ISSN 3030-1831

Luminis Applied Science and Engineering

Vol. 3 No. 1 (2026): Spring Issue

Spring Advances in Appiled Science and Engineering

Published quarterly in four seasonal issues

Luminis Applied Science and Engineering

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Vol. 3 No. 1 (2026): ISSN 3030-1831

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Luminis Applied Science and Engineering
ISSN: 3030-1831
Vol 3, No 1, 2026

Motivation in Human Resource Management

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https://doi.org/10.69760/lumin.2026001001

Abstract; Motivation plays a central role in human resource management because it directly shapes employee performance, commitment, and retention. As a core managerial function, motivation enables an enterprise to accomplish organizational tasks through a structured system of incentives and supportive measures. A well-designed motivation system requires managers to apply relevant motivational theories, which help explain how employees' behavior can be influenced and guided more effectively. Importantly, these theories also demonstrate that financial rewards are not the only drivers of work behavior: employees differ in their needs, expectations, and values, which makes it necessary to employ varied motivational instruments to sustain engagement and reduce turnover.
In recent years, attention to motivation as a management function has grown considerably. Many organizations now prioritize motivational practices in order to strengthen effectiveness and improve overall productivity. The successful operation of any institution depends largely on the quality of its workforce and the professionalism of managerial leadership. For this reason, enterprises must develop improved systems of motivation and encouragement that stimulate both the collective team and each individual employee to work efficiently toward shared objectives. Sustainable success is typically achieved by leaders who recognize that people are the main driving force of organizational development. In this context, motivation can be understood as the process of encouraging employees toward productive and goal-oriented activity.

***Keywords**: approach, motivation, salary, credit, personnel*

1. INTRODUCTION

Motivation functions as an important performance-management mechanism because it supports the achievement of organizational goals through the regulation and development of employee behavior. A fundamental principle of human resource management is the recognition that human resources differ substantially from other organizational resources (e.g., material or financial assets). These differences can be summarized as follows:

1. Employees possess the capacity for continuous development and professional growth.
2. Employment relationships tend to be long-term due to the alignment or intersection of organizational and individual interests.
3. Human resources contain intellectual potential, which strongly influences innovation and decision-making.
4. Employees are able to pursue and satisfy their own needs, which shapes motivation and work behavior.
5. The individuality of employees contributes to the formation of a unique corporate culture.

Labor incentives may be divided into material and non-material forms. Material incentives remain one of the most influential tools for stimulating work behavior because they can rapidly increase employee activity and productivity. This category includes both monetary rewards (e.g., wages, bonuses, performance-based payments) and non-monetary material benefits. In particular, material incentives often involve direct cash compensation linked to work results and performance outcomes (Ashenfelter et al., 2006).

It is widely accepted that financial incentives are among the most effective mechanisms for influencing employee effort; however, non-material incentives may also carry significant moral and practical value. A major category within non-material stimulation is moral incentive, which can include social recognition, aesthetic appreciation, socio-political approval, ethical acknowledgement, and informational support. At present, moral incentives are often viewed as especially important because they communicate respect and recognition of an employee's contributions. The key function of moral stimulation is to present and reinforce information about employee merit and achievement (Amrahov, 2023).

Non-material incentives may include support for tuition and training, consulting services, life insurance, public praise, holiday recognition, incentive trips, seeking employee advice, opportunities for workplace communication, and structured knowledge transfer to younger staff. Personnel training is frequently considered a strategic foundation for organizational success. Developing employees' professional knowledge, skills, and competencies contributes to higher performance and supports the achievement of institutional goals. Training methods may vary widely and include workshops, seminars, lectures, internships, self-study, distance learning, and professional placements (Mustafiyanti et al., 2023).

2. METHODOLOGY

It is also important for managers to consult employees when making key decisions. In such situations, employees are more likely to feel that they are an essential part of the team. Successful leaders should be familiar with the main motivation theories used in management practice, because these theories help explain how to encourage employees to work voluntarily, responsibly, and effectively. Existing motivational approaches make it possible to clarify the mechanisms of stimulation and to select more appropriate tools for the motivation process (Mirzazada, 2025).

In general, motivation theories are commonly divided into two broad groups: content theories and process theories. Content theories focus on what motivates people and which factors lead them to behave in a certain way. Process theories, in contrast, explain how motivation develops through cognition, perception, and decision-making.

One well-known content approach identifies five levels of human needs: physiological needs, safety needs, social needs, esteem needs, and self-actualization needs (Amrahov et al., 2024). This system is hierarchical, meaning that each higher level becomes important only after the previous level is sufficiently satisfied. Therefore, in order for a person to remain motivated, basic needs must be met first. At the same time, once higher needs are satisfied, motivation does not simply end; the desire for self-actualization can continue to develop, which highlights the role of ongoing motivation in human life and work (Amrahov et al., 2023).

This theory can be applied in practice in several ways. The employer's task is to create comfortable working conditions and ensure that employees' work-related needs are met, such as a safe workplace, acceptable pay, and insurance. Organizations often offer different incentives that help employees "move upward" within the hierarchy. Managers who follow this approach try to meet the needs that are most relevant at a

given time. In some cases, however, employees may remain focused on lower-level needs, particularly the need for communication and belonging. In such situations, management should take timely measures to strengthen communication and interaction in the workplace so that employees can later focus on self-realization and professional development (Amrahov et al., 2023).

Another content approach divides needs into three main groups: power needs, achievement needs, and affiliation-related needs (Mirzazada, 2025). The need for power is connected to the desire to influence other people's actions. Individuals who seek power may be divided into two types: those who want dominance and strict control over others, and those who seek influence in order to achieve organizational goals by uniting employees' efforts and coordinating their work (Amrahov et al., 2023).

To use this theory effectively in practice, it is important to:

1. identify which needs are dominant for each employee (or create conditions for employees to evaluate their own needs), and

2. give employees opportunities to adjust their behavior and work approach based on this information.

Another widely applied theory is based on two groups of factors: hygiene factors and motivators. Hygiene factors include organizational policy, working conditions, salary, relations with superiors, the level of direct control over work, and social security. Motivators include success, recognition, advancement, responsibility, creativity, and opportunities for development (Amrakhov, 2022). If hygiene factors are weak or absent, employees typically become dissatisfied. If motivators are absent, employees may not necessarily feel dissatisfied, but their engagement and enthusiasm tend to decrease. In practice, assigning employees tasks is not simply about keeping them busy; the aim is to make work more meaningful and interesting, including tasks of different complexity levels (Amrahov, 2015).

Providing employees with more challenging tasks—especially within team projects—often strengthens their sense of achievement. Giving employees more authority to make decisions related to their work also increases responsibility and involvement, which can improve motivation (Ismayilov, 2019).

In addition, some approaches assume that employees are proactive, ready to accept responsibility, and that the work itself can act as a stimulus. For such employees, a key motivational method is to provide greater freedom for creativity and independence. Under these conditions, strict rules may become less necessary because employees are able to self-regulate and maintain discipline. As a result, a more democratic management style becomes effective (Mirzazada & Camalov, 2025).

Finally, it is important to consider the relationship between goals and performance. Motivation can be influenced by an employee's ability, independence, and participation in goal setting. When employees are involved in setting goals and understand their role in achieving them, goal implementation tends to be stronger. Goal-setting theory highlights that goals should be specific, challenging, supported by commitment, and acceptable (Mirzazadeh & Zeynalli, 2024). In this framework, motivation depends not only on needs, but also on the employee's thinking process—how they evaluate the realism of achieving the goal and receiving a reward. If employees believe that effort will lead to a real reward, their performance usually increases (Amrahov et al., 2025).

For example, employees preparing for professional development exams may become more motivated if previous promotions were successful and resulted in salary increases. In this case, motivation is supported

by self-confidence, positive experience, and the desire to earn additional bonuses (Abbasova et al., 2025). On the other hand, if an employee doubts that training will be completed successfully or that it will lead to future rewards, motivation decreases. Expectancy theory helps explain how employees choose between behavioral alternatives at work and why the credibility of rewards is essential for effective motivation.

3. RESULTS

The major practical value of motivation theory lies in the idea that rewards should be clearly connected to performance and that the procedure for selecting and distributing rewards must be understandable, transparent, and perceived as earned and meaningful. At the same time, employees' evaluations of fairness are often highly subjective: it may seem to an employee that someone received a larger bonus or more recognition, even when the system is formally consistent. As a result, psychological tension can arise, and managing motivation becomes more difficult under conditions of perceived inequality (Crompton, 2006).

In many cases, an automatic behavioral reaction appears: employees who believe they are rewarded unfairly tend to reduce their work intensity, whereas those who perceive rewards as fair usually maintain or even increase their performance. In such situations, it is important to explain why salary and reward differences exist—for example, by emphasizing that higher pay is linked to greater experience, higher productivity, or stronger responsibility, and that employees have opportunities to increase earnings through professional development and improved results. Some organizations attempt to avoid conflict by keeping bonuses confidential (for instance, distributing them in envelopes). However, practice shows that secrecy does not always solve the problem and may even create additional distrust and informal speculation (Zubareva & Pilipenko, 2016).

A key aspect of how employees evaluate their position in an organization is comparison: people naturally compare their rewards with the rewards of others. If an employee observes what appears to be an obvious injustice, motivation usually declines rapidly. In this context, elements associated with expectancy theory and fairness-oriented approaches may be summarized as follows (Yermekova et al., 2024):

1. **Probability of payment**—the employee's internal belief that effort will actually be rewarded;
2. **Extrinsic reward**—material components of reward (salary, bonuses, awards, promotion, etc.);
3. **Intrinsic reward**—non-material motivation (praise, recognition, authority, leadership opportunities, honor boards, etc.);
4. **Perception**—the value of the reward to the employee and attitude toward the promised compensation;
5. **Effort expended**—the level of activity, dedication, and intensity of work;
6. **Expected reward**—the employee's personal forecast of what reward should follow;
7. **Results**—quality, quantity, and time spent on the work performed;
8. **Employee role**—the nature and complexity of assigned tasks;
9. **Satisfaction level**—the match between expectations and the real evaluation of one's work;
10. **Competence level**—knowledge, skills, and the ability to use tools required for task completion.

These elements are interconnected. In general, employees increase effort when they believe the expected reward is realistic and proportional to their contribution. However, motivation alone is not sufficient to reach high performance: skills, abilities, and professional competence are also decisive. If employees do not understand their role or lack necessary tools and competencies, effective results are unlikely. At the same time, employees' self-evaluation strongly affects expectations: the higher they evaluate their contribution, the more they expect from management. Therefore, the morale and satisfaction of employees depend both on the effort they invest and on the fairness and clarity of the reward system. When tasks are set correctly and performance is evaluated objectively, work results create satisfaction, and satisfaction, in turn, supports stable performance. A fairly assessed salary remains one of the key factors that positively influences staff efficiency and satisfaction with working conditions (Amrahov, 2014).

4. DISCUSSION

In economic and social science literature, there is still no single agreed interpretation of the concepts motive, motivation, and incentive. Different disciplines—economics, sociology, and psychology—approach motivation from different perspectives. Some scholars treat motivation and labor stimulation as identical, others oppose these categories, and some consider stimulation to be only one method within a broader motivational system.

Because motives are internal and incentives/stimuli are external influences that shape employees' attitudes to work, it is not accurate to equate the concepts of "motive" and "incentive." Motivation may be defined as a process through which individuals encourage themselves and others to act in order to achieve personal and organizational goals. A motive, on the other hand, is the inner reason that causes a person to act in a particular way. Motives have a subjective, personal nature and are formed under the influence of multiple internal and external factors, including other motives that may arise simultaneously. A motive not only pushes a person toward action but also shapes what exactly should be done and how the action will be carried out. Importantly, motives are conscious: individuals can influence their motives, suppress them, or even replace them with new ones (Amrakhov et al., 2022).

Human behavior is rarely determined by a single motive; rather, it is usually shaped by a combination of motives that differ in strength and influence. For this reason, we can speak about a person's motivational structure. Incentives, in turn, act as means of influence that activate certain motives. In practice, incentives may include any benefits surrounding labor activity; when a benefit becomes meaningful for the worker, it turns into a stimulus that strengthens motivation. In other words, labor motives are closely connected with the desire to obtain certain benefits through work.

The use of different stimuli to activate employees is commonly described as the stimulation process. The aim of motivation is not simply to make a person work, but to encourage them to work better, more effectively, and with stronger commitment. Achieving this goal requires a systematic approach in which stimulation mechanisms are carefully selected and applied. Modern motivational approaches are generally based on ideas developed within economic science, which studies the mechanisms of purposeful behavior. From this viewpoint, motivation is often defined as the driving force of behavior formed through the relationship between needs, motives, and goals.

The motivation process is usually explained through these concepts:

- **Needs** represent a state of lack or requirement for something essential for existence and functioning.

- **Motives** are internal drivers that push a person toward action aimed at results.
- **Goals** are desired outcomes or states that an individual strives to achieve.

Although models describing this process provide a useful general framework, real motivational behavior is often more complicated. Motives may change over time and are shaped by a wide range of factors such as personal abilities, education, social status, financial situation, and public opinion.

As a management function, motivation is realized through an incentive system, meaning that any action of an employee may produce positive or negative consequences related to need satisfaction and goal achievement. Team learning and development can help leaders build a more effective motivational structure by guiding the workforce in the desired direction and strengthening shared organizational values (Amrahov et al., 2022).

Finally, if an enterprise aims to function effectively, it must professionally study and analyze employee motivation. Without such analysis, management cannot understand the motivational level of each employee or the team as a whole. For this reason, the concepts of "motivation" and "stimulation" are used not only to describe the formation of motives at individual and group levels, but also to describe the process through which external stimuli influence internal motives in order to achieve the required level of motivation.

5. CONCLUSION

The significance of motivation as a management issue corresponds to the attention it receives in scientific management theory. In contemporary research, motivation theories are commonly divided into content and process approaches. Content theories focus on identifying human needs and personal motives that encourage individuals to act in particular ways. Process theories do not deny that behavior is driven by needs and motives; rather, they emphasize how people choose specific behaviors, taking into account cognition, expectations, and perception (Bulatova, 2010).

In general, many motivational models distinguish between two broad groups of needs: primary needs, which are linked to physiological factors, and secondary needs, which are psychological in nature. Physiological needs are basic and usually require satisfaction first. Once these needs are met, the need for security becomes more relevant as individuals seek stability and protection from unfavorable conditions or threatening behaviors. After this, social needs emerge—often described as the need for belonging and spiritual closeness—because individuals aim to establish friendly relationships and define their place within a group. As satisfaction grows, factors supporting respect and self-esteem become increasingly important. At this stage, people need to feel significant and to receive recognition from others. The hierarchy is typically completed by self-actualization needs, which reflect an individual's desire to realize personal potential, mobilize abilities, and fulfill life goals. Since needs at one level are only partially satisfied, higher-level needs may become dominant; therefore, only incentives that correspond to the dominant need tend to function as truly motivating.

Alongside these models, a widely discussed perspective is the two-factor model of job satisfaction, which distinguishes two sets of influences. The first group relates to self-expression, internal needs, and the environment in which work is performed. The second group is connected to the content of work itself, including responsibility, achievement, and meaningful tasks. In practice, this implies that a manager must not only provide proper conditions but also enrich the content of work so that employees can experience professional growth and engagement.

One of the modern trends in motivation research is the concept of management based on satisfaction. Work commitment becomes stronger when an employee is interested in participating in organizational life and feels involved in decision-making. Such involvement develops the ability to make independent decisions about how work is carried out, regulate quality and quantity of labor, participate in optimization activities, and propose improvements that increase the effectiveness of both employees and the organization as a whole.

From a systemic view of human activity, decision-making can be described at the levels of regulation, adaptation, and self-organization. Consequently, motivation should be supported across these levels simultaneously. In this framework, motives influencing behavior in the work collective can be grouped into: acquisition motives, security motives, energy-saving motives, subordination motives, and satisfaction motives. Acquisition motives are linked to obtaining rewards for performance. Security motives relate to the desire for stability and protection of one's position and outcomes. Energy-saving motives appear when individuals choose forms of activity that demand less effort and stress. Subordination motives reflect dependence on group norms, rules, and instructions. Satisfaction motives are connected with receiving positive emotions from work processes and achieved results. The strength of these motives varies depending on conditions and time, and when motives are equally strong, the one that can be realized faster tends to dominate. The leading group of motives shaping employee behavior forms a motivational base, which depends on real working conditions. If a stimulus requires unacceptable or unrealistic actions, it may fail to become a motive; therefore, incentive mechanisms must correspond to employees' real motivational structure.

After summarizing the main ideas of motivational theories, it is necessary to emphasize the role of stimulation. Incentives are external factors that influence employees' or teams' actions and attitudes toward work. In essence, motivation for action can be viewed as the core outcome of stimulation. Labor stimulation represents external motivation—an element of the work situation that affects behavior and serves as a practical indicator of personnel motivation.

Incentives that play an important role in satisfying human needs generally appear in four main forms: coercion, material incentives, moral incentives, and self-affirmation. Administrative coercion may include reprimands, transfer to another position, postponement of vacations, or dismissal. Material incentives include wages, performance bonuses, awards, compensation payments, and housing-related loans. Moral incentives aim to satisfy ethical and social needs and may take the form of gratitude, honorary certificates, or public recognition (Vodyasov, 2016).

In addition, incentives may be divided into two groups according to their relation to the stimulated action. The first group includes incentives (material or moral) applied after certain actions or results—rewarding outcomes or demonstrated attitudes. The second group is used to create conditions that lead to desired actions or attitudes in advance. In other words, the first group follows behavior, while the second group is intended to cause and shape behavior (Ariabod et al., 2019).

Thus, the primary purpose of establishing and maintaining a personnel motivation and incentive system is to attract and retain employees and, above all, to ensure the achievement of organizational goals through effective, strong, and sustainable motivation built on a comprehensive and systematic basis.

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Received: 12.15.2025
Revised: 12.27.2025
Accepted: 01.16.2026
Published: 01.19.2026

Luminis Applied Science and Engineering
ISSN: 3030-1831
Vol 3, No 1, 2026

Indicators of Quality Assessment of Services in the Business Sector

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Abstract; Economically developed countries are characterized by the leading position of the service sector in socio-economic life. This is confirmed by the increase in the number of people engaged in this field, the increase in the volume and range of services offered. Among the main trends inherent in the modern service sector, the following can be noted. First, the further expansion of the service sector, including the emergence of service functions and an increase in their special share in the overall activities of industrial enterprises: after-sales service, brand trade and other forms of approaching the enterprise to consumers. products. Secondly, service functions are included in the composition of products as an important component that provides competitive advantages, for example, the presence of a menu of various service functions in modern goods such as televisions, telephones, computers. Thus, the traditional concept of a product is expanding, going beyond the boundaries of direct interaction between the supplier and the consumer and reflecting the results of the supplier's internal activities to meet the requirements of the consumer. Thirdly, there is a further differentiation of service levels that characterize the capabilities and needs of customers. For example, it is necessary to note homogeneous services offered separately for professionals and amateurs, wealthy and underprivileged people, as well as exclusive services distinguished by high standards and speed of service. Fourth, significant changes have occurred in the legislation, primarily in terms of expanding the rights of customers in relations with the service sector, where the issues of protecting the rights of consumers of products and services play the role of a powerful incentive ensuring their quality. In general, it can be concluded that the level of development of the service sector is one of the most important features of the development of modern society - its social orientation. A similar position is found in the concept of a post-industrial society proposed by foreign researchers, where the advantage of the service sector over the manufacturing sector is also noted.

***Keywords**: consumption, competition, company, competitor, service sector*

INTRODUCTION

The outcome of interactions between a service provider and a consumer is typically an intangible product. Activities within the service sector may include the following:

- operations performed on tangible items supplied by customers, such as shoe repair or the preparation of legal documents;
- the delivery of tangible goods to individuals, including transport and postal services;
- the provision of intangible services, such as education, tourism, healthcare, and public catering.

Assessing service quality presents particular challenges and is characterized by several distinctive features (Mirzazadeh & Zeynalli, 2024):

- service quality evaluation is inherently complex;
- the consumer actively participates in the service delivery process;

- preliminary certification of service quality is often unreliable;
- services cannot be stored and are consumed immediately upon delivery;
- services are not purely tangible, and their quality cannot be tested in advance for a specific consumer.

Key indicators used to evaluate service quality include (Mirzazadeh, 2025):

- the quality of material resources used in service provision;
- the reliability of the service delivered;
- timeliness, meaning strict adherence to the timeframe required by the client;
- completeness, or the ability to offer a full range of services;
- socio-psychological indicators, including courtesy, adaptability, and foresight of personnel;
- accessibility, referring to the ease with which clients can use the service;
- sociability, defined as effective and prompt information exchange between the company and the client;
- safety, ensuring that services do not negatively affect consumer health or the environment;
- competence, reflecting the professional qualifications of service personnel.

A service quality indicator represents a quantitative measure of one or more characteristics that collectively define service quality. These indicators form the basis for quality control, technical support, and personnel performance evaluation. Ultimately, service quality is closely linked to the professional skills of service providers, the materials and technologies employed, and the expertise of specialists involved in service delivery (Mustafiyanti et al., 2023).

Methodology

The system of service quality assessment is based on a structured set of indicators grouped according to their functional characteristics. These indicators collectively reflect the effectiveness, safety, reliability, and overall quality of services provided.

1. Service purpose indicators describe the characteristics that determine how effectively a service fulfills its intended functions. These indicators are subdivided into four categories: application indicators, compliance indicators, enterprise-related indicators, and specific indicators relevant to particular types of services. Application indicators define the core functions of a service and its area of use, including the compatibility of the service outcome with other products or services. In material services, this may involve product compatibility, while in process-oriented services it reflects coordination with other service operations. Indicators reflecting an enterprise's capacity to deliver services include the quality of its material and technical infrastructure, sanitary, hygienic, and ergonomic conditions, the availability of supplementary services, average customer waiting time, service throughput, prioritization of specific consumer groups, and adherence to ethical communication standards (Amrakhov, Karimov, & Karimova, 2022).

2. Safety indicators assess the degree to which service processes and outcomes protect human life, health, property, and the environment. Services must be delivered under conditions that minimize potential risks to an acceptable level. Safety considerations apply both during service provision and throughout the consumption of any material results generated by the service. These indicators are classified into three subgroups: protection of life, health, and property; environmental safety; and the security of property and information (Omoshev et al., 2024).

3. Reliability indicators reflect the stability and consistency of service outcomes, as well as resistance to external influences and operational disruptions. They also characterize the dependability of service delivery to consumers. This group includes four subcategories: reliability of service results, resistance of outcomes to external factors, resistance to noise or interference, and reliability of the service provision process itself (Bulatova, 2010).

4. Indicators of personnel professionalism evaluate the human resource dimension of service quality and are divided into three main components: the level of professional training and qualifications, including both theoretical knowledge and practical skills; leadership competencies; and knowledge of and compliance with professional ethical standards.

In addition to the core indicators outlined above, service quality can also be evaluated through indicators of social purpose, aesthetics, and informativeness.

5. Social purpose indicators reflect the societal orientation of services and include the degree of social targeting, the availability of services to the population, and the correspondence between service quality and retail pricing. These indicators are primarily qualitative in nature and are not measured quantitatively (Mirzazada, 2025).

6. Aesthetic indicators characterize the visual and artistic aspects of service provision, including harmony, stylistic coherence, compositional integrity, and expressive design (Mirzazada & Camalov, 2025). These indicators encompass architectural and interior design solutions, the appearance and workplace organization of service personnel, the design of advertising and branding materials, documentation, table settings in catering establishments, presentation of culinary products, individually customized services, and the overall service script. Aesthetic standards must comply with existing regulations governing consumer service provision.

7. Indicators of service informativeness assess the availability and clarity of accurate information regarding the range of services offered, the conditions and rules of service provision, and the rights of consumers. This group also includes personnel competence in effectively communicating relevant information to clients in accordance with professional responsibilities.

Results

In evaluating service quality, it is essential to consider economic indicators that reflect service pricing, as well as the costs associated with service development and delivery. A fundamental distinction exists between the consumption of goods and services: while goods are consumed as finished outcomes, services are consumed as an ongoing process (Amrahov et al., 2023). Consequently, quality assessment in the service sector requires continuous monitoring of operational procedures and compliance with internal standards and organizational regulations.

This approach conceptualizes quality as an objective and measurable attribute; however, it does not fully account for variations in individual consumer preferences and expectations. Since consumer needs differ, perceptions of service quality are inherently subjective and depend on personal experience. From this perspective, service quality is ultimately defined by the degree to which consumer expectations are satisfied. Enhancing the competitiveness of service organizations therefore largely depends on systematic efforts to improve service quality.

As consumer expectations regarding service standards continue to rise, achieving high-quality service delivery has become a central objective for service-oriented enterprises. This objective is closely associated with several key factors (Amrahov et al., 2025): consumer satisfaction is directly influenced by service quality, execution, and outcomes; the primary determinant of service quality is the consumer's perception and evaluation of the received service; service quality can be viewed as a multidimensional construct encompassing potential quality, process quality, and cultural quality; and sustained competitiveness is achieved through continuous improvements in service quality.

Discussion

The assessment of service quality constitutes a core component of the overall quality management system. It enables effective quality control, supports analytical processes and managerial decision-making, and provides essential feedback necessary for organizational stability and long-term development. Despite its importance, the development of a comprehensive and unified methodology for service quality assessment remains unresolved. Existing approaches do not fully integrate all dimensions of evaluation, ranging from consumer feedback surveys to statistical monitoring and systematic analysis of assessment indicators (Mirzazada, 2025).

Current service quality assessment methodologies are primarily designed for organizations operating extensive service networks and typically incorporate two categories of parameters: quantitative and qualitative. Quantitative parameters are derived from statistical data related to service volumes across sales or service outlets. In contrast, qualitative parameters—although more difficult to formalize—enable the evaluation of the service delivery process rather than merely its final outcome (Ariabod et al., 2019).

The analysis of service quality indicators involves both the construction of an internal evaluation framework and comparative assessments, including benchmarking against competitors. External comparisons based on quality indicators are often more feasible than those based on quantitative metrics, as quality-related information is generally more transparent and accessible through surveys and customer feedback mechanisms (Ashenfelter et al., 2006).

While quantitative indicators are closely linked to customer satisfaction measurement techniques, numerous studies have focused on identifying and evaluating qualitative dimensions of service performance. Customer satisfaction is regarded as a broader concept that encompasses service quality itself. Accordingly, service quality assessment methodologies frequently rely on survey instruments structured around five key dimensions (Amrahov, 2023): reliability, responsiveness, credibility, empathy, and tangible elements.

Conclusion

The analysis of service quality management and its improvement in the business environment allows several generalized conclusions to be drawn. Conceptually, approaches to service quality management may be grouped into two main categories: management based on international quality standards and

management grounded in the integration of customer relationship management principles. The findings of this study indicate that the application of international standards is associated with a number of notable limitations. In particular, many standards provide only a broad and ambiguous interpretation of service quality, a concern highlighted by numerous researchers. Moreover, assessment methods embedded in these standards primarily focus on verifying the formal presence of prescribed structural elements rather than evaluating their actual effectiveness. Outcome indicators often allow for overly broad interpretations and limit comparative analysis, as they rely heavily on resource-intensive consumer surveys and questionnaires (Amrahov et al., 2023).

At the same time, international standards offer a structured and systematic description of the key components required to improve service quality. When effectively implemented, quality documentation systems play a crucial role in enhancing the efficiency of quality management processes and supporting organizational consistency (Amrahov et al., 2023). However, the absence of clear and detailed guidelines for designing an integrated service quality management mechanism—particularly in relation to documentation systems—remains a significant challenge. The results of the study demonstrate that combining standardized approaches with customer-oriented management principles enables the creation of a more advanced and effective service quality management framework (Amrakhov, 2022).

A common shortcoming of international standards is the lack of robust tools for evaluating ongoing service quality improvement activities. Existing evaluation approaches are largely advisory and limited to the specific contexts envisioned by their developers. In response to these limitations, this study proposes a new value-based indicator that facilitates a more objective assessment of service quality management effectiveness and may also be applied to the evaluation of service activities more broadly (Amrahov et al., 2024). The practical relevance of these findings is substantial for service enterprises, as the implementation of the proposed quality improvement mechanisms can enhance service efficiency, strengthen financial performance, and support evidence-based management decisions (Abbasova et al., 2025).

The proposed methodological solutions contribute to addressing several key managerial challenges (Amrahov, 2014), including: the development and application of comprehensive criteria and indicators for evaluating logistics management systems and service quality assurance; the design and implementation of pricing and cost management algorithms in service organizations; the integration of forecasting and strategic planning methods into service development processes; and the establishment of an integrated enterprise management framework encompassing mission definition, legal support, strategic databases, and operational coordination (Amrahov et al., 2022).

From both theoretical and practical perspectives, an important contribution of this study lies in its consideration of territorial aspects of service sector formation and development. In particular, the application of a system-logistics approach to socio-economic development and service provision supports the creation of integrated logistics complexes and the justification of their service functions. The development of the services market further expands the applicability of systematic performance assessment methods for service sector entities, thereby reinforcing the strategic role of services in modern economic systems (Amrahov, 2015).

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Received: 12.10.2025
Revised: 12.25.2025
Accepted: 01.16.2026
Published: 01.22.2026

Luminis Applied Science and Engineering
ISSN: 3030-1831
Vol 3, No 1, 2026

Regular Almost-Periodic Functions and the Concept of Periodicity

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Abstract; The present paper investigates the concept of regular almost-periodic functions and their fundamental properties as a natural generalization of classical periodic functions. Special attention is paid to the notion of ε-periods and their role in describing quasi-periodic behavior on the real line. The study clarifies the mathematical essence of almost periodicity in the sense of Bohr and highlights the importance of relative density of ε-periods. Key structural properties of regular almost-periodic functions are discussed, emphasizing their stability under algebraic operations and translations. The relevance of these functions in the theory of differential equations and in the modeling of physical and technical systems is also briefly addressed. The results demonstrate that regular almost-periodic functions constitute an effective analytical tool for describing complex processes that cannot be adequately modeled using classical periodic functions.

***Keywords**: almost-periodic function, regularity, ε-period, Bohr almost periodicity, relative density*

1. INTRODUCTION

Classical periodic functions play a fundamental role in mathematical analysis and its applications, particularly in the study of oscillatory phenomena. However, many natural and technical processes exhibit behavior that is close to periodic but does not satisfy strict periodicity conditions. This limitation has motivated the development of broader concepts capable of capturing such phenomena more accurately.

One of the most influential generalizations of periodicity is the notion of almost-periodic functions, introduced by H. Bohr in the early twentieth century. Unlike strictly periodic functions, almost-periodic functions allow for approximate repetitions of values with arbitrary precision. This flexibility makes them especially suitable for modeling irregular oscillations encountered in differential equations, physics, and engineering.

A central idea in Bohr's theory is the concept of ε-periods, which replaces exact periodic shifts with approximate ones. The distribution of these ε-periods, particularly their relative density on the real line, plays a crucial role in determining the structural properties of almost-periodic functions.

The purpose of this paper is to study a specific class of almost-periodic functions, referred to as **regular almost-periodic functions**, and to analyze their main characteristics. The paper begins with essential definitions and preliminary concepts, then focuses on the generalization of periodicity through ε-periods and relatively dense sets. The structure of the paper is as follows: Section 2 introduces the basic definitions and terminology, while subsequent sections (not included here) investigate fundamental properties and applications of regular almost-periodic functions.

2. PRELIMINARIES AND BASIC DEFINITIONS

This section introduces the fundamental concepts and notation required throughout the paper. All functions considered are real-valued functions defined on the real line unless stated otherwise.

2.1. Generalization of the Period Concept

In classical analysis, a function (f(x)) is said to be periodic if there exists a nonzero real number (T) such that

f(x+T)=f(x) for all x∈R.

While this definition is precise, it is often too restrictive for describing real-world phenomena.

To overcome this limitation, the concept of an **ε-period** is introduced. Let (f:\mathbb{R} \to \mathbb{R}) be a function and let (\varepsilon > 0). A real number (\tau) is called an **ε-period** of (f) if

|f(x+τ)−f(x)|<ε for all x∈R.

Clearly, every classical period is an ε-period for any ε>0, but the converse is not necessarily true. The notion of ε-periods thus provides a natural extension of periodicity, allowing approximate repetitions of function values with arbitrary accuracy.

2.2. Relatively Dense Sets

The concept of relative density plays a key role in almost-periodic function theory.

A subset (E \subset \mathbb{R}) is called **relatively dense** if there exists a positive number (l > 0) such that every interval of length (l) on the real line contains at least one point of (E).

For example, the set

$$E = \{np: n = 0, \pm 1, \pm 2, \dots\},$$

where $p > 0$, is relatively dense. In contrast, the set

$$E = \{\pm n^2: n = 1,2,3, \dots\}$$

is not relatively dense, since the gaps between consecutive elements grow without bound.

In the theory of almost-periodic functions, relative density ensures that ε-periods occur frequently enough across the real line. This property guarantees uniform recurrence and lies at the heart of Bohr's definition of almost periodicity.

3. DEFINITION OF REGULAR ALMOST-PERIODIC FUNCTIONS

The central object of this study is the class of regular almost-periodic functions, which refines Bohr's notion of almost periodicity by emphasizing uniform recurrence and continuity.

Definition 3.1. (ε-Almost Period)

Let $f: \mathbb{R} \to \mathbb{R}$be a function and let $\varepsilon > 0$. A real number $\tau$is called an **ε-almost period** of $f$if

$$| f(x+\tau) - f(x) | < \varepsilon \text{for all } x \in \mathbb{R}.$$

Definition 3.2. (Regular Almost-Periodic Function)

A continuous function $f: \mathbb{R} \to \mathbb{R}$is called a **regular almost-periodic function** if, for every $\varepsilon > 0$, the set of ε-almost periods of $f$is relatively dense in $\mathbb{R}$.

Equivalently, for each $\varepsilon > 0$there exists a number $l = l(\varepsilon) > 0$such that every interval of length $l$contains at least one real number τsatisfying

$$| f(x+\tau) - f(x) | < \varepsilon \text{for all } x \in \mathbb{R}.$$

The regularity condition ensures that approximate repetitions of the function values occur uniformly along the real axis. Intuitively, although the function may not repeat itself exactly, it does so with arbitrary precision and without large gaps between repetitions.

This definition coincides with Bohr's classical concept of almost-periodic functions on $\mathbb{R}$, emphasizing uniform convergence and relative density of ε-periods. Hence, regular almost-periodic functions may be viewed as a natural and analytically convenient generalization of periodic functions.

4. FUNDAMENTAL PROPERTIES OF REGULAR ALMOST-PERIODIC FUNCTIONS

In this section, we establish basic closure and stability properties of regular almost-periodic functions.

Proposition 4.1. (Scalar Multiplication Invariance)

If $f(x)$is a regular almost-periodic function and $\alpha \in \mathbb{R}$, then the function $\alpha f(x)$is also regular almost-periodic.

Proof.
Let $\varepsilon > 0$. Since $f$is regular almost-periodic, there exists an ε-almost period τsuch that

$$| f(x+\tau) - f(x) | < \frac{\varepsilon}{| \alpha |} \text{for all } x \in \mathbb{R}.$$

Then

$$| \alpha f(x+\tau) - \alpha f(x) | = | \alpha | \ | f(x+\tau) - f(x) | < \varepsilon,$$

which proves the claim.

Proposition 4.2. (Translation Invariance)

If $f(x)$is a regular almost-periodic function and $c \in \mathbb{R}$, then $f(x+c)$is also regular almost-periodic.

Proof.
For any ε-almost period $\tau$of f, we have

$$| f(x+c+\tau) - f(x+c) | < \varepsilon$$

for all $x \in \mathbb{R}$. Hence, the same ε-almost periods apply to the translated function.

Proposition 4.3. (Closure under Absolute Value)

If $f(x)$is a regular almost-periodic function, then $| f(x) |$is also regular almost-periodic.

Proof.
Using the inequality

$$|| f(x+\tau) | - | f(x) || \leq | f(x+\tau) - f(x) |,$$

every ε-almost period of $f$is also an ε-almost period of $| f |$.

Proposition 4.4. (Closure under Reciprocal)

Let $f(x)$be a regular almost-periodic function satisfying

$$\inf_{x \in \mathbb{R}} | f(x) | = \gamma > 0.$$

Then the function $1/f(x)$is regular almost-periodic.

Proof.
For an ε-almost period $\tau$of f,

$$\left| \frac{1}{f(x+\tau)} - \frac{1}{f(x)} \right| = \frac{| f(x+\tau) - f(x) |}{| f(x+\tau) f(x) |} \leq \frac{1}{\gamma^2} | f(x+\tau) - f(x) |.$$

Thus, ε-almost periods of $f$yield ε-almost periods of $1/f$.

Proposition 4.5. (Closure under Composition)

Let $f(x)$be regular almost-periodic and let Fbe uniformly continuous on the range of f. Then the composite function $F(f(x))$is regular almost-periodic.

Proof.
Uniform continuity of Fimplies that small variations in $f(x)$lead to small variations in $F(f(x))$. Hence, ε-almost periods of $f$induce ε-almost periods of $F \circ f$.

Proposition 4.6. (Boundedness)

Every regular almost-periodic function is bounded on $\mathbb{R}$.

Proof.
Let $\varepsilon = 1$and let $l = l(1)$be the corresponding length ensuring ε-almost periods. Since $f$is continuous on a compact interval of length l, it attains a maximum M. Using ε-almost periods, the bound extends to all $x \in \mathbb{R}$.

5. CONSEQUENCES AND DERIVED RESULTS

The fundamental properties established above lead to several important corollaries.

Corollary 5.1. (Square of an Almost-Periodic Function)

If $f(x)$is regular almost-periodic, then $f^2(x)$is also regular almost-periodic.

Proof.
Using boundedness and the identity

$$| f^2(x+\tau) - f^2(x) | = | f(x+\tau) - f(x) | \ | f(x+\tau) + f(x) |,$$

the claim follows directly.

Corollary 5.2. (Stability under Algebraic Operations)

The class of regular almost-periodic functions is closed under addition, subtraction, and multiplication.

Corollary 5.3. (ε-Period Transformation)

ε-almost periods of a regular almost-periodic function remain ε-almost periods under scalar multiplication, translation, and uniformly continuous transformations.

These results confirm that regular almost-periodic functions form a robust and analytically stable class, well-suited for applications in differential equations and mathematical modeling.

6. UNIFORM CONTINUITY OF REGULAR ALMOST-PERIODIC FUNCTIONS

One of the fundamental analytical properties of regular almost-periodic functions is uniform continuity on the entire real line. This property is essential for both theoretical investigations and practical applications.

Theorem 6.1. (Uniform Continuity)

Every regular almost-periodic function $f: \mathbb{R} \to \mathbb{R}$is uniformly continuous on $\mathbb{R}$.

Proof.
Let $\varepsilon > 0$be arbitrary. Since $f$is regular almost-periodic, there exists $l = l(\varepsilon/3) > 0$such that every interval of length $l$contains an ε/3-almost period τsatisfying

$$| f(x+\tau) - f(x) | < \varepsilon/3 \text{for all } x \in \mathbb{R}.$$

Because $f$is continuous on the compact interval $[0, l]$, it is uniformly continuous there. Hence, there exists $\delta > 0$such that

$$| x_1 - x_2 | < \delta \Rightarrow | f(x_1) - f(x_2) | < \varepsilon/3$$

for all $x_1, x_2 \in [0, l]$.

Now let $x, y \in \mathbb{R}$with $| x - y | < \delta$. Choose an ε/3-almost period τsuch that both $x + \tau$and $y + \tau$lie in $[0, l]$. Then

$$| f(x) - f(y) | \quad \leq | f(x) - f(x+\tau) | + | f(x+\tau) - f(y+\tau) | + | f(y+\tau) - f(y) | < \varepsilon/3 + \varepsilon/3 + \varepsilon/3 = \varepsilon.$$

Thus, f is uniformly continuous on $\mathbb{R}$.

Uniform continuity guarantees stability of regular almost-periodic functions under limits and ensures well-posedness in analytical and numerical applications, particularly in differential equations.

7. APPLICATIONS AND CONNECTIONS

Regular almost-periodic functions play a significant role in various branches of mathematics and applied sciences.

7.1. Differential Equations

In the theory of ordinary and partial differential equations, almost-periodic coefficients naturally arise in models with recurring but non-strictly periodic behavior. Regular almost-periodic functions provide a suitable framework for studying existence, uniqueness, and stability of solutions, especially in non-autonomous systems.

7.2. Applications in Physics

Many physical systems exhibit oscillations that are not exactly periodic, such as wave propagation in inhomogeneous media or forced vibrations with varying frequencies. Regular almost-periodic functions allow accurate modeling of such phenomena by capturing approximate repetitions without requiring strict periodicity.

7.3. Engineering and Technical Systems

In engineering, regular almost-periodic functions are applied in signal processing, control theory, and mechanical system modeling. They offer advantages over strictly periodic models by accommodating real-world irregularities while preserving analytical tractability.

7.4. Advantages over Classical Periodic Models

Compared to classical periodic functions, regular almost-periodic functions provide greater flexibility and realism. The ε-period framework ensures robustness under perturbations and makes these functions particularly suitable for complex systems.

8. DISCUSSION

The results obtained in this paper place regular almost-periodic functions within the broader context of almost-periodic function theory. The definition adopted here aligns with Bohr's classical approach, emphasizing uniform convergence and relative density of ε-periods.

Compared to alternative formulations, such as Besicovitch or Stepanov almost periodicity, regular almost-periodicity ensures stronger regularity properties, including boundedness and uniform continuity. The connections with the works of Bohr, Corduneanu, and Levitan highlight the foundational nature of this concept and its relevance to differential equations.

Possible extensions of the present study include:

- Almost-periodic functions in Banach and Hilbert spaces
- Almost-periodic solutions of nonlinear differential equations
- Generalizations to time scales and stochastic frameworks

These directions suggest that regular almost-periodic functions remain an active and promising area of research.

9. CONCLUSION

This paper has presented a systematic study of regular almost-periodic functions and their fundamental properties. By generalizing the classical notion of periodicity through ε-periods and relative density, a robust and flexible analytical framework has been established.

The main contributions include:

- A precise definition of regular almost-periodic functions
- Proof of closure, boundedness, and uniform continuity properties
- Discussion of applications in differential equations and applied sciences

The ε-period approach proves to be a powerful tool for modeling and analysis, bridging the gap between strict periodicity and real-world quasi-periodic behavior. Future research may further expand these results to abstract spaces and complex dynamical systems.

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Received: 12.20.2025
Revised: 12.25.2025
Accepted: 01.28.2026
Published: 01.30.2026

Luminis Applied Science and Engineering
ISSN: 3030-1831
Vol 3, No 1, 2026

Cultivation Conditions and Optimization Strategies for Antibiotic-Producing Microorganisms: Focus on Actinomycetes

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Abstract; Antibiotics remain indispensable for treating bacterial infections, yet accelerating antimicrobial resistance is reducing their clinical effectiveness and increasing the demand for reliable, high-yield production. Because most major antibiotics originate from microbial secondary metabolism, understanding and controlling cultivation conditions is essential for both laboratory reproducibility and industrial-scale fermentation.

This review analyzes cultivation and process factors that determine antibiotic productivity in antibiotic-producing microorganisms, with emphasis on actinomycetes (especially *Streptomyces*). The findings highlight how undefined (complex) media can support growth but reduce comparability, whereas defined media improve control and interpretation of physiological responses. Carbon and nitrogen sources strongly shape pathway activation through catabolite and nitrogen regulation, while pH and temperature influence morphology, enzyme activity, and the timing of entry into idiophase. Evidence also supports roles for lipid and fatty-acid components in selected systems, as well as precursor feeding strategies and feedback inhibition (retroinhibition) that can either enhance or suppress biosynthesis depending on pathway control. Inoculum age, mycelial state, aeration/hydrodynamics, and typical fermentation durations (often multi-day) further determine yield stability.

Optimizing these upstream variables can improve productivity and batch-to-batch reproducibility and supports future research integrating omics-guided optimization and metabolic engineering.

***Keywords**: Actinomycetes; Streptomyces; nutrient medium optimization; secondary metabolism*

1. INTRODUCTION

Antibiotics remain central to modern medicine, yet their effectiveness is increasingly undermined by antimicrobial resistance (AMR). AMR is recognized as a major global health threat that reduces the ability to treat common infections and increases the risk of severe outcomes. Recent global surveillance summaries and fact sheets emphasize that resistance is widespread and rising across multiple pathogen–drug combinations, reinforcing the need for both new antimicrobial agents and more efficient production of existing ones.

Microorganisms are the primary natural source of clinically useful antibiotics. Soil-derived bacteria—especially actinobacteria/actinomycetes (notably *Streptomyces*)—have historically yielded a large share of naturally derived antibiotics, while filamentous fungi and other bacteria also contribute important drug classes. Their metabolic diversity and ecological competitiveness explain why microbial secondary metabolites became foundational to antibacterial therapy.

Antibiotic output is not fixed; it depends strongly on cultivation and bioprocess conditions because many antibiotic pathways are part of secondary metabolism and are tightly regulated. Reviews of *Streptomyces* biology show that antibiotic gene clusters are controlled by complex regulatory networks and respond to nutritional and physiological signals. Consequently, parameters such as carbon and nitrogen sources, pH, precursor supply, aeration/hydrodynamics, and inoculum state can shift metabolism toward or away from productive antibiotic biosynthesis.

This article reviews cultivation conditions for antibiotic-producing microorganisms with emphasis on actinomycetes, synthesizing evidence on (i) defined versus complex media, (ii) carbon–nitrogen balance, (iii) pH and key environmental controls, (iv) precursor feeding and feedback regulation, and (v) inoculum and process monitoring factors that influence productivity. By organizing the literature around controllable variables, the paper aims to support more reproducible laboratory cultivation and more rational optimization for industrial fermentation, thereby contributing to improved yield and consistent production quality.

2. MATERIALS AND METHODS

Methodology of the review

A structured narrative review approach was used. Literature was searched in Scopus, PubMed, Web of Science, and Google Scholar.

Search keywords (examples):
"antibiotic-producing microorganisms", "actinomycetes" OR "Streptomyces", "secondary metabolism regulation", "fermentation medium optimization", "carbon source regulation", "nitrogen source", "pH", "precursor feeding", "inoculum", "submerged aerobic fermentation".

Inclusion criteria:

- **Time window:** primarily 2000–2026 for reviews and mechanistic studies; older "classic" sources were included when they are foundational to fermentation/secondary-metabolism concepts.
- **Language:** English.
- **Study types:** peer-reviewed reviews, primary experimental studies on cultivation variables and regulation of antibiotic biosynthesis, and (where relevant) authoritative surveillance/position documents on AMR.
- **Exclusion:** non-peer-reviewed items lacking methodological detail; studies not linking cultivation/bioprocess variables to antibiotic yield, regulation, or reproducibility.

Synthesis approach:
Findings were extracted and grouped by controllable variables and their reported effects on production: (1) nutrient medium type (defined vs complex), (2) carbon source and repression, (3) nitrogen source and ammonium effects, (4) pH and environmental parameters, (5) lipid/fatty-acid contributions (where applicable), (6) precursor feeding and feedback inhibition, (7) inoculum physiology and process monitoring, and (8) strain improvement strategies when directly connected to cultivation outcomes.

Reporting guideline (optional but recommended):
Although this is not a full systematic review, the structure of reporting (search description, inclusion logic,

and synthesis transparency) was aligned where practical with PRISMA 2020 principles for clarity and reproducibility.

3. RESULTS OF THE REVIEW

1) Producers and ecological sources

Soil ecosystems are a major reservoir of antibiotic producers, particularly actinomycetes; selective isolation strategies often exploit the ecological advantage and metabolic diversity of these organisms. Many *Streptomyces* species are prolific natural-product producers, which explains their central role in antibiotic discovery and industrial production.

2) Nutrient media: natural vs synthetic (defined)

Early screening and initial production frequently rely on complex (undefined) media derived from agricultural materials (e.g., starch products, bran, peptones). These can support robust growth but suffer from batch-to-batch variability in composition, which reduces reproducibility and complicates physiological interpretation and scale-up control. In contrast, defined/synthetic media improve comparability, mechanistic interpretation, and tighter process control—especially important when optimizing secondary metabolite production.

3) Carbon and nitrogen sources

Carbon source selection is a dominant lever because readily metabolized sugars can trigger carbon catabolite repression, delaying or suppressing antibiotic pathways, while slower/alternative carbon sources can favor entry into idiophase. This effect is widely documented in *Streptomyces* regulatory networks.

A specific example reported in *Streptomyces antibioticus* showed that a mixture containing ~0.1% glucose with 1% galactose supported production behavior consistent with rapid glucose utilization followed by a shift to galactose metabolism, aligning with the broader concept that staged carbon utilization can promote secondary metabolism.

Nitrogen source form and concentration also shape antibiotic output: nitrate salts and other “milder” nitrogen regimes are often used in actinomycete media design, while high ammonium can repress secondary metabolism in many systems (strain-dependent).

4) pH and temperature

Temperature around ~28 °C is common for many actinomycete fermentations (strain- and product-specific), reflecting their mesophilic physiology and typical industrial practice. pH effects are more nuanced: some processes run near neutral, while selective isolation or specialized groups (including acid-tolerant/acidophilic actinomycetes) can involve lower pH to limit competing microbes. Therefore, statements such as “pH 4.0–4.5” should be presented as context-specific (e.g., selective isolation or particular strains), not as a universal optimum for all actinomycetes.

5) Lipids and fatty acids

Lipid availability can influence membrane properties and precursor supply for some antibiotic pathways. In cephalosporin-producing fungi (historically *Cephalosporium/Acremonium* systems), supplementation with lipid components (e.g., oleate-related inputs) has been reported to modulate production, consistent

with the broader observation that fatty acid metabolism can interact with secondary metabolite yield in certain producers.

6) Amino acids, ammonium regulation, and metabolic control

Nitrogen assimilation routes help explain why ammonium effects can differ by condition. In many microbes, high ammonium can favor assimilation via glutamate dehydrogenase (GDH), while ammonium limitation increases reliance on the GS/GOGAT (glutamine synthetase/glutamate synthase) system. These shifts alter intracellular nitrogen status and can impact regulatory signals that gate secondary metabolism and antibiotic biosynthetic gene expression.

7) Precursors and feedback inhibition (retroinhibition)

Precursor feeding and pathway feedback are central to β-lactam productivity. Penicillin biosynthesis begins with formation of the tripeptide ACV from α-aminoadipate, cysteine, and valine, establishing α-aminoadipate availability as a key node. Classic and modern work also shows lysine-linked feedback control (e.g., via homocitrate synthase regulation) that can indirectly reduce α-aminoadipate flux and thereby constrain penicillin formation.

8) Inoculum and bioprocess control

Inoculum quality (age, physiological state, and morphology) influences downstream fermentation because it shapes growth kinetics, pellet/filament structure, oxygen transfer, and the timing of transition into idiophase. Reviews and process studies emphasize that monitoring and controlling variables related to respiration/oxygen demand, hydrodynamics, and morphology can improve reproducibility and support scale-up. Fermentation durations vary by organism/product, but industrial submerged aerobic antibiotic processes commonly operate across multi-day windows (often about ~5–10 days, depending on the system).

9) Strain improvement approaches

Classical strain improvement remains important in industry: iterative selection, random mutagenesis (e.g., UV or ionizing radiation), and screening can increase yield, and modern approaches add genome-guided strategies (omics, metabolic engineering) to target bottlenecks more precisely. In penicillin systems, for example, omics-era reviews document how genetic and regulatory understanding supports rational improvement beyond purely random mutation.

4. DISCUSSION

Overall, the literature supports a consistent interpretation: antibiotic production is not simply a function of "more growth," but of regulated secondary metabolism that emerges when nutrients, energy status, and global regulators align to activate biosynthetic gene clusters. Carbon and nitrogen are particularly powerful because they control both metabolic flux (precursor supply) and transcriptional programs (catabolite repression, nitrogen repression, stress responses), which jointly determine when and how strongly the idiophase begins.

From an industrial viewpoint, reproducibility and scale-up are often limited by variability in complex raw materials and by morphology-dependent oxygen transfer. Moving from undefined to more controlled media components, documenting raw material quality, and measuring physiological proxies (e.g., OUR/CER, off-gas analytics) can reduce batch failures and improve comparability across labs and production sites.

The nitrogen-control findings also explain why "more nitrogen" can paradoxically reduce yields: ammonium assimilation strategy, intracellular nitrogen signaling, and downstream repression mechanisms can shift the cell away from antibiotic pathway commitment. Similarly, precursor feeding can help only when it respects pathway control logic—otherwise feedback inhibition or pathway imbalance can negate the intended benefit.

Finally, connecting production to the resistance context: improving yields and process robustness can support better access and reduce shortages, but it does not substitute for stewardship. Higher productivity is most valuable when coupled with (i) responsible clinical use, (ii) quality-assured manufacturing, and (iii) continued discovery of new scaffolds/strains to stay ahead of resistance trends.

Downstream formulation innovations: liposomal anti-infectives

Liposomal delivery can improve pharmacology by increasing stability, changing tissue distribution, and reducing toxicity for certain agents. A well-known example is liposomal amphotericin B, which has a substantially improved toxicity profile compared with conventional amphotericin B formulations.

For antibacterial therapy, liposomal amikacin for inhalation is an approved/regulated product in some regions (e.g., ARIKAYCE liposomal), illustrating that liposomes can be clinically feasible for targeted delivery where conventional dosing is limited by toxicity or distribution.

However, liposomal products are not "simple substitutions": small differences in liposome composition and physical properties can alter performance, creating manufacturing, comparability, and regulatory challenges. This is why regulators explicitly warn against substituting liposomal formulations without demonstrating equivalence.

5. CONCLUSION

Cultivation optimization is a primary driver of antibiotic productivity because it governs the timing and intensity of secondary metabolism through media composition, carbon/nitrogen regulation, pH/temperature, precursor availability, and inoculum physiology.
For industry, reproducible yields depend on controlled media inputs, morphology-aware oxygen transfer, and monitoring strategies that track physiological state—not just biomass.
Future work should prioritize (1) omics-guided optimization to identify bottlenecks, (2) metabolic engineering paired with robust bioprocess control, and (3) standardized reporting of media/raw-material variability and key control parameters to improve comparability and scale-up success.

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Received: 01.10.2025
Revised: 01.15.2025
Accepted: 02.07.2026
Published: 02.08.2026

Luminis Applied Science and Engineering
ISSN: 3030-1831
Vol 3, No 1, 2026

From Fiscal Extraction to Entrepreneurial Acceleration: A Next-Generation Theoretical Architecture for Tax Policy Formation in the Business Sphere

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https://doi.org/10.69760/lumin.2026001005

Abstract; In modern market economies, tax policy is simultaneously a fiscal backbone of the state and a decisive institutional signal shaping business behavior, investment horizons, and the quality of the entrepreneurial climate. Yet, in many transitioning systems, tax reforms frequently outpace the development of coherent theoretical frameworks, producing instability, compliance costs, and incentives for informality. This article systematizes the theoretical foundations of tax policy formation in the business sphere by integrating classical, neoclassical, Keynesian, and institutional perspectives and linking them to practical mechanisms of tax administration, special tax regimes, and incentive design. Using scientific abstraction, structural-functional analysis, theoretical generalization, and comparative analysis, the study clarifies how fiscal, regulatory, and stimulating models interact in real policy mixtures and how stability, transparency, and administrative simplicity condition business responses. The results propose an integrated conceptual architecture for "balanced tax policy" that aligns budget sustainability with entrepreneurial development through predictable rules, targeted incentives, and efficient administration. The discussion emphasizes institutional quality and risk-management logic as key determinants of compliance, competitiveness, and long-term growth.

***Keywords**: tax policy; business environment; tax administration; special tax regimes*

1. INTRODUCTION

The performance of business entities is one of the strongest determinants of socio-economic progress in a market economy: it influences employment, productivity, investment, and budget revenues. Tax policy, therefore, cannot be treated as a purely technical instrument for collecting payments; it is a strategic mechanism of state influence on entrepreneurship, competitiveness, and capital allocation. When designed coherently, taxation encourages business activity, supports formalization, and creates predictable conditions for long-term planning. When designed inconsistently—through frequent revisions, unclear exemptions, and administratively complex procedures—it increases uncertainty and compliance costs, weakens investment incentives, and expands the informal economy.

A persistent concern in many developing and post-transition contexts is the mismatch between the speed of legislative reforms and the depth of scientific justification behind them. Theoretical research in taxation

often lags behind practice and thus becomes less influential in shaping policy directions. Historical features of tax system formation also matter. Early stages of market transformation frequently replaced direct tax relations with irregular profit redistribution, while indirect taxes served as components of price planning. Such path dependencies complicate the development of stable, business-friendly tax regimes.

For these reasons, the theoretical aspects of tax policy formation in the business sphere remain urgent both scientifically and practically. Taxes simultaneously perform a fiscal function (as a key source of state budget income) and a regulatory/stimulating function (affecting entrepreneurial decisions). The tax burden, rate structure, concessions, exemptions, and administration shape firm-level financial outcomes and strategic choices (Mirzazada, 2025). Accordingly, tax policy must balance state fiscal interests with the development needs of business (Amrahov et al., 2023).

Aim of the study: to systematize theoretical approaches to tax policy formation in the business sphere and to propose an integrated conceptual architecture for balanced tax policy that supports both budget sustainability and entrepreneurial development.

Objectives:

1. define the essence, functions, and principles of tax policy relevant to business;
2. compare classical, neoclassical, Keynesian, and institutional approaches;
3. analyze fiscal, regulatory, and stimulating policy models and their practical mixtures;
4. clarify the role of tax administration and special tax regimes in business formalization;
5. formulate an integrated theoretical architecture for balanced tax policy formation.

Scientific novelty: the article offers a structured "next-generation" conceptual architecture that integrates tax policy design (rates, bases, incentives) with institutional quality (stability, transparency, administrative simplicity) and enterprise-level tax planning stages.

2. CONCEPTUAL AND THEORETICAL FOUNDATIONS OF TAX POLICY

2.1. Economic nature, functions, and principles

Tax policy can be understood as a purposeful set of state decisions and instruments governing taxation in order to finance public needs and influence economic behavior. In the business sphere, its essence includes:

- determination of tax bases and rates affecting profitability;
- definition of incentives and exemptions shaping investment decisions;
- establishment of procedures, reporting rules, and enforcement mechanisms that affect compliance costs.

Two core roles are central. First, taxes provide public revenues to sustain government functions. Second, taxation influences business behavior by altering relative prices, expected returns, and risk. In this duality lies the fundamental policy dilemma: maximizing revenue without suppressing entrepreneurial dynamism.

The principles of effective tax policy include:

- **fairness** (equitable distribution of tax burdens);

- **efficiency** (minimizing distortions and deadweight losses);
- **neutrality** (avoiding unnecessary favoritism unless justified);
- **simplicity** (reducing compliance costs);
- **stability and predictability** (supporting planning and investment);
- **transparency** (strengthening trust and voluntary compliance).

Instability is particularly harmful: frequent changes in taxation rules violate the stability principle and increase risks for business entities.

2.2. Classical, neoclassical, Keynesian, and institutional views

Classical theory generally supports limited interference and cautions that heavy taxation can weaken incentives to invest and expand. Within this logic, the business sphere benefits from moderate taxation and predictable rules.

Neoclassical theory emphasizes efficiency and allocation. Tax policy is evaluated by how it influences resource distribution, market equilibria, and productivity. From this standpoint, the "quality" of tax instruments matters: broad bases and moderate rates often reduce distortions more effectively than narrow bases and high rates.

Keynesian approaches treat tax policy as an active macroeconomic tool to stabilize economic cycles. Taxation and incentives can be adjusted counter-cyclically to support demand, protect employment, and sustain investment during downturns. For business, this implies that tax policy must be coordinated with broader fiscal and developmental priorities.

Institutional theory places special focus on governance quality, legal certainty, administration, and enforcement. Here, the level of the rate is not the only determinant of business outcomes: stability, clarity, and administrative procedures can be even more influential. Risk-management logic becomes central—firms react not only to tax payments but to uncertainty and administrative friction. Research on risk management systems and enterprise governance supports the argument that institutional quality shapes economic performance (Abbasova et al., 2025; Amrakhov, 2022).

2.3. Optimal taxation and balance logic

Theoretical models of optimal taxation revolve around trade-offs: revenue sufficiency versus economic incentives; redistribution versus efficiency; simplicity versus targeted support. Business-oriented tax policy formation, therefore, must be framed as a balancing process rather than a one-dimensional pursuit of budget maximization.

A practical interpretation of optimality in the business sphere includes:

- maintaining a tax burden compatible with investment and working-capital needs;
- ensuring that incentives are targeted and time-consistent;
- preventing excessive complexity that pushes firms into informality.

3. TAX POLICY MODELS AND STATE INFLUENCE ON BUSINESS

3.1. Fiscal, regulatory, and stimulating models

In the literature, tax policy is commonly divided into three types: **fiscal**, **regulatory**, and **stimulating** (Amrahov et al., 2023).

1. **Fiscal policy** prioritizes maximum budget filling through taxes and payments. In the business sphere, this approach can be risky because excessive burdens reduce working capital and limit growth potential.
2. **Regulatory policy** seeks a balance of interests across society and redistributes tax burdens according to policy goals. It often uses differentiated rates and sectoral adjustments.
3. **Stimulating policy** reduces burdens or offers benefits to encourage development, particularly for weak or strategic sectors. It is used to boost entrepreneurship, innovation, and investment.

In practice, purely fiscal models are rarely sustainable for the business sector because the state is typically interested in developing entrepreneurship as a growth engine. Thus, mixed policy models emerge, combining fiscal needs with targeted incentives.

3.2. Tax burden, competitiveness, and investment behavior

Tax burden affects businesses through multiple channels:

- profitability and retained earnings;
- investment capacity and creditworthiness;
- competitiveness and pricing strategies;
- incentives for innovation and modernization.

Studies addressing economic effectiveness, forecasting, and financial viability underline that strategic policy frameworks must support long-term capacity building (Amrahov et al., 2024; Amrahov et al., 2025). Sectoral research (e.g., agriculture and dryland production) also illustrates that environmental and structural conditions influence economic resilience—tax policy must be flexible enough to account for such realities while remaining stable in its rules (Amrahov, 2014; Amrahov, 2023; Amrahov & colleagues, 2022).

3.3. Institutional stability, informality, and compliance

When businesses face unstable and complex tax legislation, compliance becomes costly and unpredictable. This increases the attractiveness of "shadow" strategies. Institutional theory therefore argues for simplicity, predictability, and transparency as preconditions for a healthy business environment. Risk assessment approaches in entrepreneurship reinforce this conclusion: the perceived instability of rules amplifies economic risk and discourages formal investment (Amrakhov, 2022).

4. TAX ADMINISTRATION AND SPECIAL TAX REGIMES AS POLICY INFRASTRUCTURE

4.1. Tax administration as a determinant of business costs

Tax administration includes registration, reporting, processing, control over payments, inspections, and analysis. In practice, it shapes the "administrative tax burden" that can be as important as the nominal rate

burden. Efficient administration should minimize obstacles for business while ensuring collection and fairness.

Modernization of administrative infrastructure increasingly relates to digital tools and secure systems. Although some references in the literature address blockchain applications in logistics and Industry 4.0 (Bamakan et al., 2021; Javaid et al., 2021; Saxena et al., 2021), their relevance to taxation lies in the broader theme of trustworthy, transparent, and automated systems. In principle, secure digital infrastructures can reduce compliance friction, improve reporting accuracy, and lower opportunities for manipulation—thus strengthening tax administration quality.

4.2. Special tax regimes: rationale and effects

Special tax regimes are applied as alternative procedures for calculating and paying taxes for defined categories of taxpayers and periods. They often replace parts of the general regime and aim to:

- support business entities, especially SMEs;
- simplify accounting and reporting;
- reduce the tax burden;
- increase formalization and, ultimately, revenue stability.

Research indicates that applying a general tax regime to small businesses may increase incentives to hide income or expand informality, while preferential regimes can help formalization and compliance (Amrahov, 2014). At the same time, special regimes must be designed carefully: excessive or poorly targeted benefits can weaken fiscal discipline, distort competition, and generate inefficiencies.

4.3. Incentives, equity, and long-term sustainability

The theoretical justification for incentives depends on whether they correct market failures, encourage investment, stimulate innovation, or protect vulnerable sectors. Yet incentives must be balanced against:

- revenue risks,
- equity concerns,
- administrative complexity,
- and potential misuse.

A sustainable model is one where benefits are:

- targeted to clear objectives,
- transparent and time-bound,
- simple to administer,
- and evaluated by measurable outcomes.

5. METHODOLOGY

The study applies a complex scientific-theoretical and methodological approach grounded in economic theory, tax theory, state economic policy, and business regulation.

Key methods include:

- **scientific abstraction** to define the essence, functions, principles, and goals of tax policy;
- **theoretical generalization** to systematize diverse theoretical positions on taxation (Abbasova et al., 2025);
- **systemic and structural-functional analysis** to examine tax policy as a mechanism of state–business interaction, connecting fiscal, regulatory, stimulating, and social functions with concrete elements (types of taxes, rates, benefits, administration) (Pamuji & Limei, 2023);
- **analysis and synthesis** to study components of tax policy and integrate them into a coherent model;
- **induction and deduction** to formulate general principles from specific theoretical observations;
- **comparative analysis** to compare classical, neoclassical, Keynesian, and institutional approaches and evaluate their strengths and limitations.

6. RESULTS: AN INTEGRATED ARCHITECTURE FOR BALANCED TAX POLICY FORMATION

6.1. Core result: a "balanced tax policy" architecture

The central result is the formulation of a conceptual architecture for tax policy formation in the business sphere based on three coordinated pillars:

Pillar 1 — Policy design (rates, bases, incentives):

- moderate and predictable tax burden;
- broad bases where possible to reduce distortions;
- targeted incentives for investment, innovation, and SMEs;
- equity principles to avoid unfair burden concentration.

Pillar 2 — Institutional quality (stability, transparency, trust):

- stable legal framework and clear interpretations;
- transparent rules and accessible guidance;
- predictable policy horizons enabling planning;
- governance logic supporting compliance culture (Abbasova et al., 2025; Mirzazada, 2025).

Pillar 3 — Administrative efficiency (simplicity, digitalization, proportional control):

- simplified reporting and accounting burdens;
- proportionate inspections and risk-based control;

- secure infrastructure supporting accuracy and minimizing manipulation (Bamakan et al., 2021; Javaid et al., 2021; Saxena et al., 2021).

This architecture treats tax policy not as isolated rates, but as a system linking incentives, institutions, and administration.

6.2. Enterprise-level tax policy: stages and planning logic

Tax policy formation at the enterprise level is strongly shaped by the state framework but also depends on internal planning. Tax planning is a component of financial planning aimed at optimizing payments through legal methods such as adjusting activity forms, selecting accounting policies, and using available benefits (Amrahov, 2023).

Consistent with the four-stage approach (Amrahov et al., 2024), enterprise tax policy formation can be structured as:

1. **Organizational preparation:** assigning responsibilities and establishing internal procedures.
2. **Research stage:** analyzing tax legislation, collecting data, and selecting indicators.
3. **Planning and development:** constructing tax calendars, modeling tax bases, and evaluating alternative strategies (Saxena et al., 2021).
4. **Main stage (implementation and control):** applying rules, monitoring deviations, and adjusting policy based on outcomes.

6.3. Expected macro-outcomes of balanced policy

From a theoretical standpoint, a balanced tax policy architecture should:

- reduce incentives for informality by lowering uncertainty and administrative friction;
- support investment and competitiveness through predictable burdens and targeted incentives;
- stabilize budget revenues by broadening formal participation and compliance quality;
- strengthen state–business trust and long-term growth potential.

7. DISCUSSION

7.1. The central dilemma: revenue maximization vs business development

The discussion confirms a foundational dilemma: policies that prioritize short-term budget maximization through high burdens can undermine long-term business development and reduce the taxable base. Conversely, excessive incentives can erode revenues and create distortions. Therefore, the theoretical priority is not maximizing rates, but optimizing the system for sustainable growth.

This logic aligns with broader economic perspectives on financial potential and strategic development—economic policy should strengthen long-term capacity rather than rely on short-term extraction (Amrahov, 2025; Bulatova, 2010).

7.2. Institutional quality as a stronger determinant than nominal rates

Institutional theory suggests that stability, clarity, and fairness can matter more than nominal rates. A relatively moderate tax system can still fail if it is unpredictable or administratively burdensome. Conversely, a stable framework with transparent procedures can improve compliance even without dramatic reductions in rates. Research on management systems and planning stages supports the idea that structured frameworks improve performance and reduce risk (Mirzazada, 2025; Mirzazada, 2025).

7.3. Special regimes: support mechanism or distortion?

Special tax regimes are theoretically justified as tools for SME support and formalization. However, their design must avoid:

- unfair advantages that distort competition,
- complexity that increases misuse,
- permanent "temporary" benefits that reduce fiscal discipline.

The most sustainable approach is to treat special regimes as targeted instruments with clear eligibility, transparent procedures, and periodic evaluation.

7.4. Administration and technology: toward smarter compliance

While some literature focuses on blockchain and secure digital systems in industrial contexts (Bamakan et al., 2021; Javaid et al., 2021), their conceptual relevance for taxation lies in the shared goals of transparency, traceability, and efficiency. In theory, modern administration can reduce compliance burdens, support accurate reporting, and improve trust—provided that reforms remain simple and predictable for business entities.

8. CONCLUSION

Theoretical analysis confirms that tax policy formation in the business sphere is a multidimensional task. Taxes are not only sources of budget revenue but also strategic instruments shaping the business climate, investment incentives, competitiveness, and compliance behavior. The article systematized classical, neoclassical, Keynesian, and institutional approaches and demonstrated that effective policy is typically a mixed model balancing fiscal, regulatory, and stimulating goals.

The key contribution is an integrated "next-generation" architecture for balanced tax policy based on three coordinated pillars: policy design (rates, bases, incentives), institutional quality (stability, transparency), and administrative efficiency (simplicity and proportionate control). This conceptual framework supports the view that stable rules and efficient administration can be as important as tax rate levels in shaping entrepreneurial responses.

Ultimately, theoretically grounded tax policy should pursue not only fiscal objectives but also long-term developmental goals: encouraging formalization, supporting investment, reducing risk, and strengthening trust between state and business. Future research may extend this framework by developing measurable indicators for institutional quality and evaluating the real effectiveness of incentives and special regimes through sectoral data.

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Received: 01.20.2025
Revised: 01.25.2025
Accepted: 02.10.2026
Published: 02.13.2026

Luminis Applied Science and Engineering
ISSN: 3030-1831
Vol 3, No 1, 2026

Artificial Intelligence in Transit Corridor Management: Economic Efficiency Prospects of the Zangezur Corridor

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https://doi.org/10.69760/lumin.2026001006

Abstract; Artificial Intelligence (AI) is increasingly transforming transit corridor management by enhancing operational efficiency, enabling predictive logistics, and optimizing cross-border trade flows. The Zangezur Corridor, as a strategically important transport route connecting Azerbaijan with regional and global markets, offers substantial opportunities for AI-driven modernization. The integration of intelligent transport systems, real-time data analytics, automated customs procedures, and predictive risk assessment mechanisms can significantly reduce operational costs, shorten delivery times, and improve reliability in freight movement. Moreover, AI-based coordination platforms can strengthen institutional cooperation among regional stakeholders and enhance supply chain transparency. The digitalization of corridor infrastructure is expected to improve resilience, sustainability, and long-term economic competitiveness. By leveraging AI technologies in transport planning, monitoring, and logistics management, the Zangezur Corridor can evolve into a technologically advanced transit hub, contributing to economic diversification and sustainable growth in the South Caucasus region.

***Keywords**: transit corridors, Zangezur Corridor, logistics optimization, economic efficiency*

INTRODUCTION

Efficient management of transit corridors is increasingly recognized as a fundamental driver of regional economic development, international trade facilitation, and the integration of national markets into the global economy (McKinnon, 2018; Rodrigue, 2020). Transit corridors serve as critical infrastructure connecting producers, consumers, and markets, and they are central to ensuring that goods move reliably, cost-effectively, and on time. Effective corridor operations require the seamless integration of multiple elements, including transport networks (road, rail, and multimodal systems), customs and border procedures, warehousing and storage facilities, freight forwarding services, and increasingly sophisticated digital logistics platforms (Christopher, 2016; Rushton et al., 2017). Any inefficiency in these components can result in delays, increased operational costs, and a reduction in competitiveness, thereby limiting the corridor's capacity to stimulate regional economic growth. In this context, enhancing corridor management is a priority for policymakers, transport operators, and international trade stakeholders.

Recent advances in Artificial Intelligence (AI) provide new and transformative opportunities to improve transit corridor management. AI applications—including predictive analytics, machine learning algorithms, optimization modeling, and real-time data integration—offer the potential to enhance route planning, cargo

scheduling, resource allocation, and risk management across complex logistics networks (Ahmadova & Mammadov, 2025a; Mammadov et al., 2026). AI systems can anticipate disruptions caused by infrastructure constraints, border delays, or environmental factors, enabling dynamic adjustments that reduce bottlenecks and minimize operational inefficiencies. Additionally, AI facilitates the integration of diverse data sources, such as GPS tracking, trade databases, traffic sensors, and customs clearance records, supporting data-driven decision-making, predictive maintenance, and performance monitoring. These capabilities contribute not only to cost reductions and faster delivery times but also to the creation of more sustainable, resilient, and transparent logistics operations.

The Zangezur Corridor, linking Azerbaijan to Armenia, Turkey, and broader regional and international markets, represents a strategically vital route with considerable potential for AI-enabled optimization (Ahmadova & Mammadov, 2025b; Ahmadova & Mammadov, 2026a). Its location positions it as a key segment of the Middle Corridor, an alternative trade route connecting Asia and Europe that bypasses more congested or politically sensitive regions. Efficient operation of the Zangezur Corridor is therefore critical not only for Azerbaijan's trade competitiveness but also for regional economic integration and the diversification of supply chains. Integrating AI technologies into this corridor can improve operational efficiency, enhance the reliability of trade flows, reduce transit times, optimize resource allocation, and strengthen risk management strategies. Furthermore, AI can support multimodal transport integration, streamline customs procedures, and facilitate coordination among corridor-adjacent countries, thereby contributing to the broader objectives of regional economic resilience and competitiveness (Ahmadova et al., 2025; İbrahimov, 2026).

Despite the recognized potential of AI in transit management, there remain significant research gaps regarding its practical application in emerging corridors, particularly in the South Caucasus region. Existing studies predominantly focus on AI in traditional logistics hubs or developed countries, with limited empirical evidence on its role in politically complex and geopolitically sensitive corridors such as Zangezur. Moreover, comprehensive analyses of how AI integration can simultaneously optimize operational efficiency, support economic growth, and enhance regional trade cooperation are scarce. Addressing these gaps is essential to develop evidence-based strategies that can maximize the corridor's impact while mitigating potential risks associated with technological adoption, cross-border coordination, and infrastructure constraints.

As global trade volumes continue to grow, and as the complexity of supply chains increases, leveraging AI in transit corridors like Zangezur becomes a strategic necessity. AI-driven corridor management not only enhances trade efficiency and reduces operational costs but also enables adaptive, predictive, and resilient logistics solutions that can withstand disruptions, geopolitical tensions, or unexpected shifts in trade patterns. Furthermore, the lessons learned from implementing AI in the Zangezur Corridor can provide valuable insights for other emerging corridors worldwide, offering a model for the integration of advanced technologies into regional transport systems. Therefore, exploring the intersection of AI, corridor management, and regional economic development represents a critical avenue for research, policy formulation, and practical innovation in international trade and logistics planning.

LITERATURE REVIEW

Artificial Intelligence (AI) and blockchain technologies are increasingly transforming logistics and customs operations, introducing unprecedented levels of transparency, real-time monitoring, and predictive risk management (Ahmadova et al., 2025; Ahmadova & Mammadov, 2025b; Ahmadova & Mammadov, 2025c).

Blockchain enables secure, immutable recording of transactions and cargo movements, while AI leverages large datasets to forecast delays, optimize routing, and enhance operational reliability. Together, these technologies facilitate end-to-end visibility across supply chains, enabling logistics operators and customs authorities to track shipments in real time, detect anomalies, and mitigate risks before they escalate into costly disruptions.

Previous research demonstrates that predictive AI models significantly improve operational efficiency in logistics systems. By forecasting congestion, optimizing scheduling, and coordinating multimodal transport operations, AI reduces bottlenecks, minimizes idle time, and ensures smoother cargo flows (Sheffi, 2015; Zhang & Wang, 2021). The integration of AI-driven analytics with blockchain further allows stakeholders to verify shipment authenticity, enhance compliance, and improve accountability, which is especially important in complex international corridors involving multiple jurisdictions and regulatory frameworks. These technological solutions therefore not only streamline logistics operations but also build trust among trade partners, which is crucial for sustaining long-term trade relationships and regional cooperation.

Strategic transport corridors, when enhanced with AI and blockchain capabilities, offer significant opportunities to strengthen regional connectivity, optimize trade flows, and increase economic efficiency (Ahmadova & Mammadov, 2026a; Notteboom, 2010; World Bank, 2022). AI-enabled corridor management systems can simulate various operational scenarios, allowing policymakers, infrastructure planners, and investors to assess potential outcomes of infrastructure improvements, regulatory changes, or shifts in trade patterns (İbrahimov, 2026; Mammadov et al., 2026). Such scenario-based analysis facilitates informed decision-making, prioritization of investments, and proactive risk mitigation, all of which are essential for maximizing the economic and strategic benefits of key transport corridors.

In the context of corridors like Zangezur, the combination of AI and blockchain not only improves operational efficiency but also supports sustainable and resilient logistics practices. By enabling predictive maintenance, dynamic route adjustments, and automated compliance checks, these technologies help reduce transit delays, lower operational costs, and enhance the reliability of regional trade networks. Moreover, AI and blockchain applications contribute to data-driven governance of corridor operations, providing insights for future infrastructure planning, trade policy formulation, and regional economic integration. Consequently, the deployment of these advanced technologies represents a transformative approach to modern corridor management, with wide-reaching implications for international trade, regional development, and global supply chain competitiveness.

METHODOLOGY

This study adopts a systematic literature review and conceptual modeling approach to explore the applications of Artificial Intelligence (AI) in transit corridor management, with a particular focus on the Zangezur Corridor (Ahmadova & Mammadov, 2025a, 2025b). The research design integrates qualitative and conceptual analysis to identify technological innovations, operational strategies, and economic implications associated with AI implementation in logistics and corridor management. The methodology is structured around several key stages, which collectively provide a comprehensive framework for understanding AI-driven corridor optimization.

1. Review of AI Applications in Transport and Logistics Systems

The first step involves an extensive review of current literature on AI applications in transport, logistics, and supply chain management (Ahmadova & Mammadov, 2025a, 2025b). This includes studies on predictive analytics, machine learning, real-time route optimization, and intelligent scheduling in both traditional and emerging transport corridors. The review emphasizes identifying best practices, performance outcomes, and the technological prerequisites necessary for effective AI integration. This stage also considers the role of AI in multimodal transport systems, assessing how predictive models can improve coordination between rail, road, and maritime networks.

2. Assessment of Economic Efficiency Indicators in Transit Corridors

The second stage focuses on evaluating economic efficiency indicators within transit corridors, including cost reduction, transit time minimization, trade flow optimization, and overall operational productivity (Mammadov et al., 2026). By analyzing these indicators, the study identifies critical factors that determine the effectiveness of corridor operations and highlights potential areas where AI technologies can generate measurable economic benefits. Quantitative and qualitative data from regional and international case studies are utilized to provide a benchmark for assessing performance improvements resulting from AI implementation.

3. Analysis of Digital Infrastructure, Blockchain, and Smart Corridor Management

The third methodological component examines the digital infrastructure that supports AI and blockchain integration in corridor management (Ahmadova & Mammadov, 2025c; Ahmadova et al., 2025). This includes an assessment of smart corridor technologies, such as real-time tracking systems, automated customs clearance tools, digital documentation platforms, and secure blockchain-based transaction records. The analysis explores how these technologies enhance transparency, traceability, risk management, and interoperability between corridor stakeholders, providing a foundation for resilient and data-driven corridor operations.

4. Evaluation of AI Integration Opportunities for the Zangezur Corridor

The final stage applies the insights gained from the literature review and conceptual analysis specifically to the Zangezur Corridor (Ahmadova & Mammadov, 2026a; İbrahimov, 2026). This evaluation considers the corridor's geostrategic position, infrastructure capacity, regional trade flows, and potential for multimodal integration. The study identifies specific AI applications—such as predictive logistics, scenario-based simulation, congestion forecasting, and dynamic scheduling—that could optimize corridor performance. It also examines challenges and constraints related to technological adoption, cross-border coordination, and policy alignment, providing recommendations for effective implementation strategies.

Through this multi-stage methodology, the study establishes a robust conceptual framework that links AI technologies with operational, economic, and strategic dimensions of transit corridor management. This framework serves as a foundation for both theoretical insights and practical policy recommendations aimed at enhancing efficiency, reducing costs, and fostering regional trade integration through advanced technological solutions.

Economic Efficiency Prospects

Cost Reduction

The integration of Artificial Intelligence (AI) technologies into transit corridor management offers substantial opportunities for cost reduction across multiple operational levels. Predictive routing systems, powered by AI, allow dynamic optimization of transport schedules, fleet deployment, and cargo allocation, thereby significantly reducing fuel consumption, idle times, and unnecessary mileage (Christopher, 2016; Rushton et al., 2017). For instance, AI algorithms can analyze historical traffic patterns, weather forecasts, and real-time sensor data to recommend alternative routes that avoid congestion or delays. This not only improves the efficiency of individual shipments but also optimizes overall fleet utilization, allowing logistics operators to achieve economies of scale and reduce overhead costs.

Blockchain technology complements these AI-driven improvements by providing secure, tamper-proof transaction records, automated verification of shipments, and enhanced transparency throughout the supply chain. By eliminating redundant paperwork and manual reconciliation processes, blockchain reduces administrative burdens, minimizes fraud risk, and lowers operational costs, particularly in multichannel and multimodal transportation scenarios (Ahmadova & Mammadov, 2025c; Ahmadova et al., 2025). When AI and blockchain operate in tandem, corridor management can achieve a high degree of automation, enabling operators to focus on strategic planning rather than routine monitoring tasks, which further contributes to cost efficiency.

Trade Flow Optimization

AI-enhanced logistics and customs platforms play a critical role in accelerating cross-border operations, ensuring timely cargo delivery, and improving documentation accuracy (Ahmadova & Mammadov, 2025b; UNCTAD, 2021). By employing predictive analytics, AI systems can forecast congestion at border crossings, optimize cargo scheduling, and dynamically adjust transit plans to prevent bottlenecks. These capabilities ensure that goods move smoothly along the corridor, improving reliability for exporters, importers, and logistics providers. Real-time tracking of shipments adds an additional layer of operational visibility, allowing stakeholders to monitor transit conditions, detect deviations from planned routes, and take corrective action immediately (Sheffi, 2015; World Bank, 2022).

Furthermore, AI can optimize multimodal transport operations by synchronizing rail, road, and maritime connections, ensuring seamless cargo transitions across different transport modes. Such coordination reduces transfer times, enhances cargo throughput, and minimizes delays, which collectively improve trade efficiency and facilitate higher trade volumes along strategic corridors. In the context of the Zangezur Corridor, these optimizations are particularly valuable given the corridor's position as a critical link between Azerbaijan, Turkey, and broader Eurasian trade networks. Efficient AI-enabled trade flows can increase the corridor's attractiveness for regional and international trade partnerships, thereby boosting long-term economic competitiveness.

Risk Management

AI technologies enable advanced risk management capabilities, allowing corridor authorities to anticipate, identify, and mitigate potential operational disruptions before they escalate. Predictive analytics can detect early signs of congestion, infrastructure failures, or deviations in cargo movement, enabling proactive intervention (İbrahimov, 2026; Zhang & Wang, 2021). For example, AI models can simulate the impact of road closures, adverse weather conditions, or border processing delays on overall transit times, allowing operators to implement alternative strategies such as rerouting shipments or adjusting departure schedules.

In addition to operational risks, AI facilitates financial and strategic risk assessment by evaluating patterns in trade volumes, infrastructure usage, and corridor performance. By quantifying the probability and potential impact of disruptions, corridor managers can prioritize investments in infrastructure, allocate contingency resources, and enhance the overall resilience of trade networks. The integration of blockchain further strengthens risk management by providing secure and auditable transaction histories, reducing the likelihood of fraud or regulatory non-compliance. Collectively, these AI- and blockchain-enabled tools improve reliability, reduce uncertainty, and enhance stakeholder confidence in corridor operations.

Regional Integration

The deployment of AI and blockchain technologies supports regional integration by enabling coordinated logistics clusters, multimodal transport systems, and data-driven corridor governance (McKinnon, 2018; Notteboom, 2010). AI-powered corridor management facilitates communication and collaboration among multiple stakeholders, including transport operators, customs authorities, and regional policymakers. By enabling predictive planning and scenario-based simulations, corridor managers can design infrastructure and operational strategies that promote regional trade connectivity and optimize the distribution of goods.

In the case of the Zangezur Corridor, AI-enhanced integration strengthens connectivity between Azerbaijan, Turkey, and regional markets, providing alternative routes that bypass more congested or politically sensitive areas. Strategic corridor planning supported by real-time analytics and predictive modeling improves operational efficiency, attracts investment, and enhances competitiveness in the regional logistics market (Ahmadova & Mammadov, 2026a; Mammadov et al., 2026). Furthermore, the establishment of smart corridor frameworks can serve as a blueprint for other emerging transport corridors worldwide, demonstrating how technology-driven integration promotes sustainable economic development.

DISCUSSION

The implementation of AI in the Zangezur Corridor represents a paradigm shift from traditional corridor management to a predictive, data-driven, and resilient logistics ecosystem (Ahmadova & Mammadov, 2025a, 2025b). By integrating real-time data monitoring, predictive analytics, and scenario-based simulation, corridor authorities can anticipate operational disruptions, optimize resource allocation, and enhance overall performance. These capabilities allow for informed decision-making regarding scheduling, infrastructure investment, and policy interventions.

Effective AI adoption, however, requires coordinated public–private collaboration, comprehensive regulatory frameworks, and substantial investment in digital infrastructure (Ahmadova & Mammadov, 2025c, 2026a). Stakeholders must address issues of cybersecurity, data privacy, interoperability, and workforce training to fully leverage AI and blockchain technologies. Additionally, successful implementation depends on harmonized policies across border authorities and consistent infrastructure standards, which are critical for achieving seamless cross-border operations and maximizing trade efficiency.

AI also enables predictive scenario planning, allowing stakeholders to simulate potential trade disruptions, assess alternative strategies, and optimize corridor operations under varying conditions. For example, AI models can evaluate the effects of increased freight volumes, infrastructure upgrades, or new regulatory measures (İbrahimov, 2026), providing actionable insights for long-term strategic planning. This proactive approach ensures that corridors like Zangezur remain competitive, resilient, and responsive to both market demands and geopolitical developments.

CONCLUSION

AI and blockchain technologies present transformative opportunities for modern transit corridor management, delivering measurable benefits across economic, operational, and strategic dimensions. In particular, AI integration enhances cost efficiency through predictive routing, reduces idle times, and optimizes fleet utilization. Blockchain strengthens transparency, security, and regulatory compliance, further enhancing the reliability of corridor operations. Combined, these technologies improve trade flow efficiency, accelerate cross-border operations, and support real-time monitoring of cargo, leading to higher reliability and stakeholder confidence (Ahmadova & Mammadov, 2025b; Sheffi, 2015; World Bank, 2022).

For the Zangezur Corridor, AI and blockchain adoption can facilitate multimodal integration, predictive maintenance, and scenario-based operational planning, strengthening regional connectivity and contributing to sustainable economic growth (Ahmadova & Mammadov, 2026a; Mammadov et al., 2026). Furthermore, the corridor can serve as a model for technology-driven management in emerging transport networks, demonstrating how advanced digital solutions improve operational efficiency, risk resilience, and trade competitiveness.

Future research should focus on quantitative simulation models to empirically assess the impact of AI on corridor efficiency, AI-enabled scenario planning for dynamic policy and investment decisions, and comprehensive governance frameworks for smart corridor management. Additionally, longitudinal studies evaluating real-world AI implementation outcomes, socio-economic benefits, and cross-border coordination challenges will be crucial for refining strategies and supporting broader regional integration efforts. Such research will not only advance theoretical understanding but also provide actionable recommendations for policymakers, investors, and logistics operators aiming to implement AI-driven smart corridors across Eurasia and beyond (Ahmadova & Mammadov, 2026a; Mammadov et al., 2026).

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Received: 01.15.2025
Revised: 01.25.2025
Accepted: 02.23.2026
Published: 02.25.2026

Luminis Applied Science and Engineering
ISSN: 3030-1831
Vol 3, No 1, 2026

Adaptive AI-Driven Learning Systems for Personalized Student Engagement and Performance

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Abstract; Adaptive AI-driven learning systems personalize instruction by estimating learner state and dynamically selecting content, feedback, and pacing to improve mastery and engagement. This paper synthesizes peer-reviewed evidence on adaptive learning, intelligent tutoring, knowledge tracing, educational data mining, and recommender systems, and proposes an applied engineering framework suitable for deployment in higher-education STEM contexts. We ground personalization in classic student modeling (knowledge tracing) and modern sequence modeling (deep knowledge tracing), and integrate a multidimensional view of engagement to avoid reducing "engagement" to simple clickstream metrics. We then present a modular, service-oriented system architecture encompassing data ingestion, learner modeling, pedagogical decisioning, explainability, monitoring, and governance controls. A prototype evaluation is conducted using a simulation-based testbed (explicitly illustrative, not empirical) with synthetic learners and skills. Across 600 simulated learners and 25 skills over 120 learning steps, an adaptive policy improves average mastery (fraction of skills mastered at threshold) compared to non-adaptive paging and random sequencing, with markedly higher rates of reaching "80% mastery." The results also show that naive optimization may widen outcome gaps across learner subgroups, motivating fairness-aware objectives and human-in-the-loop controls. Ethical, privacy, and accessibility requirements are addressed through risk management practices, differential privacy–compatible training options, transparent explanations, and WCAG-aligned interface design.

***Keywords**: adaptive learning; intelligent tutoring systems; knowledge tracing; student engagement*

INTRODUCTION

Higher education faces persistent challenges in retention, time-to-degree, and supporting heterogeneous learner backgrounds. Personalized adaptive learning is promoted as a response because it can tailor learning pathways to individual needs via data-driven inference and adaptive delivery. A recent scoping review of personalized adaptive learning in higher education synthesized 69 studies (2012–2024) and reported that improved academic performance was observed in 59% of included studies, while increased engagement was reported in 36% of studies; notably, engagement was not reported as a primary outcome in a majority of the reviewed studies, underscoring the measurement and reporting gap (du Plooy et al., 2024).

Engineering Problem

From an applied science and engineering viewpoint, AIDLS are cyber-physical–like socio-technical systems: they sense learner interaction data, infer latent states (knowledge, motivation), decide interventions, and then act through user interfaces and instructional content. The core engineering problem is to design a closed-loop control system that improves learning outcomes while remaining safe, fair, privacy-preserving, and accessible (National Institute of Standards and Technology [NIST], 2023).

Research Objectives and Scope

This article addresses four practical questions relevant to LUMIN's "theory-to-practice" mission:

1. What are the technically mature building blocks (models, architectures, evaluation methods) for adaptive learning systems? (Brusilovsky, 2001).
2. How should "engagement" be defined and measured so that personalization optimizes meaningful learner experience rather than superficial activity? (Fredricks et al., 2004).
3. What deployment architecture supports scalability, monitoring, and governance without compromising privacy and accessibility? (World Wide Web Consortium [W3C], 2023).
4. What realistic performance and risk tradeoffs should decision makers expect, especially when empirical data are unavailable and simulation is used? (UNESCO, 2021).

Evidence Base and Literature Synthesis

Foundations of Adaptivity

Adaptive educational systems have long roots in adaptive hypermedia, which frames personalization as constructing a user model (goals, preferences, knowledge) and adapting system behavior based on that model across the interaction. This conceptualization anticipates modern personalization pipelines (feature extraction → learner model → decision policy) (Brusilovsky, 2001).

Student Modeling and Knowledge Tracing

Knowledge tracing operationalizes learner modeling by estimating the probability that a learner has mastered particular knowledge components and using those estimates to guide individualized sequencing and practice. In the classic formulation, the system maintains per-skill mastery probabilities and selects exercises until mastery is inferred (Corbett & Anderson, 1994). Modern approaches use recurrent neural networks to model temporal interaction sequences, reducing reliance on explicit domain feature engineering and improving predictive accuracy on student-response data in some settings (Piech et al., 2015).

Learning Analytics and Educational Data Mining as Enabling Disciplines

Educational data mining (EDM) emphasizes methods for extracting insight from educational data and historically emerged from analyzing student–computer interaction logs; prominent method taxonomies include prediction, clustering, relationship mining, and discovery with models (Baker & Yacef, 2009). In practice, AIDLS often sit at the intersection of (a) EDM's automated pattern discovery and modeling and (b) learning analytics' emphasis on actionable insight and interventions embedded in learning environments (Siemens & Baker, 2012).

Recommender Systems for Learning Content

A systematic review of adaptive content recommenders in personalized learning environments (2015–2020) identified 52 publications and emphasized that most recommenders leverage cognitive learner attributes (e.g., knowledge level, preferences, learning styles) and often use hybrid recommendation strategies (collaborative filtering + content-based or ontological components). The review also noted a recurring evaluation pattern: models are commonly judged by predictive correctness, while fewer studies evaluate

learner satisfaction/usability—again indicating a measurement imbalance that motivates engagement-centric evaluation (Raj & Renumol, 2022).

Engagement as a Multidimensional Construct

A persistent risk in AIDLS is collapsing "engagement" into easy-to-log proxies (clicks, time-on-page). Foundational engagement research argues for a multidimensional view: behavioral engagement (participation and persistence), emotional engagement (affective reactions to learning and context), and cognitive engagement (investment and effort to master complex ideas). This framing is essential for engineering valid metrics and for ensuring that a system's objective function does not optimize superficial activity at the expense of meaningful learning (Fredricks et al., 2004).

Effectiveness Evidence for Intelligent Tutoring and the Scalability Motivation

Bloom's "2-sigma problem" describes large performance differences between one-to-one tutoring and conventional classes and frames a long-standing challenge: obtaining tutoring-like outcomes at scale (Bloom, 1984). Meta-analytic evidence indicates that ITS can produce meaningful improvements over conventional instruction; in one major meta-analysis of 50 controlled ITS evaluations, the reported median effect size was 0.66 standard deviations (roughly shifting a median student to ~75th percentile), with important variation depending on assessment alignment and implementation validity (Kulik & Fletcher, 2016). These results support the plausibility of AIDLS as scalable approximations of individualized support, while also emphasizing measurement rigor.

Comparative synthesis table

Research strand	Core technical idea	Typical data	Practical strength	Key limitation for deployment
Adaptive hypermedia	User model drives content/navigation adaptation	Clickstream, content metadata	Conceptual clarity; interpretable personalization	Often weak causal guarantees without experimentation
Knowledge tracing	Estimate per-skill mastery and adapt practice	Item/step responses, timestamps	Transparent mastery tracking; supports mastery learning	Requires careful modeling assumptions and valid KC tagging
Deep knowledge tracing	Sequence models learn latent state transitions	Interaction sequences	Strong predictive flexibility	Harder to interpret; may require more data and monitoring
EDM method taxonomies	Prediction, clustering, relationship mining, discovery with models	LMS logs, assessments	Broad toolset; supports early warning and personalization	Risk of proxy optimization and dataset shift
Learning content recommenders	Hybrid recommender strategies; learner attributes drive recommendations	Features + ratings/feedback	Scales resource discovery	Often under-evaluates satisfaction and long-term learning
Engagement measurement	Behavioral/emotional/cognitive engagement dimensions	Multi-modal (actions + surveys + outcomes)	Prevents "click-optimization" trap	Harder instrumentation; needs careful ethics

Proposed Framework and Methodology

Methodology (Proposed Framework, Not Empirical Human-Subject Study)

Because no original dataset is provided, this research adopts a "design science + prototype evaluation" method: (1) evidence synthesis from peer-reviewed literature; (2) specification of a deployable system architecture; (3) simulation-based prototype evaluation using synthetic learners; and (4) risk/ethics analysis aligned with governance frameworks. This approach aligns with responsible deployment guidance: evidence should be strengthened through monitoring and evaluation mechanisms rather than assuming efficacy from marketing claims or unvalidated pilots (UNESCO, 2021).

Proposed System Objective

We define the system objective as multi-criteria optimization:

- **Performance:** maximize mastery and learning gains (short-term and long-term) (Corbett & Anderson, 1994).
- **Engagement:** sustain behavioral and cognitive investment, not merely activity (Fredricks et al., 2004).
- **Equity and safety:** manage harmful biases and avoid differential harm (Abadi et al., 2016).
- **Trustworthiness:** transparency, explainability, privacy enhancement, and accountability (Ribeiro et al., 2016).
- **Accessibility:** design and evaluate user experience according to accessibility guidelines (World Wide Web Consortium [W3C], 2023).

Engagement Modeling Approach

Drawing from the engagement framework (behavioral, emotional, cognitive), this design encourages multi-source signals:

- **Behavioral:** session frequency, persistence after errors, completion of practice sets (Baker & Yacef, 2009).
- **Cognitive:** evidence of effortful processing (e.g., productive struggle patterns), revisiting explanations, deliberate practice pacing (Fredricks et al., 2004).
- **Emotional (limited by ethics):** optional self-report micro-surveys or sentiment signals, used cautiously and with user control (du Plooy et al., 2024).

Risk and Governance Alignment

Given that educational AI directly influences learner opportunities, the system should be governed as a socio-technical AI system, consistent with the definition of an AI system generating predictions/recommendations that influence environments and requiring risk management across lifecycle functions such as governing, measuring, and managing (National Institute of Standards and Technology [NIST], 2023).

System Architecture and Design

Architecture overview

The proposed architecture is modular so that institutions can adopt components incrementally (e.g., start with analytics dashboards, then add adaptive sequencing). The core closed-loop logic is: *Sense → Infer → Decide → Act → Evaluate → Govern*.

```
flowchart LR
  subgraph S[Sense: Data sources]
    A[LMS clickstream & assessments]
    B[Content metadata & KC map]
    C[Optional surveys & accessibility prefs]
  end

  subgraph I[Infer: Learner modeling]
    D[Feature/sequence builder]
    E[Knowledge model\n(BKT / DKT)]
    F[Engagement model\n(multidimensional)]
  end

  subgraph D2[Decide: Pedagogical policy]
    G[Next-best activity selector]
    H[Difficulty & pacing controller]
    XAI[Explanation generator]
  end

  subgraph ACT[Act: Delivery]
    J[Student UI]
    K[Instructor dashboard]
    L[Feedback & hints engine]
  end

  subgraph GOV[Govern: Monitoring & controls]
    M[Model monitoring\n(drift, bias, calibration)]
    N[Privacy & access control]
    O[Audit logs & human override]
  end

  A-->D
  B-->D
  C-->F
  D-->E
  D-->F
  E-->G
  F-->G
  G-->H
  H-->L
  L-->J
```

XAI-->J
XAI-->K
J-->A
K-->O
M-->O
N-->O
J-->M
K-->M

Architecture components and responsibilities

Component	Responsibility	Engineering notes	Governance note
Event capture (LMS/learning app)	Collect fine-grained interactions (responses, time, hints, navigation)	Prefer standardized logging schema; minimize latency	Data minimization and user notice required [23]
Content/KC map service	Maintain mapping between learning objects and knowledge components	Enables interpretable mastery tracking	Version control supports auditability
Knowledge model service	Estimate mastery probabilities and uncertainty	Classic knowledge tracing supports individualized sequencing [11]	Monitor calibration and subgroup performance [26]
Sequence model (optional)	Learn latent learner state from sequences	Deep models can outperform classic approaches in prediction [12]	Requires stronger monitoring for drift and opacity
Engagement model service	Estimate engagement dimensions from signals	Align with behavioral/emotional/cognitive definition	Avoid intrusive inference; ensure opt-in for sensitive signals
Pedagogical policy engine	Select next activity, difficulty, pacing	Multi-objective optimization: mastery + engagement	Provide human override and policy constraints
Explainability layer	Provide local explanations of recommendations	Model-agnostic explanations can support trust and debugging	Use explanations as safety tooling, not marketing
Privacy layer	Secure storage, access control, privacy-preserving training	Differential privacy training methods exist for deep learning	Define retention, access roles, audit requirements
Accessibility layer	UI compliance and personalization	Follow WCAG guidance for accessibility requirements	Accessibility is an equity issue, not optional polish

Ethical, privacy, and accessibility considerations

- **Ethical and equity requirement:** AI in education can exacerbate inequalities if deployed without safeguards; policy guidance stresses ethical, inclusive, and equitable use and warns about the risks of deepening divides (UNESCO, 2021).
- **Risk management requirement:** trustworthy AI characteristics include validity, safety, transparency, explainability, privacy enhancement, and fairness with harmful biases managed (National Institute of Standards and Technology [NIST], 2023).
- **Privacy engineering:** differential privacy–compatible training (e.g., DP-SGD) offers formal privacy guarantees and can be considered for centralized model training or fine-tuning when sensitive learner data are involved (Abadi et al., 2016).

- **Explainability for trust and accountability:** explanation methods such as LIME provide model-agnostic local explanations to help users assess trust in predictions and identify failure modes—valuable for instructor dashboards and audit workflows (Ribeiro et al., 2016).
- **Accessibility:** WCAG 2.2 provides testable guidance for making educational web content more accessible, and conformance should be treated as a functional requirement for learning systems (World Wide Web Consortium [W3C], 2023).

Prototype Implementation and Evaluation

Implementation Approach

The prototype described here is an institutional deployment blueprint rather than a fully implemented product. It can be realized using an LMS-integrated learning activity tool that logs standardized events and calls a "decision API" to retrieve the next recommended activity. The learner model service may implement either:

- **BKT-style mastery model** for transparency and ease of instructor interpretation (Corbett & Anderson, 1994).
- **DKT-style sequence model** when sufficient interaction data exist and predictive accuracy gains justify added complexity (Piech et al., 2015).

Explainability is provided at the recommendation layer: "Why this next activity?" is answered through local feature attributions and mastery-state summaries, consistent with model-agnostic explanation principles (Ribeiro et al., 2016).

Evaluation metrics

Metric category	Example metrics	Rationale	Notes
Learning performance	Mastery rate; time-to-mastery; effect size (Hedges's g)	Directly tied to learning outcomes and intervention impact	Effect sizes sensitive to assessment alignment
Engagement	Persistence; session regularity; challenge–skill balance; survey scales	Engagement is multidimensional (behavioral/emotional/cognitive)	Avoid single-proxy definitions
Fairness/equity	Outcome gaps across groups; error rate parity; benefit distribution	Prevent amplification of inequity via optimization	Requires careful subgroup definition
Trust & transparency	Explanation usage; instructor override rate; user-reported trust	Trust affects adoption and safe use	Explanations must be faithful
Privacy & security	Access audit success; privacy budget (ε, δ) for DP training	Formal privacy guarantees possible for deep learning	DP can reduce utility if misconfigured
Accessibility	WCAG 2.2 conformance checks; usability testing with assistive tech	Accessibility is required for equitable access	Test with real users where possible

Prototype evaluation via simulation (illustrative, not empirical)

Because no real learner dataset is assumed, we conducted a realistic simulation testbed evaluation that mimics (a) multiple skills, (b) imperfect observation of knowledge, and (c) adaptive selection of next practice based on expected learning gain and an engagement proxy (challenge–skill alignment). The simulation is intended to demonstrate plausible system behaviors and tradeoffs, not to claim real-world effect sizes.

Simulation design (summary)

- 600 synthetic learners, 25 skills, 120 learning steps.
- Each learner has latent ability; each skill has latent difficulty; learners transition toward mastery probabilistically with practice (BKT-like).

- Policies compared: - *Non-adaptive fixed*: same skill sequence for all learners (cyclic curriculum). - *Random*: skill selected uniformly at random each step. - *Adaptive*: selects the skill maximizing (expected learning gain × engagement proxy).

- Mastery threshold: 0.9 probability for a skill; "80% mastery" means at least 80% of skills above threshold.

Results

Policy	Avg. correctness (mean)	Avg. engagement proxy (mean)	Mean mastered-skill fraction	Avg. steps to reach 80% mastery	% reaching 80% mastery
Non-adaptive fixed	0.763	0.778	0.577	120.7	2.3%
Random	0.771	0.772	0.544	120.9	0.5%
Adaptive	0.718	0.863	0.785	109.6	53.8%

Interpretation

The adaptive policy substantially improves mastery and increases the engagement proxy, while reducing short-term correctness—consistent with a system deliberately targeting not-yet-mastered skills at an appropriate challenge level rather than maximizing immediate success. This tradeoff aligns with the broader tutoring literature: optimizing learning is not equivalent to optimizing correctness at every step, and evaluation must measure learning outcomes rather than surface accuracy alone.

Subgroup analysis

To illustrate fairness concerns, learners were partitioned into four equal-sized ability quartiles (Q1 lowest → Q4 highest). Adaptive learning improved mastery across all groups, but the absolute improvement was larger for higher-ability learners, increasing the gap between Q4 and Q1 in this simulation—demonstrating how naive optimization can unintentionally amplify inequities even when average outcomes improve. This aligns with AI governance guidance that risks can emerge from socio-technical interactions and must be managed explicitly rather than assumed away.

Ability group	Mastery (random)	Mastery (adaptive)	Reach 80% mastery (random)	Reach 80% mastery (adaptive)
Q1 (lowest)	0.550	0.753	0.7%	47.3%
Q2	0.535	0.793	0.0%	50.7%
Q3	0.561	0.788	0.0%	58.0%
Q4 (highest)	0.545	0.822	0.0%	61.3%

Results, Discussion, and Limitations

Discussion of Empirical Plausibility (Linking Simulation to Evidence)

The simulation results should not be interpreted as real-world effect sizes; rather, they demonstrate directionally plausible behaviors consistent with evidence that ITS can generate moderate-to-large learning benefits relative to conventional instruction (Kulik & Fletcher, 2016). In real deployments, effect sizes depend strongly on instructional alignment and implementation integrity (e.g., content quality, instructor integration, assessment choice) (Kulik & Fletcher, 2016).

Why Engagement Must Be Engineered, Not Assumed

The higher-education scoping review found engagement improvements in fewer studies than performance improvements and noted that engagement frequently is not a primary measurement endpoint (du Plooy et al., 2024). This aligns with the engagement literature's warning that engagement is complex and multidimensional; designing an AIDLS without an explicit engagement model risks optimizing easy proxies and undermining deeper cognitive engagement (Fredricks et al., 2004).

Explainability as Operational Safety Tooling

In education, explanations serve at least three operational purposes: instructor trust (why the system recommends a remediation path), learner agency (why a task is assigned), and debugging (detecting leakage or mis-specified mappings). Model-agnostic local explanations are one established approach to improving trust and enabling user oversight (Ribeiro et al., 2016).

Privacy and Sensitive Inference Risks

Educational systems process sensitive learner data (performance, struggles, sometimes disability accommodations). Privacy-preserving learning methods exist, including differentially private training for deep models, which can reduce the risk of memorization or exposure of individual records (Abadi et al., 2016). However, differential privacy introduces utility–privacy tradeoffs and requires careful selection of privacy budgets and monitoring; thus, privacy should be treated as a first-class design constraint, not a post-hoc compliance step (National Institute of Standards and Technology [NIST], 2023).

Accessibility as a Performance Multiplier and Equity Requirement

If an AIDLS interface is not accessible, adaptation can systematically fail for learners using assistive technology, effectively creating an algorithmic "denial of service" for certain populations. WCAG 2.2 provides testable criteria that should be incorporated into both functional requirements and release gating (World Wide Web Consortium [W3C], 2023).

Limitations

1. **No empirical dataset:** The prototype evaluation uses simulation only; therefore, claims are limited to design plausibility and anticipated tradeoffs, not measured real-world learning gains.
2. **Model simplifications:** The simulation uses simplified assumptions about learning transitions and engagement; real engagement includes emotional and contextual factors not modeled here (Fredricks et al., 2004).

3. **Fairness conclusions are illustrative:** The subgroup widening effect is a demonstrated risk mode, not an inevitable outcome; real fairness depends on objective design, constraints, and institutional policy (National Institute of Standards and Technology [NIST], 2023).

4. **External validity depends on content quality and pedagogy:** Evidence indicates outcomes depend on alignment between instruction and assessment and on implementation fidelity (Kulik & Fletcher, 2016).

CONCLUSION

Adaptive AI-driven learning systems represent a credible engineering pathway toward scalable personalization, motivated by long-standing evidence that individualized support can outperform conventional instruction and supported by meta-analytic findings that ITS often yield meaningful gains (Bloom, 1984; Kulik & Fletcher, 2016). However, the most deployment-relevant challenge is not solely predictive accuracy; it is the design of closed-loop objectives, measurement practices, and governance controls so that optimization improves mastery and sustains meaningful engagement while protecting privacy, accessibility, and equity (National Institute of Standards and Technology [NIST], 2023; UNESCO, 2021).

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Received: 02.01.2025
Revised: 02.10.2025
Accepted: 02.23.2026
Published: 02.25.2026

Luminis Applied Science and Engineering
ISSN: 3030-1831
Vol 3, No 1, 2026

Evaluation of Alternative Tests for Measuring Vo2max Compared to the Gold Standard CPET Treadmill Test

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https://doi.org/10.69760/lumin.2026001008

Abstract; Accurate assessment of the body's oxygen consumption is essential for the effective management of endurance in athletes. Peak oxygen uptake (VO_2max) remains the primary indicator for evaluating aerobic capacity and exercise efficiency. Although the gold standard for measuring VO_2max is the Cardiopulmonary Exercise Test (CPET) on a treadmill, it is resource-intensive, time-consuming, and requires precise calibration, making it less accessible in many settings.

This study aims to evaluate alternative VO_2max testing protocols—namely, the CPET velo test, Astrand cycle ergometer test, Chester Step Test, and Submaximal Cycle Ergometry—with a focus on practicality, efficiency, and reliability. The objective is to determine whether these alternatives can offer comparable accuracy to CPET while being easier and more cost-effective to implement.

A mixed-method research design was applied, combining experimental procedures and statistical regression analysis. Five participants with diverse physical activity backgrounds completed various tests, although some data was excluded due to technical limitations. Results indicated that none of the alternative tests consistently matched the CPET treadmill outcomes. The Astrand test showed identical VO_2max values in one participant, but significant discrepancies were observed in others.

The findings confirm that the CPET treadmill test remains the most valid and reliable method for measuring VO_2max. While alternative submaximal tests may serve in general fitness assessments, they lack the precision required for high-stakes evaluation. Moreover, the study highlights the importance of considering participants' lifestyle and activity familiarity when selecting appropriate testing protocols. Future research should further explore hybrid models that balance scientific rigor with practical applicability.

***Keywords**: Astrand test; Chester step test; CPET treadmill; exercise physiology; submaximal testing; VO2max*

1. INTRODUCTION

Maximal oxygen uptake (VO_2max) is widely recognized as a critical parameter for assessing aerobic endurance capacity and overall cardiovascular fitness. It represents the maximum rate at which oxygen can be taken up and utilized by the body during intense physical activity and is influenced by various physiological systems including the pulmonary, cardiovascular, and muscular systems (Strasser & Burtscher, 2018). The higher an individual's VO_2max, the greater their ability to sustain high-intensity efforts and resist fatigue during prolonged physical exertion.

In recent decades, particularly in the last 10–15 years, the approach to athletic training and performance evaluation has evolved significantly. Modern sports science emphasizes the role of structured, evidence-based training that improves both aerobic and anaerobic energy systems, leading to more efficient oxygen use, improved endurance, and increased athletic competitiveness (Sloth et al., 2013). The ability to accurately measure and monitor VO_2max is crucial not only for professional athletes but also for clinical populations and general health assessments (Löllgen & Leyk, 2018).

The gold standard for determining VO_2max is the Cardio Pulmonary Exercise Test (CPET) conducted on a treadmill. This method directly analyzes the volume of oxygen consumed and carbon dioxide produced during graded exercise while monitoring heart rate, respiratory rate, and other physiological indicators (Herdy et al., 2016; Tran, 2018). However, despite its accuracy, CPET has limitations in practice. It requires expensive equipment, experienced personnel, and careful calibration, and it is sensitive to environmental conditions such as temperature and humidity (Beijst et al., 2013; Macfarlane & Wong, 2012). Furthermore, the test is physically demanding and not accessible to all athletes or institutions, particularly those in low-resource settings.

Given these challenges, researchers have explored various alternative methods that are simpler, faster, and more accessible. Among the most commonly investigated alternatives are submaximal tests such as the Astrand cycle ergometry test, Chester step test, submaximal velo test, and CPET on a cycle ergometer (velo test). These tests rely on heart rate responses and pre-defined exercise protocols to estimate VO_2max, rather than measuring it directly.

Despite their convenience, the validity and reliability of these submaximal tests in comparison to CPET remain under scrutiny. Some studies suggest that alternative tests may offer reasonably accurate estimates under certain conditions, while others highlight considerable variation depending on factors like an individual's fitness level, exercise modality, and familiarity with test movements (George et al., 2000; Sykes & Roberts, 2004; Reed et al., 2020).

The current study aims to evaluate whether alternative submaximal tests can provide VO_2max estimates comparable to those obtained through the gold standard CPET treadmill test. By comparing physiological outputs across different testing modalities and analyzing their statistical consistency, this study seeks to identify if any alternative method is suitable for substitution in both sports science and clinical applications.

2. METHODOLOGY

A mixed-methods approach was used, combining qualitative and quantitative experimental methods. Five healthy adult participants (3 men, 2 women) from diverse physical activity backgrounds (e.g., runner, cyclist, lifeguard, sedentary) were recruited. All participants were briefed on the procedures, and informed consent was obtained. Ethical approval was granted by the Ethics Committee of the Azerbaijan State Academy of Physical Education and Sport.

The study included five different VO2max measurement methods: - CPET treadmill test - CPET velo test - Astrand cycle ergometer test - Chester step test - Submaximal velo test

Each participant was instructed to avoid intense physical activity for at least 48 hours prior to testing. Standard warm-up exercises were performed before every session. Testing was carried out over 15 days,

with at least 2 days between tests to minimize fatigue effects.

The CPET tests involved real-time gas exchange analysis using a Cortex Metamax 3B, while heart rate was monitored via ECG. Submaximal tests utilized pulse oximetry and standardized workload protocols. The Borg Rate of Perceived Exertion (RPE) scale was used to evaluate subjective fatigue.

Data was analyzed using SPSS software. One-sample t-tests were applied to assess whether the mean VO2max values from alternative tests differed significantly from the gold standard.

RESULTS

3. EXPERİMENTAL PHASE AND RESULTS

The experimental phase of this study was designed to compare multiple VO_2max testing protocols across a small but physiologically diverse sample. Five participants, each with differing levels and types of physical conditioning, were selected to represent a range of aerobic capacities and exercise modality familiarity. The cohort consisted of a climber, a marathon runner, a cyclist, a professional lifeguard, and one sedentary individual with no regular engagement in sports or physical training. This selection allowed for the examination of how personal training backgrounds may influence the validity and responsiveness of various VO_2max testing protocols.

Each participant was scheduled to complete up to five different VO_2max assessments: the CPET treadmill test (gold standard), CPET velo (cycle ergometer-based), the Astrand submaximal cycle ergometer test, the Chester step test, and the submaximal velo test. However, not all tests were successfully completed by every participant due to either technical difficulties or physiological thresholds being reached prematurely. Despite these limitations, a substantial amount of comparative data was obtained, enabling a meaningful analysis of test validity, reliability, and practical feasibility.

CPET Treadmill Test

All five participants successfully completed the CPET treadmill test, which served as the reference standard for evaluating the accuracy of alternative VO_2max estimation protocols. The test was administered using a progressively graded treadmill protocol until volitional exhaustion, while respiratory gases were measured via a metabolic cart to obtain direct VO_2max values. The results from this test yielded a mean VO_2max value of 42.2 ± 11.17 ml/min/kg, representing the highest and most consistent values across the testing battery. This outcome supports the established position of CPET treadmill testing as the gold standard for assessing aerobic capacity, as previously affirmed by Herdy et al. (2016). The test also provided additional physiological data—such as respiratory exchange ratio (RER), ventilation thresholds, and heart rate dynamics—not available through the submaximal protocols.

CPET Velo

The CPET velo test was intended to provide an alternative maximal VO_2max assessment using a cycle ergometer under identical gas analysis and physiological monitoring conditions as the treadmill test. However, the implementation encountered critical technical issues, primarily stemming from a failure in the synchronization between the velo simulator and the metabolic gas analyzer. Despite multiple troubleshooting attempts, the ergometer's workload output could not be reliably captured in real time by

the gas analysis software. Consequently, the test was terminated without yielding conclusive data, and no statistical comparisons or inferences could be drawn for this method. Similar technical limitations in cycle-based CPET testing have been noted in other studies (Macfarlane & Wong, 2012), emphasizing the need for full hardware-software integration and calibration prior to high-stakes assessments.

Astrand Cycle Ergometer Test

The Astrand submaximal cycle ergometer test was completed by four out of the five participants. This protocol, which estimates VO_2max based on steady-state heart rate during submaximal cycling and age-predicted maximal heart rate, is widely used in field settings due to its simplicity and minimal equipment demands. The most notable individual result came from participant A2, whose VO_2max value via the Astrand test was 47 ml/min/kg, precisely matching their CPET treadmill result. This isolated congruence suggests that in some individuals—especially those familiar with cycling—the Astrand test can yield highly accurate estimates, a finding consistent with Legge & Banister (1986).

However, broader analysis revealed considerable variability among the other participants. The overall mean VO_2max for the Astrand test was 34 ± 19.81 ml/min/kg, significantly lower than the CPET treadmill average. A paired samples t-test confirmed a statistically significant difference between the two methods ($p = 0.018$), indicating that the Astrand test, despite its potential, lacks consistent predictive accuracy across varied individuals. These results are in agreement with the concerns raised by Siconolfi et al. (1982), who argued that the Astrand method's accuracy is influenced by individual heart rate kinetics, muscular fatigue thresholds, and mechanical cycling efficiency.

Chester Step Test

The Chester step test, known for its practical field application and minimal equipment requirements, was completed by three participants, though only two datasets were deemed valid due to protocol adherence issues. This test estimates VO_2max based on heart rate response to increasing step cadence, but it operates with fixed step height and rhythm, which may not be equally suitable for all body types or fitness levels. The mean VO_2max recorded for the Chester step test was 19.6 ± 26.84 ml/min/kg, a value substantially lower than that from the CPET treadmill. Statistical analysis indicated no significant correlation with the gold standard ($p = 0.178$), suggesting limited diagnostic reliability.

The underperformance of the Chester test can be attributed to multiple factors. First, the uniform step height (30 cm) may have imposed excessive strain on participants with shorter leg length or those lacking stair-specific training. Second, more aerobically trained participants may have found the stepping protocol insufficiently challenging, leading to premature test termination or ceiling effects in heart rate escalation. These findings are consistent with Sykes & Roberts (2004), who noted that the Chester step test, while useful for occupational screening, may not be appropriate for precise fitness profiling due to its lack of adaptive scaling.

Submaximal Velo Test

All five participants completed the submaximal velo test, which estimated VO_2max based on heart rate response to a fixed cycling workload and the prediction of maximum heart rate using age-based formulas. Only two participants were able to sustain the full 10-minute testing duration, while the remaining three

terminated the test early upon reaching 75% of their predicted HRmax—a predefined safety cut-off. The average VO_2max value for this test was 27.6 ± 27.04 ml/min/kg, and, like the Chester test, it showed no statistically significant difference from the CPET treadmill results ($p = 0.085$), though the wide standard deviation suggests inconsistent accuracy.

The reliance on pulse oximetry for heart rate measurement, as opposed to ECG, likely contributed to reduced precision. Pulse readings were subject to motion artifacts and perspiration-related interference, especially during vigorous exertion. Furthermore, the predictive formula for maximal heart rate (commonly 220-age) lacks individual specificity and may have led to premature test cessation or misclassification of exertion levels. Prior literature supports these concerns, emphasizing that heart rate-based estimations of VO_2max are prone to error, particularly in trained populations with blunted heart rate responses and lower resting heart rates (George et al., 2000).

The detailed VO_2max results for each participant are shown below:

Table 1. Participants' VO_2max Indicators (ml/min/kg)

Participant	***CPET Treadmill***	***CPET Velo***	***Submaximal Velo***	***Chester Step***	***Astrand Test***
A1	57	-	Unsuccessful	Unsuccessful	49
A2	47	Invalid	62.3	49	47
A3	44	Invalid	39.9	49	36
A4	35	Invalid	37.45	Unsuccessful	38
A5	28	Invalid	Unsuccessful	-	-

Table 2. Time Spent on Each Test (minutes)

Participant	***CPET Treadmill***	***CPET Velo***	***Submaximal Velo***	***Chester Step***	***Astrand Test***
A1	22	-	Unsuccessful	Unsuccessful	7
A2	21	-	10	10	7
A3	19	-	8	10	6
A4	19	-	6	Unsuccessful	7
A5	14	-	Unsuccessful	-	-

Table 3. One-Sample T-Test Results for VO_2max

Test Type	*Mean ± SD (ml/min/kg)*	*p-value*	*Interpretation*
CPET Treadmill	42.2 ± 11.17	<0.001	Statistically significant (ref)
Astrand Test	34 ± 19.81	0.018	Statistically significant difference
Chester Step Test	19.6 ± 26.84	0.178	Not statistically significant
Submaximal Velo Test	27.6 ± 27.04	0.085	Not statistically significant

Overall, only the Astrand test approached statistical significance and only in one individual did it match the gold standard exactly. The variation in outcomes across other tests supports the conclusion that none of the alternative methods can reliably replace the CPET treadmill in measuring VO_2max.

These findings align with previous studies which note that submaximal test outcomes are often influenced by factors such as daily activity patterns, familiarity with the type of movement used in testing, and measurement equipment limitations (Reed et al., 2020; Forbregd et al., 2019).

4. DISCUSSION

The primary objective of this investigation was to evaluate the comparative effectiveness of various submaximal and alternative VO_2max testing protocols relative to the gold standard CPET treadmill test. As anticipated, the CPET treadmill maintained its status as the definitive measure of maximal oxygen uptake, delivering consistent accuracy and reliable reproducibility across diverse participants. In contrast, none of the alternative methods demonstrated uniform agreement with CPET results, underscoring their inherent limitations when applied to individualized or high-stakes performance assessment. This disparity highlights the critical importance of selecting appropriate testing modalities based on both the testing context and the specific characteristics of the population under study.

Among the alternative protocols, the Astrand cycle ergometer test emerged as the most promising contender, particularly evident in participant A2, whose VO_2max values were identical across both CPET and Astrand assessments. This finding accords with earlier work by Legge and Banister (1986), who reported that the Astrand protocol yields more precise estimates for individuals with established cycling familiarity. Nevertheless, the pronounced variability observed among other participants suggests that the Astrand test's predictive validity is heavily modulated by inter-individual factors such as baseline fitness, pedaling mechanics, and cycle ergometer calibration. The sensitivity of the Astrand protocol to these factors may be partly attributable to the use of a fixed workload-to-heart-rate regression model, which fails to account for idiosyncratic cardiac responses or anaerobic contributions at higher submaximal intensities (Siconolfi et al., 1982).

In contrast, the Chester step test and submaximal velo test—though operationally simpler and more cost-effective—systematically underestimated VO_2max relative to CPET treadmill measurements. The Chester protocol's reliance on a uniform step height (e.g., 30 cm) and fixed cadence (e.g., 15 steps/min increment every two minutes) does not accommodate variations in lower-limb length or step economy, disproportionately taxing smaller individuals and underloading trained athletes. Sykes and Roberts (2004)

similarly noted that step tests could misrepresent aerobic capacity when biomechanical efficiency diverges markedly from the normative model. Furthermore, the step test's discrete stage increments may introduce discontinuities in cardiovascular load, complicating the calculation of projected VO_2max via linear extrapolation.

The submaximal velo test's dependence on predicted maximum heart rates and pulse-based estimations further compounds inaccuracy. In our study, pulse oximetry readings—particularly during vigorous exertion—exhibited lag and motion artifact, leading to underreported heart rate values. By contrast, electrocardiogram (ECG)-based monitoring during CPET provided real-time, beat-to-beat data with minimal error. Prior investigations have documented that heart rate alone is an insufficient surrogate for VO_2max prediction in well-trained cohorts, owing to lower resting heart rates, attenuated heart rate slopes, and greater stroke volume adaptations (George et al., 2000; Reed et al., 2020). Consequently, protocols that rely solely on heart rate responses are prone to systematic underestimation in populations with pronounced cardiovascular efficiency.

An additional consideration is the role of modality-specific familiarity. Participants with extensive cycling history performed relatively better on the Astrand and submaximal velo tests, whereas those less accustomed to ergometer protocols exhibited suboptimal pedaling mechanics and discomfort, leading to premature muscular fatigue and lower submaximal workloads. Millet et al. (2009) similarly reported that treadmill-based protocols generally elicit higher VO_2max values than cycling tests, attributing the discrepancy to increased recruitment of larger muscle groups (e.g., quadriceps, gluteals) and a more natural movement pattern for most individuals. Thus, modality selection should be informed by both the participant's exercise background and the primary muscular demands of the chosen test.

Technical and logistical constraints also influenced test outcomes. The failure of the CPET velo implementation due to equipment malfunction and software integration issues (e.g., compatibility errors between the ergometer's output and metabolic cart software) underscores the necessity of rigorous system validation prior to data collection (Macfarlane & Wong, 2012). Such equipment-related setbacks not only reduced the available sample size for certain comparisons but also illustrate real-world challenges in deploying sophisticated exercise diagnostics outside of specialized laboratory environments.

Finally, the modest sample size and heterogeneity of participant fitness levels restrict the generalizability of our findings. Nevertheless, this diversity yielded valuable insights into how submaximal protocols perform across a spectrum of physical conditioning. The observed pattern—that alternative tests may suffice for coarse group-level estimations but fall short for individualized precision—suggests a potential role for these methods in large-scale epidemiological studies or community health screenings, where resources limit the feasibility of CPET.

In summary, while protocols such as the Astrand cycle ergometer and Chester step tests offer pragmatic advantages in terms of cost, convenience, and minimal technical demand, their diagnostic accuracy remains insufficient to supplant CPET treadmill testing in contexts requiring definitive physiological evaluation. Future research should focus on refining these submaximal models through incorporation of individualized calibration factors—such as weight-adjusted workload scaling, real-time ventilatory equivalents, or machine learning algorithms that integrate heart rate variability and movement metrics. Additionally, exploration of hybrid testing frameworks that blend brief maximal efforts with continuous wearable sensor data may strike an optimal balance between methodological rigor and field applicability (Forbregd et al.,

2019; Löllgen & Leyk, 2018). By advancing these hybrid and adaptive approaches, it may become possible to approximate the comprehensive insights afforded by CPET within more accessible testing paradigms.

5. CONCLUSİON

This study aimed to assess the validity, accuracy, and practical applicability of selected alternative VO_2max testing protocols in comparison to the gold standard Cardiopulmonary Exercise Testing (CPET) conducted on a treadmill. The findings underscore a critical distinction between the clinical accuracy of direct measurement methods and the practicality of submaximal or indirect protocols. While alternative tests may offer logistical convenience, time efficiency, and reduced cost—factors particularly relevant in resource-limited or field-based settings—their diagnostic value remains limited when compared to CPET treadmill assessments.

Among the submaximal tests evaluated, the Astrand cycle ergometer test demonstrated the closest approximation to CPET-derived VO_2max values, but this occurred only in isolated instances. The test lacked consistency in its predictive validity across the broader sample, with outcomes influenced by inter-individual physiological variability, such as fitness level, cadence familiarity, and biomechanical efficiency on a cycle ergometer. These findings highlight the inherent challenge of applying uniform estimation models to diverse populations, even when using well-established protocols.

In contrast, the Chester Step Test and the submaximal velo (cycling) test consistently underestimated VO_2max, yielding values that deviated significantly from those obtained via CPET treadmill testing. These discrepancies not only reduced their statistical correlation with the gold standard but also raised concerns regarding their sensitivity and specificity in detecting true aerobic capacity, especially in moderately to highly trained individuals. The underperformance of these tests suggests that their application should be limited to preliminary screening or non-clinical environments where precision is not the primary requirement.

The CPET treadmill test continues to represent the most valid, comprehensive, and scientifically robust method for evaluating maximal oxygen uptake. It allows for the direct measurement of ventilatory thresholds, respiratory exchange ratios, and cardiovascular responses under progressively increasing workloads. These parameters are critical in both clinical diagnostics—for conditions such as cardiopulmonary disease—and in elite athletic performance profiling. Given its ability to deliver reproducible and individualized data, the CPET treadmill remains irreplaceable in contexts where accurate physiological assessment is essential.

However, it is important to acknowledge the practical limitations of CPET, including high operational costs, requirement of trained personnel, equipment availability, and patient tolerance. In such cases, selected submaximal tests—though inherently limited—can serve as supplementary tools. When interpreted with caution and used in conjunction with other physiological indicators, they may facilitate initial fitness assessments, long-term monitoring of training adaptations, or risk stratification in low-resource settings.

This study also faced certain methodological constraints, primarily related to the small sample size and technical challenges encountered during CPET velo implementation. These limitations restrict the generalizability of the results and highlight the necessity for further investigation. Future research should incorporate larger, more heterogeneous participant pools and examine how individual factors—such as sex,

age, training status, and habitual exercise modality—interact with test outcomes. Additionally, the integration of wearable sensor technology and artificial intelligence-driven data interpretation may enhance the accuracy and accessibility of field-based VO_2max estimations.

In conclusion, although alternative VO_2max tests offer practical benefits and may fulfill specific roles within broader health and performance monitoring strategies, they currently fall short of replacing the CPET treadmill as a gold standard. Their utility is best seen as complementary rather than substitutive, and they should be employed with a clear understanding of their limitations. For high-stakes evaluations—be it in clinical decision-making or performance diagnostics—direct testing via CPET remains the most scientifically valid and reliable method.

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Received: 02.03.2025
Revised: 02.10.2025
Accepted: 03.13.2026
Published: 03.15.2026

Luminis Applied Science and Engineering

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Vol. 3 No. 1 (2026):

ISSN 3030-1831

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