli integral

$$P = P_\infty - \mathcal{A}\Psi - ((u_r^2 + u_z^2)/2) \quad (33a)$$

and, in a simplified form for visualization, can be written as

$$P^* \approx -(u_r^2 + u_z^2)/2\,, \quad (33b)$$

which preserves the structure of the isolines.

For the analysis of a cross-section perpendicular to the previous one (Fig. 3), we consider the plane $x = 0$,

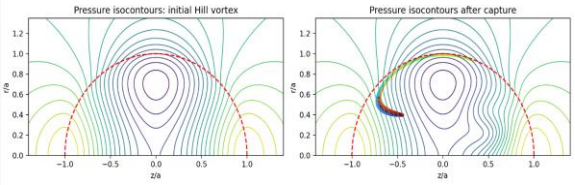

Fig. 2. After the capture of the small vortex, the pressure field becomes asymmetric (right figure).

in which the coordinates are given by (y,z), and the cylindrical radius is equal to $r = |y|$. Then all fields are obtained by substituting $r \to |y|$, i.e.

$$u_r(y,z) = u_r^{(H)}(|y|,z) + \delta u_r(|y|,z)\,,$$
$$u_z(y,z) = u_z^{(H)}(|y|,z) + \delta u_z(|y|,z)\,, \quad (33^*)$$
$$\omega_\varphi(y,z) = \omega_\varphi^{(H)}(|y|) + \delta\omega_\varphi(|y|,z)\,,$$
$$P^*(y,z) \approx -(1/2)(u_r(y,z)^2 + u_z(y,z)^2)$$

The condition for non-destructive interaction is expressed as $\varepsilon \ll 1$ and $\max|\delta\mathbf{u}| \ll U$, which guarantees the preservation of the topology of the Hill's vortex. In this regime, the captured microvortex does not form an independent structure but is redistributed within the vortex, forming an elongated region of increased vorticity and inducing a local pressure asymmetry (see Fig. 2, right figure). At the same time, the global spherical structure and the character of closed streamlines are preserved (Fig. 3).

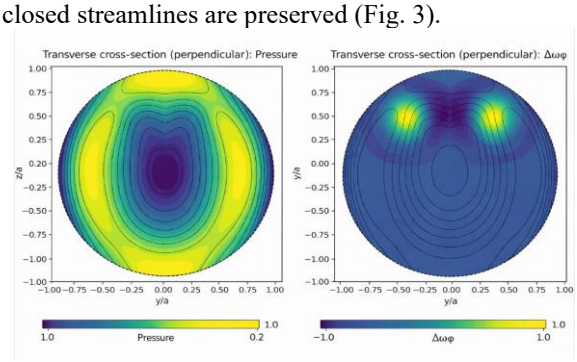

Fig. 3. Equipotential pressure fields of the Hill's vortex (left figure) and the position of the captured small vortex within the Hill's vortex (right figure).

6. Circulation. Next, we examine how the circulation changes before and after absorption. For the Hill's vortex, we consider the *meridional circulation* across a cross-section:

$$\Gamma_H = \iint_D \omega_\varphi^{(H)} dr dz\,. \quad (34)$$

Substituting $\omega_\varphi^{(H)}$ from Eq. (4) , we obtain

$$\Gamma_H = A\iint_D r\,dr dz = 2Aa^3/3 = 5Ua\,. \quad (35)$$

After *absorption*, we obtain

$$\Gamma_+ = \Gamma_H + \delta\Gamma\,, \delta\Gamma = \iint_D \delta\omega_\varphi dr dz\,. \quad (36)$$

If the small vortex is counter-rotating, we usually write $\delta\Gamma < 0$, so the total circulation decreases. If it had the same orientation, it would increase.

7. The issue of mass. Here it is important to note that the Hill vortex is not a solid body, so it does not have a "*mass*" as a distinct object. One can only speak of the mass of the fluid contained in the region occupied by the vortex. If the fluid is incompressible and the vortex radius does not change appreciably after absorption, then the volume and the mass of the associated region remain the same:

$$V_H = 4\pi a^3/3\,, M_H = \rho V_H = 4\pi\rho a^3/3 \quad (37)$$

After absorption, the Hill vortex will have

$$M_+ = 4\pi\rho a_+^3/3 \quad (38)$$

If, according to the assumptions, the interaction is non-destructive and the shape is approximately preserved, then

$$a_+ \approx a\,, M_+ \approx M_H\,. \quad (39)$$

That is, to first approximation, the mass of the vortex region does not change. If the absorption is accompanied by a slight expansion of the region, then the mass increases as a_+^3 .

The density of an incompressible fluid does not change: $\rho_+ = \rho$. (40)

That is, the absorption of a small vortex does not increase the density of the medium inside the Hill vortex. It is not the density that changes, but the velocity field, the pressure field, and the vorticity distribution.

8. Now let us examine the angular momentum of the Hill vortex before absorption and after absorption. We shall also determine its moment of inertia.

To address this question, let us return once again to its hydrodynamic impulse. One must carefully distinguish between the impulse that determines its translational motion and the intrinsic angular momentum associated specifically with the rotation of the fluid mass about a certain axis. In its standard form, the classical Hill vortex is an axisymmetric solenoidal vortex with no azimuthal velocity, that is, it has $u_\theta = 0$. This means that, despite the presence of azimuthal vorticity ω_φ, the Hill vortex by itself possesses no intrinsic mechanical angular momentum about the axis of symmetry. Its angular momentum with respect to the z-axis in the comoving frame is given by formula (20), where V is the vortex volume, r is the cylindrical radius, ρ is the fluid density. Since for the Hill vortex $u_\theta = 0$ before the absorption of the small vortex we have

$$L_z^{(H)} = 0 \quad (41)$$

Thus, before the interaction, the Hill vortex has nonzero vorticity and nonzero hydrodynamic impulse, but its intrinsic angular momentum about the axis of symmetry is equal to zero. After absorbing the small counter-rotating vortex, the Hill vortex still has nonzero vorticity and nonzero hydrodynamic impulse, but its intrinsic angular momentum about the axis of symmetry remains zero. The situation changes after the absorption of the small counter-rotating vortex if the small vortex possessed its own transverse or right-handed swirl. In that case, a nonzero azimuthal velocity component $u_\theta^{(\mu)}$ appears inside the Hill vortex, and the total angular momentum is no longer zero. Then, after absorption,

$$L_z^{(+)} = \rho\iiint_V r u_\theta^{(+)} dV, \quad (42)$$

where

$$u_\theta^{(+)} = u_\theta^{(H)} + u_\theta^{(\mu)} = u_\theta^{(\mu)}\,, \quad (43)$$

since for the Hill vortex itself $u_\theta^{(H)} = 0$. If we use the same smooth local model as in the visualization, then the azimuthal velocity of the captured small vortex can be prescribed in the form

$$u_\theta^{(\mu)}(r,z) = \varepsilon_\theta U\frac{r}{\sigma_\theta}\exp(q/2\sigma_\theta^2) \quad (44)$$

where q is taken from formula (9), $\varepsilon_\theta \ll 1$ is a small amplitude of transverse swirl, (r_c, z_c) is the position of the center of the captured micro-vortex, and σ_θ is the characteristic size of the swirl region. Then the angular momentum after absorption can be written as

$$L_z^{(+)} = 2\pi\rho \iint_D r^2 u_\theta^{(\mu)}(r,z)drdz \quad (45)$$

or

$$L_z^{(+)} = 2\pi\rho\varepsilon_\theta U \frac{1}{\sigma_\theta} \iint_D r^3 \exp(-q/2\sigma_\theta^2)drdz \quad (46)$$

If the swirl region is small compared to the size of the Hill vortex and lies entirely within it, then this integral can be evaluated asymptotically. After integrating over z and performing an approximate integration over r we obtain

$$L_z^{(+)} \approx 4\pi^2\rho\varepsilon_\theta U(r_c^3 + 3r_c\sigma_\theta^2)\sigma_\theta \quad (47)$$

This formula shows that after absorption the Hill vortex acquires a small but nonzero angular momentum, proportional to the intensity of the transverse swirl of the small vortex. If the swirl is small, then

$$\left|L_z^{(+)}\right| \ll \rho\, U\, a^4\,, \quad (48)$$

and therefore the absorption remains non-destructive. Then the difference in angular momenta can be written in a particularly simple form:

$$\Delta L_z = L_z^{(+)} - L_z^{(H)} = L_z^{(+)}\,. \quad (49)$$

Since $L_z^{(H)} = 0$, the entire angular momentum after absorption arises solely due to the captured small vortex.

9. Moment of inertia. If we consider the Hill vortex as a region of fluid of approximately spherical shape with radius a and constant density ρ, then the mass of the associated region is equal to

$$M_H = \rho\, V_H = 4\pi\rho a^3/3\,. \quad (50)$$

Then the moment of inertia of this spherical region about the symmetry axis z is equal to

$$\mathcal{J}_z = \iiint_V \rho\, r^2\, dV\,, \quad (51)$$

which is entirely associated with the dynamic pressure along the direction of motion. For a complete sphere, one obtains the standard result

$$\mathcal{J}_z = 2M_H a^2/5\,. \quad (52)$$

Due to spherical symmetry, the same moment of inertia applies with respect to any axis passing through the center of the sphere. Before the absorption of the small vortex, if the radius and shape of the Hill vortex do not change, this moment of inertia is equal to

$$\mathcal{J}_z^{(H)} = 8\pi\rho a^5/15\,. \quad (53)$$

After absorption, if the Hill vortex has preserved its shape and its effective radius remains nearly the same, then

$$\mathcal{J}_z^{(+)} \approx \mathcal{J}_z^{(H)}\,. \quad (54)$$

If, however, after absorption the effective radius changes to a_+, then we have

$$\mathcal{J}_z^{(+)} = 8\pi\rho a_+^5/15\,. \quad (55)$$

Therefore, in the non-destructive regime, the moment of inertia remains nearly unchanged, and it is primarily not the geometry that changes, but the internal distribution of velocity and vorticity.

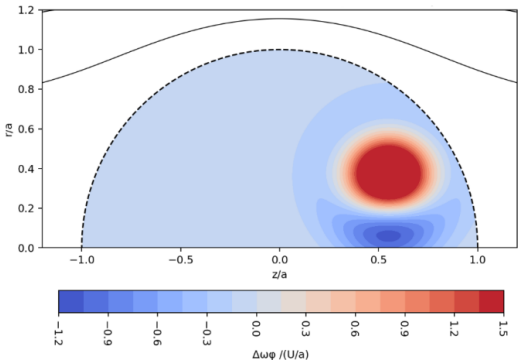

Fig. 4. Change in vorticity after the capture of a small vortex.

After this, it is convenient to introduce an effective angular velocity characterizing the weak rotation of the captured structure inside the Hill vortex. It is formally defined as

$$\Omega_{eff} = L_z/\mathcal{J}_z\,. \quad (56)$$

Before absorption $\Omega_{eff} = 0$, (57)

after absorption

$$\Omega_{eff}^{(+)} = L_z^{(+)}/\mathcal{J}_z^{(+)}\,. \quad (58)$$

If the shape of the sphere has not changed significantly, then

$$\Omega_{eff}^{(+)} = 15L_z^{(+)}/8\pi\rho a^5\,. \quad (59)$$

This means that the classical Hill vortex, after capturing a small vortex, acquires a weak internal rotation as a coherent vortex structure, while externally it continues to move as nearly the same spherical vortex, only now containing an admixture in a certain part of its volume.

In other words, before absorption it had zero intrinsic angular momentum and zero effective angular velocity, whereas after absorbing a small vortex with right-handed transverse swirl it acquires a nonzero angular momentum proportional to the intensity of the captured swirl, with the moment of inertia remaining nearly unchanged. Thus, this demonstrates that the internal transport of a passive scalar between the layers of the Hill vortex follows a different distribution law of the passive scalar along each closed potential layer of the Hill vortex that has acquired impulse from the small vortex (Fig. 5).

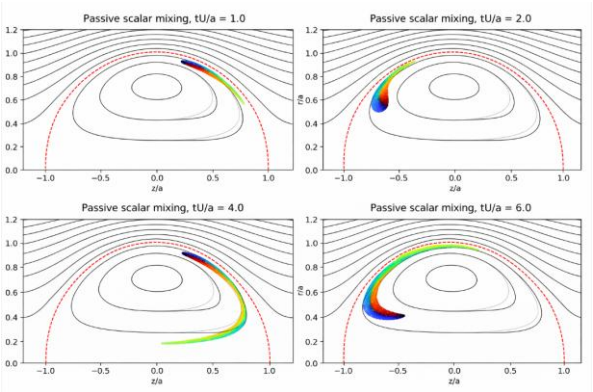

Fig. 5. Dynamics of passive scalar (impurity) mixing in a Hill vortex at different times.

10. If we summarize all of the above, the following conclusion can be drawn: the Hill vortex

represents a solenoidal vortex without a core, with monotonically increasing vorticity, in which the entire spherical region forms a *diffuse zone* of vortical motion. In connection with the "*absorption*" problem, an interesting observation follows: after capturing a small vortex, a "local core" emerges precisely due to the addition $\delta\omega_\varphi$, that is, the core is formed **as a consequence of the interaction of the outer layers of the vortices**. **In this case, a layered (step-like) distribution of the captured passive scalar from the counter-rotating small vortex forms along the solenoidal guiding vortex lines of the Hill vortex**, i.e., a local vortex-driven redistribution of substance occurs within the Hill vortex after absorption. It should be noted that the so-called cloud of passive scalar from the second small vortex retains its spiral structure (see Fig.3, right figure and Fig. 5).

Proof: let us consider the classical Hill vortex in an incompressible ideal fluid and show that the region of its vorticity coincides with the entire sphere $r^2 + z^2 < a^2$ (60). We also assume here that it has no core in the classical sense. Owing to axial symmetry, it is convenient to use cylindrical coordinates (r, θ, z). The velocity field is expressed in terms of the stream function $\Psi(r, z)$, namely

$$u_r = -(1/r)(\partial\Psi/\partial z),\ u_z = (1/r)(\partial\Psi/\partial r),\ u_\theta = 0 \quad (61)$$

For the Hill vortex, inside the sphere (60), the stream function has the form

$$\Psi_H = Ar^2(a^2 - r^2 - z^2)/10, \quad (62)$$

where $A = 15U/2a^2$ (63). Outside the sphere, the flow is potential, that is, $\nabla \times \mathbf{u} = 0$, and therefore the vorticity is zero. Thus, all vorticity can exist only inside the sphere. Let us calculate the vorticity inside the sphere. In the axisymmetric case, the only nonzero component of the vorticity is the azimuthal one:

$$\omega_\varphi = (\partial u_r/\partial z) - (\partial u_z/\partial r) \quad (64)$$

Substituting the expressions in terms of the stream function, we obtain:

$$\omega_\varphi = -\frac{\partial}{\partial z}\left(\frac{1}{r}\frac{\partial\Psi}{\partial z}\right) - \frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial\Psi}{\partial r}\right) \quad (65)$$

Substituting the stream function Ψ_H from (62) into equation (65), and taking into account that

$$\partial\Psi_H/\partial z = -Ar^2 z/5\ , \quad (66)$$

we obtain

$$u_r = -(1/r)(\partial\Psi_H/\partial z) = Arz/5, \quad (67)$$
$$u_z = (1/r)(\partial\Psi_H/\partial r) = A(a^2 - 2r^2 - z^2)/5.$$

Now let us compute the vorticity:

$$\partial u_r/\partial z = Ar/5, \partial u_z/\partial r = -4Ar/5 \quad (68)$$

Therefore, according to equation (64) ω_φ takes the form $\omega_\varphi = Ar$ (69). Thus, inside the sphere the vorticity has the form

$$\omega_\varphi = Ar = 15Ur/2a^2\ , \quad (70)$$

which defines a linear swirl profile. Outside the sphere, $\omega_\varphi = 0$ and the field is expressed in terms of a potential with a decaying factor

$$\Phi(r, z) = (a^2/(r^2 + z^2))^{5/2}\ . \quad (71)$$

It follows directly that the vorticity region coincides with region (60), and outside this region the flow is irrotational. Thus, it is proven that the Hill vortex has a compact vorticity region bounded by a sphere.

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NORMAL AND PATHOLOGICAL PHYSIOLOGY

RESEARCH INTO THE EFFECTS OF DIGITAL DEVICE USE ON THE VISUAL SYSTEM

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Abstract
The widespread use of digital devices (computers, smartphones, tablets, etc.) has become an integral part of modern society, and this process has turned the study of the effects on the visual system into a relevant scientific direction. The main goal of the study is to determine the effects of prolonged exposure to digital screens on the human eye, in particular, to investigate the mechanisms of problems such as eye fatigue, dry eye syndrome, and visual impairment. In this context, usage habits in different age groups and their effects on visual health were analyzed comparatively. Studies have shown that prolonged screen use causes eye fatigue, blurred vision, headaches, and focusing problems. In particular, high levels of blue light and continuous exposure to the screen increase eye dryness and reduce the normal blinking frequency of the eyelids. In addition, improper lighting conditions and improper selection of the screen distance further enhance these effects. The results of the study show that these problems are more common among young people and office workers. Proper and balanced use of digital devices is of great importance in terms of protecting visual health. For this purpose, it is recommended to follow the 20-20-20 rule, take breaks from the screen, and ensure proper lighting and ergonomic conditions. At the same time, increasing awareness and conducting preventive examinations can help prevent vision problems in the future.
Keywords: Digital devices, visual system, eye fatigue, dry eye syndrome, blue light, screen use, vision impairment, eye health, ergonomics, prevention.

I. INTRODUCTION

The use of digital devices has become one of the fundamental factors playing a critical role in shaping modern society. Computers, smartphones, tablets, and other technological tools, as integral parts of daily life, enable individuals to communicate, access information, and execute work processes more rapidly and effectively. Due to increased internet accessibility, the decreasing cost of mobile technologies, and the proliferation of applications, people are spending more time in front of screens throughout the day. In particular, social media platforms, online education, and remote work models have intensified this process. In modern society, the use of digital devices encompasses almost all age groups; from children to the elderly, a broad audience actively utilizes these technologies. For the younger generation, digital devices serve not only as a means of entertainment but also as platforms for education and self-development (Mataftsi A., Seliniotaki A. K., Moutzouri S. 2023).

The prevalence of digital devices is especially high in urban environments. Urbanization, the development of technological infrastructure, and the high pace of life increase the demand for these devices. Additionally, as internet and mobile networks expand into rural and remote areas, the use of digital devices is steadily rising, and this gap is gradually narrowing. The pandemic era further strengthened the role of digital devices, with remote education, online work regimes, and digital services becoming central to people's lives (Orman G., Sungur G., Candan Ö. 2022).

The impact of digital screens on the visual system primarily manifests as physiological and functional changes. Prolonged screen time causes continuous strain on the eye muscles, leading to disruptions in the accommodation process. Physiologically, the blue light emitted from screens affects the retina, accelerating eye fatigue. Long-term exposure to blue light can damage retinal cells and cause a gradual decline in visual quality. A decrease in blink frequency is observed while working in front of a screen, which leads to dryness and irritation of the ocular surface (Sheppard A. L., Wolffsohn J. S. 2023).

Among functional impacts, one of the most common issues is Computer Vision Syndrome (CVS). This syndrome is characterized by symptoms such as eye strain, blurred vision, double vision, and headaches. During continuous, uninterrupted screen use, the eyes' ability to focus weakens, resulting in decreased visual performance (Hipólito V., Coelho J. M. 2024). The effects of digital screens are not limited to the eyes; they can also cause functional changes related to the nervous system. Prolonged screen use leads to reduced attention span, increased visual fatigue, and disruption of sleep patterns. Particularly, screen use during nighttime hours reduces the secretion of the hormone melatonin, thereby lowering sleep quality.

II. MATERIALS AND METHODS

1. Materials

In this study, various scientific sources and empirical data were utilized to investigate the effects of digital device use on the visual system. The material base of the research consists of scientific articles, medical studies, statistical reports, and data published by international organizations. Furthermore, the existing literature on the subject was systematically analyzed.

2. Methods

From a methodological perspective, comparative analysis, observation, and analytical methods were employed in the research. The collected data were systematized, presented through tables, and the results were summarized. At the same time, an analytical approach was applied to determine cause-and-effect relationships.

III. RESULTS AND DISCUSSION

Preserving visual health is of great importance in the modern era, particularly against the backdrop of intensive digital device use. In this regard, the proper regulation of screen time is primarily essential. Since working continuously for long periods causes fatigue in the eye muscles, it is recommended to take breaks at specific intervals. This helps the eyes rest and supports the recovery of their functional activity.

Among preventive measures, one of the most widespread and effective methods is the **20-20-20 rule**. According to this rule, every 20 minutes, one should look at an object 20 feet (approximately 6 meters) away for 20 seconds. This method reduces the continuous focusing strain on the eyes and facilitates the relaxation of the accommodative system.

Table

The Impact of Digital Device Use on the Visual System

Parameter	Observed Result	Analysis
Prolonged screen use	High daily usage duration	Continuous screen exposure causes eye muscle strain and fatigue.
Eye fatigue (Asthenopia)	Frequently observed	Continuous focusing weakens accommodation, leading to rapid eye fatigue.
Dry eye symptoms	Prevalent condition	Reduced blink rate leads to dryness of the ocular surface.
Blurred vision	Observed in specific cases	Prolonged near-distance viewing temporarily reduces visual acuity.
Headache and tension	Observed in some cases	Screen brightness and improper lighting affect the nervous system.
Implementation of preventive measures	Insufficient	The majority of users do not fully comply with eye health guidelines.

Placing the screen at eye level, maintaining an optimal distance between the eyes and the screen (approximately 50–70 cm), and ensuring proper lighting conditions reduce the strain on the eyes. Appropriate adjustment of screen brightness and contrast also enhances visual comfort. To prevent dryness of the ocular surface, frequent blinking and, if necessary, the use of artificial tear drops are recommended. These measures are particularly relevant for individuals working in air-conditioned or dry environments. A balanced diet and the consumption of foods rich in vitamins A, C, and E also have a positive impact on preserving eye health (Aydın G. Ö., Turan N., 2025).

In conclusion, regular ophthalmological examinations are a vital part of prevention. Visual problems detected at an early stage can be treated more effectively. Furthermore, strengthening awareness among users and adhering to digital hygiene rules play a crucial role in the long-term preservation of visual health.

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PEDAGOGY

INTERACTIVE METHODS OF TEACHING

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Abstract
This article discusses the peculiarities and aims of using interactive methods in teaching foreign languages. The role of interactive methods in activating students and improving their learning outcomes on the basic of psychologic and didactic factors are analyzed and highlighted.
Keywords: interactive, activity, effective, learning outcomes, motivation, activate, creative, acquire, improve, skills.

At present, the globalization and integration processes, which is going on throughout of the world, exists a need to gain integrated knowledge related on different spheres of social activity. It has become the reason for working out different methods of activating students in the process of acquiring knowledge, which based on the interpersonal and intrapersonal abilities, interests, desire and motivation of students.

The word “interactive method” is taken from the English word “interactive” which means interpersonal and intrapersonal activity, aimed to activate the learners in gaining knowledge effectively. The main aim of interactive method is to involve all the students in the group to active participation at the lesson. This gives the students opportunity to acquire knowledge with interest and without psychological pressure. In interactive approach, organizing teaching process is based on the following factors:

- the relation of the teacher with students;
- all round communication;
- developing the knowledge of students;
- using feedback after presentation the teaching material;

(this helps to define comprehension).

- activating students by using different tools and methods;
- creating self-control;

Interactive methods belong to a group of methods based on the modern psychological conception of interaction. In other words, it is a cooperative activity of the learners during interpersonal communication. The main feature of interaction is realization the ability of a person in acting the role of the other person, to understand a partner in the process of communication, act according to the situations, and construct his / her own activity.

Interactive methods of teaching are worked out according to the project “Reading and writing for critical thinking” (RWCT) which is being implemented into cooperative activity of the teachers from many countries. The main purpose of this project is to implement into education the methods, which serve for improving critical thinking in the learners in spite of their age. In other words they are universal methods of teaching. These methods can easily be used in teaching foreign languages in traditional forms of organizing teaching too. The main idea of interactive methods is to improve critical thinking as constructive intellectual activity, which suppose intraconciouse activity of a person in receiving information. Within the framework of the interactive methods there have been worked out the basis of teaching and learning. It consists of three stages: challenging stage, comprehension stage and reflective stage. At the challenging stage the learners are motivated to learn the theme which is being presented and on the bases of their previous knowledge make diagnosis concerning to the meaning of new information.

At the comprehension stage, the learners work on the text and integrate ideas put in the text based on their own ideas so that they understand the new information better and clearly. At the stage of reflection, the learner’s analyses the new information creatively with the purpose of enlarging their knowledge and be able to use it in their further activities.

At present, the following methods as cluster, comparative diagram, puzzle, oriented teaching and others are widely used in teaching foreign languages. Cluster is used for motivating learners to the theme they are learning. In using this method, a teacher writes a word in the center of the blackboard and asks the learners to write around it all the words, which have relations with the key word. After that, they exchange their ideas working in pairs.

The methodology of using interactive methods turn learners into active participants at the lessons, so that they acquire knowledge not passively as in traditional method but actively taking an active part at the discussions. Interactive methods help the foreign language learners to overcome the difficulties, by asking questions because they want to know the reasons of existing difficulties. The active participation of the foreign language learners at the lessons creates favorable conditions for conscious learning, which leads to better understanding the topic.

Interactive methods are not used only for activating learners, but they are the best means of achieving guaranteed results in teaching a foreign language too. Here are we would like to present some positive features of using interactive methods:

1. The learners acquire knowledge with interests and this activates them in the process of learning;
2. The activity of the learners during the lessons create favorable conditions for improving problem-solving skills in them;

3. Require individual approach in teaching i.e. favours for student oriented teaching, which takes into account personal features of the learners;

4. A pair work and group work are emphasized and this will improve the feeling of responsibility in the learners;

5. The skills of independent work are developed in the learners, and the learners using interactive methods acquire knowledge, improve analyzing and creative thinking skills.

6. The interactive methods create strong motivation for learning and involve the learners into active work in implementing the acquired knowledge into practice;

7. Creates a need and high desire to use a foreign language for communication. Moreover, these are good facilities for the learners to express their own ideas and being involved into conversation;

8. A belief for their own strength is formed in the learners and this will help them to overcome such psychological barriers as threat of making mistakes and hesitation;

9. Create favourable opportunities for out of lesson activities, improve the skills of defending their ideas in the process of discourse.

In traditional methods all efforts of the teachers are focused on creating different ways of transforming information and the learners acquire this information passively so that to retell it the next time.

In interactive methods, gaining or acquiring knowledge is the first step and the next steps in this sphere include the activities relating to use this information in practice. This is an active process because the learners actively try to use the gained knowledge in different speech situations. This of course improves their communicative skills. The activity of the learners positively influences on their behavior. The only disadvantage here is noise in the class because the learners actively express their own ideas, feelings with joy and satisfaction. They are not afraid of making mistakes while discussing the problems and exchanging informations.

The module of multilevel communication, which is characteristic for interactive method, creates such an atmosphere in which the learners try to exchange their opinions, express emotions, impressions freely without any hesitation. The module of multilevel communication speech and improves listening skills and sub – skills.

Gamefication is the best tool of activating learners of a foreign language. Using games in organizing teaching process is characteristic not only in teaching young children, but also beneficial in teaching adults. Games involve both weak and strong students by improving interest and desire, which creates motivation in acquiring knowledge and forming speech skills. Such activities that based on games give satisfaction to the learners, improve collaborative, communicative and problem-solving skills in them. Therefore, teacher's task in using interactive methods is to select appropriate to the educational task exercises and speech situations. The role of speech situations should also be enhanced as they create favourable conditions for activating students. In such conditions, the learners feel themselves free and this will help them to overcome psychological obstacle as fear of making mistakes.

Role-playing is also characteristic for interactive method. It brings joy into teaching process and makes it more interesting. In using this method, a teacher should take into account the individual characteristic features of the students. While acting their roles the students try to express their feelings freely and demonstrate their creative ability. Everybody try to act well. Such high motive in their activities will guarantee the effectivity of teaching and serve as a stimulating tool for further development of the learning outcomes of the students in learning a foreign language.

In conclusion, we would like to stress once more the effectivity of using interactive methods in the educational process in creating motivation in the learners and turning them from passive listeners into active participants. The main goal of using interactive methods is to activate students in the process of acquiring knowledge. Interactive methods involve the students into active participation while acquiring knowledge and improving their speech skills. In this case, they acquire knowledge with interest, desire and high motivation.

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THE ORETICAL AND TECHNOLOGICAL ASPECTS OF ORGANIZING AND MANAGING LEARNER-CENTERED INSTRUCTION

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Abstract

The article highlights that the challenges of the 21st century require the adoption of learner-centered instruction as an effective approach to educational practice. It identifies essential learner competencies, such as problem-solving and decision-making, as well as types of thinking, categories of knowledge and activity, and their application in task design, along with the development of metacognitive skills. The study further characterizes forms of work, instructional strategies, techniques, and methods in learner-centered teaching, in addition to learners' learning styles and the models and formats of this approach. Furthermore, it examines pedagogical and psychological approaches, including relevant theories and the creation of a healthy psycho-social classroom environment, which play a significant role in ensuring the effectiveness of learner-centered instruction, and provides a critical perspective on these issues.

Keywords: theory; learner-centered instruction; teaching strategies; methods; forms of work; instructional models; psycho-social environment; teaching and learning environment.

Relevance of the Study:

The characteristics of the 21st century (the contemporary era in which we live) require individuals to develop essential qualities for creative activity, including skills such as decision-making, problem-solving, independent learning, collaboration, teamwork, evaluating diverse perspectives, generating new ideas, and demonstrating initiative in a rapidly changing and evolving world. To achieve this, two key conditions must be ensured: 1) the existence of a process aimed at developing the qualities necessary for creative activity; and 2) the transformation of the individual into an active subject (agent) capable of organizing and managing this process in order to acquire these qualities.

In light of the above, it can be concluded that, in the present context, the existence of instruction aligned with "Education 4.0," corresponding to the "techno-democratic information society" as a foundational framework, is essential. Moreover, it is necessary for the learner to act as a subject in the organization and management of this process. Determining optimal ways of developing technological literacy, information culture, and intellectual skills, as well as regulating an educational environment that incorporates these approaches, is of critical importance. Despite this necessity, research in this area remains insufficient, and methodological systems for addressing pedagogically significant cognitive issues have not been adequately developed on a scientific basis. Based on these arguments, the relevance of the study entitled "Theoretical and Technological Aspects of Organizing and Managing Learner-Centered Instruction" is substantiated.

Purpose of the study: The aim of this work is to identify the directions of regulating the environment that affects the development of students' skills in the process of implementing general education in accordance with the challenges of modern society, in other words, the development of their technological literacy and information culture, intellectual skills. We hope that this idea will give rise to hypotheses as a form of scientific cognition, which in turn will develop into a theory such as "Fundamentals of the Organization and Management of Student-Centered Learning", and a contribution will be made to "Didactics".

Methodological basis of the research. In the process of conducting the research, based on L. Bertalanfi's "Idea of System Analysis" [2;8] (the idea, which is explained as an attempt to study the properties of an object based on the properties of its parts - italics are ours - F.I), the "System-structural approach", which has been formed as an important branch of dialectics and has risen to the level of its alternative, empirical, empirical-theoretical and theoretical methods of scientific cognition, the internal relationships of the forms of scientific cognition, and various pedagogical and psychological research generalizations were used as a methodological basis.

Interpretation of generalizations from research materials: The Fourth Industrial Revolution is having an impact on the education system as well as on the socio-economic fields. Education, which is a process of sharing knowledge and experience of change, has developed in stages (including the specific characteristics of industrial revolutions) in accordance with the industrial revolutions. In the era of the Fourth Industrial Revolution, an Education system that can form a creative, innovative and globally competitive generation is required, and currently, the impact of the aforementioned revolution on the education process and the issue of "education of the future" are being discussed on various platforms and the necessary steps are being taken accordingly[11], [12; 92-97]. The expected paradigmatic changes in the education system and the implementation of global education reform have been further accelerated by the impact of the Fourth Industrial Revolution.[21; 147-171]

The Fourth Industrial Revolution has different implications for different areas of our lives. From this perspective, there are both opportunities and challenges for education. The use of different technologies such as IoT, 3D printing, Quantum computing, Artificial Intelligence, etc. allows for more effective information transfer and the development of a new "educational framework".[14; 78-94].

It is necessary to distinguish two main reasons for the reforms carried out in the education system and its implementation system in connection with the challenges of the Fourth Industrial Revolution. The first is the training of a workforce with knowledge (information) and skills in accordance with the needs of a rapidly changing global economy, and the second is the establishment of an education and implementation system that can bring to the fore the productive forces (labor force) necessary for the development of an adequate information society during the industrial revolution. [9;288]

It is undeniable that education should adapt to the environment in which learners live and provide them with a secure and successful future. Intellectual and creative activity of everyone living in a "techno-democratic-information society" becomes a paramount requirement, and for this it is desirable that every member of this society rises to the level of a subject of intellectual skills, they must have information culture and technological literacy.

Information culture: is the knowledge, intellectual skills and habits necessary for a person to adapt to the information society; is the ability to use information resources and information communication tools of society; is the application of advanced achievements in the field of informatization and the development of information technology tools in society; is the ability to obtain and transmit information using modern technical means and methods, computer technologies.

Technological literacy is the ability of people to use various digital technologies, analyze information and operate safely in a digital environment. "This skill is not limited to using a computer and the Internet, but also includes: 1) Compliance with digital safety and cybersecurity rules; 2) Working with artificial intelligence and automation; 3) Digital analytics and data processing skills; 4) Using cloud technologies; 5) Quickly adapting to new technologies"[5]. Technological literacy includes the ability to use information and communication technologies.

Developing digital skills is essential to ensure that they can engage safely and effectively with digital technologies in the future. Education systems need to take a comprehensive and holistic approach, supporting all learners to develop the skills to be active and ethical users of digital technologies.[17; 57-79]

Digital education, allowing people to participate independently in social life. In addition, the reality of digital education and the digital revolution requires fundamental changes in the forms and methods of moral education, leading to the emergence of digital skills as the most important ability [16;58-64]. There is no doubt that the development of digital skills of learners will lead to their more active participation in society as digital citizens in the future. [15], [17; 57-79]

Due to the rapid development of technology, the knowledge and skills that students acquire during their education are outdated by the time they graduate. In order to help develop and shape the use of today's fastest-growing technologies in scientific and technical education, it is necessary to train students and prepare them for the digital environment. Adapting to a rapidly changing environment will make it necessary for students to stay in touch with educational institutions even after graduation, providing both workers with updated skills and young students (and faculty) with a new direction related to the rapidly changing realities of the industrial and corporate sectors.[18; 25-30], [19; 579-592]

In line with the "Techno-democratic-information society" that exists as a basis in the modern era, Education 4.0 uses unique technologies and tools to cope with these tasks and helps learners to develop themselves in accordance with changes in society. Therefore, Education 4.0 is a more realistic and practical learning approach that can provide high results for learners' learning. It is important to adapt to a rapidly changing world, and Education 4.0 is a system that educational institutions use to ensure this. This new system uses "smart" school management systems, learning management programs, communication tools, and teaching and learning tools.[13; 238-254], [16;3558-3564].

In the Education 4.0 approach, it has been determined that, going beyond constructivist education systems and Bloom's taxonomy, a teaching process based on the following areas will be applied: 1) 3R (Recalling, Relating, Refining) regulating understanding; 2) 3I (Inquiring, Interacting, Interpreting) encouraging research; 3) 3P (Participating, Processing, Presenting) based on drawing conclusions.[22; 92-98], [23; 40-45]

Education 4.0 is a "smart" and digital revolution for the benefit of all stakeholders in education. Education 4.0 introduces the best methods (methods) for teaching and reduces the administrative burden by automating many processes while modernizing these methods. In addition, it aims to increase the skills of educators and improve the learning outcomes of learners. [16;3558-3564].

The most important goal of Education 4.0 for all educational institutions is to motivate learners and improve their outcomes. By using technology, learners can better communicate with other stakeholders in the system, such as educators, management, etc. The learning outcomes of learners are directly proportional to the level of implementation of Education 4.0.[21;147-171]

Education 4.0 has the following features: 1) learning regardless of time and place (lifelong learning, e-learning, etc.); 2) the opportunity to receive personalized education according to the skills and abilities of students; 3) taking into account the suggestions of students when preparing the curriculum; 4) the priority of project-based learning; 5) the formation of skills to solve real-world problems; 6) the formation of students' ability to conduct analysis on big data; 7) the assessment of students' knowledge in the process of applying it to projects; 8) the transformation of new developing technologies into a part of the education system, etc. [11-12]

It is undeniable that there is a specificity in the appeals of each industrial revolution. This is manifested against the background of global changes taking place in the world, and at the same time it determines the existence of new shades in information culture and the content of technological literacy. At different stages of world history, humanity has faced serious changes and achieved results with the reforms carried out.

In order for students to demonstrate their skills and abilities in new areas emerging under the influence of the Fourth Industrial Revolution, it is necessary to implement fundamental changes in technology and the curricula of the subjects taught. By reviewing the curricula of the subjects formed on the basis of chemistry, biology, physics, etc., which are considered "basic sciences" in the new curricula, more attention should be paid to the teaching of computer science subjects, which play a key role in the formation of the Fourth Industrial Revolution literacy. Naturally, more attention should be paid to the teaching of the subjects in question. [20; 432-466]

Against the backdrop of the industrial revolutions, educational program developers had to seek answers to the following fundamental questions: 1) What knowledge, skills, and values should be reflected in educational programs?; 2) Will these knowledge, skills, values, and competencies form the necessary life skills in learners?; 3) How can the process of implementing education be made relevant and interesting for learners?; 4) How can assessment (an integral part of the process of implementing education) be made more productive and effective?

In our modern era, parameters such as relevance, practicality, effectiveness, and sustainability are the focus of attention as indicators of the quality of an educational program, while the indicator of its success is the quality of acquisition by learners and the extent to which learners can effectively use what they have acquired for their personal, social, cognitive, psychological, and emotional development.

UNESCO has the following criteria for a quality education program: the educational program must have clear objectives; meet the demands of today; be relevant to the current and future lives, experiences, desires and aspirations of learners; aim to build a prosperous future for learners in social and economic terms, taking into account the history and culture of the country in which they live; be fair and inclusive (taking into account the individuality and individual needs of learners, etc.); be learner-oriented (takes into account the needs of the learner, is appropriate to the age of the learner, helps in personal development and the formation of life skills, and does not overload learners); be open and flexible (integrates emerging innovations into the content); be consistent and relevant. [3; 5]

By the way, let us emphasize that the changes taking place in society are not possible only with the changes taking place in industry and technology. In parallel, the systematic implementation of changes and development in the superstructures that will guide the main dynamics of society - education, health, culture, etc. - is one of the main needs. Preventing the problems brought by the IV industrial revolution and preparing human resources that can compete on a global scale are among the tasks facing the education system. This revolution is continuously affecting all components related to education, such as the structure of the curriculum, the development of the skills of educators, the inclusion of new technologies in the curriculum, and approaches to the implementation processes of education. In the era of the fourth industrial revolution, education must have potential opportunities that can develop society.

In learner-centered learning, the joint creative activity between the educator and the learner has the character of "subject⇔subject" (S⇔S), based on the paradigm of "opportunity⇒action⟹new quality", the educator performs the function of a facilitator, this process proceeds as the learner's research on the "learning problem". The inclusion of the learner as a main component in the learning system begins with the transformation of the goal formulated by the educator with reference to sound arguments into the goal of the learner.

In the aforementioned learning process, when the material to be mastered by the learner is perceived as the object of satisfying his cognitive needs, he directs (organizes and manages) the educational activity in an appropriate direction. This process is of a research nature and has the following components in its structure: educational situation (or tasks); 2) educational operations; 3)control; 4)price [1;150].

As can be seen from the presented structure, the student's educational activity begins with the solution of educational tasks.

By the way, let's comment on what is meant by educational tasks. Although its essence is reflected in the meaning of "task", its character is related to the meaning of "teaching". Educational tasks are distinguished from any scientific, military, sports, etc. tasks by one important feature. Educational tasks involve the discovery and mastering of general methods (principles, regularities) of solving various problems and specific practical exercises by students in their educational activities.

By presenting learning tasks, the educator, who performs the function of a facilitator, includes learners in a unique learning situation: in this situation, they become familiar with the content of general methods for solving learning tasks, taking into account all specific and concrete options, and acquire the appropriate knowledge, skills, and habits.

A system of special tasks is applied to form intellectual skills in students (determined by the requirements of the modern era). These tasks are designed on the principle of modeling the structure of various intellectual skills. As students complete them, they acquire intellectual skills such as determining the purpose of their work, systematizing educational material in this regard, independently collecting material, writing an essay, etc. From the point of view of the principle of developmental training, this method is considered effective. However, in order to use it purposefully, the system and content of intellectual skills in classes and subjects must be thoroughly developed.

Tasks and their system: should be consistent with the purpose of the lesson and aimed at solving the research problem set (according to the type of thinking, information sources, form of presenting results, etc.);

should be appropriate to the age, knowledge and intellectual level, abilities and interests of students, and should be differentiated; should be based on the state program and national values; should be relevant, related to real life and students' experiences; should be interesting, attractive, and encourage discovery; should be clearly stated; should contain clear and open questions.

It is possible for the learner to act in the position of a researcher when the content of the training material, the form of action of the means and methods (in the training process, the content of the training material, the means and methods act in place of the content, in relation to the organizational form) are in accordance with the research process. If we accept that the organizational form of training established in accordance with the research process has a unique structure, and this is reminiscent of the stages of the research process (in our opinion, by taking such a position, we would not have made such a serious mistake).

There are many specific features of educational tasks, but one thing is clear: in order to solve them, students must master the necessary educational operations. Educational operations are diverse. Many of them are of a general nature and are used almost equally in the mastering of various educational materials. Some educational operations are more typical for the mastering of certain educational materials (mathematical, linguistic, etc.). Educational operations applied in special cases are also distinguished. Intellectual processes - analysis, composition, comparison, generalization, etc. occupy a special place in the structure of educational operations. Intellectual processes are always implemented by applying them to the content of a certain subject (calculus, geometry, grammar, etc.) and "therefore appear in the form of various arithmetic, geometric, etc. operations". From this point of view, the formation of educational operations is directly related to the mastering of mental activity principles by students.

It is worth noting that human self-awareness has always been an urgent problem of world philosophy, psychology and pedagogy. Scientists have approached human self-awareness from the perspective of personality and have sought its roots in the process of forming a person's ideas about his own "I". Unfortunately, until recently, researchers have not sufficiently assessed a person's understanding of the characteristics of his own mental world, the world of thinking, and cognitive processes. In modern American psychology, this issue has been brought into the spotlight and has begun to be studied as a metacognitive system. It has been established that as children develop, certain ideas about cognitive (cognitive) processes are formed in them and they begin to regulate their mental activity. It is worth emphasizing that self-monitoring, self-regulation, self-assessment are metacognitive skills, which are related but different concepts. It is a person's awareness and understanding of his own cognitive processes.

Flavell studied and described in detail some of the functions of metacognition. The following can be noted among them: 1) Problem formulation and identification of possible solutions; 2) Knowledge of which cognitive processes are necessary for solving the task; 3) Activation of cognitive rules and methods; 4) Confidence in the possibilities of thinking; 5) Attempt to solve tasks more efficiently. These functions are interconnected. The first function is conditioned by the formation of ideas about the goals of activity in children. As they grow older, they learn to apply known methods to various situations. Gradually, students develop ideas about cognitive processes. [1; 60], [7; 74]

Control also plays an important role in the formation of educational activity. The effectiveness of the activity is directly related to the level of control, as well as to the educational operations. Control is directly related to evaluation, which has an important feature as a unique component of educational activity. In the control process, not the final result of educational activity, but the results of individual educational operations are examined. In the evaluation process, the final result of educational activity is analyzed, and its compliance with the purpose of educational activity is determined.

When assessment is psychologically effective, it gradually turns into self-assessment, playing an important role in the formation of the learner's self-awareness; Self-monitoring, self-regulation, self-evaluation are metacognitive skills, which are related but different concepts. It is a person's awareness and understanding of his own cognitive processes; Self-monitoring consists of observing and following a person's actions, behaviors and cognitive processes during a task. Here, the learner does not try to control himself, does not judge or evaluate his own performance. He simply collects information about his performance by observing himself; Self-regulation is the ability of a person to control and manage his cognition, emotional state and behavior to achieve a goal. Its main components include: goal setting; planning; adaptation; Self-evaluation is the judgment or evaluation of his own activity or learning. Its main components include: evaluation; reflection; Self-monitoring is about observation and awareness, self-regulation is about actively managing cognitive and emotional processes to achieve goals, and self-assessment is about making judgments about and reflecting on one's own performance. Collectively, these are metacognitive skills that enable learners to become more effective learners by understanding and controlling their own learning processes.

Psychological research clearly shows that when educational activity is formed, the learner literally becomes the subject of his or her own activity.

In learner-centered learning, the main concern of the educator (facilitator) is to give special importance to the development of problem-solving skills in addition to the formation of cognitive skills of learners. Problem-solving skills are the ability to identify, analyze and solve problems efficiently and effectively. People with high problem-solving skills can evaluate situations, consider various options and choose the most appropriate way to achieve a solution. These skills are important in various areas of life, including work, education and daily decision-making. Also, problem-solving means facing new problems, finding a method and a successful solution to solve them. Correct problem-solving is applying the knowledge we have acquired to a problem we have never encountered before. This helps develop critical thinking and decision-making skills and prepares us to cope with some unlearned

situations in the future. For this reason, problem-solving is considered one of the essential 21st century skills. Properly teaching problem-solving not only benefits students' academic development, but also prepares them to succeed in an ever-evolving world where adaptation and collaboration are essential.[3;37]

In order to develop problem-solving skills in learners, the facilitator should focus on introducing them to problem-solving methods. An example of a cognitive action form that includes the following stages can be the substrate for the methods in question: 1) defining the problem; 2) planning a solution; 3) implementing the plan; 4) evaluating the process; 5) evaluation.

In the process of developing problem-solving skills in learners, the educator should focus on the need for them to have sufficient information about the various types of thinking, the analytical and heuristic logics of mental activity, and the integration of these into aspects of the unit.

It is known that thinking is a person's cognitive (cognitive) activity, a thinking process. During cognitive activity, a person's ideas, thoughts, and mental representations are formed or used. Thinking is a mental process that occurs in the brain that helps a person form psychological associations and various models. Thinking comes into play the moment a person starts thinking. Thinking is formed and develops during activities such as searching for information, processing it, grouping and generalizing these ideas to express them verbally or in writing to others, etc. Being able to think effectively is a skill in itself. In the teaching process, the facilitator must form the ability to think effectively in the learner. Depending on how a person thinks, there are different types of thinking and different forms of thinking: logical, critical, creative, convergent, divergent, verbal, non-verbal, deductive, inductive, analytical, etc. Instilling critical and creative thinking forms in learners creates conditions for their development. Therefore, each of these is very important in itself and needs to be formed during education. It should be taken into account that a person does not use only one type of thinking when thinking.

A critical thinker: correctly defines the problem; investigates the cause of the problem; collects information about the problem by investigating; processes and groups data and results; is able to solve the problem systematically; determines which solution is effective; tries to improve the solution to the problem; is able to detect inconsistencies and misunderstandings when reasoning; uses evidence correctly and impartially when justifying an opinion; is able to distinguish between logically sound and unsound ideas; sets aside judgment when there is insufficient evidence; is able to see the possible consequences of an action before doing it; is able to learn independently or at least has an interest in learning in this way; is able to see the difference between the acceptance of an idea by many and whether that idea is valid or not; is able to present different points of view without distorting, artificially exaggerating or ridiculing; accepts that his own opinions may be wrong, perhaps preferring personal preferences over evidence.

Creative thinking is a cognitive process that helps to look at objects, events, and problem-solving from a new and different perspective, a kind of "thinking outside the box." Creative thinking is not just about talent. It is a way of thinking that allows for different outcomes in different situations and different ways of solving problems.

When a person thinks creatively, they are able to solve difficult problems in a more appropriate, efficient, and different way, and they are able to look at things and issues from different perspectives. To do this, a person must have the ability to make connections between different concepts, draw analogies, and look at things from new perspectives.

To develop creative thinking in learners, it is necessary to repeat some activities frequently and develop skills in this direction. When these activities are applied together, they create the opportunity to look at problems and issues from a new perspective.

There are various techniques for developing creative thinking. The application and use of these techniques ensures the generation of ideas in the learner, solving problems in different ways, and ultimately a creative approach to the issue.

Information about various forms and models of learner-centered learning has been partially included in scientific sources. These include: 1) Synchronous and asynchronous learning; 2) Inquiry and research-based learning; 3) Problem-based learning; 4) Project-based learning (Project Based Learning-PBL); 5) Game-based learning, etc. Examples can be:

Here, in order to clarify the concept of "Different forms and models of learner-centered learning" and some of the considerations we have presented above, we consider it necessary to present a concise interpretation of the "Problem-Based Learning" and "Project-Based Learning" models.

Problem-based learning is a “learner-centered learning model.” When introducing this model, learners are involved in solving real-life problems in accordance with the content of the subject. Effective learning is possible both in the context of using existing knowledge and acquiring new knowledge and skills. Thinking about a problem, discussing it thoroughly, and trying to solve it develops skills such as critical thinking, problem solving, and communication. Since problem-based learning is conducted in a group, it instills and forms cooperation skills in learners. At the same time, solving any problem and working for it activates their internal motivation and turns learning into a meaningful activity. Problem-based learning includes a number of stages. The stages in question are: 1) Presenting an open-ended question that expresses the problem; 2) Clarifying and discussing the problem; 3) Classifying knowledge (What do we know about the problem? What do we need to know about the problem?); 4) Suggesting possible solutions; 5) Sharing the results and the solution.[3; 93]

There are also experts who present problem-based learning as a subform of project-based learning with many features. Despite all their similarities, both have different features. Both project and problem-based learning models are learner-centered and have common

features in terms of creating learning activity in learners, developing critical thinking, problem solving, and cooperation. Unlike problem-based learning, the project-based learning model does not end with the acquisition of theoretical knowledge alone. It involves finding a solution to a problem using theoretical knowledge. Project-based learning is a model that reconciles the knowledge learned with their application and addresses real-life problems. At the same time, it allows for the development of skills such as collaboration, communication, and problem-solving during the process. In PBL, finding solutions to difficult and real problems is used for learners to learn various concepts and principles. The goal here is not for learners to learn and speak knowledge and facts as information, but to ensure that they are able to use this knowledge at the right time. The steps to be taken in project-based learning are: problem formulation; plan development; research and product preparation; scaffolding (providing the right direction) and monitoring; verification of results and evaluation of the process (activity). [3; 94-96]

It should be noted that the implementation of various projects in lessons and Project-Based Learning are not the same. In lessons, the implementation of the project is given to the students after the knowledge and skills are formed and then applied. In project-based learning, knowledge and skills are acquired during the implementation of the project. It is possible to apply project-based learning in all subjects. You just need to look at the issues from the perspective of the subject and think about what problem will be solved.

In the study of the theoretical and technological aspects of the organization and management of learner-centered learning, and in the generalization of the research materials obtained, we have accepted the need to keep the dialectical dependence "general↔specific↔exclusive" in focus as a necessary approach, and we consider it the right choice to consider it necessary to give importance to the aforementioned dialectical dependence in the application of the "Learner-centered learning model".

Pedagogical practice confirms that in the implementation of education, general pedagogical requirements should be expected on the basis of mutual cooperation between educators and learners in accordance with the "subject↔subject" principle. The requirements in question are: 1) completeness of the pedagogical process - educational, educational and developmental in nature; 2) creation of equal opportunities for learners - ensuring the same learning conditions for learners in accordance with the educational infrastructure of the institution, regulating the educational process taking into account the inclinations, interests and potential capabilities of learners; 3) personality orientation - developing the vital skills of learners based on their cognitive, communicative and psychomotor activities, and forming national and human values in them; 4) learner orientation - directing educational activities directly to protecting the interests of learners, meeting educational requirements, realizing their talents, and forming their personalities; 5) development orientation - implementation of complex measures that include the development prospects of students based on the results obtained from the analysis of their educational achievements; 6) stimulation of activity - taking measures to monitor and evaluate the achievements of students in order to increase the efficiency of the learning process and increase their interest in learning; 7) creation of a supportive environment - providing the necessary infrastructure, a healthy moral and psychological environment, and creative and safe educational conditions to improve the quality indicators of education.

Based on the dialectic we emphasized above, we accept that in the implementation of education, based on mutual cooperation between educators and learners in accordance with the "subject↔subject" principle, general pedagogical requirements should be met (creatively) in accordance with specific conditions in the research, organization, and management of "Learner-centered learning".

Despite the stated approach, "Didactics" is considered a general term for "Theory of Education and Training","If we assume that the theory of "learner-centered learning" (as the highest form of scientific cognition) is an interpretation in its special status, then the theories of "Multiple Intelligences" (Harvard Gardner), "Stages of Mental Development" (Jan Piaget), "Social Development" (Lev Vygotsky), "Thinking Style" (Karol Dweck), "Spiritual Development" (Lawrence Kohlberg), "Conditions of Learning" (Robert Gagne), "Emotional Intelligence" (Daniel Goleman), "Personality Formation and Development" ("Introverted and Extraverted Personality" - K. Jung) can only be considered as a higher form of spiritual learning about (some aspect, aspect, component of learning). Therefore, it would be in the interest of the general cause to refer to these theories (the latter) that we have presented in accordance with the specific conditions in the organization and management of "learner-centered learning" (creatively).

It is worth emphasizing here that the most important requirements that are guided by are the principles that arise from the "dialectical dependencies between wholes and parts" - regularities and laws - in the system to which they belong. These principles form the basis for the formation of the methodological system of teaching and determine its nature.

Scientific novelty of the research: The idea of "Theoretical and Technological Aspects of the Organization and Management of Student-Centered Learning" (considering that the idea is an important value) aimed at regulating the environment that affects the development of students' skills (the development of their technological literacy and information culture, intellectual skills) in the process of implementing general education in accordance with the challenges of modern society, has been defined, which, as a form of scientific cognition, will give rise to hypotheses, which, in turn, will develop into a theory such as "Fundamentals of the Organization and Management of Student-Centered Learning".

Theoretical significance of the study: The research on the presented topic has a specific function in directing further scientific activities for a broad study of theoretical and practical ways to solve the problem of creating conditions for sustainability for the future development of society.

The practical significance of the research is that in the real pedagogical process, practical educators have the opportunity to benefit from the idea of "Theoretical and Technological Aspects of the Organization and Management of Student-Centered Learning" in their practical activities, which is aimed at regulating the environment that affects the development of students' skills (the development of their technological literacy and information culture, intellectual skills) in the process of implementing general education in accordance with the challenges of modern society.

Conclusion. 1. The existence of information culture and technological literacy in every member of the society formed in accordance with the calls of the IV industrial revolution is a desirable quality; 2. The education system adequate to the "Techno-democratic-information society" has taken its place in scientific sources and pedagogical practice under the term "Education 4.0" and has been interpreted as a superstructure on logical grounds; 3. "Education 4.0", which exhibits an effective environment for the existence of information culture and technological literacy, has specific characteristics and it is possible to divide the skills that need to be formed in this system into groups on a certain logical basis; 4. At the stage of modern socio-economic development, intellectual and creative activity of everyone living in the "Techno-democratic-information society" has become a paramount requirement: 4.1. In order for a person to become a creatively active subject of that society, he (a person) must be surrounded by an educational environment that conditions the development of the necessary qualities; 4.2. In the "techno-democratic-information society", there must be an adequate training model for the implementation of education, which is formed as a superstructure; 4.3. In order to acquire the qualities corresponding to the demands of the base, the person (here - the student) must become an "enabler" of the function of an active subject of the organization and management of the implementation of education, which is formed as a superstructure; 5. In the implementation of education, general pedagogical requirements should be kept in focus based on mutual cooperation between educators and learners in accordance with the "subject↔subject" principle; 6. In the implementation of education, general pedagogical requirements formed on the basis of mutual cooperation between educators and learners in accordance with the "subject↔subject" principle should be anticipated (creatively) in accordance with specific conditions in the research, organization and management of "Learner-centered learning".

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PSYCHOLOGY

ÜNİVERSİTE ÖĞRENCİLERİNDE BELİRSİZLİĞE TAHAMMÜLSÜZLÜĞÜN ARAŞTIRILMASI

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INVESTİGATİON OF INTOLERANCE TO UNCERTAİNTY AMONG UNİVERSİTY STUDENTS

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Özet

Bu çalışma, Üniversite öğrencilerinin belirsizliğe tahammülsüzlük düzeyini araştırmayı amaçlamaktadır. Çalışma örneklemi, farklı fakülte ve bölümlerde öğrenim gören 115'i kadın ve 85'i erkek olmak üzere 200 üniversite öğrencisinden oluşmuştur. Veri toplama aracı olarak Belirsizliğe Tahammülsüzlük Ölçeği kullanıldı ve güvenilirlik analizi, 0,942'lik bir iç tutarlılık katsayısı ortaya koydu. Çalışmanın sonuçları, öğrencilerin belirsizliğe tahammül puanlarında cinsiyet ve yaşa bağlı olarak istatistiksel olarak anlamlı farklılıklar olduğunu gösterdi. Shapiro-Wilk testi sonuçları verilerin normal dağılıma sahip olmadığını gösterirken, korelasyon analizi ölçeğin alt ölçekleri ile toplam puan arasında çok güçlü bir ilişki olduğunu ortaya koydu. Belirsizlikten kaynaklanan stresin, öğrencilerin pasifliği ve olumsuz öz değerlendirmeleriyle doğrudan ilişkili olduğu sonucuna varılmıştır. Çalışmanın sonuçları, belirsizliğe tahammülsüzlüğün, demografik özelliklerinden bağımsız olarak, üniversite öğrencileri için tanısal bir risk faktörü olduğunu ve bu altta yatan mekanizmanın psikolojik danışmanlık sürecinde ele alınması gerektiğini vurgulamaktadır.

Abstract

This study aims to investigate the level of uncertainty intolerance among university students. The study sample consisted of 200 university students, 115 women and 85 men, studying in different faculties and departments. The Intolerance of Uncertainty Scale was used as the data collection tool, and reliability analysis revealed an internal consistency coefficient of 0.942. The results of the study showed that there were statistically significant differences in students' uncertainty tolerance scores depending on gender and age. While the Shapiro-Wilk test results showed that the data did not have a normal distribution, correlation analysis revealed a very strong relationship between the subscales of the scale and the total score. It was concluded that the stress caused by uncertainty is directly related to students' passivity and negative self-evaluations. The study's findings highlight that intolerance of uncertainty is a diagnostic risk factor for university students, regardless of their demographic characteristics, and that this underlying mechanism should be addressed in the psychological counseling process.

Anahtar Kelimeler: Belirsizliğe Tahammülsüzlük, Üniversite Öğrencileri, Psikolojik Danışma, Belirsizlik, Kaygı, Gelecek.

Keywords: Intolerance of Uncertainty, University Students, Psychological Counseling, Uncertainty, Anxiety, Future.

Giriş

Psikoloji literatüründeki son çalışmalar, herhangi bir bozukluğa özgü olmayan, çeşitli klinik belirtilerin ortak bir temelini sağlayan transdiagnostik faktörlere odaklanmıştır. Bu faktörler arasında, bir zamanlar yalnızca yaygın anksiyete bozukluğunu açıklamak için öne sürülen belirsizliğe tahammülsüzlük, artık travma sonrası stres bozukluğundan yeme bozukluklarına kadar geniş bir yelpazedeki durumlarda semptomları devam eden evrensel bir risk mekanizması olarak kabul edilmektedir (Yığman ve Fidan, 2021). Bireyler belirsiz durumları tehdit edici ve kabul edilemez olarak algıladıklarında, bu durum bilgi işlemede sistematik aksamalara ve sıradan günlük olayların bozulmasına yol açar. Bu durumun Türkiye bağlamındaki sonuçlarının incelenmesi, belirsizliğin yalnızca duygusal gerilim yaratmakla kalmayıp, bireylerin kararsızlıklarını yetersizlik belirtisi olarak kodladıkları olumsuz öz değerlendirme süreçlerini de tetiklediğini göstermektedir (Sarı ve Dağ, 2009). Bilişsel davranışçı bir bakış açısından, belirsizliğe karşı toleransın azalması otomatik düşüncelerin sıklığını artırarak işlev bozukluğuyla başa çıkma stratejilerinin geliştirilmesine zemin hazırlar (Parmaksız, 2021). Üniversite yılları, bireyin yaşamındaki eşsiz bir gelişim evresine karşılık

gelir ve yaklaşık olarak 18-25 yaşlarını kapsar; bu dönem "yetişkinliğe geçiş dönemi" olarak tanımlanır (Demir ve Epli, 2024). Bu dönem, akademik kariyer kurma, ekonomik bağımsızlık arayışı ve sosyal rolleri yeniden tanımlama gibi birçok yapısal belirsizliği içerir. Yetişkinliğe adım atan bireyler sayısız seçenek ve sorumlulukla karşı karşıyadır ve belirsizliğe tahammül edebilme yetenekleri, bu geçişi başarıyla atlatıp atlatamayacaklarını belirlemede kilit bir faktördür. Üniversite öğrencilerinin ailelerinden ayrılıp kendi kimliklerini oluşturmaya çalıştıkları birey olma süreci, belirsizliğe tahammülsüzlük düzeylerinden doğrudan etkilenir (Karakaş, Güngör ve Sapancı, 2025). Tolerans seviyeleri azaldıkça, öğrencilerin bağımsız olarak işlev görme yetenekleri azalır ve reddedilme veya ayrılık kaygısı daha yaygın hale gelir. Bu gelişimsel direncin kökenlerine ilişkin araştırmalar, ebeveyn tutumlarının önemli bir rol oynadığını göstermektedir. Demokratik bir aile ortamında büyüyen ve yeni durumlarla karşılaşma fırsatı verilen çocuklar belirsizliğe daha iyi tolerans gösterirken, aşırı koruyucu veya otoriter bir ortamda büyüyen çocukların bu kapasiteleri önemli ölçüde daha düşüktür (Geçgin ve Sahranç, 2017). Öğrencinin zihinsel süreçlerindeki esneklik derecesi, belirsiz durumlarla nasıl başa çıkacağını belirleyen bir diğer önemli değişkendir. Bilişsel esneklik seviyeleri azaldıkça, bireyler belirsizlik karşısında felç olur ve alternatif çözümler üretmek yerine takıntılı düşünce kalıplarına hapsolurlar (Berdan ve Sütçigil, 2023). Bu durum sadece kaygıya neden olmakla kalmaz, aynı zamanda depresif belirtilerin gelişmesinde de önemli bir rol oynar. Duyguları tanıma ve ifade etmede zorlukla karakterize edilen bir durum olan aleksitimya, belirsizliğe tahammülsüzlükle pozitif bir korelasyon gösterir; bu da insanların sosyal çevrelerini öngörülemez ve tehdit edici olarak algılamalarına yol açar (Yıldız ve Güllü, 2018). Duygusal dünyasını anlamakta zorlanan bir öğrenci, belirsizliğin yarattığı boşluğu korkuyla doldurma eğilimindedir. Bu bilişsel ve duygusal sınırlamalar genellikle mükemmeliyetçi bir kişilik yapısına dayanır. Mükemmeliyetçiliği hedefleyen öğrenciler, kontrolleri dışındaki küçük belirsizlikleri bile büyük bir başarısızlık riski olarak algılar ve belirsiz bir durumda eksik bilgiyi yaklaşan bir felaket olarak yorumlarlar (Başcı ve Hamamcı, 2022). Üniversite hayatında belirsizlikten kaçınma davranışının en somut sonuçlarından biri, akademik çalışmaların sistematik olarak ertelenmesidir. Araştırmalar, belirsizlikten kaçınma isteğinin akademik ertelemenin güçlü bir göstergesi olduğunu ortaya koymaktadır (Kayıtmaz, 2024). Bu durum, öğrencilerin notlarını olumsuz etkilemekle kalmıyor, aynı zamanda geleceğe olan güvenlerini de zedeliyor. Karşılanmayan beklentiler ve belirsizlik anında, stres kaynağı olarak kodlanan bu durumda, öğrencilerin kendilerine gösterdikleri şefkat ve anlayışın yerini sert öz eleştiri alıyor (Başcı ve Hamamcı, 2022). Öz şefkati düşük olan öğrenciler, olumsuzlukları herkesin başına gelebilecek doğal bir süreç olarak değil, kendi yetersizliklerinin kanıtı olarak görme eğilimindedirler. Bu içselleştirilmiş aksama süreci, bireyin genel mutluluğunu ve psikolojik refahını baltalayabilir ve yaşam memnuniyetini azaltabilir (Turan Torun, 2023). Pandemiler gibi hayatın her alanını öngörülemez hale getiren küresel krizler sırasında, dışsal belirsizliğin öğrencilerin içsel hoşgörüsüzlüğünü daha da kötüleştirdiği gözlemlenmiştir (Duman, 2020). Tüm bu akademik ve klinik bulgulara rağmen, üniversite öğrencileri arasında belirsizlik toleranssızlığı konusunda literatürde hala önemli bir boşluk bulunmaktadır. Çalışmaların çoğu, değişkenler arasındaki doğrudan ilişkileri ölçen ve zaman içindeki değişiklikleri tam olarak hesaba katamayan kesitsel tasarımlara dayanmaktadır (Parmaksız, 2021). Mevcut çalışma, yalnızca öznel olarak bildirilen nicel ölçümlerle sınırlı olduğundan, öğrencilerin belirsizliği iç dünyalarında öznel bir deneyim olarak nasıl yaşadıklarını anlamayı zorlaştırmaktadır (Berdan ve Sütçigil, 2023). Öz saygı ve psikolojik iyilik hali gibi koruyucu faktörler olarak tanımlanan yapıların belirsizliğin zararlı etkilerine karşı nasıl koruma sağladığını derinlemesine incelemek için nitel araştırmalara ihtiyaç duyulmaktadır. Ayrıca, ebeveyn reddinin çocukların gelecekle ilgili endişelerini nasıl etkilediğini incelerken babaların rolünün annelerden daha önemli olması gibi bulgular, aile dinamiklerinin daha geniş bir toplumsal bağlamda ele alınması gerektiğini göstermektedir (Demir ve Epli, 2024). Literatürde, sosyal medyanın etkisi, ekonomik kriz ve mezuniyet sonrası işsizlik kaygısı gibi güncel gerçeklerin öğrencilerde transdiagnostik risk faktörlerini nasıl tetiklediği konusu henüz yeterince ele alınmamıştır. Hem içsel süreçler hem de dışsal sosyal gerçeklik baskıları, belirsizlik algılarının şekillenmesinde rol oynar. Duygusal başa çıkma becerileri sınırlı olan bireylerde, aleksitimi ve belirsizlik korkusu, tüm sosyal ortamı tehlikeli olarak görmelerine yol açabilir (Yıldız ve Güllü, 2018). Bu durum, üniversite rehberlik hizmetlerinin yalnızca akademik destek sağlamakla kalmayıp, bireylerin belirsizlikle başa çıkmalarına yardımcı olacak transdiagnostik müdahale programları geliştirmesini de gerektirmektedir. Mevcut literatür, psikolojik iyi oluşun belirsizliğe tolerans ile mutluluk arasındaki boşluğu doldurduğunu öne sürmektedir (Turan Torun, 2023).

Araştırmanın Amacı

Bu araştırmanın temel amacı, üniversite öğrencilerinin belirsizliğe tahammülsüzlük düzeylerinin araştırılmasıdır.

Alt Amaçlar

1. Üniversite öğrencilerinin belirsizliğe tahammülsüzlük ölçeğindeki toplam puanlar ve alt ölçek puanları (stres, olumsuz öz değerlendirme, gelecek ve pasiflik) cinsiyete göre anlamlı farklılık gösteriyor mu?

2. Üniversite öğrencilerinin Belirsizliğe Tahammülsüzlük Ölçeği'ndeki toplam puanlar ve alt ölçek puanları (stres, olumsuz öz saygı, gelecek ve pasiflik) cinsiyete göre anlamlı farklılık gösteriyor mu?

3. Üniversite öğrencilerinin belirsizliğe tahammülsüzlük ölçeğindeki toplam puanlar ve alt ölçek puanları, sınıf düzeyine göre anlamlı farklılık gösteriyor mu?

4. Üniversite öğrencilerinin Belirsizliğe Tahammülsüzlük Ölçeği'ndeki toplam puanlar ve alt ölçek puanları, sınıf düzeyine göre anlamlı farklılık gösteriyor mu?

Yöntem

Bu bölümde araştırmanın modeli, evreni/ örneklemi, veri toplama araçları ve verilerin toplanması ile ilgili bilgiler bulunmaktadır.

Araştırma modeli

Bu çalışma, genel bir araştırma tasarımı olan nicel bir araştırma yöntemini kullanarak, üniversite öğrencilerinin çeşitli değişkenlere karşı belirsizliğe tahammülsüzlük düzeyini araştırmıştır.

Evren/ Örneklem

Çalışma grubu, 2025-2026 akademik yılının bahar dönemine kayıtlı gönüllü üniversite öğrencilerinden oluşmaktadır. Örneklem seçimi, erişilebilirlik ve zaman kısıtlamaları dikkate alınarak "uygun örnekleme" yöntemi kullanılarak yapılmıştır. Buna göre, araştırma grubu, çalışmaya gönüllü olarak katılan farklı fakülte ve bölümlerden toplam 200 üniversite öğrencisinden oluşmaktadır. Örneklem grubunu oluşturan öğrenciler Tablo 1'de gösterilmiştir.

Tablo 1.

Katılımcıların Demografik Özelliklerine Göre Dağılımı

		Kişi Sayısı	Yüzde %		Kişi Sayısı	Yüzde %		Kişi Sayısı	Yüzde %
Değişken	Cinsiyet			Sınıf Düzeyi			Yaş		
	Kadın	115	57,5	Hazırlık	5	2,5	18	28	14
	Erkek	85	42,5	1. Sınıf	61	30,5	19	27	13,5
				2. Sınıf	45	22,5	20	40	20
				3. Sınıf	32	16	21	31	15,5
				4. Sınıf	48	24	22	26	13
				5. Sınıf	5	2,5	23	31	15,5
				6. Sınıf	4	2	24	7	3,5
							25	3	1,5
							26	2	1
							27	1	0,5
							29	1	0,5
							31	2	1
							34	1	0,5
Toplam		200	100		200	100		200	100

Veri Toplama Araçları

Çalışma için veri toplamak amacıyla, katılımcıların demografik özelliklerini belirlemek için araştırmacı tarafından hazırlanan bir "Kişisel Bilgi Formu" ve temel değişkenleri ölçmek için bir "Belirsizliğe Tahammülsüzlük Ölçeği" kullanılmıştır.

Belirsizliğe Tahammülsüzlük Ölçeği (BTÖ)

Freeston ve ark. (1994) tarafından geliştirilen ölçek, üniversite öğrencilerinin belirsiz durumlara karşı bilişsel, duygusal ve davranışsal tepkilerini ölçmek için kullanılmıştır. Türk Kültürü Ölçeği'nin geçerliliği ve güvenilirliği üzerine bir çalışma Sarı (2007) tarafından yapılmıştır. Sarı ve Dağ (2009) tarafından Türkçeye çevrilen bu ölçek, 5'li likert tipinde ve dört alt ölçekten oluşan 27 maddeden oluşmaktadır. Geçerlilik çalışmasında, tüm ölçekler için Cronbach'ın Alfa iç tutarlılık katsayısı .93 olarak bildirilmiştir. Bu çalışmada elde edilen veriler üzerinde yapılan analizde ise iç tutarlılık katsayısı .94ahmin edilmiştir.

Bulgular

Bu bölümde, çalışmaya katılan öğrencilerden toplanan verilerin istatistiksel analiz sonuçları sunulmaktadır. Çalışmanın sonuçları aşağıdaki sırayla sunulmuştur: veri toplama aracının güvenilirliği, katılımcıların demografik özellikleri, tanımlayıcı istatistikler, normal dağılım, grup karşılaştırmaları (varyans analizi) ve değişkenler arasındaki ilişkiler.

Güvenilirlik

Araştırmada veri toplama aracı olarak kullanılan "Belirsizliğe Tahammülsüzlük Ölçeği"nin (BTÖ) ölçmek istediği yapıyı ne derece tutarlı ve hatasız ölçtüğünü kanıtlamak amacıyla yapılan güvenilirlik analizi sonuçları Tablo 1'de gösterilmiştir.

Tablo 1

Ölçek Güvenilirlik Analizi Sonuçları

	Cronbach's α
scale	0.942

Tablo 1'de gösterildiği gibi, ölçeğin Cronbach'ın Alfa iç tutarlılık katsayısı 0,942'dir. Literatürde 0,70 ve üzeri değerlerin güvenilir kabul edildiği göz önüne

alındığında, veri toplama aracının oldukça güvenilir olduğu ve ölçmeyi amaçladığı yapıyı tutarlı bir şekilde yansıttığı belirlenmiştir.

Cinsiyet Ve Sınıf Düzeyi Dağılımı

Araştırma örneklemini oluşturan 200 öğrencinin cinsiyet açısından dengeli bir dağılım gösterip göstermediğini betimlemek amacıyla elde edilen veriler Tablo 2'de gösterilmiştir

Örnekleme dahil olan öğrencilerin hazırlık sınıfından 6. sınıfa kadar olan akademik seviyelerinin sayısal dağılımı Tablo 3'te gösterilmiştir.

Tablo 2

Katılımcıların Cinsiyet Dağılımı

Cinsiyet	Counts	% of Total	Cumulative %
Erkek	85	42.5%	42.5%
Kadın	115	57.5%	100.0%

Tablo 3

Katılımcıların Sınıf Düzeylerine Göre Dağılımı

Sınıf	Counts	% of Total	Cumulative %
1	61	30.5%	30.5%
2	45	22.5%	53.0%
3	32	16.0%	69.0%
4	48	24.0%	93.0%
5	5	2.5%	95.5%
6	4	2.0%	97.5%
Hazırlık	5	2.5%	100.0%

Çalışmaya katılanların cinsiyet dağılımına bakıldığında, grubun %57,5'inin kadın (n=115) ve %42,5'inin erkek (n=85) olduğu görülmüştür. Katılımcıları sınıf düzeyine göre sınıflandırdığımızda ise en yüksek katılım oranı %30,5 ile birinci sınıf öğrencilerinde ve %24 ile dördüncü sınıf öğrencilerinde olmuştur. Sosyal bilimler araştırmaları örnekleminde cinsiyet dengesinin olduğu söylenebilir. Bununla birlikte, özellikle üniversite hayatının başlangıç ve son aşamaları olan birinci ve dördüncü yıllarda katılımın yoğunlaşması, öğrencilerin bu dönemlerde araştırmaya ilgi duyduklarını göstermektedir. Bu durum, eğitimin ilk ve son yıllarındaki belirsizlik faktörünün öğrencilerin bu tür araştırmalara katılma isteğini etkilemesiyle açıklanabilir.

Toplam Puanlara İlişkin Betimsel İstatistikler ve Normallik Testi Sonuçları

Katılımcıların belirsizliğe tahammülsüzlük düzeylerinin ortalamasını belirlemek ve verilerin "normal dağılım" sergileyip sergilemediğini (Shapiro-Wilk) test etmek için yapılan analizler Tablo 4 ve Tablo 5'te gösterilmiştir.

Tablo 4

Betimsel Analiz

	BTO_Toplam
N	199
Missing	1
Mean	81.6
Median	82.0
Standard deviation	20.4
Minimum	25.0
Maximum	125
Skewness	-0.286
Std. error skewness	0.172
Kurtosis	-0.501
Std. error kurtosis	0.343

Tablo 5

Normallik Testi

	BTO_Toplam
Skewness	-0.286
Std. error skewness	0.172
Shapiro-Wilk W	0.984
Shapiro-Wilk p	0.021

Çalışmada kullanılan ölçekten elde edilen toplam puanın ortalaması 81,60 (SD = 20,4) olarak hesaplanmıştır. Puanların dağılımını belirlemek için yapılan Shapiro-Wilk testi 0,984 (p = 0,021) değerini vermiştir. Bu p değeri verilerin normal dağılımdan hafifçe sapma gösterdiğini belirtse de, çarpıklık değeri -0,286 ve basıklık değeri -0,501'dir. Bu değerler -1 ile +1 arasında değişmekte olup, normdan sapmanın önemli olmadığını göstermektedir. Bununla birlikte, çalışmanın bilimsel geçerliliğini korumak için, analize devam etmek amacıyla Mann-Whitney U testi gibi parametrik olmayan bir test kullanılmasına karar verilmiştir. Ayrıca, ölçekteki olası puanların 27 ile 135 arasında değiştiği göz önüne alındığında, 81,60'lık ortalama puan, katılımcıların belirsizlik düzeyinin ortalamanın biraz üzerinde olduğunu göstermektedir.

Cinsiyete Göre Toplam Puan Farklılaşması

Belirsizliğe tahammülsüzlük düzeyinin kadın ve erkek öğrenciler arasında istatistiksel olarak anlamlı bir farklılık gösterip göstermediğini belirlemek amacıyla yapılan fark analizi sonuçları Tablo 6 ve Tablo 7'de gösterilmiştir.

Tablo 6

Cinsiyete Göre Farklılık (Independent Samples T-Test)

		Statistic	p
BTO_Toplam	**Mann-Whitney U**	4325	0.196

Note. $H_a\ \mu_{Erkek} \neq \mu_{Kadın}$

Tablo7:

Cinsiyete Göre Farklılık (Group Descriptives)

	Group	N	Mean	Median	SD	SE
BTO_Toplam	**Erkek**	85	79.1	81.0	21.4	2.33
	Kadın	114	83.5	82.5	19.4	1.81

Cinsiyet ile Belirsizliğe Tahammülsüzlük Ölçeği puanları arasındaki ilişkiye dair yapılan analizde, gruplar arasında istatistiksel olarak anlamlı bir fark bulunmadığı tespit edildi (U = 4325.0, p = .196). Analizden elde edilen p değeri >.05 olup, bu da kadın ve erkek öğrencilerin belirsizliğe karşı benzer tolerans seviyelerine sahip olduğunu göstermektedir. Literatürdeki bazı çalışmalar kadınların daha yüksek stres seviyelerine sahip olduğunu öne sürse de, bu çalışmanın sonuçları, belirsizliğe karşı tutumların cinsiyetten ziyade bireysel özellikler, başa çıkma mekanizmaları ve öğrencilerin yaşadığı eğitim ortamıyla daha yakından ilişkili olabileceğini göstermektedir. Bu bulgu, çalışmanın başında ortaya atılan "cinsiyetin belirsizliğe tahammülsüzlük üzerinde belirleyici bir etkisi yoktur" hipotezini doğrulamaktadır.

Tablo 6

Sınıf Düzeyine Göre Toplam Puan Farklılaşması (Tek Yönlü ANOVA)

	F	df1	df2	p
BTO_Toplam	1.66	6	18.5	0.186

Analiz sonuçları, üniversite öğrencilerinin sınıf düzeyleri (Hazırlık, 1., 2., 3., 4., 5., 6. yıl) ile toplam belirsizlik puanı arasında istatistiksel olarak anlamlı bir fark olmadığını ortaya koymuştur (F(6, 18.5) = 1.66, p = .186). Elde edilen p değeri (.186), standart anlamlılık düzeyi olan .05'ten daha büyüktür; bu da öğrencilerin akademik aşamalarının (ilköğretim, ortaöğretim ve lisansüstü aşamaları) belirsizliğe karşı tutumları üzerinde belirleyici bir etkiye sahip olmadığını göstermektedir. Bu durum, üniversite yaşamının genel yapısı nedeniyle her sınıfta benzer akademik ve geleceğe yönelik belirsizliğin ortaya çıkmasıyla açıklanabilir.

Yaş ve Alt Boyutlar Arasındaki İlişki (Korelasyon Matrisi)

Araştırmadaki tüm değişkenlerin (yaş ve dört alt boyut) birbirleriyle olan ilişkisini tek bir tabloda ortaya koyan veriler Tablo 7'de gösterilmiştir.

Tablo 7

Korelasyon Matrisi

		YAS	BTO_Stres	BTO_Benlik	BTO_Gelecek	BTO_Eylemsizlik	BTO_Toplam
YAS	Pearson's r	—					
	df	—					
	p-value	—					
	Spearman's rho	—					
	df	—					
	p-value	—					
BTO_Stres	Pearson's r	53	—				
	df	198	—				
	p-value	454	—				
	Spearman's rho	124	—				
	df	198	—				
	p-value	80	—				
BTO_Benlik	Pearson's r	45	658	—			
	df	198	198	—			
	p-value	526	<.001	—			
	Spearman's rho	68	647	—			
	df	198	198	—			
	p-value	337	<.001	—			
BTO_Gelecek	Pearson's r	68	752	659	—		
	df	198	198	198	—		
	p-value	340	<.001	<.001	—		
	Spearman's rho	119	752	648	—		
	df	198	198	198	—		
	p-value	93	<.001	<.001	—		
BTO_Eylemsizlik	Pearson's r	73	730	710	682	—	
	df	198	198	198	198	—	
	p-value	307	<.001	<.001	<.001	—	
	Spearman's rho	163	720	688	675	—	
	df	198	198	198	198	—	
	p-value	21	<.001	<.001	<.001	—	
BTO_Toplam	Pearson's r	64	912	877	853	863	—
	df	198	198	198	198	198	—
	p-value	368	<.001	<.001	<.001	<.001	—
	Spearman's rho	148	903	869	853	853	—
	df	198	198	198	198	198	—
	p-value	36	<.001	<.001	<.001	<.001	—

İncelenen değişkenler arasındaki ilişkilerin yönünü ve büyüklüğünü belirlemek için yapılan korelasyon analizleri, katılımcıların yaşı ile Belirsizliğe Tahammülsüzlük Ölçeği'nin (IUS) toplam puanı ve alt ölçekleri arasında istatistiksel olarak anlamlı bir ilişki olmadığını ortaya koymuştur ($r = .081$, $p = .253$). Yaş ve belirsizlik puanları arasındaki bu anlamsız ilişki, 18-24 yaş arası bireylerin üniversite eğitim yıllarını kapsayan bu bilişsel yapının, yaşa bağlı gelişim süreçlerinden ziyade bireysel farklılıklar tarafından belirlendiğini düşündürmektedir.

Tartışma, Sonuç ve Öneriler

Bu çalışma, üniversite öğrencilerinin belirsizliğe tahammülsüzlük düzeyini cinsiyet, yaş ve ölçeğin alt ölçekleri arasındaki ilişki açısından incelemiştir. Sonuçlar, literatürdeki benzer çalışmalarla tutarlıdır ve üniversite örneklemine özgü bazı ilginç bulgular ortaya koymaktadır.

Çalışmanın en önemli bulgularından biri, üniversite öğrencilerinin belirsizliğe tolerans puanlarının cinsiyet değişkenine bağlı olarak anlamlı bir farklılık göstermemesidir ($p > .05$). Literatür taraması, belirsizliğe tahammülsüzlük ile cinsiyet arasındaki ilişki konusunda karışık sonuçlar göstermektedir. Bazı çalışmalar kadınların belirsizliğe daha duyarlı olduğunu ve daha yüksek kaygı düzeylerine sahip olduğunu savunurken (Sarı & Dag, 2009), diğer çalışmalar bunun cinsiyetten ziyade bireysel başa çıkma stratejilerinden kaynaklandığını öne sürmektedir. Mevcut çalışmanın sonuçları, üniversite hayatında ortaya çıkan akademik sorumluluklar, gelecek kaygıları ve sosyal uyum süreçlerinin hem kadın hem de erkek öğrenciler için benzer belirsizlik baskıları yarattığını göstermektedir.

Yaş ile belirsizliğe tahammülsüzlük arasındaki düşük korelasyon, bu psikolojik yapının üniversite yıllarının kronolojik olgunlaşmasından ziyade istikrarlı bir bilişsel şema olduğunu düşündürmektedir. Katılımcıların çoğunluğu genç yetişkinlerden (18-24 yaş arası) oluşmaktaydı; bu da grubun benzer gelişimsel hedeflerle (kariyer planlaması, kişilik özellikleri) karşı karşıya olduğunu göstermektedir. Bu anlamda, belirsizliğe tahammülsüzlüğün yaşla birlikte azalmadığı, aksine bireylerin bu yapıyı transdiagnostik bir mekanizma olarak koruduğu söylenebilir.

Ölçeğin alt ölçekleri (Stres, Olumsuz Benlik Algısı, Gelecek Hakkında Belirsizlik ve Hareketsizlik) arasındaki yüksek korelasyonlar ($r > .60$), belirsizliğe tahammülsüzlüğün ayrı bir yapı değil, karmaşık bir etkileşim olduğunu göstermektedir. Özellikle "Hareketsizlik" ve "Stres" boyutları arasındaki güçlü korelasyonlar, belirsizliğe karşı güçlü duygusal tepkiler veren öğrencilerin karar verme ve eylem süreçlerinde felç olduklarını göstermektedir. Bu durum, psikolojik danışmanlık ve rehberlik (PDR) literatüründe sıklıkla vurgulanan "karar verme güçlükleri" ve "erteleme" ile doğrudan ilişkilendirilebilir. Belirsizliği bir eksiklik olarak algılayan (Negatif Benlik Kavramı) öğrenciler strese girer ve bu nedenle harekete geçmekten kaçınırlar.

Son olarak, Belirsizlik Toleransı Testi'nin (UTT) transdiagnostik doğası göz önüne alındığında, bu çalışmada elde edilen yüksek ortalama puanlar ($M=81,60$), üniversite öğrencilerinin sadece akademik performans açısından değil, genel psikolojik iyilik halleri açısından da risk altında olabileceğini göstermektedir. Belirsizliğe düşük tolerans, insanları yaygın anksiyete bozukluğu ve obsesif-kompulsif bozukluk gibi klinik durumlara karşı daha savunmasız hale getirir (Yığman ve Fidan, 2021). Bu noktada, üniversite psikolojik danışmanlık birimlerinin öğrencilerin belirsizlikle başa çıkmalarına ve direnç geliştirmelerine yardımcı olmak için yapılandırılmış müdahaleler sunmaları gerekmektedir.

Üniversite öğrencilerinin belirsizliğe tahammülsüzlüğünü inceleyen bu çalışma, öğrencilerin belirsizliğe ilişkin genel anlayışlarının ortalamanın üzerinde olduğu sonucuna varmıştır. Analiz, cinsiyet ve kronolojik yaşın belirsizliğe tahammülsüzlükte belirleyici bir rol oynamadığını; bu bilişsel yapının demografik özelliklerden bağımsız olarak benzer bir seyir izlediğini göstermiştir. Bu durum, üniversite hayatıyla ilişkili akademik sorumlulukların ve geleceğe yönelik planlama sürecinin tüm öğrenciler için benzer psikolojik baskılar yaratmasıyla açıklanabilir. Ölçeğin alt ölçekleri arasındaki güçlü korelasyonlar, belirsizliğin yalnızca duygusal stres kaynağı olmadığını, aynı zamanda doğrudan öz-eyleme yol açan karmaşık bir mekanizma olduğunu ve olumsuz öz-değerlendirmelerle birleştiğinde kısır bir döngü oluşturduğunu göstermektedir. Sonuç olarak, belirsizliğe tahammülsüzlük, öğrencilerin kaygı düzeylerini sınırlamakla kalmayıp, karar verme mekanizmalarını ve genel psikolojik durumlarını da etkileyen, tanı ötesi bir faktör haline gelmektedir.

Çalışmanın genel sonuçlarına dayanarak, her bir istatistiksel sonuç için aşağıdaki önerilerde bulunulabilir:

1. Kullanılan ölçeğin iç tutarlılık katsayısının oldukça yüksek (0,942) olduğu sonucuna dayanarak, bu ölçeğin üniversite psikolojik danışmanlık merkezlerinde öğrencilerin belirsizlik kaygısını ölçmek ve risk gruplarını belirlemek için standart bir tarama aracı olarak kullanılması önerilebilir.

2. Araştırmaya katılımın üniversiteye yeni başlayan (birinci sınıf) ve mezuniyete yaklaşan (dördüncü sınıf) öğrenciler arasında yoğunlaştığı bulgularına dayanarak, bu geçiş dönemlerindeki öğrenciler için "üniversiteye uyum" ve "mesleki hazırlık" konularında destek sağlayacak özel programlar oluşturulmalıdır.

3. Öğrencilerin belirsizliğe tolerans puanlarının ortalamanın üzerinde olduğu bulguları ışığında, öğrencilerin psikolojik dayanıklılıklarını ve stresle başa çıkma becerilerini artırmak amacıyla kampüs genelinde önleyici psiko-eğitim atölyeleri düzenlenmesi önerilir.

4. Kız ve erkek öğrenciler arasında belirsizliğe tahammülsüzlük düzeyinde anlamlı bir fark bulunmadığı bulgusuna dayanarak, psikolojik destek ve müdahale programlarının belirli cinsiyet özelliklerine odaklanmak yerine, tüm öğrencileri kapsayan evrensel temalar üzerine kurulması önerilmektedir.

5. Sınıf düzeyinin belirsizliğe tahammül etme yeteneğini önemli ölçüde etkilemediği (tüm sınıf düzeylerinde benzer kaygı seviyeleri gözlemleniyor) bulgusu göz önüne alındığında, üniversitelerdeki psikolojik destek hizmetleri, oryantasyon ve mezuniyet dönemleriyle sınırlı kalmak yerine, tüm lisans eğitim yılı boyunca yaygınlaştırılmalıdır.

6. Yaş ile belirsizliğe tahammülsüzlük arasında anlamlı bir ilişki bulunmadığı bulgusuna dayanarak, psikolojik müdahaleler öğrencilerin kronolojik yaşlarından ziyade bireysel başa çıkma stratejilerine ve duygusal dayanıklılıklarına odaklanmalıdır.

7. Stres, olumsuz benlik algısı, gelecek kaygısı ve pasiflik gibi alt ölçekler arasında güçlü pozitif korelasyonlar göz önüne alındığında, klinik araştırmalar yalnızca kaygıyı azaltmakla kalmayıp aynı zamanda öğrencilerin özgüvenini artıran ve karar verme sürecinde "pasifliği" aşmalarını sağlayan bilişsel-davranışçı müdahalelere öncelik vermelidir.

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STATE AND LAW

IMPROVING THE LABOR LEGISLATION OF THE REPUBLIC OF KAZAKHSTAN: INTERNATIONAL EXPERIENCE AND THE USE OF ARTIFICIAL INTELLIGENCE TOOLS

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Abstract

This article examines the issues of improving the labor legislation of the Republic of Kazakhstan through the lens of international experience and the application of artificial intelligence tools. At the present stage, the transformation of labor relations, the rapid development of digitalization processes, and the emergence of new labor market formats necessitate the modernization of labor legislation. In this regard, the study analyzes the comparison of national labor legislation with international legal standards, as well as modern approaches to improving the legal regulation of labor relations. The research explores best practices in the labor legislation of leading countries and assesses the possibilities of adapting them to the legal system of Kazakhstan. In addition, the potential of using artificial intelligence technologies is examined for the purposes of analyzing legal norms, identifying legislative inconsistencies, and enhancing law enforcement practices in the field of labor relations. Artificial intelligence tools enable the acceleration of legal information processing, the identification of inconsistencies between regulatory legal acts, and the determination of directions for the systematic updating of labor legislation.

Keywords: labor legislation, labor relations, legal regulation, international experience, artificial intelligence, legal analysis, labor code reform.

At the present stage, the nature of labor relations is undergoing significant transformation as a result of globalization, digitalization, and structural changes in the labor market. The development of the digital sectors of the economy, the expansion of remote work formats, and the emergence of platform-based employment models necessitate the formation of new approaches to the legal regulation of labor relations. In this context, the issue of improving the labor legislation of the Republic of Kazakhstan and aligning it with international legal standards has become particularly relevant. The labor legislation of the Republic of Kazakhstan is aimed at protecting the rights and freedoms of employees, ensuring the stability of labor relations, and maintaining a legal balance between employers and employees. However, current socio-economic conditions and changes in the labor market require further improvement of national labor legislation. In this regard, it is important to study the experience of developed countries, take into account the labor standards of international organizations, and introduce effective mechanisms of legal regulation.

In addition, in recent years, the use of artificial intelligence technologies in legal research and law enforcement practice has become widespread. Artificial intelligence is considered an important tool for systematizing legal norms, identifying inconsistencies between regulatory legal acts, analyzing judicial practice, and assessing the effectiveness of legislative reforms. In this regard, the application of artificial intelligence tools in the process of improving labor legislation makes it possible to enhance the quality of legal analysis and strengthen the scientific validity of legislative reforms.

The purpose of this study is to identify the main directions for improving the labor legislation of the Republic of Kazakhstan based on international experience and to provide a scientific justification for the use of artificial intelligence tools in legal analysis. The study employs comparative legal analysis, system analysis, and legal modeling methods, and develops scientific recommendations aimed at improving labor legislation.

At the present stage, the use of digital technologies and artificial intelligence tools in the system of legal regulation is rapidly developing. Artificial intelligence enables the effective processing of legal information, the analysis of regulatory acts, and the identification of legal inconsistencies.

Artificial intelligence technologies can perform several important functions in the analysis of labor legislation. First, artificial intelligence makes it possible to analyze large volumes of regulatory legal acts and identify inconsistencies between them. This plays an important role in systematizing and improving labor legislation.

Second, artificial intelligence can identify key trends in law enforcement practice by analyzing judicial practice related to labor disputes. Such analysis makes it possible to identify problematic provisions in labor legislation and to develop scientifically grounded recommendations for their improvement.

Third, artificial intelligence enables the study of international experience through comparative legal analysis. For example, by automatically comparing the labor legislation of different countries, it becomes possible to identify effective models of legal regulation of labor relations [1].

In the context of globalization, aligning national labor legislation with international standards is one of the key conditions for ensuring social stability and economic development. From this perspective, the labor legislation of the Republic of Kazakhstan is also evolving towards improving the legal regulation of labor relations, taking into account international labor norms and principles. Therefore, a scientific analysis of the main issues, challenges, and possible solutions related to aligning Kazakhstan's labor legislation with international standards is of particular relevance.

The process of reforming the Labor Code plays an important role in improving the system of labor law in the Republic of Kazakhstan and enhancing the effectiveness of legal regulation of labor relations. These reforms are directly linked to the need to incorporate international labor standards into the national legal system and to adapt legislation to global requirements. At the same time, legal regulation in the field of labor not only ensures the protection of workers' rights but also contributes to increasing the investment attractiveness of the state. In this regard, improving labor legislation in accordance with international standards is one of the key factors in ensuring social justice and sustainable economic development [2].

The labor legislation of the Republic of Kazakhstan must comply with international legal norms and principles, as this serves as a prerequisite for the country's integration into the global legal space, the protection of citizens' labor rights, and the promotion of social justice. In this context, international labor standards, particularly the conventions and recommendations adopted by the International Labour Organization (ILO), play a significant role.

One of the key functions of the ILO is the development of international labor standards aimed at ensuring fairness and equality in the field of labor. These standards primarily focus on safeguarding human rights within labor relations between employees and employers. Core issues of labor law addressed in these standards include the prohibition of forced labor, the elimination of child labor, the prevention of discrimination, freedom of association, and the right to collective bargaining.

International experience shows that the continuous updating of labor legislation is essential for responding to the dynamic development of the labor market in the context of globalization. In this regard, the 2015 Labor Code of the Republic of Kazakhstan was aimed at ensuring flexible regulation of labor relations and maintaining a legal balance between employers and employees [3]. However, some provisions of this Code are not yet fully aligned with international labor standards. In particular, issues related to working time and rest periods, the legal protection of workers in the informal sector, and the insufficient development of social dialogue institutions remain relevant challenges.

Since 1993, as a member of the International Labour Organization, the Republic of Kazakhstan has ratified a number of important conventions. These include Convention No. 29 on Forced or Compulsory Labour; Convention No. 87 on Freedom of Association and Protection of the Right to Organise; Convention No. 98 on the Right to Organise and Collective Bargaining; Convention No. 100 on Equal Remuneration; Convention No. 111 on Discrimination in Employment and Occupation; and Conventions No. 138 and No. 182 aimed at the elimination of child labor [4].

These international norms have been incorporated into the Labor Code of the Republic of Kazakhstan. For instance, the Code explicitly prohibits discrimination based on gender, nationality, religion, or social status (Article 6 of the Labor Code of the Republic of Kazakhstan). In addition, employers are obliged to ensure working conditions that meet occupational safety and health requirements (Articles 180–184 of the Labor Code) [3].

Furthermore, the organization of trade union activities, the conclusion of collective agreements, and mechanisms for the peaceful resolution of labor disputes are also legally established in accordance with international legal requirements. This reflects Kazakhstan's commitment to fulfilling its social obligations to the international community.

However, the incorporation of international norms into national legislation should not be limited to formal alignment. The practical implementation of these norms, their support through effective legal mechanisms, and their realization at the institutional level are of paramount importance. In this regard, the incomplete implementation of certain international standards in Kazakhstan - such as restrictions on the free functioning of trade unions or the high share of informal labor relations - may reduce the effectiveness of labor legislation.

In general, international labor standards have been taken into account and incorporated into the labor legislation of the Republic of Kazakhstan to a certain extent. Nevertheless, there remains a need to deepen their substantive content, improve implementation mechanisms, and bring law enforcement practices closer to international standards. This is an important step toward enhancing the protection of labor rights and ensuring social justice [5].

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One of the key functions of the ILO is the development of international labor standards aimed at ensuring fairness and equality in the field of labor. These standards are designed to guarantee the observance of human rights in labor relations between employees and employers. Core issues of labor law addressed in these standards include the prohibition of forced labor, the

restriction of child labor, the prevention of discrimination, freedom of association, and the right to collective bargaining.

Since 1993, the Republic of Kazakhstan, as a member of the ILO, has ratified a number of important conventions. According to 2024 data, Kazakhstan has ratified 29 ILO conventions, including all 8 fundamental conventions. This represents a significant step in fulfilling international obligations [4].

These international norms are reflected in the Labor Code of the Republic of Kazakhstan. For example:

- Article 6 prohibits discrimination;
- Articles 180-184 regulate occupational safety and health;
- Article 154 guarantees the non-restriction of trade union activities;
- Article 159 defines the procedure for collective bargaining;
- Article 203 provides for state control over labor protection [3].

In addition, according to the Ministry of Labor and Social Protection, as of 2022, more than 16,000 collective agreements are officially registered in the country. This indicator reflects the level of development of collective mechanisms for protecting workers' rights. However, these agreements do not cover all workplaces - more than 20% of workers are employed in the informal sector, which hinders full compliance with international standards. Furthermore, the legal mechanisms and human resource capacity of the labor inspectorate may not fully meet international requirements, which reduces the effectiveness of supervision and legal protection mechanisms [6].

Judicial practice is an important indicator of the effective implementation of international norms. For example, according to the Supreme Court's 2023 review, the majority of labor disputes concern the legality of termination of employment contracts, delayed wage payments, and unlawful dismissal. In such cases, courts often refer to ILO conventions; however, the lack of well-developed enforcement mechanisms complicates the execution of certain decisions. In addition, the development of alternative dispute resolution mechanisms, such as mediation and arbitration, should also be aligned with international practice [7].

The results of the study demonstrate that improving the labor legislation of the Republic of Kazakhstan is a highly relevant issue at the present stage. In the context of globalization, the content and structure of labor relations are changing, and new legal relations are emerging in the labor market. Therefore, aligning national labor legislation with international labor standards and developing effective mechanisms for legal regulation of labor relations are among the key priorities.

The analysis of international experience conducted in this study highlights the importance of international labor standards in forming an effective system of legal regulation in the labor sphere. In particular, the full implementation in national legislation of principles such as the protection of workers' rights, ensuring occupational safety, preventing discrimination, and developing social partnership constitutes one of the main directions for improving labor legislation.

At the same time, the use of digital technologies, including artificial intelligence tools, in the legal regulation system enhances the effectiveness of legislative analysis. Artificial intelligence technologies facilitate the systematization of regulatory legal acts, the identification of legal inconsistencies, and the analysis of law enforcement practice. This, in turn, strengthens the scientific basis of labor law reform and improves the overall quality of legal regulation.

Thus, the improvement of the labor legislation of the Republic of Kazakhstan should be carried out by taking into account international experience, regulating new forms of labor relations, and applying modern technologies in legal analysis. The implementation of these approaches will enhance the effectiveness of legal regulation of labor relations, strengthen the protection of workers' rights, and ensure the sustainable development of labor policy.

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