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A Comprehensive Evaluation Framework for AI and Human Skill Complementarity Across Industry Sectors

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The paper presents a comprehensive evaluation framework to assess the complementarity between artificial intelligence (AI) technologies and human skills across diverse industries. AI has transformed business operations, enhancing productivity, reducing costs, and reshaping workforce dynamics. The rise of Industry 5.0 emphasizes human-centric, sustainable production, highlighting the need for AI to complement rather than replace human expertise. The proposed framework evaluates AI-human collaboration through eight key dimensions: productivity, adaptability, skill enhancement, collaborative efficiency, safety, cognitive load management, innovation, and technological integration. Utilizing Multi-Criteria Decision Analysis (MCDA) and elements of the Analytic Hierarchy Process (AHP), the framework provides a structured, quantitative approach to measure AI's impact on human skill enhancement and overall productivity. Validation was conducted in companies across Georgia and the UK, revealing the framework's adaptability and effectiveness in real-world settings. The study found that successful AI integration not only improves operational efficiency but also requires a strategic focus on human skill development and adaptability. Practical recommendations for AI adoption emphasize gradual implementation, regular monitoring, targeted training, and fostering a culture of innovation. Future research aims to develop a digital model of the framework for real-time analysis, addressing the ongoing need for optimization and employee training as AI technologies evolve. This study contributes to the growing body of knowledge on human-AI complementarity, aligning with Industry 5.0 principles, and offers a practical tool for organizations aiming for sustainable, human-centric AI integration. *© 2024 Bull. Georg. Natl. Acad. Sci.*

artificial intelligence, human skill complementarity, multi-criteria decision analysis, human-centric AI integration

The transformative integration of artificial intelligence (AI) technologies has reached a pivotal stage across various industry sectors. AI has dramatically changed business operations, optimizing processes, reducing waste, and achieving new levels of automation and flexibility. This transformation extends beyond manufacturing, influencing sectors such as logistics, healthcare, finance, agriculture, and services. AI technologies like machine learning (ML), computer vision, natural language processing (NLP), and robotic process automation (RPA) are

increasingly being adopted to streamline complex workflows and improve decision-making.

Recent studies show a significant increase in AI adoption rates across industries. According to a McKinsey report, approximately 45% of firms worldwide have implemented at least one AI technology on a large scale, representing a significant jump from 20% in 2017 [1]. This upward trend reflects a global effort to leverage AI for competitive advantages, including enhanced operational efficiency, reduced costs, and improved quality of services and products. For instance, predictive analytics using ML in financial services has reduced fraud detection times, while in agriculture, AI-driven analysis optimizes crop yields. In Georgia, AI adoption has mirrored these global trends with a slower rate of adoption, particularly in sectors such as finance, agriculture, and healthcare. Companies are employing AI for predictive analytics, risk assessment, process automation, and quality control, aligning with the country's economic development goals. AI technologies not only enhance operational efficiency but also influence the job market by reshaping workforce demands, requiring a shift in skills from traditional roles to those involving AI management and human-AI collaboration.

While the Fourth Industrial Revolution (Industry 4.0) has revolutionized the production sector through the integration of advanced technologies such as artificial intelligence, the Internet of Things (IoT), and big data analytics [2], a new paradigm is now emerging – *Industry 5.0.* This evolution focuses on creating human-centered, sustainable, and resilient production systems. Industry 5.0 not only continues to drive operational efficiency and productivity optimization through technological advancements but also emphasizes the role of human workers in the production process. Its key characteristics include prioritizing human well-being, environmental sustainability, and system resilience to unforeseen risks. By advancing technologies such as AI and IoT in a manner that complements and enhances human skills, Industry 5.0 aims to address the growing need for flexible, adaptable, and inclusive industrial processes. The European Commission's 2021 publication on Industry 5.0 underscores its importance, advocating for a human-centric approach in future research and innovation endeavors [3]. This shift has significant implications, as it reorients industrial practices towards not only achieving maximum productivity but also fostering collaboration between human capabilities and AI technologies. By contributing to the knowledge gap in AI-human interaction and complementarity, this research aligns with Industry 5.0 principles, offering insights that can aid in developing strategies for sustainable and human-centric technological integration.

Artificial intelligence (AI) technologies are increasingly integrated across various industries to complement human skills. Machine learning, for example, supports decision-making by analyzing large datasets for tasks such as fraud detection in finance and optimizing agricultural processes. Similarly, computer vision enhances quality control and medical diagnostics by quickly identifying defects or anomalies, reducing errors, and supporting human expertise. Automation tools, including robotic process automation (RPA) and collaborative robots, streamline repetitive tasks, allowing human workers to focus on more complex activities. Natural language processing (NLP) further eases human-machine interaction by efficiently managing large volumes of information, reducing cognitive load, and enabling professionals to concentrate on higher-value work. Overall, these technologies improve productivity, safety, and decision-making without replacing human input. The growing adoption of AI across diverse sectors necessitates a comprehensive framework to evaluate its impact on human skill enhancement, adaptability, and overall productivity. AI's transformative potential extends beyond operational efficiency to influence job roles, workforce skills, and employee satisfaction. Current research underscores the importance of understanding how AI technologies

complement human skills rather than replacing them. As industries increasingly integrate AI into their processes, the focus must shift to optimizing human-AI collaboration.

While AI offers significant benefits, such as improved decision-making, cost reduction, and enhanced safety, its successful integration requires a strategic approach that prioritizes human skill development and adaptability. For instance, financial institutions report that AI-driven tools have reduced the time required for credit risk assessments, but also highlight the need for skilled analysts to interpret the AI-generated insights effectively. Similarly, in the healthcare sector, while AI-powered diagnostics enhance accuracy, human expertise remains crucial in making complex, patient-centric decisions.

Therefore, evaluating AI's role in various industry sectors involves considering multiple dimensions, including its impact on human skills, cognitive load, adaptability, and workplace satisfaction. The framework proposed in this research aims to provide such a comprehensive evaluation method, ensuring that AI technologies enhance human capabilities, foster collaborative efficiency, and contribute to sustainable organizational growth.

The proposed evaluation framework addresses eight critical dimensions: productivity and effectiveness, adaptability, skill enhancement, collaborative efficiency, safety and ergonomics, cognitive load management, innovation, and technological integration. By employing a multi-criteria decision analysis (MCDA) approach, the framework allows organizations to quantify the success of AI-human collaboration.

The theoretical foundation of the research lies in *General Systems Theory (GST)* as formulated by Von Bertalanffy (1968) [4], which posits that complex systems consist of interconnected elements functioning as a unified whole. Within the context of AI integration, businesses and organizations are viewed as complex, dynamic systems composed of numerous subsystems, including human labor, AI technologies, and operational processes. The GST framework emphasizes that the behavior and performance of the overall system depend not only on individual components but also on the interrelations between them. By adopting a systemic approach, this research seeks to understand how AI technologies interact with various organizational subsystems. This holistic perspective is essential for evaluating the impact of AI integration on overall performance, human-AI collaboration, and workforce satisfaction. The systemic approach also facilitates the modeling of AI's influence on diverse business processes, allowing for an assessment of AI-human collaboration in terms of productivity, safety, cognitive load, and adaptability.

Ergonomics and human centric design plays a pivotal role in assessing how AI technologies can complement human skills in the workplace. As defined in the Civil Education Lexicon [5], ergonomics is the scientific study of human interactions within a working environment, focusing on optimizing tools, tasks, and workflows to improve safety, efficiency, and worker well-being. In this research, ergonomic principles guide the evaluation of AI integration, particularly in terms of reducing cognitive load, enhancing safety, and fostering a more human-centered work environment. The research incorporates *socio-technical systems theory* elements proposed by Smith & Sainfort in 1989 [6], which emphasizes the interdependence of social and technical factors within an organization. According to this theory, technological integration – such as AI – must consider the social context, including the impact on human workers and the organizational culture. This perspective is crucial for understanding how AI technologies can support human skill development and collaboration without compromising worker autonomy and satisfaction.

Incorporating elements from organizational psychology, the study also employs the *Demand-Control Model* by Karasek and Theorell (2017) [7],

which explores the relationship between job demands, worker control, and stress levels. This model is especially relevant in the context of AI integration, as it helps identify how AI can alleviate job demands by automating routine tasks while potentially increasing worker control over more complex, decision-making responsibilities. By balancing job demands with appropriate resources, AI can contribute to a more satisfying and productive work environment. Additionally, this research draws on the *Job Demands-Resources (JD-R) Model* (Bakker & Demerouti, 2007) [8], which expands upon the demand-control model by including various job resources that can mitigate the negative effects of job demands. In the context of AI-human collaboration, this model provides insights into how AI technologies can serve as resources that enhance worker skills, reduce workload, and increase job satisfaction. This theoretical grounding informs the design of the evaluation framework's dimensions and criteria.

The process of developing the evaluation framework involved a collaborative process of consultation with industry experts and scholars to identify the key dimensions for evaluating AI-human skill complementarity. An extensive literature review further informed the selection of dimensions, ensuring that the framework is both comprehensive and adaptable to various business environments.

Evaluation Framework for AI and Human Skill Complementarity

The comprehensive evaluation framework developed in this research is designed to assess the complementarity between AI technologies and human skills across various industry sectors. The goal is to measure how AI technologies can enhance human capabilities rather than replace them. Based on research findings, literature review, and expert consultations, this framework incorporates both qualitative and quantitative criteria tailored for different types of businesses. The framework provides a systematic approach to understanding AI's impact on enhancing human skills, productivity, and workplace satisfaction. It helps identify actions that support decision-making in implementing new technologies, workforce retraining, and process optimization. The primary objective of this evaluation framework is to systematically assess how AI technologies effectively enhance human skills, increase productivity, and contribute to workplace satisfaction.

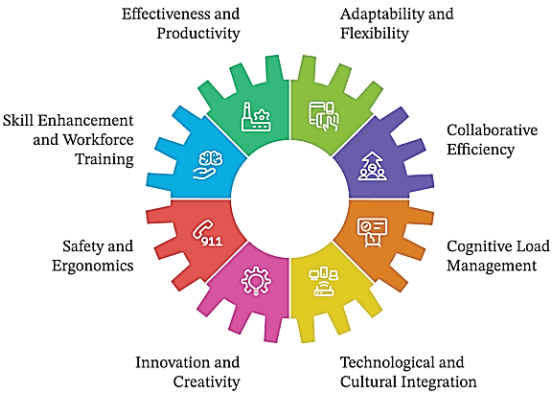

Fig. 1. AI-human collaboration evaluation framework.

The framework is adaptable to various AI technologies and encompasses eight key dimensions. The table below summarizes the eight dimensions of this evaluation framework.

A key methodological tool employed during the framework application process is the *Multi-Criteria Decision Analysis (MCDA)*. MCDA provides a structured approach to evaluate AI technologies across multiple dimensions, considering both quantitative data (e.g., productivity metrics) and qualitative assessments (e.g., employee satisfaction). The criteria within the framework are compared against an organization's strategic goals using a matrix. This matrix enables a systematic evaluation of each criterion's relevance to factors like productivity, safety, adaptability, and worker well-being. To systematically assess and prioritize the criteria within the proposed framework, elements

Table 1. Evaluation Framework and its eight dimensions

Dimension	Key Sub-Criteria
1. Effectiveness and Productivity: Evaluates the efficiency of AI-human collaboration in optimizing productivity and production processes.	- Reduction in process duration - Decrease in production costs - Improvement in product quality and consistency - Increase in hourly human labor output - Reduction in operational costs
2. Adaptability and Flexibility: Measures the AI technology's ability to adapt to different operational environments and changing production conditions.	- Time and resources required for adaptation - Optimization of productivity with varying production volumes and product types
3. Skill Enhancement and Workforce Training: Assesses how AI technology facilitates workforce skill development, professionalism, and multifaceted abilities.	- Number of new skills acquired due to AI integration - Employee satisfaction with new technologies - Time required for mastering new tasks and technologies - Reduction in manual interventions
4. Collaborative Efficiency: Evaluates the effectiveness of AI-human collaboration through the analysis of interactions and employee feedback.	- Reduction in interruptions during collaborative tasks - Frequency of human intervention - Employee feedback on AI support in daily tasks
5. Safety and Ergonomics: Measures AI's contribution to a safer and more ergonomic work environment.	- Reduction in workplace incidents and near-misses - Improvements in ergonomic assessments post-AI integration
6. Cognitive Load Management: Assesses AI's impact on reducing employees' cognitive workload.	- Changes in the necessity and quality of cognitive effort - Reduction in decision-making errors and fatigue levels
7. Innovation and Creativity: Evaluates how AI enables employees to spend more time on creative and innovative tasks.	- Time spent on creative vs. routine tasks - Number of new ideas or improvements proposed by employees
8. Technological and Cultural Integration: Measures the ease of integrating AI technologies within an organization's existing infrastructure and cultural environment.	- Ease of integration with existing systems - Degree of cultural resistance or acceptance within the workforce

of the *Analytic Hierarchy Process (AHP)* were employed. AHP is a widely used decision-making tool that helps allocate weights to multiple criteria based on their relative importance, thereby facilitating a more structured and objective evaluation.

Each dimension is scored and assigned a weight (ω_i) based on its relevance to the company's strategic goals, such as productivity, safety, and adaptability. This process involves the following steps. For each criterion, a qualitative evaluation is conducted. Each criterion is rated according to its importance in relation to the company's goals using a scale of high (3 points), medium (2 points), and low (1 point). This step allows organizations to assess the impact of each dimension of AI integration on their specific objectives. The scores for each criterion are then summed to form the total score (T). Each criterion's score (S_i) is divided by the total score to derive the normalized weight (ω_i) for that criterion. The formula for this calculation is:

$$\omega_i = \frac{S_i}{T}.$$

This normalization ensures that the sum of all criterion weights equals 1 $\left(\sum \omega_i = 1\right)$, providing a balanced view of each dimension's influence in the overall evaluation process.

To assess the integration of AI technologies, the framework employs a multi-dimensional approach, allowing organizations to select a combination of at least three dimensions for evaluation. It is crucial to ensure that no single dimension constitutes more than two-thirds of the total evaluation, thereby maintaining a comprehensive assessment. Once the relevant criteria are selected and weighted, the final evaluation is reflected in the Overall Performance Score (OPS). The OPS captures the impact of AI-human collaboration and considers additional correction factors (λ_i) to account for the organization's current priorities, such as seasonality or spe-

cific technology implementation goals. The formula for calculating the OPS is:

$$OPS = \sum_{i=1}^{n} \left(\frac{R_i}{\sum_{j=1}^{n} R_j} \times 100 \times \omega_i \times \lambda_i \right),$$

where: R_i is the raw score for each criterion; $\sum_{j=1}^{n} R_j$ – the sum of the raw scores for all selected criteria; ω_i – the weight assigned to each criterion; λ_i – the correction factor, which adjusts the score based on current business priorities.

For simplification, the formula can also be represented as:

$$OPS = \sum_{i=1}^{n} (\phi_i \times \omega_i \times \lambda_i).$$

In this expression, ϕ_i represents the normalized score for each criterion, making it easier to apply the formula across various contexts and business scenarios. The outcome of each evaluation is recorded within the company's system, forming a cumulative database that tracks the performance of AI-human collaborations over time. This evolving data repository serves multiple purposes:

Identifying new synergies and correlations as more AI technologies are integrated.

Informing future decisions about technology implementation and workforce training.

Providing a historical perspective on the success and areas for improvement in AI-human collaboration.

Validation of the Evaluation Framework

The evaluation framework for AI technologies and human skill complementarity, developed through extensive research and expert consultations, was empirically validated in companies across Georgia and the UK, encompassing various industry sectors like manufacturing, finance, healthcare, and logistics. This validation aimed to assess the framework's practical value and adaptability in real-world technological integration scenarios.

The validation process involved several key activities:

1. *Empirical Validation:* The framework was implemented in four companies across different sectors. In each case, at least three dimensions from the framework were used to evaluate the integration of AI technologies. The resulting Overall Performance Score (OPS) was then calculated to gauge the success of AI adoption. The OPS ranges used were:
   - *30 or above*: Indicates successful AI technology integration, showing improvement in selected criteria.
   - *20-30*: Shows improvements, but further optimization is needed to maximize benefits.
   - *Below 20*: Indicates limited or ineffective AI integration, suggesting the need for adjustment, additional training, or other improvements.
2. *Quantitative Data Analysis:* Data collected from these companies were statistically analyzed to measure changes in productivity, adaptability, safety, and skill enhancement. Key indicators included reductions in errors, processing times, and operational costs. For example, companies observed a significant reduction in error rates, increased accuracy in processes, and improved skill levels post-AI integration. The framework allowed normalization of each dimension's scores and incorporated a weighting system to reflect their strategic importance to the organization.
3. *Expert Feedback and Qualitative Assessment:* Beyond empirical data, industry experts from participating companies provided qualitative feedback on the framework's effectiveness. Their insights were instrumental in refining the evaluation criteria, highlighting the relevance of dimensions such as cognitive load management and skill enhancement in AI-human collaboration. A structured survey employing a Likert scale was used to gather opinions on the clarity and relevance of each dimension, revealing

trends in their applicability and suggesting areas for further refinement.

The empirical studies revealed that AI integration positively impacted the companies involved, with OPS values consistently exceeding 30, indicating a successful integration process. However, the validation process also underscored the necessity of adjustments based on industry-specific requirements. The structured feedback from practitioners emphasized that technology adaptation and employee training are pivotal for maximizing AI's benefits in human-centric operations. The survey further supported the framework's validity, with companies rating dimensions such as "Effectiveness and Productivity," "Safety and Ergonomics," and "Adaptability and Flexibility" as both clear and highly relevant. These results affirmed the framework's applicability across diverse sectors and its potential in guiding organizations towards a sustainable, human-centered AI integration strategy.

Additionally, This research has resulted in the development of practical recommendations for businesses that are implementing or planning to integrate AI-based technologies. The study emphasizes a gradual and structured approach to AI adoption, coupled with regular quantitative and qualitative monitoring, to ensure effective complementarity between AI and human skills. It highlights the importance of targeted training programs tailored to the specific AI systems in use, as well as the need to optimize user interfaces, manage cognitive load, and foster an innovation-driven culture. By establishing open feedback mechanisms and regularly updating safety and ergonomic practices, companies can maximize the benefits of AI integration, creating a work environment where AI technologies and human labor complement each other efficiently.

Conclusions and Future Directions

This research introduces a holistic evaluation framework to measure AI-human skill complementarity across industries, aligning with the principles of Industry 5.0. The framework's multi-criteria decision analysis (MCDA) approach allows organizations to tailor AI integration to their strategic goals, emphasizing productivity, adaptability, and human-centric operation. Validation in Georgian and British companies demonstrates the framework's real-world applicability and adaptability to various AI contexts.

Future research could focus on developing a digital model of the proposed evaluation framework using advanced software tools, enabling real-time analysis and visualization of assessment criteria. Plans are underway to secure funding for further research to create digital solutions for specific AI technologies. Industry experts emphasize that AI integration is an ongoing process requiring constant optimization. Thus, future research should explore innovative methods for continuous improvement and employee training programs to ensure that human-AI collaboration evolves alongside technological advancements. By fostering a culture driven by innovation and feedback, businesses can harness AI as a powerful tool for ongoing growth and development.

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ინფორმატიკა

ხელოვნური ინტელექტისა და ადამიანის უნარების კომპლემენტარულობის შეფასების ყოვლისმომცველი ჩარჩო სხვადასხვა ინდუსტრიულ სექტორში

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ნაშრომი წარმოადგენს ხელოვნური ინტელექტის (AI) ტექნოლოგიებისა და ადამიანის უნარების კომპლემენტარულობის შეფასების ყოვლისმომცველ ჩარჩოს სხვადასხვა ინდუსტრიაში. AI-ს აქვს ტრანსფორმაციული გავლენა ბიზნესის ოპერაციებზე, ზრდის პროდუქტიულობას, ამცირებს ხარჯებს და ცვლის სამუშაო ძალის დინამიკას. ინდუსტრია 5.0-ის აღზევება ხაზს უსვამს ადამიანზე ორიენტირებულ, მდგრად წარმოებას და ყურადღებას ამახვილებს, რომ AI უნდა ავსებდეს და არა ანაცვლებდეს ადამიანის ექსპერტიზას. წარმოდგენილი ჩარჩო აფასებს AI-ადამიანის თანამშრომლობას რვა ძირითადი განზომილებით: პროდუქტიულობა, ადაპტირებადობა, უნარების გაუმჯობესება, კოლაბორაციული ეფექტიანობა, უსაფრთხოება, კოგნიტური დატვირთვის მართვა, ინოვაცია და ტექნოლოგიური ინტეგრაცია. მრავალკრიტერიული გადაწყვეტილების ანალიზის (MCDA) და ანალიტიკური იერარქიის პროცესის (AHP) ელემენტების გამოყენებით, ჩარჩო უზრუნველყოფს სტრუქტურულ, რაოდენობრივ მიდგომას AI-ის გავლენის გაზომვაზე ადამიანური უნარების გაუმჯობესებასა და საერთო პროდუქტიულობაზე. ვალიდაცია ჩატარდა კომპანიებში, საქართველოსა და გაერთიანებულ სამეფოში, რაც აჩვენებს ჩარჩოს ადაპტირებასა და ეფექტურობას რეალურ გარემოში. კვლევამ აჩვენა, რომ AI-ის წარმატებული ინტეგრაცია არა მხოლოდ აუმჯობესებს ოპერაციულ ეფექტიანობას, არამედ საჭიროებს ადამიანური უნარების განვითარებასა და ადაპტირებაზე სტრატეგიულ ფოკუსს. AI-ის დანერგვის პრაქტიკული რეკომენდაციები მოიცავს ეტაპობრივ იმპლემენტაციას, რეგულარულ მონიტორინგს, მიზანმიმართულ ტრენინგს და ინოვაციის კულტურის წახალისებას. სამომავლო კვლევების მიზანია ჩარჩოს ციფრული მოდელის განვითარება რეალურ დროში ანალიზისთვის, AI ტექნოლოგიების ევოლუციის პარალელურად ოპტიმიზაციისა და თანამშრომელთა ტრენინგის მუდმივი საჭიროების გათვალისწინებით. ამ კვლევას შეაქვს კონტრიბუცია ადამიანის-AI კომპლემენტარულობის მზარდ ცოდნაში, ინდუსტრია 5.0-ის პრინციპებთან შესაბამისობაში, და სთავაზობს პრაქტიკულ ინსტრუმენტს ორგანიზაციებს, რომლებიც ისწრაფვიან მდგრად, ადამიანზე ორიენტირებულ AI ინტეგრაციისკენ.

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