MINISTRY OF EDUCATION AND SCIENCE OF UKRAINE
KYIV NATIONAL UNIVERSITY OF CONSTRUCTION AND ARCHITECTURE

Qualification scientific
work on manuscript rights

TAO LI

UDC 004.9+681.3

PHD THESIS

INFORMATION TECHNOLOGY FOR THE FORMATION OF BUSINESS PROCESSES THROUGH THE INTRODUCTION OF VIRTUAL REALITY IN THE EDUCATIONAL SPACE

122 Computer Science
12 Information Technology

Applying for the Doctor of Philosophy degree

The PhD Thesis contains the results of own research. The use of ideas, results and texts of other authors are linked to the corresponding source

_________________ Li Tao

数字签名人：李涛LiTao
DN：cn=李涛LiTao，
c=CN，
email=little321@126.com
日期：2024.12.5 13:12:29

Supervisor – **Tetyana Honcharenko**, Doctor of Technical Science, Associate Professor

KYIV – 2024

SUMMARY

Tao Li. Information technology for the formation of business processes through the introduction of virtual reality in the educational space. – *Qualifying scientific work as a manuscript.*

Thesis for the Doctor of Philosophy Degree in Specialty 122 “Computer Science». – Kyiv National University of Construction and Architecture, Kyiv, 2024.

Abstract content. The dissertation addresses the scientific and practical problem of developing methods, models, and information technology to enhance the effectiveness of Virtual Reality (VR) technology implementation for forming and transforming business processes in educational content-providing enterprises and organizations. The research focuses on the urgent need for innovative information technology to manage the implementation of virtual reality systems in educational institutions, particularly in the context of increasing technological complexity and rapid evolution of changes in educational space business processes.

The research relevance is emphasized by the growing recognition of virtual reality technology's potential for revolutionary changes in various aspects of business operations and educational practices. As educational organizations seek to utilize immersive technologies to improve decision-making, learning, and client engagement, there is a pressing need for empirically verified approaches to integrating virtual reality systems into their operations. This research aims to bridge the gap between theoretical understanding of virtual reality's potential and its practical implementation, providing applied tools for identifying opportunities related to immersive technology implementation for educational organizations.

A key contribution of this work is the development of new information technology based on the existing VR-BPMN (Virtual Reality-Business Process Model and Notation) concept. The testing of this innovative IT solution for business process visualization and analysis demonstrates significant advantages compared to traditional approaches, offering a more intuitive and engaging visualization tool for understanding complex organizational and educational business processes. The proven

effectiveness of this information technology shows a 21% increase in task execution speed without error identification compared to PC-based tools, highlighting its efficiency for business process transformation in virtual environments. VR-BPMN is a core component of the proposed information technology that demonstrates how virtual reality can be effectively integrated into existing information systems for forming and transforming educational institution business processes.

The research advances the field of human-computer interaction in virtual environments through the development of an enhanced method that integrates natural language processing and gesture recognition methods. This approach to multimodal interaction demonstrated a 35% reduction in command interpretation errors compared to traditional interfaces, with 85% of users noting increased intuitiveness when working in the virtual environment. The system's adaptive learning capability shows a 15% improvement in command recognition accuracy over time, highlighting the potential of virtual reality systems for personalized experiences.

A significant theoretical contribution of this work lies in developing a technology acceptance model for virtual reality applications. Using structural equation modeling provides a framework for understanding factors influencing virtual reality technology adoption in organizational settings. The identification of perceived enjoyment as a critical factor in usefulness and ease of use provides valuable information for virtual reality system developers and users, emphasizing the importance of creating engaging user experiences.

A comprehensive framework for implementing virtual reality strategy in business and educational contexts has been developed and presented. The structured approach encompasses content evaluation, resource allocation, testing, implementation, and continuous reassessment, demonstrating significant advantages in real-world conditions.

Furthermore, the study has advanced virtual reality technology in B2B and B2C contexts, revealing significant potential benefits across various sectors. Results demonstrating increased client engagement, conversion rates, employee training effectiveness, and knowledge retention confirm the transformational potential of virtual reality technology. However, the research also identifies key challenges to widespread VR adoption, particularly in data privacy and hardware limitations, providing a balanced view of the current state of immersive technology implementation.

The dissertation research results make significant contributions to both theoretical understanding and practical application of virtual reality technology in educational sphere business processes. The developed methods, models, and information technology offer comprehensive analytical and applied tools for organizations seeking to utilize virtual reality to enhance efficiency and innovation in educational space. By addressing the complex interaction of technological, organizational, and human factors in virtual reality technology implementation, this research creates a solid foundation for future IT achievements, paving the way for more efficient, effective, and user-oriented virtual reality applications across various fields.

The object of the study is the processes of integrating virtual reality systems into the activities of enterprises and organizations that provide educational content.

The subject of the research is models, methods, and information technology for developing, evaluating, and implementing virtual reality systems for forming and transforming business processes in educational space.

Research methods. The study employs a complex of methods, including: modeling and data analysis methods, including structural equation modeling to verify the technology acceptance model within the proposed information technology; software engineering methods for developing core components of virtual reality-based information technology, including virtual reality interfaces and data processing algorithms; experimental design and user research to evaluate the effectiveness of the VR-BPMN concept and human-computer interaction model within the developed information technology; statistical analysis of system performance indicators to optimize the efficiency and responsiveness of information technology; systems analysis and design methods for creating implementation frameworks and ensuring scalability and adaptability of information technology; simulation and modeling methods for testing and refining VR components of information technology in controlled environments before real-world deployment.

The aim of the study is to develop information technology for effective implementation of virtual reality systems in educational sector business processes.

To achieve this aim, the following tasks must be solved:

1. Analyze the possibilities of implementing virtual reality technology in business processes and educational context, identify existing challenges and limitations in modern immersive technologies.
2. Propose a technology acceptance model for applying virtual reality systems and their applications in educational space.
3. Develop a human-computer interaction model for virtual reality systems.
4. Develop methods for evaluating the effectiveness of VR simulations in business processes and optimizing user experience in virtual environments.
5. Develop a method for integrating natural language processing and gesture recognition in VR interfaces for educational simulations and visualization of complex business processes.
6. Develop information technology for business process formation based on implementing virtual reality systems in educational space.
7. Develop software modules and conduct testing of the developed information technology through testing, case studies, and empirical evaluations in various business and educational environments.
8. Develop a strategy for evaluating the effectiveness and development of virtual reality systems in business and educational contexts.

The main study hypothesis is that by solving the set tasks, the research results should bridge the gap between theoretical understanding and practical implementation of virtual reality systems in educational institutions' activities, providing information and applied tools for identifying challenges and opportunities associated with immersive technology implementation.

The scientific novelty of the obtained results:

Developed for the first time:

- a human-computer interaction model for virtual reality systems which, through a unique combination of defined components, enables increased system response speed to user actions in the virtual environment. Unlike existing models, it enables reduced command interpretation errors and improves recognition accuracy through adaptive learning, determining its potential for shaping user experience;
- a method for evaluating the effectiveness of VR simulations in business processes, which enables quantitative determination of virtual reality systems' effectiveness indicators: task completion time, error levels, user satisfaction and perception of the virtual environment, and enables identification of indicators for optimizing business processes and decision-making processes;
- a method for optimizing user experience in virtual environments, which through aggregation of data analytics and machine learning methods offers a new approach to collecting and analyzing user behavior data in virtual environments and ensures VR experience accumulation;
- information technology for business process formation in educational space, which through developed and improved models and methods, ensures increased effectiveness of virtual reality systems implementation in organizations providing educational content.

Improved:

- technology acceptance model, which by considering specific factors for virtual reality systems provides an analytical basis for predicting the results of implementing the developed information technology in educational institutions;

- structural equation modeling method for evaluating virtual reality perception by potential users, which, unlike existing ones, through using an extended factors model of virtual reality technology perception, enables quantitative determination of relationships between key constructs in organizational conditions.

Further developed:

- virtual reality technology perception factors model, which considers the complex structure of interaction between technological, organizational, and human factors affecting virtual reality systems use, and serves as a basis for improving the structural equation modeling method;
- method of integrating natural language processing and gesture recognition in VR interfaces, which, through aggregation of these components, increases intuitiveness and efficiency of user interaction in virtual environments, enabling its application for educational simulations and complex business process visualization.

The first chapter provides a comprehensive review of immersive technologies and virtual reality systems, identifying opportunities for their integration into business processes and educational institutions. The current state of virtual reality implementation in various business processes is analyzed, drawing on recent industry works and scientific literature. A critical analysis of potential benefits and challenges of existing virtual reality technology implementation results is conducted, including enhanced data visualization, spatial representation, and more engaging learning experiences, as well as hardware limitations and user perception factors of immersive technologies. The theoretical foundations of technology acceptance models and their applicability to virtual reality systems are thoroughly examined. Analysis of scientific works on technology acceptance theory enabled identifying the relevance and applicability level of existing models, methods, and tools of immersive technologies. The VR-BPMN concept is defined as the foundation for developing information technology for business process formation in educational space based on virtual reality systems. Key gaps in existing research on virtual reality systems implementation are identified, particularly in user interface development and integration of natural language processing and gesture recognition. Strategic objectives of this work are outlined, forming the research goals for subsequent chapters.

The second chapter presents significant achievements in developing new information technology for integrating virtual reality into educational institutions. A key contribution is the improvement of the technology acceptance model, specifically designed for applying virtual reality systems in educational space. The improved model considers virtual reality-specific factors. The developed model was thoroughly tested using the structural equation modeling method, which provides a foundation for understanding and predicting virtual reality implementation in organizational conditions. The model's consistency with numerous data indicators is proven, highlighting its reliability and applicability in various contexts.

Additionally, the chapter develops a human-computer interaction model for virtual reality systems based on natural language processing and gesture recognition methods. The model defines PC-user interaction and enables reduced system response time in virtual environments, representing a significant contribution compared to traditional interfaces. This model enables reduced command interpretation errors, improves recognition accuracy over time through adaptive learning, and demonstrates its potential for shaping user experience in virtual reality.

The chapter also presents a virtual reality technology perception factors model, which has been further developed by considering the interaction of technological, organizational, and human factors for business process formation in educational space. The model offers nuanced understanding of complex variables affecting virtual reality perception and use, providing valuable information for both researchers and practitioners. By identifying and analyzing factors that contribute to user engagement, efficiency, and satisfaction, this model deepens theoretical understanding of human-computer interaction in virtual environments.

The third chapter focuses on evaluation and optimization methods within the developed information technology, which determine scientific results for assessing perception and effectiveness of virtual reality application in educational space. A key contribution is the improvement of structural equation modeling method for evaluating virtual reality perception by potential users, providing a more reliable and accurate approach to understanding factors affecting virtual reality adoption in organizational conditions. This enhanced method enables empirical verification of relationships between key constructs, offering valuable information about virtual reality adoption dynamics.

A method for evaluating VR simulation effectiveness in business processes has been developed, enabling the development of tools for determining indicators such as task completion time, error rates, and user satisfaction, and allowing comparison with traditional methods. Comparison results demonstrate the advantages of virtual reality's potential for improving visualization and understanding of complex business processes, while also identifying indicators for future optimization.

An innovative method for optimizing user experience in virtual environments is proposed, addressing unique challenges of immersive technologies while focusing on increasing user engagement and satisfaction levels. Integrating advanced analytics and machine learning methods, this approach employs a new methodology for collecting and analyzing user behavior data in virtual environments, paving the way for more personalized and effective VR experiences.

Furthermore, the chapter details a method for integrating natural language processing and gesture recognition in VR interfaces, aimed at enhancing user interaction efficiency in virtual environments. This integration represents a significant step in method development for creating more natural and seamless user experiences, with potential applications ranging from simple educational simulations to complex business process visualizations.

The fourth chapter is dedicated to practical implementation and validation of the developed information technology, presenting a comprehensive approach to implementing virtual reality systems in educational space. It presents innovative instrumental modules for implementing the VR-BPMN concept based on developed models and methods, providing a systematic foundation for effective virtual reality technology utilization. These modules cover the complete lifecycle of virtual reality systems implementation – from initial design to optimization.

The implementation of the proposed information technology is validated through extensive testing, case studies, and empirical evaluations in various business and educational environments. Testing results demonstrate significant improvements in task performance indicators, user interaction, and learning outcomes, while also identifying areas for further improvement. The chapter concludes by summarizing the obtained results, highlighting practical research outcomes, and suggesting promising directions for future research in immersive technologies.

The chapter also presents a strategy for evaluating the effectiveness and development of virtual reality systems in business and educational contexts. This strategy offers a structured approach to evaluating virtual reality implementation, ensuring alignment with educational institutions' goals for continuous improvement. It includes feedback mechanisms and adaptive learning processes for optimizing virtual reality experience utilization over time.

The practical significance of the obtained results lies in their comprehensive contribution to the development and application of advanced information technology for implementing virtual reality systems in educational space. The developed information technology provides educational organizations with a reliable and end-to-end solution for effective implementation and optimization of virtual reality systems in their activities, improving decision-making business processes, teaching methods, and overall productivity. The proposed strategy for evaluating the effectiveness and development of virtual reality systems is based on a holistic approach to improving virtual reality implementation in business and educational contexts.

The developed software modules provide users with applied tools for visual understanding and representation of complex business processes, enhancing operational efficiency of educational organizations through immersive interactive visualizations. The practical significance of this tool is important for various industries – from manufacturing to finance, where business process optimization is crucial for maintaining competitiveness.

Conclusion. For use in educational space, information technology and valuable recommendations for improving the learning process based on virtual reality systems implementation have been proposed, offering potential for transforming pedagogical approaches to teaching various disciplines. Empirically validated evaluation modules within the information technology offer educators reliable tools for assessing virtual reality's impact on learning outcomes, facilitating decision-making regarding virtual reality investment feasibility in educational institutions.

Furthermore, the technology acceptance model integrated into the developed information technology serves as a practical tool for educational organizations to predict and improve user perception of virtual reality technology. This predictive capability can guide the development of more user-centered VR applications, potentially increasing the success rate of virtual reality implementation in various organizational contexts. The comprehensive nature of the developed information technology bridges the gap between theoretical research on virtual reality technology and its practical application. It offers educational organizations applied tools for planning, implementing, and optimizing their virtual reality initiatives, comprising software modules for user interface development, data processing, performance analysis, and real-time IT adaptation based on user behavior and learning models.

By offering a structured and technological approach to virtual reality systems implementation, this research will enable educational institutions to more effectively utilize immersive technologies' potential, stimulating innovation and providing competitive advantages in the digital business landscape. The practical implementation of the developed information technology emphasizes its importance for developing virtual reality applications in educational organizations.

Keywords: virtual reality, human-computer interaction, business process modeling, educational technology, technology acceptance model, VR-BPMN, user experience optimization, natural language processing, gesture recognition, immersive technologies, effectiveness evaluation, strategic frameworks, VR analytics.

LIST OF THE APPLICANT'S PUBLICATIONS ON THE THEME OF THE DISSERTATION AND INFORMTION ON THE APPROVL OF THE RESULTS OF THE DISSERTATION

Articles in professional publications of Ukraine (included in the list of the Ministry of Education and Science of Ukraine)

1. Tsiutsiura, M., Tsiutsiura, S., Kryvoruchko, O., & **Li, Tao** (2022). The Method of harmonizing decision of the divergent methodology of the development of higher education institutions. Management of Development of Complex Systems, 50, 85 – 92. DOI: 10.32347/2412-9933.2022.50.85-92 [category «B», Index Copernicus] https://urss.knuba.edu.ua/files/zbirnyk-50/85-92_0.pdf
2. **Li, Tao** (2023). Evaluating the Effectiveness of VR Simulations in Business Process Formation. Management of Development of Complex Systems, 56, 97 – 104. DOI: 10.32347/2412-9933.2023.56.97-104 [category «B», Index Copernicus] http://mdcs.knuba.edu.ua/article/view/299711
3. **Li, Tao** (2024). Human-computer interaction in virtual reality environments for educational and business purposes. Management of Development of Complex Systems, 57, 112 – 117. DOI: 10.32347/2412-9933.2024.57.112-117 [category «B», Index Copernicus] http://mdcs.knuba.edu.ua/article/view/301837
4. **Li, Tao,** Honcharenko, T. (2024). Integrating advanced human-computer interaction and machine learning models for optimizing VR systems in educational and business applications. Bulletin of the National Technical

University «KhPI» A series of “Information and Modeling”, 1 – 2 (11 – 12), 105 – 120. DOI: 10.20998/2411-0558.2024.01.09 [category «B», Index Copernicus]

Materials of international scientific conferences indexed in the scientometric database Scopus

5. Tsiutsiura, M., Kostyshyna, N., Yerukaiev, A., Danylyshyn, S., Honcharenko, Y., & **Li, Tao.** (2022). Research of Housing Comfort Using Linguistic Variables. 2022 International Conference on Smart Information Systems and Technologies (SIST), 1 – 5. DOI: 10.1109/SIST54437.2022.9945736 [***Scopus***].
6. Levytskyi, V., Tsiutsiura, M., Yerukaiev, A., Rusan, N., & **Li, Tao.** (2023). The Working Principle of Artificial Intelligence in Video Games. 2023 IEEE International Conference on Smart Information Systems and Technologies (SIST), 246 – 250. DOI: 10.1109/SIST58284.2023.10223491 [***Scopus***].
7. **Tao, Li,** Dolhopolov, S., & Honcharenko, T. (2024). Strategizing VR Integration in Business and Education: Extending the Technology Acceptance Model through Project Management Perspectives. *International Workshop IT Project Management*, Vol. 3709, 250 – 263 [***Scopus, Q4, ISSN 1613-0073***].

Abstracts of reports of scientific and scientific-practical conferences

8. Tsiutsiura, M., Dolhopolov, S., & **Li, Tao.** (2021). Audio-visual assistant for learning foreign languages using machine learning technology. Eighth international scientific-practical conference “Management of the development of technologies”, 15 – 16.
9. **Li, Tao,** Kopcha, O., & Lukeniv, D. (2022). Using the REST API to create and receive information. Ninth international scientific-practical conference “Management of the development of technologies”.

10. Tsiutsiura, M., Nechyporenko, D., & **Li, Tao** (2023). Development of automatic “clever refrigitator” technology with the help of “AI – system product control” artificial intelligence. Tenth international scientific-practical conference “Management of the development of technologies”, 12 – 14.
11. **Li, Tao** (2023). Enhancing Learning Through Immersive Virtual Reality (VR) Technologies in Education. BMC-2023 – International Scientific-Practical Conference of young scientists “Build-Master-Class-2023”, 425–426.

АНОТАЦІЯ

Тао Лі. Інформаційна технологія формування бізнес-процесів на основі віртуальної реальності в освітньому просторі. – *Кваліфікаційна наукова праця на правах рукопису.*

Дисертація на здобуття наукового ступеня доктора філософії за спеціальністю 122 «Комп'ютерні науки». – Київський національний університет будівництва і архітектури, Київ, 2024.

Зміст анотації. Дисертація присвячена вирішенню *науково-практичної задачі* – розроблення методів, моделей та інформаційної технології для підвищення ефективності застосування технології віртуальної реальності (анг. Virtual Reality, VR) для формування та трансформації бізнес-процесів підприємств та організацій, які надають освітній контент. Дослідження спрямоване на нагальну потребу у наявності інноваційної інформаційної технології, яка б керувала впровадженням систем віртуальної реальності в освітні установи, особливо в контексті зростаючої технологічної складності та швидкої еволюції змін у бізнес-процесах освітнього простору.

Актуальність дослідження підкреслюється зростаючим визнанням потенціалу технології віртуальної реальності для революційних змін у різних аспектах бізнес-операцій та освітніх практик. Оскільки освітні організації прагнуть використовувати імерсивні технології для покращення процесу прийняття рішень, навчання та залучення клієнтів, існує гостра потреба в емпірично перевірених підходах до інтеграції систем віртуальної реальності в їх діяльність. Це дослідження має на меті подолати розрив між теоретичним розумінням щодо потенціалу віртуальної реальності та її практичним впровадженням, забезпечуючи прикладний інструментарій визначення можливостей, пов'язаних із впровадженням імерсивних технологій, для освітніх організацій.

Ключовим внеском цієї роботи є розробка нової інформаційної технології, яка спирається на існуючу концепцію VR-BPMN (Virtual Reality- Business

Process Model and Notation, *укр*. модель та нотація бізнес-процесів в віртуальній реальності). Апробація такого інноваційного ІТ-рішення для візуалізації та аналізу бізнес-процесів демонструє значні переваги порівняно з традиційними підходами, пропонуючи більш інтуїтивний та захоплюючий засіб візуалізації для розуміння складних організаційних та навчальних бізнес-процесів. Доведена ефективність цієї інформаційної технології, яка демонструє збільшення швидкості виконання завдань без ідентифікації помилок у порівнянні з інструментами на базі персонального комп'ютера (ПК) на 21%, що підкреслює її ефективність для трансформації бізнес-процесів у віртуальному середовищі. VR-BPMN є основним компонентом запропонованої інформаційної технології, який дає змогу продемонструвати, як віртуальна реальність може бути ефективно інтегрована в існуючі інформаційні системи формування та трансформації бізнес-процесів освітньої установи.

Дослідження розвиває сферу взаємодії людини з комп'ютером у віртуальному середовищі завдяки розробленню вдосконаленого методу, який інтегрує методи обробки природної мови та розпізнавання жестів. Такий підхід до мультимодальної взаємодії продемонстрував зменшення помилок інтерпретації команд на 35% порівняно з традиційними інтерфейсами, а 85% користувачів відзначили підвищення інтуїтивності при роботі у віртуальному середовищі. Здатність системи до адаптивного навчання демонструє підвищення точності розпізнавання команд з плином часу на 15%, що підкреслює потенціал використання систем віртуальної реальності для персоналізованого досвіду.

Значний теоретичний внесок цієї роботи полягає в розробленні моделі прийняття технологій для додатків віртуальної реальності. Використання методу моделювання структурними рівняннями забезпечує основу для розуміння факторів, що впливають на прийняття технології віртуальної реальності в організаційних умовах. Виявлення сприйнятого задоволення як критичного чинника корисності та легкості використання дає цінну інформацію для розробників і користувачів систем віртуальної реальності, підкреслюючи важливість створення цікавого користувацького досвіду.

Розроблено і представлено комплексну структуру для впровадження стратегії віртуальної реальності у бізнес- та освітньому контекстах. Структурований підхід охоплює оцінювання змісту, розподіл ресурсів, тестування, впровадження та постійну переоцінку й демонструє значні переваги в реальних умовах.

Крім того, у дослідженні набуло подальшого розвитку технологія віртуальній реальності в контекстах B2B і B2C, виявляючи значні потенційні переваги в різних секторах. Результати, що демонструють збільшення рівня залучення клієнтів, коефіцієнтів конверсії, ефективності навчання працівників та збереження знань, підтверджують трансформаційний потенціал технології віртуальної реальності. Однак дослідження також визначає ключові виклики на шляху до широкого впровадження VR, зокрема у сферах конфіденційності даних та апаратних обмежень, що забезпечує збалансований погляд на поточний стан впровадження імерсивних технологій.

Результати дисертаційного дослідження здійснюють значний внесок як у теоретичне розуміння, так і в практичне застосування технології віртуальної реальності в бізнес-процеси освітньої сфери. Розроблені методи, моделі та інформаційна технологія пропонують комплексний аналітичний та прикладний інструментарій для організацій, які прагнуть використовувати віртуальну реальність для підвищення ефективності та впровадження інновацій в освітньому просторі. Розглядаючи складну взаємодію технологічних, організаційних і людських факторів при впровадженні технології віртуальної реальності, дане дослідження створює міцну основу для майбутніх досягнень у галузі IT, прокладаючи шлях до створення більш ефективних, результативних і орієнтованих на користувача додатків віртуальної реальності в різних галузях.

Об'єктом дослідження є процеси інтеграції систем віртуальної реальності в діяльність підприємств і організацій, які надають освітній контент.

Предметом дослідження є моделі, методи та інформаційна технологія для розроблення, оцінювання та впровадження систем віртуальної реальності для формування та трансформації бізнес-процесів в освітньому просторі.

Методи дослідження. У дослідженні використано комплекс методів, серед яких: методи моделювання та аналізу даних, включаючи метод моделювання структурними рівняннями для перевірки моделі прийняття технологій в рамках запропонованої інформаційної технології; методи програмної інженерії для розробки основних компонентів інформаційної технології на основі віртуальної реальності, включаючи інтерфейси віртуальної реальності та алгоритми обробки даних; експериментальне проектування та дослідження користувачів для оцінювання ефективності концепції VR-BPMN та моделі взаємодії людини та комп'ютера в рамках розробленої інформаційної технології; Статистичний аналіз показників продуктивності системи для оптимізації ефективності та швидкості реагування інформаційної технології; методи системного аналізу та проектування для створення фреймворків реалізації та забезпечення масштабованості та адаптивності інформаційної технології; методи симуляції та моделювання для тестування та доопрацювання VR-компонентів інформаційної технології в контрольованих середовищах перед розгортанням у реальному світі.

Метою дослідження є розроблення інформаційної технології для ефективного впровадження систем віртуальної реальності в бізнес-процеси освітньої галузі.

Для досягнення поставленої мети необхідно розв'язати ***такі завдання***:

1. Здійснити аналіз можливостей впровадження технології віртуальної реальності в бізнес-процеси та освітній контекст, виявити існуючі виклики та обмеження в сучасних імерсивних технологіях.

2. Запропонувати модель прийняття технологій для застосування систем віртуальності реальності та її додатків в освітньому просторі.

3. Розробити модель взаємодії людини з комп'ютером для систем віртуальної реальності.

4. Розробити методи оцінювання ефективності VR-симуляцій у бізнес-процесах та оптимізації користувацького досвіду у віртуальному середовищі.

5. Розробити метод інтеграції обробки природної мови та розпізнавання жестів у VR-інтерфейсах для навчальних симуляцій та візуалізації складних бізнес-процесів.

6. Розробити інформаційну технологію формування бізнес-процесів на основі впровадження систем віртуальної реальності в освітній простір.

7. Розробити програмні модулі та здійснити апробацію розробленої інформаційної технології за допомогою тестування, тематичних досліджень та емпіричних оцінок у різних бізнес- та освітніх середовищах.

8. Розробити стратегію оцінювання ефективності та розвитку систем віртуальної реальності у бізнес- та освітньому контекстах.

Основна гіпотеза дослідження полягає в тому, що завдяки вирішенню поставлених завдань результати дослідження мають подолати розрив між теоретичним розумінням та практичним впровадженням систем віртуальної реальності в діяльність освітніх установ, забезпечуючи інформаційно-прикладний інструментарій для визначення викликів і можливостей, пов’язаних із впровадженням імерсивних технологій.

Наукова новизна отриманих результатів:

Вперше розроблено:

- модель взаємодії людини з комп'ютером для систем віртуальної реальності, яка, за рахунок унікальної комбінації визначених компонентів, дає змогу збільшити швидкість реакції системи на дії користувача у віртуальному середовищі. На відміну від існуючих, така модель уможливлює зменшення помилок інтерпретації команд та підвищує точність їх розпізнавання завдяки адаптивному навчанню, що визначає її потенціал для формування користувацького досвіду;

- метод оцінювання ефективності застосування VR-симуляцій у бізнес-процесах, який дає змогу кількісно визначити показники ефективності застосування систем віртуальної реальності: час виконання завдань, рівні помилок, задоволеності та сприйняття користувачем віртуального середовища, і дає змогу виявити показники для оптимізації бізнес-процесів та процесів прийняття рішень;
- метод оптимізації користувацького досвіду у віртуальному середовищі, який за рахунок агрегації методів аналітики даних та машинного навчання пропонує новий підхід до збору та аналізу даних про поведінку користувачів у віртуальному середовищі та забезпечує накопичення VR-досвіду;
- інформаційну технологію формування бізнес-процесів в освітньому просторі, яка за рахунок розроблених і вдосконалених моделей та методів, забезпечує підвищення ефективності впровадження систем віртуальної реальності в діяльність організацій, які надають освітній контент.

Удосконалено:

- модель прийняття технологій, яка за рахунок врахування специфічних факторів для систем віртуальної реальності забезпечує аналітичний базис для прогнозування результатів впровадження розробленої інформаційної технології в освітні установи;
- метод моделювання структурними рівняннями для оцінювання сприйняття віртуальної реальності потенційними користувачами, який, на від відміну від існуючого, за рахунок використання моделі розширених факторів сприйняття технології віртуальної реальності, дає змогу кількісно визначити міру взаємозв'язків між ключовими конструктами в організаційних умовах.

Отримали подальший розвиток:

- модель факторів сприйняття технології віртуальної реальності, яка враховує складну структуру взаємодії технологічних, організаційних і людських факторів, що впливають на використання систем віртуальної реальності, та є основою для удосконалення методу моделювання структурними рівняннями;

- метод інтеграції обробки природної мови і розпізнавання жестів у VR-інтерфейсах, який, за рахунок агрегації зазначених компонентів, підвищує інтуїтивність і ефективність взаємодії користувачів у віртуальному середовищі, що уможливлює його застосування для освітніх симуляцій та візуалізації складних бізнес-процесів.

У першому розділі здійснено всебічний огляд імерсивних технологій і систем віртуальної реальності, виявлено можливості їхньої інтеграції в бізнес-процеси й освітні установи. Проаналізовано поточний стан впровадження віртуальної реальності в різноманітні бізнес-процеси, спираючись на останні галузеві праці та наукову літературу. Здійснено критичний аналіз потенційних переваг та викликів наявних результатів впровадження технології віртуальної реальності, включаючи удосконалену візуалізацію даних, просторове уявлення та більш захопливий навчальний досвід, а також апаратні обмеження та фактори сприйняття користувачами імерсивних технологій. Детально досліджено теоретичні основи моделей прийняття технологій та їхня застосовність до систем віртуальної реальності. Аналіз наукових праць вчених з теорії прийняття технологій надав змогу виявити актуальність та рівень застосовності існуючих моделей, методів та засобів імерсивних технологій. Визначено концепцію VR-BPMN як основу розроблення інформаційної технології формування бізнес-процесів в освітньому просторі на основі систем віртуальної реальності. Виявлені ключові прогалини в існуючих дослідженнях щодо впровадження систем віртуальної реальності, зокрема в розробленні інтерфейсу користувача, в інтеграції обробки природної мови і розпізнавання жестів. Окреслені стратегічні завдання цієї роботи, які формують дослідницькі цілі наступних розділів.

У другому розділі представлено значні досягнення в розробленні нової інформаційної технології для інтеграції віртуальної реальності в освітні установи. Ключовим внеском є вдосконалення моделі прийняття технологій, спеціально розробленої для застосування систем віртуальної реальності в освітньому просторі. Вдосконалена модель враховує специфічні для віртуальної реальності фактори. Розроблена модель була ретельно перевірена за допомогою методу моделювання структурними рівняннями, який забезпечує основу для розуміння і прогнозування впровадження віртуальної реальності в організаційних умовах. Доведена узгодженість моделі з багатьма показниками даних, що підкреслює її надійність і застосовність у різних контекстах.

Крім того, у розділі розроблено модель взаємодії людини з комп'ютером для систем віртуальної реальності, яка базується на методі обробки природної мови та розпізнавання жестів. Модель визначає взаємодію ПК з користувачем і дає змогу зменшити швидкість реакції системи у віртуальному середовищі, що є суттєвим внеском порівняно з традиційними інтерфейсами. Така модель уможливлює зменшення помилок інтерпретації команд, підвищує точність розпізнавання з часом завдяки адаптивному навчанню, і демонструє свій потенціал для формування користувацького досвіду у віртуальній реальності.

У розділі також представлено модель факторів сприйняття технології віртуальної реальності, яка набула подальшого розвитку завдяки врахуванню взаємодії технологічних, організаційних і людських факторів для формування бізнес-процесів в освітньому просторі. Модель пропонує тонке розуміння складних змінних, які впливають на сприйняття та використання віртуальної реальності, надаючи цінну інформацію як для дослідників, так і для практиків. Визначаючи та аналізуючи фактори, які сприяють залученню, ефективності та задоволеності користувачів, ця модель поглиблює теоретичне розуміння взаємодії людини з ПК у віртуальному середовищі.

Третій розділ присвячено методам оцінювання та оптимізації в рамках розробленої інформаційної технології, який визначають наукові результаті для оцінки сприйняття та визначення ефективності застосування віртуальної реальності в освітньому просторі. Ключовим внеском є вдосконалення методу моделювання структурними рівняннями для оцінювання сприйняття віртуальної реальності потенційними користувачами, що забезпечує більш надійний і точний підхід до розуміння факторів, що впливають на прийняття віртуальної реальності в організаційних умовах. Такий удосконалений метод дає змогу емпірично перевірити взаємозв'язки між ключовими конструктами, пропонуючи цінну інформацію про динаміку прийняття віртуальної реальності.

Розроблено метод оцінки ефективності VR-симуляцій у бізнес-процесах, який дає змогу розробити інструментальні засоби визначання таких показників, як час виконання завдань, рівень помилок і задоволеність користувачів та дає змогу порівняти їх з традиційними методами. Результати порівняння демонструють переваги потенціалу віртуальної реальності для покращення візуалізації та розуміння складних бізнес-процесів, а також дає змогу виявити показники для майбутньої оптимізації.

Запропоновано інноваційний метод оптимізації користувацького досвіду у віртуальному середовищі, який вирішує унікальні проблеми імерсивних технологій, зосереджуючись на підвищенні рівнів залученості та задоволеності користувачів. Інтегруючи передові методи аналітики та машинного навчання, метод використовує новий підхід до збору та аналізу даних про поведінку користувачів у віртуальному середовищі, прокладаючи шлях до більш персоналізованого та ефективного VR-досвіду.

Крім того, в розділі детально розглядається метод інтеграції обробки природної мови і розпізнавання жестів в інтерфейси VR, який спрямований на підвищення ефективності взаємодії користувачів у віртуальному середовищі. Означена інтеграція є значним кроком для розвитку методу у створенні більш природного і безперешкодного користувацького досвіду з потенційними застосуваннями як для простих освітніх симуляцій так і для складних візуалізацій бізнес-процесів.

Четвертий розділ присвячено практичному впровадженню та валідації розробленої інформаційної технології, представляючи комплексний підхід до впровадження систем віртуальної реальності в освітній простір. Він представляє інноваційні інструментальні модулі для впровадження концепції VR-BPMN на основі розроблених моделей та методів, забезпечуючи систематичну основу для ефективного використання технології віртуальної реальності. Ці модулі охоплюють повний життєвий цикл впровадження систем віртуальної реальності – від початкового проектування до оптимізації.

Підтверджено впровадження запропонованої інформаційної технології за допомогою широкого тестування, тематичних досліджень та емпіричних оцінок у різних бізнес- та освітніх середовищах. Результати апробації демонструють значне покращення показників виконання завдань, взаємодії з користувачами та програмних результатів навчання, а також визначають сфери для подальшого вдосконалення. Наприкінці розділу узагальнюються отримані результати, висвітлюються практичні результати дослідження та пропонуються перспективні напрямки подальших досліджень в галузі імерсивних технологій.

У розділі також представлено стратегію оцінювання ефективності та розвитку систем віртуальної реальності в бізнес- та освітньому контекстах. Ця стратегія пропонує структурований підхід до оцінки впровадження віртуальної реальності, забезпечуючи узгодженість з цілями освітніх установ на постійне вдосконалення. Вона включає механізми зворотного зв'язку та адаптивні процеси навчання для оптимізації досвіду використання віртуальної реальності у часі.

Практичне значення отриманих результатів полягає в тому, що вони є комплексним внеском у розроблення та застосування передової інформаційної технології для впровадження систем віртуальної реальності в освітній простір. Розроблена інформаційна технологія надає освітнім організаціям надійне та наскрізне рішення для ефективного впровадження та оптимізації використання систем віртуальної реальності у своїй діяльності, покращуючи бізнес-процеси прийняття рішень, методи навчання та загальну продуктивність. Запропонована стратегія оцінювання ефективності та розвитку систем віртуальної реальності базується на цілісному підході до вдосконалення впровадження віртуальної реальності в діловому та освітньому контекстах.

Розроблені програмні модулі надають користувачам прикладний інструментарій для наочного розуміння та уявлення складних бізнес-процесів, що підвищує операційну ефективність діяльності освітніх організацій за допомогою інтерактивних візуалізацій з ефектом занурення. Практичне значення цього інструменту є важливим для різних галузей – від виробництва до фінансів, де оптимізація бізнес-процесів має вирішальне значення для підтримки конкурентоспроможності.

Висновок. Для використання в освітньому просторі запропоновано інформаційну технологію та надані цінні рекомендації щодо удосконалення навчального процесу на основі впровадження систем віртуальної реальності, що має потенціал для трансформації педагогічних підходів до викладання різних дисциплін. Емпірично підтверджені модулі оцінювання в рамках інформаційної технології пропонують освітянам надійні інструментальні засоби для оцінки впливу віртуальної реальності на результати навчання, полегшуючи прийняття рішень щодо доцільності інвестицій у віртуальну реальність в освітніх установах.

Крім того, модель прийняття технологій, інтегрована в розроблену інформаційну технологію, слугує практичним інструментом освітнім організаціям для прогнозування та удосконалення сприйняття користувачами технології віртуальної реальності. Ця прогностична можливість може спрямовувати розробку більш орієнтованих на користувача VR-додатків, потенційно підвищуючи рівень успішності впровадження віртуальної реальності в різних організаційних контекстах. Комплексний характер розробленої інформаційної технології долає розрив між теоретичними дослідженнями технології віртуальної реальності та її реальним застосуванням. Вона пропонує освітнім організаціям прикладний інструментарій для планування, впровадження та оптимізації їхніх ініціатив у сфері віртуальної реальності, який складається з програмних модулів для розробки користувацького інтерфейсу, обробки даних, аналізу продуктивності та адаптації IT в реальному часі на основі поведінки користувачів і моделей навчання.

Пропонуючи структурований та технологічний підхід до впровадження систем віртуальної реальності, це дослідження надасть змогу освітнім установам більш ефективно використовувати потенціал імерсивних технологій, стимулюючи їх до інновацій, та надасть їм конкурентні переваги у цифровому бізнес ландшафті. Здійснене практичне впровадження розробленої інформаційної технології підкреслює її важливість для розвитку сфери застосування віртуальної реальності в освітніх організаціях.

Ключові слова: віртуальна реальність, людино-комп'ютерна взаємодія, моделювання бізнес-процесів, освітні технології, модель прийняття технологій, VR-BPMN, оптимізація користувацького досвіду, обробка природної мови, розпізнавання жестів, імерсивні технології, оцінка ефективності, стратегічні рамки, аналітика VR.

СПИСОК ПУБЛІКАЦІЙ ЗДОБУВАЧА ЗА ТЕМОЮ ДИСЕРТАЦІЇ ТА ВІДОМОСТІ ПРО АПРОБАЦІЮ РЕЗУЛЬТАТІВ ДИСЕРТАЦІЇ

Статті у фахових виданнях України (входять до переліку МОН України)

1. Tsiutsiura, M., Tsiutsiura, S., Kryvoruchko, O., & **Li, Tao** (2022). The Method of harmonizing decision of the divergent methodology of the development of higher education institutions. Management of Development of Complex Systems, 50, 85 – 92. DOI: 10.32347/2412-9933.2022.50.85-92 [category «B», Index Copernicus] https://urss.knuba.edu.ua/files/zbirnyk-50/85-92_0.pdf
2. **Li, Tao** (2023). Evaluating the Effectiveness of VR Simulations in Business Process Formation. Management of Development of Complex Systems, 56,

97 – 104. DOI: 10.32347/2412-9933.2023.56.97-104 [category «B», Index Copernicus] http://mdcs.knuba.edu.ua/article/view/299711

3. **Li, Tao** (2024). Human-computer interaction in virtual reality environments for educational and business purposes. Management of Development of Complex Systems, 57, 112 – 117. DOI: 10.32347/2412-9933.2024.57.112-117 [category «B», Index Copernicus] http://mdcs.knuba.edu.ua/article/view/301837
4. **Li, Tao,** Honcharenko, T. (2024). Integrating advanced human-computer interaction and machine learning models for optimizing VR systems in educational and business applications. Bulletin of the National Technical University «KhPI» A series of "Information and Modeling", 1 – 2 (11 – 12), 105 – 120. DOI: 10.20998/2411-0558.2024.01.09 [category «B», Index Copernicus]

Матеріали міжнародних наукових конференцій, що індексуються в наукометричній базі даних Scopus

(не входять до переліку МОН України)

5. Tsiutsiura, M., Kostyshyna, N., Yerukaiev, A., Danylyshyn, S., Honcharenko, Y., & **Li, Tao.** (2022). Research of Housing Comfort Using Linguistic Variables. 2022 International Conference on Smart Information Systems and Technologies (SIST), 1 – 5. DOI: 10.1109/SIST54437.2022.9945736 [***Scopus***].
6. Levytskyi, V., Tsiutsiura, M., Yerukaiev, A., Rusan, N., & **Li, Tao.** (2023). The Working Principle of Artificial Intelligence in Video Games. 2023 IEEE International Conference on Smart Information Systems and Technologies (SIST), 246 – 250. DOI: 10.1109/SIST58284.2023.10223491 [***Scopus***].
7. **Tao, Li,** Dolhopolov, S., & Honcharenko, T. (2024). Strategizing VR Integration in Business and Education: Extending the Technology Acceptance Model through Project Management Perspectives. *International*

Workshop IT Project Management, Vol. 3709, 250 – 263 [***Scopus, Q4, ISSN 1613-0073***].

Тези доповідей наукових та науково-практичних конференцій

8. Tsiutsiura, M., Dolhopolov, S., & **Li, Tao.** (2021). Audio-visual assistant for learning foreign languages using machine learning technology. Eighth international scientific-practical conference "Management of the development of technologies", 15 – 16.
9. **Li, Tao,** Kopcha, O., & Lukeniv, D. (2022). Using the REST API to create and receive information. Ninth international scientific-practical conference "Management of the development of technologies".
10. Tsiutsiura, M., Nechyporenko, D., & **Li, Tao** (2023). Development of automatic "clever refrigitator" technology with the help of "AI – system product control" artificial intelligence. Tenth international scientific-practical conference "Management of the development of technologies", 12 – 14.
11. **Li, Tao** (2023). Enhancing Learning Through Immersive Virtual Reality (VR) Technologies in Education. BMC-2023 – International Scientific-Practical Conference of young scientists "Build-Master-Class-2023", 425–426.

CONTENT

INTRODUCTION

In the contemporary world, where technological innovations are rapidly reshaping the landscape of business and education, virtual reality (VR) emerges as a powerful transformative tool. However, despite VR's significant potential, its integration into organizational processes and educational practices remains a challenging task. Enterprises and educational institutions face numerous obstacles, ranging from technical limitations and high implementation costs to user acceptance issues and the absence of clear implementation strategies. These challenges create a gap between the theoretical possibilities of VR and its practical applications, stifling innovation and limiting the potential benefits of this technology.

The central problem lies in the lack of a comprehensive approach to integrating VR into business processes and educational environments. Existing models and methods often fail to consider the unique characteristics of VR technologies, leading to inefficient implementation and low user adoption. Additionally, the scarcity of empirical research on VR's effectiveness in various contexts creates uncertainty for decision-makers regarding investment in this technology.

This dissertation aims to address these issues by developing a comprehensive framework for the effective integration of VR into organizational processes. Our approach is based on three key aspects: expanding theoretical models, developing innovative tools, and empirical validation.

Firstly, we expand the Technology Acceptance Model (TAM) by adapting it to the specificities of VR. This expansion includes new constructs such as the sense of presence and immersion level, which are critical for understanding user acceptance of VR. By applying structural equation modeling (SEM), we validate this extended model, providing a reliable basis for predicting and facilitating VR adoption in organizations.

Secondly, we develop VR-BPMN (Virtual Reality Business Process Model and Notation), an innovative system for visualizing and interacting with business processes in a virtual environment. This tool represents a significant advancement in business process modeling, offering a more intuitive and efficient understanding of complex organizational systems. Through a rigorous comparative study, we assess the effectiveness of VR-BPMN against traditional modeling tools, providing empirical evidence of its advantages and identifying areas for future optimization.

Thirdly, we integrate advanced human-computer interaction (HCI) models into VR systems, focusing on natural language processing and gesture recognition technologies. By developing and testing innovative algorithms for multimodal interaction in VR environments, we aim to create more intuitive and effective user interfaces, thereby enhancing the overall VR experience in business and educational contexts.

The dissertation work was carried out at the Faculty of Information Technologies of Kyiv National University of Construction and Architecture following the plan of research works of Kyiv National University of Construction and Architecture, in particular the topic “Study of the possibilities of using virtual reality technologies (VR-technologies) in the educational space”, No. 0123U104646.

The object of the study is the processes of integrating virtual reality systems into the activities of enterprises and organizations that provide educational content.

The subject of the research is models, methods, and information technology for developing, evaluating, and implementing virtual reality systems for forming and transforming business processes in educational space.

Research methods. The study employs a complex of methods, including: modeling and data analysis methods, including structural equation modeling to verify the technology acceptance model within the proposed information technology; software engineering methods for developing core components of virtual reality-based information technology, including virtual reality interfaces and data processing algorithms; experimental design and user research to evaluate the effectiveness of the VR-BPMN concept and human-computer interaction model within the developed information technology; statistical analysis of system performance indicators to optimize the efficiency and responsiveness of information technology; systems analysis and design methods for creating implementation frameworks and ensuring scalability and adaptability of information technology; simulation and modeling methods for testing and refining VR components of information technology in controlled environments before real-world deployment.

The aim of the study is to develop information technology for effective implementation of virtual reality systems in educational sector business processes.

To achieve this aim, the following tasks must be solved:

1. Analyze the possibilities of implementing virtual reality technology in business processes and educational context, identify existing challenges and limitations in modern immersive technologies.
2. Propose a technology acceptance model for applying virtual reality systems and their applications in educational space.
3. Develop a human-computer interaction model for virtual reality systems.
4. Develop methods for evaluating the effectiveness of VR simulations in business processes and optimizing user experience in virtual environments.
5. Develop a method for integrating natural language processing and gesture recognition in VR interfaces for educational simulations and visualization of complex business processes.
6. Develop information technology for business process formation based on implementing virtual reality systems in educational space.
7. Develop software modules and conduct testing of the developed information technology through testing, case studies, and empirical evaluations in various business and educational environments.
8. Develop a strategy for evaluating the effectiveness and development of virtual reality systems in business and educational contexts.

The main study hypothesis is that by solving the set tasks, the research results should bridge the gap between theoretical understanding and practical implementation of virtual reality systems in educational institutions' activities, providing information and applied tools for identifying challenges and opportunities associated with immersive technology implementation.

The scientific novelty of the obtained results:

Developed for the first time:

- a human-computer interaction model for virtual reality systems which, through a unique combination of defined components, enables increased system response speed to user actions in the virtual environment. Unlike existing models, it enables reduced command interpretation errors and improves recognition accuracy through adaptive learning, determining its potential for shaping user experience;
- a method for evaluating the effectiveness of VR simulations in business processes, which enables quantitative determination of virtual reality systems' effectiveness indicators: task completion time, error levels, user satisfaction and perception of the virtual environment, and enables identification of indicators for optimizing business processes and decision-making processes;
- a method for optimizing user experience in virtual environments, which through aggregation of data analytics and machine learning methods offers a new approach to collecting and analyzing user behavior data in virtual environments and ensures VR experience accumulation;
- information technology for business process formation in educational space, which through developed and improved models and methods, ensures increased effectiveness of virtual reality systems implementation in organizations providing educational content.

Improved:

- technology acceptance model, which by considering specific factors for virtual reality systems provides an analytical basis for predicting the results of implementing the developed information technology in educational institutions;

- structural equation modeling method for evaluating virtual reality perception by potential users, which, unlike existing ones, through using an extended factors model of virtual reality technology perception, enables quantitative determination of relationships between key constructs in organizational conditions.

Further developed:

- virtual reality technology perception factors model, which considers the complex structure of interaction between technological, organizational, and human factors affecting virtual reality systems use, and serves as a basis for improving the structural equation modeling method;
- method of integrating natural language processing and gesture recognition in VR interfaces, which, through aggregation of these components, increases intuitiveness and efficiency of user interaction in virtual environments, enabling its application for educational simulations and complex business process visualization.

The first chapter provides a comprehensive review of immersive technologies and virtual reality systems, identifying opportunities for their integration into business processes and educational institutions. The current state of virtual reality implementation in various business processes is analyzed, drawing on recent industry works and scientific literature. A critical analysis of potential benefits and challenges of existing virtual reality technology implementation results is conducted, including enhanced data visualization, spatial representation, and more engaging learning experiences, as well as hardware limitations and user perception factors of immersive technologies. The theoretical foundations of technology acceptance models and their applicability to virtual reality systems are thoroughly examined. Analysis of scientific works on technology acceptance theory enabled identifying the relevance and applicability level of existing models, methods, and tools of immersive technologies. The VR-BPMN concept is defined as the foundation for developing information technology for business process formation in educational space based on virtual reality systems. Key gaps in existing research on virtual reality systems implementation are identified, particularly in user interface development and integration of natural language processing and gesture recognition. Strategic objectives of this work are outlined, forming the research goals for subsequent chapters.

The second chapter presents significant achievements in developing new information technology for integrating virtual reality into educational institutions. A key contribution is the improvement of the technology acceptance model, specifically designed for applying virtual reality systems in educational space. The improved model considers virtual reality-specific factors. The developed model was thoroughly tested using the structural equation modeling method, which provides a foundation for understanding and predicting virtual reality implementation in organizational conditions. The model's consistency with numerous data indicators is proven, highlighting its reliability and applicability in various contexts.

Additionally, the chapter develops a human-computer interaction model for virtual reality systems based on natural language processing and gesture recognition methods. The model defines PC-user interaction and enables reduced system response time in virtual environments, representing a significant contribution compared to traditional interfaces. This model enables reduced command interpretation errors, improves recognition accuracy over time through adaptive learning, and demonstrates its potential for shaping user experience in virtual reality.

The chapter also presents a virtual reality technology perception factors model, which has been further developed by considering the interaction of technological, organizational, and human factors for business process formation in educational space. The model offers nuanced understanding of complex variables affecting virtual reality perception and use, providing valuable information for both researchers and practitioners. By identifying and analyzing factors that contribute to user engagement, efficiency, and satisfaction, this model deepens theoretical understanding of human-computer interaction in virtual environments.

The third chapter focuses on evaluation and optimization methods within the developed information technology, which determine scientific results for assessing perception and effectiveness of virtual reality application in educational space. A key contribution is the improvement of structural equation modeling method for evaluating virtual reality perception by potential users, providing a more reliable and accurate approach to understanding factors affecting virtual reality adoption in organizational conditions. This enhanced method enables empirical verification of relationships between key constructs, offering valuable information about virtual reality adoption dynamics.

A method for evaluating VR simulation effectiveness in business processes has been developed, enabling the development of tools for determining indicators such as task completion time, error rates, and user satisfaction, and allowing comparison with traditional methods. Comparison results demonstrate the advantages of virtual reality's potential for improving visualization and understanding of complex business processes, while also identifying indicators for future optimization.

An innovative method for optimizing user experience in virtual environments is proposed, addressing unique challenges of immersive technologies while focusing on increasing user engagement and satisfaction levels. Integrating advanced analytics and machine learning methods, this approach employs a new methodology for collecting and analyzing user behavior data in virtual environments, paving the way for more personalized and effective VR experiences.

Furthermore, the chapter details a method for integrating natural language processing and gesture recognition in VR interfaces, aimed at enhancing user interaction efficiency in virtual environments. This integration represents a significant step in method development for creating more natural and seamless user experiences, with potential applications ranging from simple educational simulations to complex business process visualizations.

The fourth chapter is dedicated to practical implementation and validation of the developed information technology, presenting a comprehensive approach to implementing virtual reality systems in educational space. It presents innovative instrumental modules for implementing the VR-BPMN concept based on developed models and methods, providing a systematic foundation for effective virtual reality technology utilization. These modules cover the complete lifecycle of virtual reality systems implementation – from initial design to optimization.

The implementation of the proposed information technology is validated through extensive testing, case studies, and empirical evaluations in various business and educational environments. Testing results demonstrate significant improvements in task performance indicators, user interaction, and learning outcomes, while also identifying areas for further improvement. The chapter concludes by summarizing the obtained results, highlighting practical research outcomes, and suggesting promising directions for future research in immersive technologies.

The chapter also presents a strategy for evaluating the effectiveness and development of virtual reality systems in business and educational contexts. This strategy offers a structured approach to evaluating virtual reality implementation, ensuring alignment with educational institutions' goals for continuous improvement. It includes feedback mechanisms and adaptive learning processes for optimizing virtual reality experience utilization over time.

The practical significance of the obtained results lies in their comprehensive contribution to the development and application of advanced information technology for implementing virtual reality systems in educational space. The developed information technology provides educational organizations with a reliable and end-to-end solution for effective implementation and optimization of virtual reality systems in their activities, improving decision-making business processes, teaching methods, and overall productivity. The proposed strategy for evaluating the effectiveness and development of virtual reality systems is based on a holistic approach to improving virtual reality implementation in business and educational contexts.

The developed software modules provide users with applied tools for visual understanding and representation of complex business processes, enhancing operational efficiency of educational organizations through immersive interactive visualizations. The practical significance of this tool is important for various industries – from manufacturing to finance, where business process optimization is crucial for maintaining competitiveness.

For use in educational space, information technology and valuable recommendations for improving the learning process based on virtual reality systems implementation have been proposed, offering potential for transforming pedagogical approaches to teaching various disciplines. Empirically validated evaluation modules within the information technology offer educators reliable tools for assessing virtual reality's impact on learning outcomes, facilitating decision-making regarding virtual reality investment feasibility in educational institutions.

Furthermore, the technology acceptance model integrated into the developed information technology serves as a practical tool for educational organizations to predict and improve user perception of virtual reality technology. This predictive capability can guide the development of more user-centered VR applications, potentially increasing the success rate of virtual reality implementation in various organizational contexts. The comprehensive nature of the developed information technology bridges the gap between theoretical research on virtual reality technology and its practical application. It offers educational organizations applied tools for planning, implementing, and optimizing their virtual reality initiatives, comprising software modules for user interface development, data processing, performance analysis, and real-time IT adaptation based on user behavior and learning models.

By offering a structured and technological approach to virtual reality systems implementation, this research will enable educational institutions to more effectively utilize immersive technologies' potential, stimulating innovation and providing competitive advantages in the digital business landscape. The practical implementation of the developed information technology emphasizes its importance for developing virtual reality applications in educational organizations.

The information technology presented in this research offers a comprehensive solution for organizations to plan, implement, and continuously optimize their VR initiatives. This practical toolkit bridges the gap between theoretical research and real-world application, providing actionable strategies for leveraging VR to drive innovation and competitive advantage. The author published the work's primary results in the following publications [1–11].

Personal contribution of the acquirer. The author personally obtained the main provisions and results of the dissertation work. The research findings were disseminated through several publications in reputable journals and conference proceedings.

The work [1] proposes a method for harmonizing decisions in the development of higher education institutions, contributing to the broader context of educational management in which VR technologies can be applied.

The work [2] evaluates the effectiveness of VR simulations in business process formation, providing crucial insights into the practical applications of VR technology in organizational settings. This study lays the foundation for understanding how VR can enhance business process modeling and decision-making.

In article [3] investigates human-computer interaction in virtual reality environments, focusing on educational and business purposes. This work contributes to the understanding of user experience and interface design in VR applications, which is essential for effective implementation in various sectors.

The collaborative work [4] integrates advanced human-computer interaction and machine learning models to optimize VR systems for educational and business applications. This research represents a significant step forward in enhancing the capabilities and usability of VR systems through innovative technological integration.

The collaborative work [5], published in a Scopus-indexed proceeding, investigates the research of housing comfort using linguistic variables, demonstrating the application of AI and data analysis techniques in urban planning.

Work [6], also published in a Scopus-indexed proceeding, explores the working principle of artificial intelligence in video games, providing insights into the application of AI in interactive digital environments.

The collaborative work [7], published in a Scopus-indexed proceeding, extends the Technology Acceptance Model through project management perspectives to strategize VR integration in business and education. This research offers a comprehensive framework for understanding and implementing VR technologies in organizational contexts.

The conference paper [8] explores the development of an audio-visual assistant for learning foreign languages using machine learning technology, demonstrating the application of AI in educational contexts.

Work [9] discusses the use of REST API for creating and receiving information, contributing to the technical foundation necessary for developing VR applications.

The collaborative work [10] presents the development of an automatic "clever refrigerator" technology using AI for product control, showcasing the application of AI in everyday technologies.

Finally, the conference paper [11] discusses the enhancement of learning through immersive Virtual Reality technologies in education. This work provides valuable insights into the potential of VR to transform educational practices and improve learning outcomes.

Approval of the results of the dissertation. The main results of the work were reported, discussed, and received positive evaluations at international conferences including the international scientific-practical conference “Management of the development of technologies” in Kyiv (2021–2023), the International Scientific-Practical Conference of young scientists “Build-Master-Class-2023” in Kyiv (2023) and the International Workshop on IT Project Management (2024). The research findings have been published in respected journals such as “Management of Development of Complex Systems” and the “Bulletin of the National Technical University «KhPI» A series of Information and Modeling”, both of which are category

“B” publications in Ukraine. Additionally, the work has received international recognition through publications in a Scopus-indexed conference proceeding, demonstrating the global relevance and impact of this research in the field of VR technology integration in business and education.

Publications. Based on the dissertation materials, 11 scientific works have been published, including: 4 scientific articles in specialized publications of Ukraine, 4 article in a publication that is not included in the list of the Ministry of Education and Science, 3 materials of international conference proceedings indexed in the Scopus database. The main results of the work were obtained by the author personally. Some of the scientific works published in co-authorship, the dissertation research describes those provisions resulting from the author’s work.

Structure and scope of work. The dissertation consists of an introduction, four chapters, chapter conclusions, main conclusions, a list of references and appendices. The total volume of the dissertation is 218 pages, including 29 figures, 9 tables, a bibliography of 114 titles and 2 appendixes.

CHAPTER 1. THE CHALLENGE OF INTEGRATING VIRTUAL REALITY IN BUSINESS PROCESSES AND EDUCATION

1.1. Challenges and Opportunities in Integrating VR in Business Processes and Education

The integration of Virtual Reality into business processes and educational practices represents a significant leap forward in technological innovation. This transformative technology offers immersive and interactive experiences that have the potential to revolutionize traditional approaches across various sectors.

J. Steuer's seminal work on telepresence in virtual environments laid crucial groundwork for understanding how VR can create a sense of presence and immersion [12]. His research established fundamental concepts that continue to inform VR development today, particularly in creating engaging educational and business simulations. Steuer's emphasis on the importance of vividness and interactivity in virtual environments provides a theoretical foundation for many current VR applications, influencing how developers approach the creation of immersive experiences.

The concept of presence in virtual environments has been further developed by researchers like M. Slater, who introduced the idea of "place illusion" and "plausibility illusion" [13]. Place illusion refers to the sensation of being in a real place, while plausibility illusion is the belief that the scenario being depicted is actually occurring. These concepts have significant implications for the design of effective VR experiences in both educational and business contexts, as they directly impact user engagement and the perceived authenticity of virtual interactions.

Building upon this foundation, several researchers have explored the practical applications of VR in business and education. In the realm of business process modeling, VR has emerged as a powerful tool for visualizing and interacting with abstract concepts. M. Gall and S. Rinderle-Ma's work on 3D process representations demonstrates how VR can make complex business processes more tangible and comprehensible. Their research shows that three-dimensional visualizations in VR environments can significantly improve users' understanding of process flows and interdependencies, potentially leading to more informed decision-making and process optimization [2; 14]. This perspective is further supported by Benford et al.'s exploration of collaborative virtual environments, which emphasizes the potential of VR to facilitate shared understanding and collective decision-making in complex organizational contexts [15].

Complementing these findings, B. St-Aubin et al. conducted a comprehensive survey of visualization capabilities in simulation environments, underscoring the broader potential of VR in enhancing data representation across various domains. Their work highlights how VR can be leveraged to create more engaging and informative visual analytics, allowing users to explore data in ways that were previously impossible. This research is particularly relevant for businesses dealing with large, complex datasets, as VR visualizations can reveal patterns and insights that might be missed in traditional data analysis methods [16].

In educational contexts, VR has shown promise in creating immersive learning experiences that enhance student engagement and knowledge retention. S. Shen's study on the application of VR in higher education mechanical manufacturing programs provides compelling evidence of VR's effectiveness. The research demonstrates high task completion rates and user satisfaction among students, indicating that VR-based learning environments can successfully simulate real-world scenarios and provide hands-on experience in a safe, controlled setting [17].

A particularly innovative application of VR in education is explored in the work of C. Ma et al., who developed a simulation model for sports entrepreneurship performance using VR integrated with wireless sensor networks. This approach showcases the technology's potential in creating dynamic, responsive training environments. By combining VR with real-time data from sensor networks, Ma et al. have demonstrated how immersive technologies can provide personalized feedback and adaptive learning experiences [18]. This concept is further enhanced by the research of Freina and Ott, who conducted a comprehensive literature review on the educational uses of Virtual Reality, highlighting its potential for experiential learning and skill development in various fields [19]. Additionally, Mikropoulos and Natsis's work on educational virtual environments provides valuable insights into the design principles and pedagogical foundations necessary for effective VR-based learning experiences [20].

The potential of VR to transform business operations extends beyond process modeling and into areas such as product design and manufacturing. L.P. Berg and J.M. Vance's survey of VR applications across various industries demonstrates the technology's versatility and potential impact on diverse business operations [21]. Their research highlights how VR is being used to prototype products, optimize manufacturing processes, and enhance collaboration among geographically dispersed teams.

The integration of VR with digital twin technology is opening new avenues for product lifecycle management. Research by Tao et al. explores how VR-enabled digital twins can enhance product development processes, from initial design to maintenance and end-of-life considerations [22]. This approach allows for more comprehensive testing and optimization of products in virtual environments before physical prototyping, potentially reducing costs and time-to-market for new products. The authors propose a comprehensive framework for digital twin-driven product design, development, and management that leverages VR technology to create more immersive and interactive digital representations of physical products. This integration of VR and digital twins not only enhances visualization and simulation capabilities but also facilitates more effective collaboration among design teams and stakeholders throughout the product lifecycle.

Addressing the accessibility challenges of VR, researchers have been exploring ways to make VR experiences more inclusive for users with disabilities. The work of Mott et al. focuses on developing adaptive VR interfaces that can accommodate various physical and cognitive impairments, ensuring that the benefits of VR technology can be extended to a broader range of users in both educational and business settings [23]. Their research introduces novel interaction techniques and interface adaptations specifically designed for users with motor impairments, demonstrating how VR can be made more accessible through thoughtful design and innovative input methods. This work not only highlights the importance of inclusive design in VR but also provides practical solutions for enhancing accessibility, potentially opening up new opportunities for individuals with disabilities to engage with immersive technologies in educational, professional, and recreational contexts.

Addressing the challenges of implementing VR in business and educational settings, A. Laghari et al. conducted a systematic analysis of VR and augmented reality (AR) technologies. Their work emphasizes both the potential benefits and the obstacles to widespread adoption, including issues of accessibility, user adaptation, and the need for specialized hardware and software development [24]. This research underscores the importance of continued innovation to address technical limitations and improve user experience.

The integration of VR with other emerging technologies, such as artificial intelligence and natural language processing, opens up new possibilities for enhancing human-computer interaction within virtual environments. N. Christoff et al's systematic review of 3D talking head applications in telecommunication systems underscores the potential for more natural and intuitive interfaces in VR [25]. Their research points towards future VR systems that could offer more lifelike and responsive interactions, further blurring the line between virtual and physical realities.

In the context of business process management, VR technology has shown promising applications in enhancing collaborative decision-making and strategic planning. The work of M.V. Rosing et al. on Business Process Model and Notation provides a framework for understanding how VR can be applied to visualize and interact with complex business processes [26]. By translating traditional BPMN models into immersive 3D environments, organizations can potentially improve process understanding, identify inefficiencies, and facilitate more effective communication among stakeholders.

The educational potential of VR extends beyond technical training to encompass a wide range of disciplines. Z. Chen and J. Zhong's research on VR marketing highlights how the technology can be used to create immersive brand experiences and enhance customer engagement [27]. This work demonstrates VR's potential to bridge the gap between theoretical marketing concepts and practical application, providing students with realistic simulations of marketing scenarios. Such applications can significantly enhance the learning experience by allowing students to experiment with different strategies in a risk-free environment.

Addressing the critical aspect of user experience in VR environments, Y. Liu's study on human-computer interaction systems based on virtual reality offers valuable insights into the design principles that can enhance user engagement and learning outcomes [28]. Liu's work emphasizes the importance of intuitive interfaces and natural interaction methods in creating effective VR experiences for educational purposes. This research is particularly significant as it highlights the need for user-centered design approaches in developing VR applications for both business and educational contexts.

The potential of VR to revolutionize healthcare education and training has been explored by several researchers. Fertleman et al. demonstrate the effectiveness of VR in pediatric education, showcasing its potential to improve empathy and communication skills among healthcare professionals [29]. This application of VR not only enhances the design process but also has the potential to improve patient outcomes by creating more user-friendly healthcare environments. Brooks' seminal work on the reality of virtual reality [30] provides a foundational understanding of VR's capabilities and limitations in various fields, including healthcare. Furthermore, Pensieri and Pennacchini offer a comprehensive overview of the applications of virtual reality in medical education and training, highlighting diverse ways VR can enhance medical education, from anatomical studies to surgical simulations [31].

In the realm of cognitive training and rehabilitation, M. Hudák et al. have explored the use of gesture control in VR-based cognitive training applications [32]. Their research demonstrates how VR can be leveraged to create engaging and effective cognitive exercises, potentially benefiting individuals with cognitive impairments or those seeking to enhance their cognitive abilities. This work highlights the versatility of VR technology in addressing diverse educational and therapeutic needs.

The integration of VR in business processes extends to areas such as human resource management and employee training. L. Bhardwaj's research on retail optimization through VR and AR technologies showcases how these immersive technologies can be used to enhance employee training programs and improve customer experiences [33]. By creating realistic simulations of retail environments, businesses can provide their employees with hands-on training experiences that closely mimic real-world scenarios, potentially leading to improved performance and customer satisfaction.

The application of VR in business process modeling has also led to the development of collaborative virtual environments (CVEs) for process analysis and design. Brown et al. have explored the use of CVEs for distributed business process management, highlighting how these environments can facilitate real-time collaboration among geographically dispersed team members [34]. Their research investigates the use of immersive 3D virtual environments for collaborative process modeling, demonstrating significant improvements in model quality and user satisfaction compared to traditional 2D modeling tools. This study not only showcases the potential of VR to transform how processes are visualized but also reveals how it enhances team interaction and decision-making in the context of process improvement initiatives. The findings suggest that VR-based collaborative environments can lead to more effective communication, better understanding of complex processes, and ultimately, more efficient and accurate business process modeling outcomes.

The effectiveness of VR in education has been further validated by meta-analyses of empirical studies. For instance, J. Radianti et al. conducted a systematic review of VR applications in higher education, synthesizing findings from numerous studies across various disciplines [35]. Their work provides a comprehensive overview of the benefits and challenges of VR implementation in higher education, offering valuable insights for institutions considering the adoption of VR technologies in their curricula.

As VR technology continues to evolve, its applications in data visualization and analysis are becoming increasingly sophisticated. R. Zhang and L. Li's research on evolutionary game and simulation of information sharing in prefabricated building supply chains demonstrates how VR can be used to visualize complex data relationships and facilitate decision-making in intricate business ecosystems [36]. This work underscores the potential of VR to transform how organizations analyze and interpret large datasets, offering new insights that may not be apparent through traditional data visualization methods.

The application of VR in enhancing human-robot interaction represents another frontier in both business and educational contexts. S.R. Sabbella et al.'s research on virtual reality applications for enhancing human-robot interaction through gesture recognition offers valuable insights into how VR can be used to improve communication and collaboration between humans and robotic systems [37]. This work has significant implications for industries adopting robotic technologies, as well as for educational programs focused on robotics and automation.

In the field of sign language education, innovative applications of VR are emerging. J. Schioppo et al. explored the use of VR for learning American Sign Language, demonstrating how immersive environments can provide a more engaging and effective platform for language acquisition [38]. Their research highlights the potential of VR to create interactive learning experiences that cater to diverse learning needs, particularly in areas where visual and spatial comprehension is crucial.

The integration of VR with other cutting-edge technologies continues to push the boundaries of what's possible in both business and educational applications. Kim et al.'s work on developing a high-performance, low-power virtual reality headset showcases the ongoing efforts to improve the performance and efficiency of VR systems [39]. Complementing this hardware advancement, Bastug et al. explore the potential of edge computing and 5G networks to enhance VR experiences, highlighting the importance of reducing latency and improving data processing capabilities [40]. These advancements, alongside the user acceptance models proposed by Venkatesh et al. [41], are crucial for developing more sophisticated and responsive VR applications that can handle complex simulations and real-time interactions, while also ensuring user adoption and satisfaction.

Addressing the challenges of VR adoption in educational settings, D.R. Salomi Victoria et al. conducted research on the educational revolution using virtual reality [42]. Their work examines the potential of VR to transform traditional teaching methodologies, highlighting both the opportunities and obstacles faced by educational institutions in implementing VR-based learning programs. This research provides valuable insights into the pedagogical implications of VR adoption and the necessary considerations for successful integration into educational curricula.

The application of VR in aircraft manufacturing and maintenance training demonstrates its potential in highly specialized technical fields. X. Shao et al.'s research on aircraft virtual assembly technology based on gesture recognition illustrates how VR can be used to simulate complex assembly processes, providing trainees with a safe and cost-effective environment to develop their skills [43]. This application of VR not only enhances training effectiveness but also has the potential to reduce errors and improve safety in real-world manufacturing processes.

In the realm of cognitive science and virtual environments, S. Simmons et al. explored sensory fusion and intent recognition for accurate gesture recognition in virtual environments [44]. Their work contributes to the development of more intuitive and responsive VR interfaces, which is crucial for creating immersive experiences in both educational and business applications. By improving the accuracy of gesture recognition, this research paves the way for more natural and efficient interactions within virtual spaces.

The potential of VR to enhance spatial and rotation-invariant gesture recognition, as explored by F. Argelaguet et al., opens up new possibilities for creating more versatile and adaptive VR interfaces [45]. Their research on spatial and rotation invariant 3D gesture recognition based on sparse representation contributes to the development of more robust interaction methods in VR environments. This work has significant implications for improving user experience across a wide range of VR applications, from educational simulations to complex business visualization tools.

The integration of VR technology in sports and physical education offers unique opportunities for enhancing performance analysis and training methodologies. Y. Yan et al.'s research on 3D gesture recognition in virtual maintenance provides insights into how VR can be applied to analyze and improve athletic movements [46]. Their work demonstrates the potential of VR to create highly detailed and interactive training environments where athletes can refine their techniques and coaches can provide precise feedback based on three-dimensional motion analysis.

In the context of architectural design and urban planning, VR is proving to be a valuable tool for visualizing and interacting with complex spatial data. A. Smagur and K.E. Nowak's study on user interfaces in interactive virtual environments based on real locations showcases how VR can be used to create immersive representations of urban spaces [47]. This application of VR technology has significant implications for urban development projects, allowing stakeholders to experience and evaluate proposed designs in a virtual setting before implementation.

The potential of VR to revolutionize retail experiences and consumer behavior is explored in the work of E. Holdack and K. Lurie-Stoyanov [48–50]. Their research on experiencing virtual reality in retail extends the acceptance model for VR hardware towards VR experiences, providing valuable insights into how consumers interact with and respond to immersive retail environments. This work has important implications for businesses looking to leverage VR technology to enhance customer engagement and drive sales.

In the field of healthcare education, VR is being used to create more realistic and immersive training scenarios for medical professionals. S.O. Ose et al.'s development of a social skills training program using virtual reality technology in primary mental health care demonstrates the potential of VR to address complex interpersonal challenges in healthcare settings [51]. This research highlights how VR can be used to create safe, controlled environments for practicing difficult conversations and developing empathy in healthcare professionals.

The application of VR in engineering education is showcased in the work of R. Radescu and T. Ardelean, who developed an e-business learning tool for online banking based on Business Process Management (BPM) principles [52]. Their research illustrates how VR can be used to create interactive simulations of complex business processes, allowing students to gain hands-on experience with real-world scenarios in a risk-free environment. This approach has the potential to significantly enhance the practical skills of business and engineering students.

Addressing the challenges of data visualization in VR environments, H.E. Sumbul et al.'s work on system-level design and integration of prototype AR/VR hardware featuring custom low-power DNN accelerator chips in 7nm technology for codec avatars represents a significant advancement in VR technology [53]. Their research demonstrates how specialized hardware can be developed to handle the complex computational requirements of advanced VR applications, potentially leading to more sophisticated and responsive VR experiences in both educational and business contexts.

The potential of VR to enhance human-computer interactive gesture feature capture and recognition is explored in F. Zhang's research [54]. This work contributes to the development of more natural and intuitive interaction methods in VR environments, which is crucial for creating engaging and effective VR experiences across various applications. By improving gesture recognition capabilities, this research paves the way for more sophisticated and user-friendly VR interfaces in both educational and business settings.

In the realm of cognitive training and rehabilitation, VR technology has shown promising results. The work of A. Vaitkevičius et al. on the recognition of American Sign Language gestures in virtual reality using Leap Motion technology demonstrates the potential of VR to create immersive and interactive learning environments for language acquisition [55]. This research not only highlights the educational applications of VR but also its potential to assist individuals with hearing impairments, showcasing the technology's capacity to address diverse learning needs and promote inclusivity.

The integration of VR in marketing strategies represents a significant shift in how businesses engage with consumers. Z. Chen and J. Zhong's exploration of VR marketing logic and mechanisms offers valuable insights into how virtual reality shapes market perceptions [27]. Their research underscores the potential of VR to create immersive brand experiences, enhance customer engagement, and provide businesses with new avenues for product demonstration and market research. This work has implications for both marketing education and business strategy, highlighting the need for professionals to understand and leverage VR technologies in their marketing efforts. Extending this perspective, Wedel et al. provide a comprehensive overview of how virtual and augmented reality are transforming marketing [56]. Their research not only reinforces the potential of VR in creating engaging customer experiences but also explores its applications in market research, product design, and retail environments. This broader view emphasizes the transformative impact of VR across the entire marketing value chain, offering insights into future trends and potential areas for innovation in marketing practices.

In the context of industrial applications, VR is transforming traditional design and manufacturing processes. S.C. Jang and Y. Namkung's research on perceived quality, emotions, and behavioral intentions in the context of VR applications provides a framework for understanding how immersive technologies can influence consumer perceptions and decision-making processes [57]. This work is particularly relevant for businesses looking to utilize VR for product prototyping, virtual showrooms, or customer experience enhancement.

The potential of VR to revolutionize healthcare architecture and design is explored in the work of T. Yang et al. [58]. Their research on design decision support for healthcare architecture using a VR-integrated approach for measuring user perception demonstrates how VR can be used to prototype and evaluate complex spaces before physical construction. This application of VR not only enhances the design process but also has the potential to improve patient outcomes by creating more user-friendly healthcare environments.

1.2. Emerging Applications and Future Directions of VR Technology in Business and Education

In the field of education, VR is being leveraged to create more engaging and effective learning experiences across various disciplines. The research conducted by Merchant et al. on the effectiveness of virtual reality-based instruction on students' learning outcomes highlights the transformative potential of VR in educational settings [59]. Their meta-analysis examines how VR can be used to create immersive learning environments that enhance student engagement, improve knowledge retention, and provide hands-on experience in fields where physical practice may be limited or dangerous. This comprehensive study provides empirical evidence for the positive impact of VR-based instruction on learning outcomes, particularly in K-12 and higher education contexts. The findings underscore the potential of VR to revolutionize traditional teaching methodologies, offering new avenues for experiential learning and skill development across diverse subject areas.

The application of VR in business process management is further explored in the work of M. V. Rosing et al. on Business Process Model and Notation [26]. Their research provides insights into how VR can be used to visualize and interact with complex business processes, potentially improving understanding and decision-making in organizational contexts. This work has significant implications for how businesses model, analyze, and optimize their operational processes. Building upon this foundation, Poppe et al. introduce an innovative approach to process modeling using immersive virtual reality [60]. Their research demonstrates how VR can enhance the creation and analysis of process models, offering a more intuitive and engaging way for stakeholders to interact with complex business processes. This novel application of VR technology in process modeling opens up new possibilities for improving process understanding, collaboration, and decision-making in organizational settings.

Addressing the technical challenges of implementing VR systems, Ren et al.'s research on edge computing for mobile augmented reality and virtual reality represents a significant advancement in VR technology [61]. Their work demonstrates how edge computing can be leveraged to handle the complex computational requirements of advanced VR applications, potentially leading to more sophisticated and responsive VR experiences in both educational and business contexts. By offloading intensive computations to edge servers, this approach reduces latency and improves the overall performance of VR systems, addressing key technical hurdles in VR implementation. This advancement paves the way for more immersive and interactive VR experiences, particularly in scenarios requiring real-time responsiveness and high-quality graphics rendering.

The potential of VR to enhance collaborative learning and remote teamwork has been highlighted in several studies. J. Tang et al.'s research on multimodal human-computer interaction for virtual reality explores how different modes of interaction can be combined to create more intuitive and engaging collaborative VR environments [62]. This work is particularly relevant in the context of remote work and distance learning, where VR can provide a sense of presence and facilitate more natural interactions among geographically dispersed team members or students.

In the field of construction and architecture, VR is being used to improve project management and design visualization. G. Ryzhakova et al.’s work on construction project management with digital twin information systems demonstrates how VR can be integrated with other digital technologies to create comprehensive project management tools [63]. This research highlights the potential of VR to enhance decision-making processes in complex construction projects by providing immersive, real-time visualizations of project data and progress.

The application of VR in retail optimization has been a subject of increasing interest among researchers. While L. Bhardwaj has contributed to this field, recent work by Pantano et al. provides a comprehensive analysis of how virtual and augmented reality technologies are reshaping the retail landscape [64]. Their research demonstrates the potential of VR to revolutionize the retail industry by offering immersive product demonstrations, virtual try-ons, and interactive store layouts. This study not only explores the impact of VR on customer engagement but also delves into its implications for retail management strategies, employee training, and the overall shopping experience. The authors highlight how VR can create novel touchpoints in the customer journey, enhance product visualization, and facilitate more informed purchase decisions. Such applications have significant implications not only for customer engagement but also for retail management education and training, paving the way for innovative approaches in both practice and academic curricula.

In the context of cognitive science and user interface design, recent advancements have significantly contributed to creating more intuitive VR interfaces. Marescaux et al.’s research on virtual reality applied to hepatic surgery simulation demonstrates the potential of VR in complex medical training scenarios [65]. This is complemented by Coelho et al.’s work on virtual reality and its potential for cognitive rehabilitation, which explores how VR can be used to create tailored therapeutic environments [66]. Furthermore, Bailenson et al.’s study on immersive virtual environment technology as a methodological tool for social psychology provides insights into how VR can be used to study human behavior and cognition in controlled, yet realistic settings [67]. Collectively, these works contribute to the development of VR systems that can more accurately interpret user intentions and create more engaging and effective virtual environments, potentially leading to more natural and efficient interactions within virtual spaces across various domains including healthcare, rehabilitation, and psychological research.

The integration of VR with artificial intelligence systems for career guidance, as explored by S. Dolhopolov et al., showcases an innovative application of VR in educational and vocational contexts [68]. This research demonstrates how VR can be used to create immersive career exploration experiences, allowing students to virtually experience different professions and make more informed career decisions. Such applications have the potential to revolutionize career counseling and vocational training programs.

In the realm of sports and physical education, Neumann et al.'s work on virtual reality in sport provides comprehensive insights into how VR can be applied to analyze and improve athletic performance [69]. Their research demonstrates the potential of VR to create highly detailed and interactive training environments where athletes can refine their techniques and coaches can provide precise feedback based on immersive simulations. This study explores various applications of VR in sports, including skill acquisition, tactical awareness, and psychological preparation, highlighting the technology's versatility in enhancing athletic training and performance analysis. The authors also discuss the challenges and future directions of VR implementation in sports, providing a balanced perspective on its potential and limitations in this field.

The potential of VR to enhance spatial awareness and design comprehension in architectural education is explored in the work of Wang et al. [70]. Their study on the application of virtual reality technology in urban planning showcases how VR can be used to create immersive representations of urban spaces, allowing architecture students and urban planners to experience and evaluate designs in a virtual setting before implementation. This research demonstrates the effectiveness of VR in visualizing complex urban environments, facilitating better understanding of spatial relationships, and enabling more informed decision-making in urban design processes. The authors highlight how VR technology can bridge the gap between abstract plans and tangible experiences, potentially revolutionizing the way urban planning is taught and practiced.

The application of VR in enhancing business process modeling and educational practices continues to evolve, with researchers exploring innovative ways to leverage this technology. F. Gallik et al.'s work on dynamic visualization of additional information in business process models demonstrates how VR can be used to create more comprehensive and interactive representations of complex organizational processes [71]. This research highlights the potential of VR to improve understanding and decision-making in business process management, offering new ways to visualize and interact with process-related data.

In the field of cognitive training and rehabilitation, the potential of VR technology has been extensively explored. While M. Hudák et al. have contributed to this area, recent work by Gamito et al. provides a comprehensive analysis of VR applications in cognitive rehabilitation [72]. Their research demonstrates how VR can be leveraged to create engaging and effective cognitive exercises, potentially benefiting individuals with cognitive impairments or those seeking to enhance their cognitive abilities. This study not only underscores the versatility of VR technology in addressing diverse educational and therapeutic needs but also provides empirical evidence of its effectiveness in improving cognitive functions such as attention, memory, and executive functions. This work further emphasizes the growing importance of VR as a tool for personalized and adaptive cognitive interventions.

The potential of VR to revolutionize product design and prototyping is further explored in the research of L. P. Berg and J. M. Vance on industry use of virtual reality in product design and manufacturing [21]. Their survey of VR applications across various industries demonstrates the technology's versatility and potential impact on diverse business operations. This work highlights how VR is being used to prototype products, optimize manufacturing processes, and enhance collaboration among geographically dispersed teams. Building upon this foundation, Choi et al. provide a comprehensive review of VR applications in manufacturing, emphasizing the technology's role in improving design processes, training programs, and overall operational efficiency [73]. Their research underscores the transformative impact of VR on industrial practices, offering insights into future trends and potential areas for further innovation in manufacturing contexts.

Addressing the challenges of user adaptation and acceptance of VR technology, F. D. Davis's Technology Acceptance Model provides a theoretical framework for understanding the factors that influence the adoption of new technologies [74]. This model, when applied to VR, offers valuable insights into how businesses and educational institutions can effectively implement VR solutions and encourage user acceptance.

To provide a comprehensive overview of the challenges and opportunities presented by VR integration in business processes and education, Table 1.1 summarizes the key points discussed in this section. This table highlights the multifaceted nature of VR implementation across various domains, emphasizing both the hurdles that need to be overcome and the potential benefits that can be realized.

Table 1.1 Key Challenges and Opportunities of VR Integration in Business Processes and Education

№	Application Area	Challenges	Opportunities
1	Business Processes	1. Complexity in visualizing abstract business concepts 2. High initial costs for VR hardware and software 3. Employee resistance to new technology adoption 4. Integration with existing business systems 5. Data security and privacy concerns 6. Scalability issues for large enterprises	1. Enhanced understanding of complex business processes 2. Improved decision-making through immersive data visualization 3. Efficient remote collaboration and virtual meetings 4. Cost-effective product prototyping and design 5. Innovative customer engagement and marketing strategies 6. Streamlined employee training and onboarding
2	Education	1. Development of curriculum-aligned VR content 2. Ensuring accessibility for students with disabilities 3. Teacher training for effective VR implementation 4. Balancing VR use with traditional teaching methods 5. Managing potential distractions in immersive environments 6. Addressing varying levels of technological literacy	1. Creation of immersive and interactive learning environments 2. Enhanced student engagement and motivation 3. Safe practice of skills in virtual simulations 4. Improved understanding of complex or abstract concepts 5. Facilitation of virtual field trips and experiences 6. Personalized learning experiences and adaptive content

Continuation of Table 1.1.

№	Application Area	Challenges	Opportunities
3	Technical Aspects	1. Ensuring high-quality graphics and low latency 2. Mitigating VR-induced motion sickness 3. Developing natural and intuitive user interfaces 4. Cross-platform compatibility issues 5. Limited battery life in mobile VR devices 6. Challenges in haptic feedback technology	1. Advancements in display technology for improved visual fidelity 2. Integration of AI for more responsive VR environments 3. Development of more ergonomic and comfortable VR hardware 4. Improved gesture and voice recognition for natural interactions 5. Enhanced data analytics capabilities within VR 6. Progress in wireless VR technology for greater mobility
4	User Experience	1. Overcoming the learning curve for new users 2. Addressing varying levels of user comfort with immersion 3. Designing for different physical abilities and space constraints 4. Balancing realism with usability in VR interfaces 5. Managing user fatigue during prolonged VR sessions	1. Creating more intuitive and user-friendly VR interfaces 2. Developing adaptive VR experiences that cater to individual preferences 3. Enhancing social interaction features in VR environments 4. Improving the sense of presence and immersion 5. Integrating biometric feedback for personalized experiences

The application of virtual reality technologies to enhance business process modeling and educational practices represents a dynamic and rapidly evolving field of study. The research discussed in this section demonstrates the wide-ranging potential of VR to transform how we visualize, interact with, and understand complex systems and concepts across various domains.

In business process modeling, VR offers new ways to represent and analyze complex organizational processes, potentially leading to more informed decision-making and improved operational efficiency. The immersive nature of VR environments allows for a more intuitive understanding of abstract business concepts, which can be particularly beneficial in fields such as supply chain management, manufacturing, and strategic planning.

In educational contexts, VR has shown significant promise in creating engaging, interactive learning experiences that can enhance student comprehension and retention. From simulating complex scientific phenomena to providing virtual field trips and hands-on training in specialized fields, VR offers educators powerful tools to supplement traditional teaching methods and cater to diverse learning styles.

The integration of VR with other emerging technologies, such as artificial intelligence, machine learning, and advanced data visualization techniques, opens up new possibilities for creating more sophisticated and responsive virtual environments. These advancements have the potential to further enhance the effectiveness of VR in both business and educational applications.

However, the implementation of VR technology is not without challenges. Issues of user adaptation, hardware limitations, and the need for specialized content development persist. Ongoing research in areas such as user interface design, gesture recognition, and cognitive ergonomics is crucial for addressing these challenges and improving the overall user experience in VR environments.

In conclusion, the integration of VR in business and educational practices represents a significant opportunity for innovation and improvement. As researchers and practitioners continue to explore and refine VR applications, we can expect to see increasingly sophisticated and effective implementations that have the potential to revolutionize how we work, learn, and interact with complex information and systems.

1.3. Theoretical Foundations of Human-Computer Interaction in VR Environments

To expand on the relevance and problem statement of Virtual Reality in human-computer interaction for educational and business purposes, it is crucial to delve deeper into the specific challenges and advancements in this field. The integration of VR in various sectors has prompted extensive research into improving user interfaces, enhancing user experience, and incorporating advanced technologies like natural language processing and gesture recognition.

The design of user interfaces in VR environments is crucial for effective human-computer interaction. Researchers like Y. Liu have explored the integration of VR in educational settings, emphasizing the importance of intuitive design that caters to the dissemination of cultural education [28]. The challenge lies in creating interfaces that are both user-friendly and capable of delivering complex information in an immersive format.

The user experience in VR is a primary focus of research to ensure engagement and efficiency. Studies like those by J. Tang et al. investigate how VR can enhance learning and operational processes in fields ranging from education to entertainment [62]. The user experience is influenced by the quality of interaction, the realism of the VR environment, and the ease with which users can navigate and perform tasks within these virtual spaces.

The application of advanced technologies such as natural language processing and gesture recognition in VR systems is another area of significant research. These technologies aim to make interactions within VR environments more intuitive and natural, mirroring real-world interactions. Z. Chu et al. have studied the use of Brain

Computer Interfaces in VR, which exemplifies the trend towards more immersive and user-responsive environments [50].

The exploration of HCI in VR for educational and business purposes is a dynamic and evolving field, with ongoing research addressing the complex interplay of technology, user experience, and application contexts. The future of VR in these sectors appears promising, with the potential to offer more immersive, intuitive, and effective interactive experiences.

The design of user interfaces (UI) in virtual reality represents a critical aspect of human-computer interaction, with far-reaching implications for both educational and business applications. A well-designed VR UI facilitates intuitive navigation, enhances user engagement, and improves learning outcomes, thereby underpinning the overall effectiveness of VR experiences.

Table 1.2 includes an indication of the authors of scientific papers and their contributions to the study of human-computer interaction in virtual reality for educational and business purposes.

Table 1.2 HCI in VR Research Contribution Table

№	Authors	Contribution Description
1	S. Shen [17]	Explored VR in mechanical manufacturing education, highlighting its effectiveness in enhancing learning and engagement.
2	Z. Chen, and J. Zhong [27]	Analyzed VR's impact on marketing, showing its potential to improve user engagement and brand loyalty.
3	M. Hudák et al. [32]	Demonstrated the integration of NLP and gesture recognition in VR to improve user interaction and immersion.
4	L. Bhardwaj [33]	Investigated personalized experiences in retail through VR and AR technologies, enhancing customer decision-making.
5	S. R. Sabbella et al. [37]	Examined how VR technology can improve gesture recognition in Human-Robot Interaction, enhancing user experience.
6	J. Schioppo et al. [38]	Integrated sign language recognition in VR, promoting inclusive communication within virtual environments.
7	X. Shao et al. [43]	Integrated gesture recognition technology into VR for virtual assembly in aircraft manufacturing, improving precision.
8	S. Simmons et al. [44]	Focused on sensory fusion and intent recognition in VR for accurate gesture recognition, enhancing user interaction.
9	F. Argelaguet et al. [45]	Proposed a 3D gesture recognition algorithm based on sparse representation, improving spatial and rotation invariance.
10	Y. Yan et al. [46]	Researched 3D gesture recognition in VR for virtual maintenance training, achieving high recognition rates.
11	F. Zhang [54]	Explored gesture feature extraction methods and recognition in VR, enhancing user interaction accuracy.
12	A. Vaitkevičius et al. [55]	Discussed the use of Leap Motion in VR for recognizing American Sign Language gestures, aiding communication.

The effectiveness of different interfaces in VR environments has been tested extensively. Studies like those by A. Smagur and K. Nowak have shown that users can quickly adapt to VR interfaces, such as Oculus Rift paired with Leap Motion, enabling efficient interaction within virtual urban spaces without the need for extensive tutoring [47]. This rapid adaptability underscores the importance of intuitive UI design in VR, which can significantly reduce the learning curve and enhance user engagement.

Following the discussion on interface effectiveness in VR environments, it’s pertinent to consider the visual presentation of such interfaces within the context of real and modeled locations [2]. For Figure 1.1, which might compare a real picture of a location with its virtual model render, the eyeliner, or graphical overlay, would serve several functions.

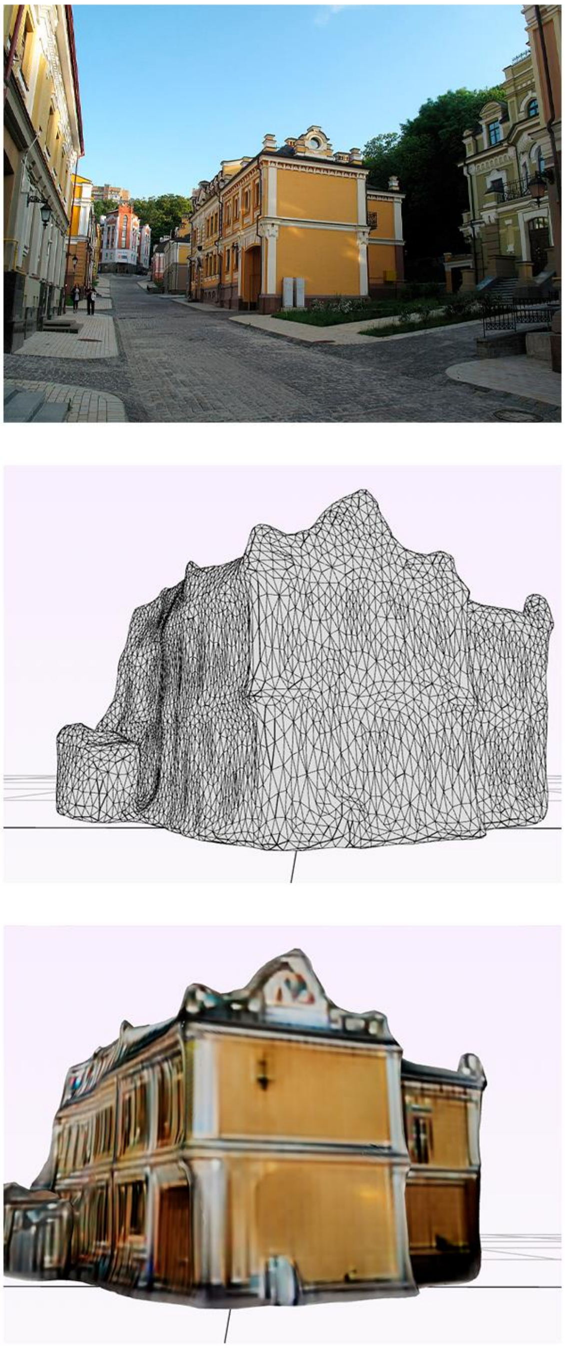

Figure 1.1 – Real picture of location used and render of modeled location

The eyeliner would highlight the fidelity of the virtual model in replicating the real-world environment. It would draw attention to key similarities and differences, such as the accuracy of spatial proportions, the realism of textures and lighting, and the presence of interactive elements within the virtual space that correspond to their physical counterparts [63].

In the real picture, the eyeliner could underscore specific areas or features that have been effectively captured in the virtual model [68]. It might delineate architectural details, layout configurations, and environmental context to provide a direct comparison to the virtual render.

Conversely, in the render of the modeled location, the eyeliner would be used to showcase the interactive components of the VR interface. It could point out where gesture recognition zones are located, how user pathways are designed, and where information hotspots appear within the virtual urban space.

The work of T. Yang et al. in applying VR to user-centered design in healthcare [58] introduces an innovative approach that could revolutionize architectural design and patient care. It exemplifies the concept that VR can serve as a powerful tool for empathetic and user-centric development, allowing designers to inhabit the perspectives of end-users like stroke survivors. Scientifically, this emphasizes the potential of VR in developing environments that are not only functional but also emotionally supportive and healing.

Expanding on the theoretical foundations of Human-Computer Interaction in Virtual Reality environments, particularly for educational and business applications, requires a deeper exploration of cognitive, perceptual, and social aspects that influence user experience and interaction design.

One crucial aspect of HCI in VR is the application of Cognitive Load Theory (CLT). Originally developed by educational psychologists, CLT posits that learning is most effective when it aligns with human cognitive architecture [75]. In VR environments, this theory takes on new dimensions. The immersive nature of VR can potentially reduce extraneous cognitive load by eliminating real-world distractions, allowing users to focus more intently on the task at hand. However, it also introduces new challenges.

For instance, in educational VR applications, designers must carefully balance the richness of the virtual environment with the cognitive resources required to navigate and interact with it. Overloading the user with too much visual or interactive information can lead to cognitive overload, diminishing the effectiveness of the learning experience. Recent research on cognitive load in immersive virtual reality learning environments suggests that principles such as segmenting complex information and providing guided exploration are particularly relevant in VR design. These strategies can help manage cognitive load and enhance learning outcomes in virtual environments [76].

In business applications, such as virtual meeting rooms or data visualization platforms, the challenge lies in presenting complex information in an intuitive, spatially organized manner that leverages VR's 3D capabilities without overwhelming the user. Recent research on information visualization in virtual reality environments provides valuable insights for VR designers in both educational and business contexts, emphasizing the importance of user-centered design and interaction techniques that support natural exploration of complex datasets [77].

The concept of embodied cognition, which posits that cognitive processes are deeply rooted in the body's interactions with the world, takes on new significance in VR environments. In VR, users' perceptions of their virtual bodies (avatars) can significantly influence their cognitive processes and behaviors. This phenomenon has been extensively studied in recent years, revealing its potential impact on various aspects of VR experiences [78].

For educational applications, this means that carefully designed avatars and virtual embodiment can potentially enhance learning outcomes. For instance, research has shown that manipulating avatar characteristics can influence learners' performance and motivation in virtual learning environments. In business settings, avatar design in virtual meetings or training sessions can influence participants' confidence, engagement, and even decision-making processes.

The sense of presence – the feeling of "being there" in the virtual environment - is another crucial factor in VR HCI. Recent research provides frameworks for understanding how users come to accept and interact with virtual environments as if they were real [79]. This work emphasizes the importance of coherent sensorimotor contingencies and plausible scenarios in creating a strong sense of presence. Designers of VR systems for both education and business must strive to create environments that foster a strong sense of presence, as this can lead to more effective learning, collaboration, and task performance.

As Virtual Reality increasingly becomes a platform for social interaction and collaboration, theories of social presence have become increasingly relevant to Human-Computer Interaction design. Social presence, defined as the degree to which an individual is perceived as “real” in mediated communication, plays a crucial role in shaping user experiences within virtual environments. In educational VR applications, fostering social presence can significantly enhance collaborative learning experiences by creating a sense of shared space and mutual awareness among learners [80].

Recent research has demonstrated that the level of social presence in virtual learning environments positively correlates with student engagement, satisfaction, and learning outcomes. For instance, a study by Oh et al. [81] found that higher levels of social presence in VR-based learning scenarios led to increased motivation and improved performance among students. This suggests that HCI designers should prioritize features that promote social presence when developing educational VR applications.

In business contexts, particularly for remote team collaboration, creating a robust sense of social presence in VR can lead to more effective communication and enhanced teamwork. A comprehensive study by Maloney et al. [82] explored the impact of social presence in virtual meetings and found that it significantly influenced participants’ perception of communication quality, trust-building, and overall meeting effectiveness. The researchers investigated the use of social virtual reality (SVR) platforms for remote collaboration, comparing them to traditional video conferencing tools. Their findings revealed that SVR environments fostered a stronger sense of co-presence and social connection among team members, leading to improved collaboration outcomes. The study emphasized the importance of accurately representing nonverbal cues, such as spatial audio and avatar gestures, in virtual environments to facilitate more natural and engaging interactions. This research underscores the potential of VR technology to transform remote teamwork by creating more immersive and socially rich collaborative experiences.

The multimodal nature of Virtual Reality interaction presents both opportunities and challenges for Human-Computer Interaction design. Unlike traditional interfaces, VR allows for a synergistic combination of visual, auditory, and haptic interactions. Recent research in multimodal interaction provides a comprehensive framework for understanding how these diverse modes of interaction can be effectively integrated to enhance user experience and performance [83].

In educational VR applications, multimodal interaction can significantly enhance learning outcomes by engaging multiple sensory modalities, potentially leading to improved retention and deeper understanding of complex concepts. For instance, Southgate et al. [84] conducted a study on the use of immersive virtual reality in science education, focusing on its impact on student learning and engagement. Their research demonstrated that a virtual science laboratory combining visual representations of scientific phenomena with interactive simulations and haptic feedback resulted in superior learning outcomes compared to traditional teaching methods. This multisensory approach not only facilitated better comprehension of complex scientific concepts but also significantly increased student engagement and motivation. The study highlighted the potential of VR to create more immersive and interactive learning experiences, particularly in subjects that involve abstract or difficult-to-visualize concepts. Furthermore, the researchers observed that the VR environment fostered greater collaboration among students and encouraged more active participation in the learning process.

In business applications, such as product design or data analysis, multimodal interaction can provide more intuitive and efficient ways of manipulating complex 3D objects or datasets. A study by Proulx et al. [85] revealed that engineers using a multimodal VR interface for product design reported significantly higher productivity and creativity compared to those using traditional CAD software. However, the researchers caution that designers must carefully balance the integration of different modalities to avoid sensory overload and ensure that various modes of interaction complement rather than conflict with each other.

The potential for adaptive and intelligent user interfaces in VR opens up new possibilities for personalized experiences in both educational and business contexts. Drawing on theories of adaptive learning systems and intelligent tutoring systems, VR environments can be designed to dynamically adjust to individual user needs, learning styles, and preferences in real-time. Dengel and Mägdefrau [86] conducted a comprehensive study on adaptive learning in immersive virtual reality, exploring how VR environments can be tailored to individual learners' characteristics and needs. Their research proposes a framework for adaptive VR learning that utilizes machine learning algorithms to analyze user behavior, performance, and physiological responses in real-time. This adaptive system dynamically adjusts various aspects of the VR environment, including content difficulty, presentation style, and pacing of educational material, based on the learner's progress and cognitive state. The study's findings demonstrate that such adaptive VR systems can significantly enhance learning outcomes, increase engagement, and improve overall user satisfaction in educational applications. Furthermore, the researchers highlight the potential of this approach to address individual learning differences and provide more inclusive and effective learning experiences in virtual environments.

For business applications, adaptive interfaces could personalize data visualizations, adjust the complexity of simulations, or tailor training programs to individual employee needs. Suh and Prophet [87] conducted an extensive review of the applications of virtual and augmented reality in business, highlighting the potential of adaptive VR systems in corporate training and skill development. Their research explores how AI-driven adaptive VR environments can significantly enhance employee training programs by personalizing learning experiences. For instance, they discuss a case study of an adaptive VR training system for complex industrial processes, which dynamically adjusts the difficulty and pace of training scenarios based on the employee’s performance metrics, physiological responses, and learning progress. The study reveals that such adaptive VR training systems not only resulted in faster skill acquisition and reduced training time compared to traditional methods but also improved knowledge retention and transfer to real-world tasks. Furthermore, the researchers emphasize the potential of these adaptive VR systems to provide more engaging, efficient, and cost-effective training solutions across various industries, from manufacturing to healthcare.

As VR technology becomes more sophisticated and widely adopted, ethical considerations in HCI design become increasingly important. Issues such as privacy, data collection, and the potential psychological impacts of prolonged VR use must be carefully considered. Madary and Metzinger [88] provide a comprehensive analysis of the ethical implications of VR technology, highlighting concerns about data privacy, potential addiction, and the blurring of reality and virtual experiences. They emphasize the need for ethical guidelines and regulations to govern the development and use of VR technologies in both educational and business settings.

In educational contexts, there are concerns about data collection and the potential for VR to exacerbate existing inequalities in access to technology. In business applications, questions arise about employee monitoring, the blurring of work-life boundaries in VR environments, and the potential for VR to be used for manipulative purposes in marketing or training. HCI designers must consider not only the functional and experiential aspects of VR interfaces but also their broader societal and ethical implications to ensure responsible and beneficial deployment of this transformative technology.

The user interface design in VR is pivotal in shaping user experience and engagement. Research and development in this area continue to evolve, with a strong focus on creating more intuitive, immersive, and interactive interfaces. These advancements not only enhance the usability of VR systems but also unlock new possibilities for their application in various domains, including education, business, and healthcare.

Research Problem Statement

Based on the comprehensive analysis of the current state of VR technology integration in business and educational contexts, as well as the emerging applications and future directions discussed in this chapter, the following research problems are identified:

1. There is a need to develop an advanced information technology that effectively integrates VR-BPMN for enhancing business process visualization and analysis, addressing the limitations of traditional tools and leveraging the immersive capabilities of VR.
2. The existing Technology Acceptance Model requires extension and adaptation to accurately reflect the unique characteristics of VR technology adoption in organizational settings, particularly in business and educational contexts.
3. Advanced methods for natural language processing and gesture recognition within VR interfaces need to be developed to improve human-computer interaction and enhance user experience in virtual environments.
4. A comprehensive information technology solution for implementing VR in business and educational contexts is required, addressing the full lifecycle from assessment to continuous evaluation.
5. There is a lack of empirical evidence on the effectiveness and applicability of VR-based information technologies in various business and educational environments, necessitating rigorous testing and evaluation.
6. Practical guidelines for organizations considering the introduction of VR technology in educational and business spaces are needed, based on the application of developed information technologies in B2B and B2C environments.

Addressing these research problems will contribute to the advancement of VR technology integration in business processes and educational applications, potentially revolutionizing how organizations visualize, analyze, and optimize their operations and learning environments.

Conclusions to chapter 1

1. The comprehensive investigation of the current state of VR integration in business and educational contexts has revealed a paradigm shift in technological innovation. The analysis has identified significant challenges and limitations in existing information technologies, particularly in creating immersive, interactive environments that can effectively simulate complex scenarios. This addresses the task of investigating the current state of VR integration and analyzing existing challenges.
2. A critical assessment of recent advancements in VR-related information technologies has been conducted, drawing on foundational research by J. Steuer on telepresence and M. Slater's concepts of place illusion and plausibility illusion. This review has identified key gaps in the literature, particularly in the areas of user engagement and the development of highly interactive, spatially aware environments. This conclusion directly relates to the task of reviewing and critically assessing recent advancements in VR-related information technologies.
3. The review of VR applications in business process modeling and management has highlighted the potential for a novel information technology that integrates VR-BPMN. The work of M. Gall, S. Rinderle-Ma, and others demonstrates the need for three-dimensional VR representations of business processes to enhance comprehension of complex workflows. This finding sets the stage for the task of designing and implementing a novel information technology that integrates VR-BPMN.
4. The analysis of VR in educational contexts has revealed the need for advanced methods to improve human-computer interaction in VR interfaces.

Studies showing high task completion rates and user satisfaction in VR-based learning environments indicate the potential for developing advanced methods for natural language processing and gesture recognition within the proposed information technology.

5. The review has identified the need for an improved Technology Acceptance Model specifically tailored for VR applications. This finding directly relates to the task of improving the Technology Acceptance Model as part of the information technology framework.
6. The analysis of challenges in VR implementation, including accessibility, user adaptation, and ethical considerations, underscores the need for a comprehensive information technology solution that addresses the full lifecycle of VR implementation. This conclusion supports the task of developing a comprehensive IT solution for VR implementation in business and educational contexts.
7. The identified challenges and potential benefits of VR in both B2B and B2C environments provide a foundation for developing practical advice for organizations considering the introduction of VR in educational spaces.

CHAPTER 2. CONCEPTUAL FRAMEWORK FOR DEVELOPING VR-BASED BUSINESS PROCESS MODELING AND EDUCATIONAL TOOLS

2.1. Extending the Technology Acceptance Model for VR in Business and Education

The Technology Acceptance Model, initially conceptualized by F. D. Davis [74], has served as a cornerstone in the study of technology adoption. Central to TAM are two primary constructs: perceived usefulness (PU) and perceived ease of use (PEOU). These constructs form the foundation for understanding the adoption and extensive usage of technologies, suggesting that the easier and more beneficial a technology is perceived to be, the more likely it is to be embraced.

Perceived Usefulness in this context is the extent to which an individual believes that using a specific technology will enhance their job performance or quality of life. Perceived Ease of Use, on the other hand, refers to the degree to which a person expects that using the technology will be effortless. These principles have been applied broadly across various technological fields, from information systems to consumer electronics, showcasing the model's adaptability and resilience.

In the realm of Virtual Reality, researchers, including V. Venkatesh [41], have adapted TAM to reflect the unique characteristics of VR technologies. This adaptation includes additional constructs tailored to VR's immersive and experiential nature, which go beyond traditional usability and utility. Perceived Enjoyment, which gauges the intrinsic enjoyment derived from using technology, becomes particularly relevant in VR due to its potential for entertainment and rich, experiential interactions.

Furthermore, external variables such as age, curiosity, past use, and price willingness have been woven into the VR-specific TAM framework. These elements offer a deeper insight into the diverse factors influencing VR technology acceptance:

- Age examines how demographic factors shape technology adoption rates.

- Curiosity assesses an individual’s eagerness to explore new technologies, which can drive the adoption of innovative systems like VR.
- Past Use considers the impact of previous experiences with VR or related technologies on current perceptions and adoption choices.
- Price Willingness measures the economic considerations that influence decisions to adopt VR technologies.

The enhanced TAM for VR, enriched by the contributions of H. E. Sumbmul et al. [53] and V. Venkatesh et al. [41], strategically captures the distinctive attributes of VR and its impact on user acceptance. This refined model provides a comprehensive framework for understanding VR adoption dynamics, filling the void left by traditional TAM applications and better aligning with VR’s specific characteristics.

The expanded TAM model can serve as a pivotal tool in project management, particularly in projects involving the deployment of VR technologies. Project managers can utilize insights from this model to design adoption strategies that consider both the technological and human factors influencing the successful integration of VR into business processes and educational settings. Understanding these factors aids in the effective planning, execution, and evaluation of VR projects, ensuring that such initiatives meet their intended goals and are embraced by users.

Figure 2.1 illustrates the initial model of technology acceptance as proposed by F. D. Davis, highlighting how perceptions of utility and ease influence technology adoption decisions. However, TAM’s simplicity limits its applicability in contexts where user choices are voluntary, such as with VR hardware [24; 36; 48; 68].

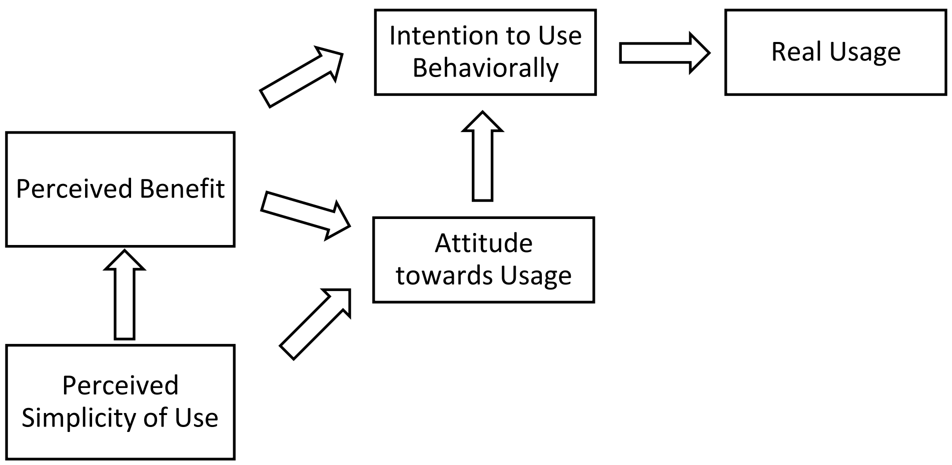

Figure 2.1 – The initial model of technology acceptance by F. D. Davis.

The adoption of Virtual Reality technology in business and education sectors highlights its broad and transformative applications – from revolutionizing training protocols and simulations to reshaping design and marketing strategies. In business, VR emerges as a pivotal tool, enabling organizations to construct highly immersive and interactive training environments. These environments accelerate learning processes and deepen engagement, offering realistic simulations of workplace scenarios. Such simulations are instrumental in boosting the preparedness and response capabilities of employees, significantly enhancing operational readiness and risk management in real-world settings.

Project management within these sectors benefits greatly from VR by improving scope definition, risk assessment, and stakeholder communication. By simulating complex project scenarios, VR allows project teams to identify potential issues and test solutions in a virtual environment, which leads to better planning and decision-making.

In the educational sector, the impact of VR is equally transformative, shifting the pedagogical approach from traditional didactics to more interactive, experiential learning modalities. The work of C. Ma and colleagues [18] underlines the significant role of VR in fostering immersive educational experiences. These experiences, by simulating real-world environments in a controlled, virtual setting, enable students to engage with, explore, and understand complex subjects in innovative and intuitive ways. This method enhances student engagement and significantly deepens comprehension of theoretical concepts, allowing for hands-on interaction and manipulation of learning materials.

Additionally, VR's application in data visualization represents a leap forward in how we interpret complex data sets. As noted by M. Gall and S. Rinderle-Ma [14], VR elevates data visualization beyond traditional two-dimensional interfaces into rich, interactive three-dimensional spaces. This advancement transforms data interaction, offering users an enhanced perspective and a more nuanced understanding of intricate data structures, which is crucial for informed decision-making and effective problem-solving across business, science, and educational fields.

Incorporating VR into project management processes in educational and business environments not only streamlines project execution but also enhances outcome predictability and project deliverables. It enables project managers to conduct comprehensive feasibility studies and impact assessments with greater accuracy and less risk. By facilitating a deeper understanding and improved visualization of project goals, VR technology serves as a cornerstone for innovative project management strategies.

Addressing the complex nature of Virtual Reality technology, this study introduces a detailed nested definition framework designed to methodically differentiate among the three principal components of VR: the content, the hardware, and the user experience. This framework serves as a crucial analytical tool, enabling a detailed dissection and nuanced understanding of VR technology, thereby enhancing our comprehension of its acceptance and utilization across diverse sectors.

The VR Content Component includes all digital assets and interactive elements that make up the virtual environment, ranging from graphical and narrative elements to the software applications that facilitate these experiences. In a project management context, understanding VR content is vital for assessing project scope, deliverables, and the quality of the VR experience provided to end-users. It influences user engagement levels and is a key factor in the immersive quality of the VR environment, directly impacting project outcomes in terms of user satisfaction and technological adoption.

The VR Hardware Component involves the physical devices and equipment that allow users to interact with the virtual world. This includes a variety of devices such as head-mounted displays (HMDs), motion tracking sensors, gloves, and other tactile feedback systems. For project managers, the hardware component is critical in determining the technological requirements and procurement strategies of VR projects. It affects not only the budgeting and scheduling facets of project management but also the user experience in terms of visual clarity, motion tracking accuracy, and overall comfort and immersion.

The VR Experience Component represents the subjective perception and cognitive interaction of the user with the virtual environment, encompassing sensory, emotional, and intellectual engagement. This component is pivotal for project managers to understand as it directly influences user acceptance and the overall success of VR implementations in business or educational settings. The VR experience affects stakeholder satisfaction and is a significant determinant in the continuous improvement and iterative development of VR projects.

By employing this nested definition framework, our study provides a comprehensive view of VR technology, promoting a deeper understanding of its complex nature. This systematic approach is instrumental for project managers to effectively plan, execute, and evaluate VR projects. It facilitates the identification of critical elements that influence the success of VR technology adoption and highlights potential areas for further research and development to optimize the integration and effectiveness of VR systems in various applications.

Recognizing the limitations of the traditional Technology Acceptance Model to fully encapsulate the unique attributes of Virtual Reality technology, this study expands the model to include additional constructs. These enhancements, forming the

VR Hardware Acceptance Model (VR-HAM), are crafted to specifically assess the acceptance of VR hardware, focusing notably on VR goggles.

Perceived Enjoyment is introduced as a crucial construct to capture the intrinsic motivation and enjoyment derived from using VR technology. This is particularly pertinent in project management, where the user's engagement level can directly influence the adoption and sustained use of VR systems in a business or educational setting. The entertainment and immersive nature of VR are seen as significant factors that can affect a project's acceptance rate and overall success.

External variables are incorporated into the VR-HAM to account for the broader range of factors that may affect the adoption of VR technology. Age is considered to analyze generational differences in technology adoption, essential for project managers to tailor VR solutions that meet the technological fluency of different user groups. Curiosity measures an individual's eagerness to engage with new and advanced technologies, indicating a readiness to adopt innovations that can be critical during the planning and implementation phases of VR projects.

Past use reflects on how previous experiences with VR or related technologies can ease the integration process, suggesting that familiarity may enhance user competence and comfort, thus supporting smoother project transitions. Lastly, price willingness assesses the financial impact on the decision-making process, highlighting budgetary considerations that project managers must account for when deciding on VR implementations.

By integrating these constructs into the established TAM framework, the VR-HAM offers a more detailed and nuanced understanding of the factors influencing user attitudes and behaviors towards VR technology adoption, especially regarding hardware like VR goggles. This expanded model not only aids in a deeper exploration of the complex nature of technology acceptance but also serves as a valuable tool for project managers. It enables them to strategize more effectively, ensuring that VR projects are not only technically feasible but also aligned with user expectations and budgetary constraints, thereby enhancing the potential for successful adoption and integration of VR technologies in various domains.

For this part of the research, a comprehensive two-stage nonprobability snowball sampling method was utilized to gather data from a diverse group of respondents, thereby capturing a broad spectrum of perspectives on Virtual Reality hardware. The first phase of this sampling strategy involved targeted outreach within the professional networks of the researchers, specifically through the LinkedIn platform. Individuals identified as having a professional or academic interest in VR technology were directly contacted and invited to participate in a detailed survey that focused on their experiences with and perceptions of VR hardware.

Upon agreeing to participate, these initial respondents were then involved in the second phase of the snowball sampling process. They were asked to share the survey link with their professional contacts who met specific eligibility criteria set by the research team to ensure relevance and a potential interest in VR technology. These criteria were deliberately designed to include individuals who either had firsthand experience with VR hardware, such as VR goggles, or those with a professional interest in the technological, educational, or business applications of VR.

The strategic use of this two-stage nonprobability snowball sampling method was intended to progressively expand the reach to a broader yet relevant segment of the population, capable of providing insightful contributions to the acceptance and usage of VR technology. This approach was designed to produce a representative sample of individuals deeply engaged with or interested in VR, thereby enhancing the validity and applicability of the research findings. The snowball sampling method proved particularly beneficial for this study as it exploited existing professional networks to access a wider and more diverse group of participants, who might otherwise be difficult to engage through conventional sampling techniques.

Employing the snowball sampling method in project management, particularly in projects involving innovative technologies like VR, provides critical advantages. This approach allows project managers to gather in-depth insights from a targeted yet expansive network of stakeholders, ensuring that the project's direction and outcomes align closely with user expectations and market needs. Furthermore, leveraging professional networks enhances stakeholder engagement, which is crucial for the iterative development and successful deployment of new technologies. This method also aids in identifying potential risks and barriers to adoption early in the project lifecycle, allowing for more informed decision-making and strategic planning.

In developing the survey instrument for this study, considerable care was taken to construct a comprehensive tool capable of precisely assessing the constructs identified in the extended Technology Acceptance Model. The survey was meticulously crafted by adapting and modifying validated scales to align closely with the unique characteristics of VR technology acceptance. Core constructs of the extended TAM, such as perceived usefulness, ease of use, enjoyment, and various external variables, were operationalized through a series of carefully formulated questions.

A 5-point Likert scale was utilized to quantitatively measure these constructs, providing respondents with choices ranging from "strongly disagree" to "strongly agree". This scale was instrumental in evaluating participants' attitudes and perceptions regarding the usability, utility, and enjoyment of VR hardware, facilitating a detailed analysis of how these factors influence technology acceptance.

Additionally, the survey featured a specialized section to evaluate price willingness, presenting respondents with a range of price points to determine the financial thresholds that might influence their decision to adopt VR technology. This section aimed to gather insights into price sensitivity, a crucial external factor in VR acceptance.

Another essential component of the survey was the collection of data on past usage of VR technology, where respondents were asked to self-report their previous experiences with VR devices. This information was crucial for understanding how prior exposure could affect current perceptions and levels of acceptance.

To ensure the validity and reliability of the survey instrument, the draft version underwent a rigorous review process involving marketing experts. These specialists meticulously evaluated the survey content to ensure that each question was clear, unambiguous, and directly related to the study's objectives. Their invaluable feedback was integrated into the final version of the survey, enhancing its structure and content to maximize clarity, relevance, and engagement from respondents.

This rigorous development process of the survey instrument underscores the importance of precise project planning and execution in research involving new technologies like VR. Project managers can apply similar strategies in their projects by ensuring that every tool and process is carefully designed to meet the project's specific objectives. This includes aligning project resources and activities to capture essential data that informs project direction and decision-making, ultimately leading to more successful outcomes.

Furthermore, the integration of feedback from domain experts highlights a proactive approach to quality assurance in project management. This practice not only improves the project deliverables but also enhances stakeholder trust and satisfaction, crucial for the sustained success of projects, especially in fields as dynamic and rapidly evolving as virtual reality technology.

The VR-HAM suggests that the adoption of virtual reality technology depends on users' beliefs about its utility, simplicity, and enjoyment, along with external influences. This model is based on the subsequent hypotheses:

1. **Perceived Usefulness (PU)** refers to the extent to which an individual thinks that utilizing virtual reality technology will improve their work efficiency or everyday tasks.
2. **Perceived Ease of Use (PEOU)** indicates how much an individual expects that operating virtual reality technology will require minimal effort.
3. **Perceived Enjoyment (PE)** denotes how much using virtual reality technology is considered enjoyable independently of any expected performance outcomes.

To quantify the relationships among the constructs of the VR-HAM, the following formulas are proposed:

- **Perceived Usefulness (PU).** Formula (2.1) calculates the perceived usefulness of VR technology, incorporating the influences of PEOU, PE, and a summation of impacts from external variables such as age, curiosity, past use, and price willingness. The coefficients β_1 and β_2 represent the strength of the relationships between PEOU and PE on PU, respectively, while β_{ext} coefficients quantify the impact of each EV (external variable) on PU.

$$PU = \beta_1 \cdot PEOU + \beta_2 \cdot PE + \sum(\beta_{ext} \cdot EV), \qquad (2.1)$$

where coefficients β_1 and β_2 represent the strength of the relationships between PEOU and PE on PU, respectively, while β_{ext} coefficients quantify the impact of each EV (external variable) on PU.

- **Perceived Ease of Use (PEOU).** Formula (2.2) defines the PEOU of VR technology, factoring in the effect of PE and the cumulative influence of external variables. The coefficient γ_1 denotes the impact of PE on PEOU, and γ_{ext} coefficients measure the influence of external variables on PEOU.

$$PEOU = \gamma_1 \cdot PE + \sum(\gamma_{ext} \cdot EV), \qquad (2.2)$$

where coefficient γ_1 denotes the impact of PE on PEOU, and γ_{ext} coefficients measure the influence of external variables on PEOU.

- **Intention to Use (ITU).** Formula (2.3) expresses the intention to use VR technology, integrating the effects of PU, PEOU, and PE. Coefficients δ_1, δ_2, and δ_3 represent the strengths of the relationships between PU, PEOU, and PE on ITU, respectively.

$$ITU = \delta_1 \cdot PU + \delta_2 \cdot PEOU + \delta_3 \cdot PE, \qquad (2.3)$$

where coefficients δ_1, δ_2, and δ_3 represent the strengths of the relationships between PU, PEOU, and PE on ITU, respectively.

- **Actual Use (AU).** Formula (2.4) calculates the actual use of VR technology based on the intention to use (ITU). The coefficient ζ_1 indicates the degree to which ITU translates into AU.

$$AU = \zeta_1 \cdot ITU, \tag{2.4}$$

where coefficient ζ_1 indicates the degree to which ITU translates into AU.

- **Modification for External Variables.** Formula (2.5) quantifies the cumulative impact of external variables on the core constructs of the VR-HAM model. The η_{ext} coefficients measure the influence of each external variable, providing a comprehensive view of how factors such as age, curiosity, past use, and price willingness affect the acceptance and use of VR technology.

$$EI = \sum \eta_{ext} \cdot EV, \tag{2.5}$$

where η_{ext} coefficients measure the influence of each external variable, providing a comprehensive view of how factors such as age, curiosity, past use, and price willingness affect the acceptance and use of VR technology.

Understanding these mathematical relationships is critical for project managers overseeing VR technology implementation projects. By comprehending how various factors influence user acceptance, project managers can tailor their strategies to address specific barriers and leverage enablers to technology adoption. This theoretical framework not only assists in predicting the outcomes of introducing VR technologies but also aids in the strategic planning of training programs, marketing strategies, and user engagement initiatives that align with the predicted model outputs. Such alignment ensures that projects are not only executed effectively but also resonate well with the target audience, thereby maximizing the likelihood of successful technology integration and adoption.

To address the unique characteristics of Virtual Reality (VR) technology and its application in business and educational contexts, we propose the Extended VR Technology Acceptance Model (EVRTAM). This model builds upon the traditional Technology Acceptance Model (TAM) by incorporating VR-specific constructs and considering the distinctive aspects of VR adoption in organizational settings. Figure 2.2 illustrates the EVRTAM, showcasing the interrelationships between various factors influencing VR acceptance.

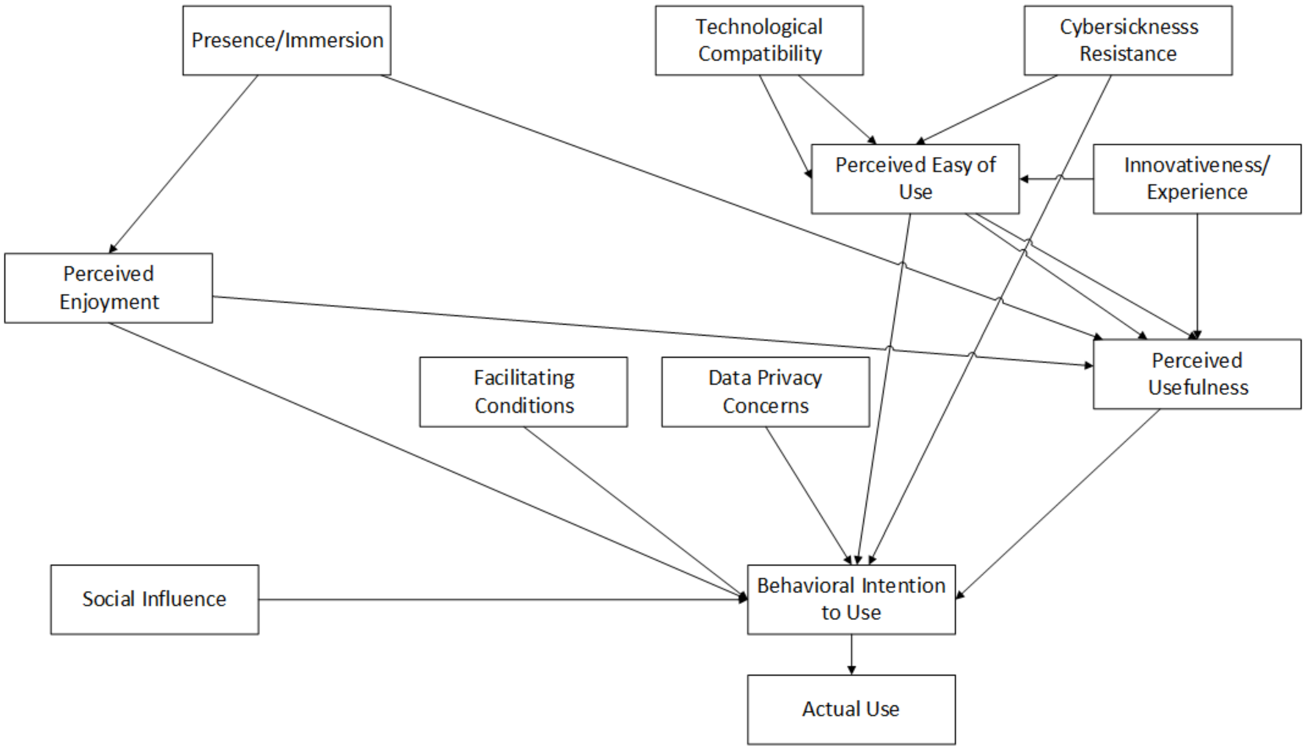

Figure 2.2 – Extended VR Technology Acceptance Model (EVRTAM)

The EVRTAM expands on the core constructs of perceived usefulness (PU) and perceived ease of use (PEOU) from the original TAM, introducing several new elements crucial to understanding VR adoption. Perceived enjoyment (PE) is included as a key factor, recognizing the immersive and often entertaining nature of VR experiences. The model also incorporates social influence (SI) and facilitating conditions (FC), acknowledging the importance of organizational and peer support in VR implementation.

A significant addition to the EVRTAM is the presence/immersion (PI) construct, which captures the unique ability of VR to create a sense of "being there" in a virtual environment. This factor directly influences both perceived usefulness and perceived enjoyment, reflecting the critical role of immersion in VR effectiveness.

The model also addresses potential barriers to VR adoption, including cybersickness resistance (CS) and data privacy concerns (DP). These factors can significantly impact users' willingness to engage with VR technology, especially in professional and educational settings where prolonged use may be required.

Technological compatibility (TC) is introduced as a crucial factor, particularly relevant in business and educational contexts where VR must integrate seamlessly with existing systems and workflows. This construct influences both perceived ease of use and perceived usefulness, highlighting the importance of VR's alignment with current technological ecosystems.

The EVRTAM also considers individual differences through the innovativeness/experience (IE) construct, recognizing that personal traits and prior experience with similar technologies can significantly affect perceptions of VR's ease of use and usefulness.

As in the original TAM, these factors collectively influence the behavioral intention to use (BI) VR technology, which in turn predicts actual use (AU). This relationship between intention and actual use is particularly important in organizational settings, where the gap between intended and actual adoption can have significant implications for ROI and strategic technology implementation.

By incorporating these VR-specific constructs and relationships, the EVRTAM provides a more comprehensive and nuanced framework for understanding VR acceptance in business and educational environments. This model can guide researchers in formulating more targeted hypotheses about VR adoption and assist practitioners in developing strategies to enhance VR acceptance and effective implementation in their organizations.

The EVRTAM's holistic approach to VR acceptance acknowledges the multifaceted nature of VR technology and its potential impacts on users and organizations. By considering a broader range of factors, from technological characteristics to individual and organizational contexts, this model offers a robust foundation for future research and practical applications in the rapidly evolving field of VR technology adoption.

2.2. Advanced Factors in VR Technology Acceptance for Business and Educational Applications

The evolving landscape of VR technology necessitates a more nuanced approach to understanding user acceptance. While the core constructs of perceived usefulness (PU) and perceived ease of use (PEOU) remain fundamental, the immersive and experiential nature of VR introduces additional complexities. The concept of presence, which refers to the subjective experience of being in one place or environment even when physically situated in another, becomes a critical factor in VR acceptance. This sense of presence can significantly influence both PU and PEOU, as users who experience a higher degree of presence may find the VR environment more useful and easier to navigate.

Moreover, the role of embodiment in VR adds another layer to the acceptance model. Unlike traditional technologies, VR often involves the user adopting a virtual body or avatar. This embodiment can affect the user's perception of self and their interactions within the virtual environment. Research in embodied cognition suggests that the characteristics of one's avatar can influence behavior, decision-making, and even cognitive processes. Consequently, the extent to which users identify with and feel comfortable in their virtual embodiment may be a crucial factor in VR acceptance, particularly in educational and business contexts where self-representation can impact performance and interpersonal dynamics.

The concept of technological self-efficacy, originally proposed by Bandura and later adapted to information systems research, takes on new dimensions in the context of VR [87]. Users' beliefs about their ability to successfully use VR technology can significantly impact their willingness to adopt it. In educational settings, students' technological self-efficacy regarding VR may influence their engagement with virtual learning environments and their perceived ability to achieve learning outcomes through these platforms. Similarly, in business contexts, employees’ VR self-efficacy could affect their willingness to participate in virtual meetings, training sessions, or collaborative design processes.

The social aspect of VR introduces another critical dimension to the acceptance model. Unlike many traditional technologies that are used individually, VR often involves social interaction in shared virtual spaces. This social component can influence acceptance through mechanisms such as social presence (the feeling of being with others in a virtual environment) and social influence (the impact of others' opinions and behaviors on one’s own technology adoption decisions). In educational contexts, the quality of social interactions in virtual classrooms or collaborative learning environments may significantly impact students’ acceptance and continued use of VR technology. In business settings, the effectiveness of virtual team collaborations and the perceived social presence in VR meetings could be crucial factors in organizational adoption decisions.

The concept of flow, originally proposed by Csikszentmihalyi [90], also plays a significant role in VR acceptance, particularly in educational and training applications. Flow refers to a state of complete absorption in an activity, characterized by a sense of energized focus, full involvement, and enjoyment. VR environments have the potential to create highly immersive experiences that can induce flow states, potentially enhancing learning outcomes and task performance. The ability of VR applications to facilitate flow experiences may therefore be an important factor in their acceptance and continued use.

The extended TAM for VR must also consider the potential negative aspects of VR use, which could impact acceptance. Issues such as cybersickness (a form of motion sickness induced by VR), eye strain, and the potential for addiction or escapism need to be factored into the model. These potential drawbacks may influence users’ perceptions of the technology’s usefulness and ease of use, as well as their attitudes towards long-term adoption.

In the context of business adoption, the concept of organizational readiness becomes crucial. This encompasses not only the technological infrastructure required to support VR implementation but also the organizational culture and employee attitudes towards technological innovation. The extended TAM should consider factors such as management support, resource allocation, and the alignment of VR capabilities with organizational goals and strategies.

The role of training and support in VR acceptance cannot be overstated. Given the novelty and complexity of VR systems, particularly in early stages of adoption, the availability and quality of training programs can significantly influence users' perceptions of ease of use and, consequently, their acceptance of the technology. In both educational and business contexts, well-designed onboarding processes and ongoing support mechanisms may be critical factors in successful VR adoption.

The concept of perceived behavioral control, derived from the Theory of Planned Behavior, is another important consideration in the extended TAM for VR [91]. This refers to an individual's perception of the ease or difficulty of performing a particular behavior, in this case, using VR technology. In the context of VR, perceived behavioral control may be influenced by factors such as the perceived complexity of VR hardware and software, the user's physical environment and available space for VR use, and the perceived compatibility of VR with existing work or study practices.

The extended TAM should also consider the role of experiential factors in VR acceptance. Unlike many traditional technologies where functionality is the primary concern, the quality of the user experience is paramount in VR. Factors such as the fidelity of graphics, the naturalness of interactions, and the overall immersive quality of the VR environment may significantly influence user acceptance. In educational contexts, the ability of VR to create engaging and memorable learning experiences may be a key factor in its acceptance by both students and educators. In business settings, the capacity of VR to facilitate more engaging presentations, more effective product visualizations, or more immersive training experiences may drive acceptance and adoption.

The concept of technology-task fit, originally proposed by Goodhue and Thompson, is particularly relevant in the context of VR adoption in business and education [92]. This theory suggests that technology adoption and use depend on how well the technology's capabilities match the requirements of the task at hand. In extending the TAM for VR, it's crucial to consider how well VR technology aligns with specific educational objectives or business processes. The perceived fit between VR capabilities and task requirements may significantly influence perceptions of usefulness and, consequently, acceptance and adoption.

The role of individual differences in VR acceptance should not be overlooked. Factors such as age, gender, prior technology experience, cognitive style, and personality traits may all influence how individuals perceive and interact with VR technology. For example, research has shown that factors such as spatial ability and immersive tendency (the propensity to become immersed in activities) can affect user performance and satisfaction in VR environments. Incorporating these individual difference factors into the extended TAM can provide a more nuanced understanding of VR acceptance patterns across diverse user populations.

In the context of educational VR applications, the extended TAM should consider pedagogical factors. The perceived alignment of VR technology with established learning theories and instructional design principles may influence educators' acceptance and adoption decisions. Factors such as the ability to support different learning styles, facilitate active learning, provide immediate feedback, and enable experiential learning may all contribute to the perceived usefulness of VR in educational contexts.

For business applications, the extended TAM should incorporate considerations of return on investment and competitive advantage. The perceived potential of VR to deliver tangible business benefits, such as increased productivity, reduced costs, or enhanced customer engagement, may be critical factors in organizational acceptance and adoption decisions. Moreover, the potential of VR to provide a competitive edge by enabling new forms of product development, customer interaction, or operational efficiency may drive adoption even in the face of implementation challenges.

In conclusion, extending the Technology Acceptance Model for VR in business and education contexts requires a multifaceted approach that considers the unique characteristics of VR technology, the specific needs and constraints of educational and business environments, and the complex interplay of individual, social, and organizational factors that influence technology adoption. By incorporating these diverse elements, the extended TAM can provide a more comprehensive and nuanced understanding of VR acceptance, guiding both research and practice in this rapidly evolving field.

To comprehensively understand the complex dynamics of Virtual Reality (VR) technology adoption in business and educational settings, we propose the Advanced VR Acceptance Factors Model (AVRAFM). This model extends beyond traditional technology acceptance frameworks by incorporating a multifaceted approach specifically tailored to the unique characteristics of VR and its applications in organizational contexts. Figure 2.3 illustrates the AVRAFM, showcasing the intricate relationships between various factors influencing VR acceptance.

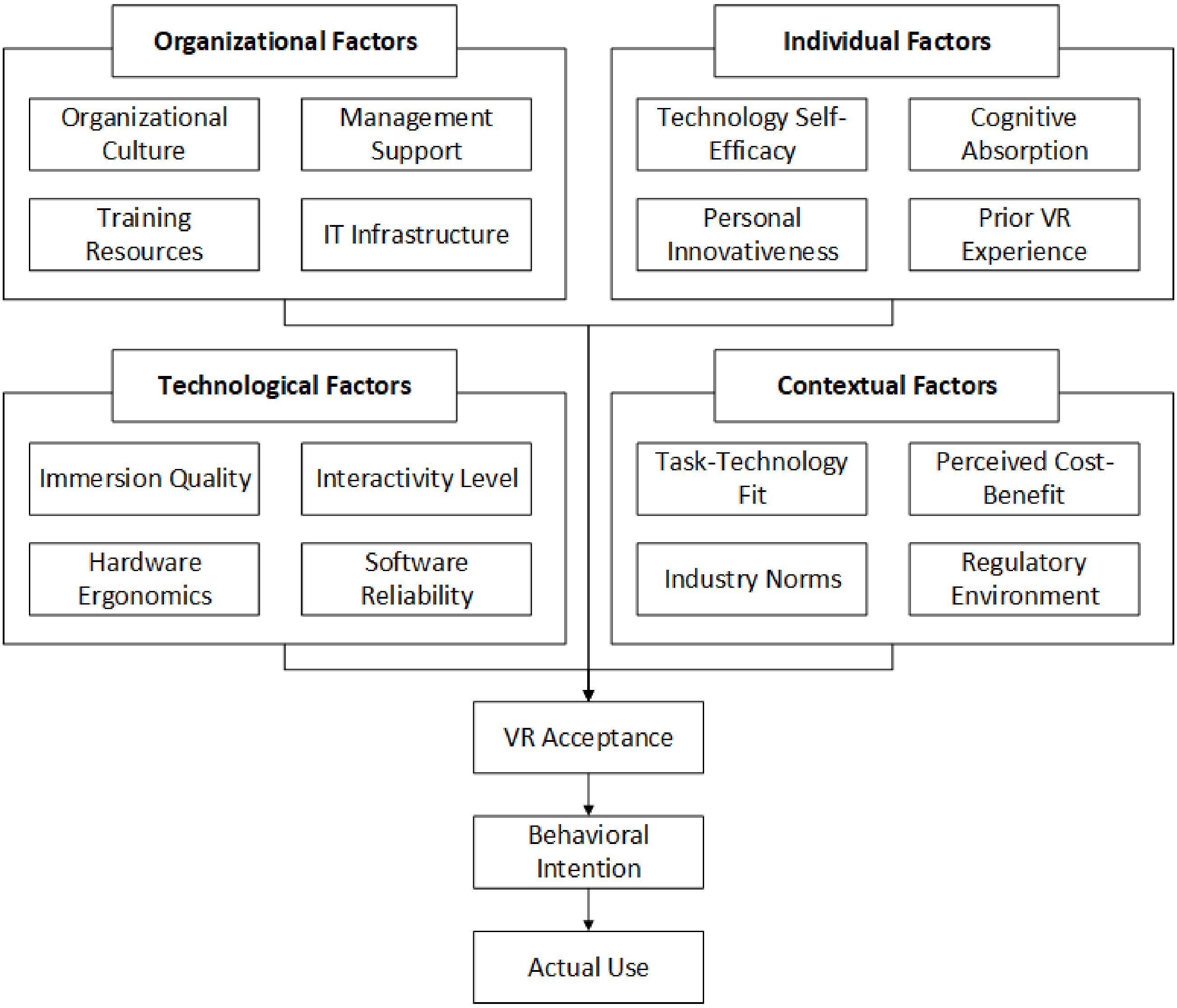

Figure 2.3 – Advanced VR Acceptance Factors Model (AVRAFM)

The AVRAFM categorizes the determinants of VR acceptance into four primary dimensions: Technological Factors, Organizational Factors, Individual Factors, and Contextual Factors. Each of these dimensions encompasses several key elements that collectively shape the overall acceptance and adoption of VR technology.

Technological Factors in the AVRAFM focus on the inherent characteristics of VR systems that directly impact user experience and functionality. These include Immersion Quality, which refers to the degree of sensory fidelity and presence achieved in the VR environment; Interactivity Level, reflecting the extent and naturalness of user interactions within the virtual space; Hardware Ergonomics, addressing the comfort and usability of VR devices during extended use; and Software Reliability, which encompasses the stability and performance of VR applications.

Organizational Factors recognize the crucial role of the institutional environment in facilitating VR adoption. This dimension includes Organizational Culture, assessing the degree to which the organizational ethos supports innovation and technology adoption; Management Support, reflecting the level of endorsement and resource allocation from leadership for VR initiatives; Training Resources, which considers the availability and quality of VR user training programs; and IT Infrastructure, evaluating the robustness of existing systems to support VR integration.

Individual Factors in the AVRAFM acknowledge the significant impact of user characteristics on VR acceptance. These factors include Technology Self-Efficacy, measuring an individual's belief in their ability to effectively use VR technology; Cognitive Absorption, which assesses the extent to which users become fully engaged in VR experiences; Personal Innovativeness, reflecting an individual's willingness to embrace new technologies; and Prior VR Experience, considering the user's familiarity with VR or similar immersive technologies.

Contextual Factors address the broader environmental and situational aspects that influence VR adoption. This dimension encompasses Task-Technology Fit, evaluating how well VR capabilities align with specific business or educational task requirements; Perceived Cost-Benefit, assessing the value proposition of VR in terms of investment versus returns; Industry Norms, considering the prevalence and acceptance of VR within specific sectors; and Regulatory Environment, addressing legal and compliance considerations surrounding VR use in various contexts.

The AVRAFM posits that these four dimensions collectively influence overall VR Acceptance, which in turn affects the Behavioral Intention to use VR technology. This intention ultimately translates into Actual Use in business and educational settings, completing the adoption cycle.

By integrating these diverse factors, the AVRAFM offers a nuanced and comprehensive framework for understanding VR acceptance in organizational contexts. It recognizes that successful VR adoption is not solely determined by technological features but is deeply influenced by organizational dynamics, individual user characteristics, and broader contextual factors.

This model provides valuable insights for both researchers and practitioners. For researchers, it offers a structured approach to investigating the multifaceted nature of VR acceptance, enabling more targeted and comprehensive studies. For practitioners, the AVRAFM serves as a strategic tool for identifying potential barriers and drivers of VR adoption, allowing for more effective planning and implementation of VR initiatives.

The AVRAFM's holistic approach enables organizations to develop tailored strategies that address the full spectrum of factors influencing VR acceptance. By considering technological, organizational, individual, and contextual dimensions, institutions can create more supportive environments for VR adoption, design more effective training programs, and align VR implementations with specific task requirements and industry norms.

In conclusion, the Advanced VR Acceptance Factors Model provides a robust framework for navigating the complexities of VR adoption in business and educational settings. Its comprehensive nature reflects the multifaceted challenges and opportunities presented by VR technology, offering a valuable tool for advancing our understanding and enhancing the successful implementation of VR in diverse organizational contexts.

2.3. Advanced Human-Computer Interaction Models for VR Systems

Development of Human-Computer Interaction Model. The integration of Human-Computer Interaction within Virtual Reality environments is pivotal for creating immersive and effective experiences. The core components of the HCI model, including User Interface Design (UID), User Experience Optimization (UXO), Natural

Language Processing (NLP), and Gesture Recognition (GR), among others, interact intricately to ensure a seamless and intuitive VR environment (fig. 2.4).

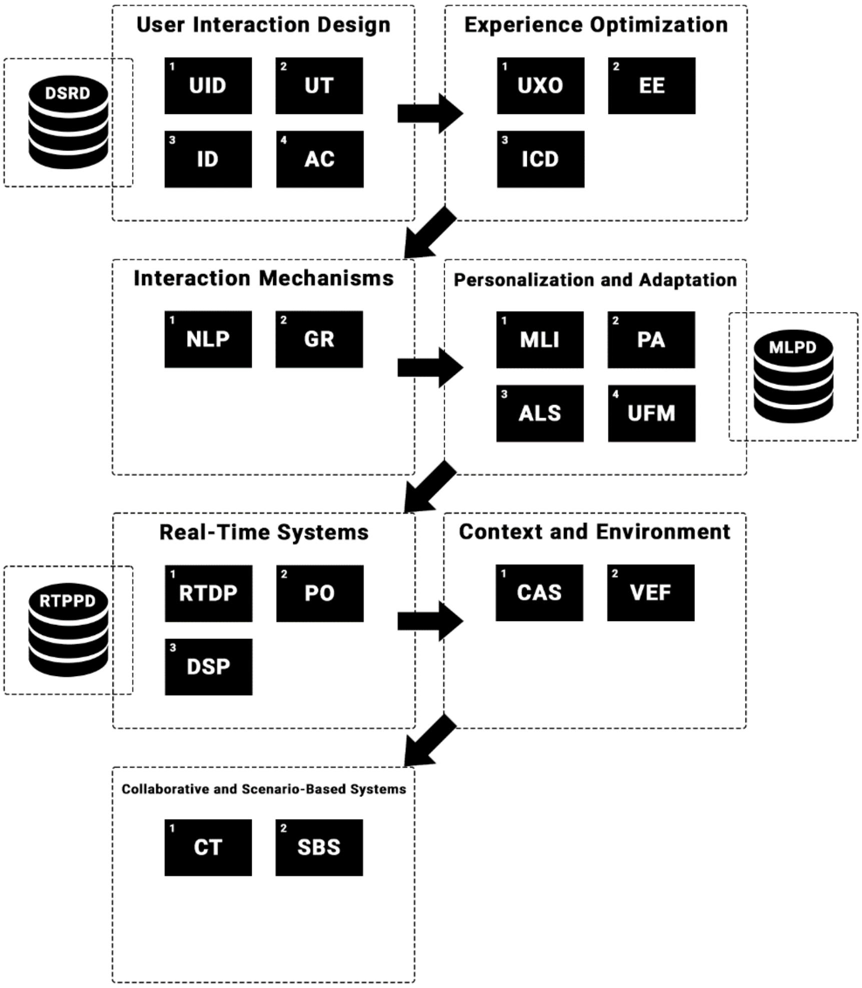

Figure 2.4 – Human-Computer Interaction (HCI) Model for VR Systems

User Interface Design (UID). The process of designing the layout and interactive elements of the VR environment. UID significantly affects and is influenced by UXO, Interaction Design (ID), Usability Testing (UT), Accessibility Considerations (AC), and NLP. Effective UID ensures that the user can interact intuitively with the VR system, enhancing overall usability and accessibility. For instance, UXO relies on well-designed interfaces to deliver a satisfying user experience, while NLP enhances the interface by enabling voice interactions. Studies by Y. Liu have shown that intuitive interface design is crucial for user satisfaction and engagement [28].

User Experience Optimization (UXO). Enhancing the overall experience of the user within the VR environment. UXO influences and is influenced by Personalization Algorithms (PA), Emotional Engagement (EE), Immersive Content Development (ICD), and Real-Time Data Processing (RTDP). Optimizing user experience involves creating personalized, engaging, and responsive VR environments. As L. Bhardwaj notes, the complexity of integrating these elements can lead to performance issues if not managed properly [33].

Natural Language Processing (NLP). The use of NLP to enable voice-based interactions within the VR environment. Enhances UID and Context-Aware Systems (CAS). NLP allows users to interact with VR systems using natural language, making interactions more intuitive and contextually relevant. This is particularly important for accessibility and enhancing user engagement, as highlighted by Z. Chen [27].

Gesture Recognition (GR). Using gestures to interact with the VR environment. Improves ID and RTDP. Gesture recognition facilitates natural interactions, allowing users to perform tasks using hand and body movements, thereby enhancing the realism of the VR experience. Z. Chen emphasizes that ensuring seamless gesture recognition across different contexts remains a significant challenge [27].

Machine Learning Integration (MLI). Incorporating machine learning to personalize and adapt VR experiences in real-time. Vital for PA, Adaptive Learning Systems (ALS), and RTDP. Machine learning algorithms analyze user behavior and preferences to adapt the VR environment, providing personalized experiences. S. R. Sabbella discusses the balance needed between personalization and data privacy [37].

User Feedback Mechanism (UFM). Collecting user feedback to improve VR experiences. Feeds into PA and ALS. User feedback is essential for continuously improving the VR system, ensuring it meets user needs and expectations. This iterative improvement process is crucial for maintaining user satisfaction, as noted by S. R. Sabbella [37].

Personalization Algorithms (PA). Algorithms that tailor the VR experience to individual users. Dependent on UXO, MLI, and UFM. Personalization algorithms use data from various sources to create unique user experiences. This personalized approach enhances user engagement and satisfaction, as observed by L. Bhardwaj [33].

Adaptive Learning Systems (ALS). Systems that adapt learning content based on user performance. Relies on MLI and UFM. Adaptive learning systems adjust the difficulty and content of educational materials in VR, enhancing learning outcomes. This adaptability is essential for effective educational simulations, as discussed by F. Argelaguet [45].

Immersive Content Development (ICD). Creating engaging and realistic VR content. Influences UXO and Scenario-Based Simulations (SBS). High-quality content is essential for user engagement and effective learning or training scenarios. F. Argelaguet highlights the resource-intensive nature of developing high-fidelity VR content [45].

Real-Time Data Processing (RTDP). Processing data in real-time to adapt the VR environment. Essential for GR, MLI, Performance Optimization (PO), and Data Security and Privacy (DSP). Real-time processing ensures that the VR environment responds immediately to user actions, maintaining immersion and functionality. S. R. Sabbella emphasizes the importance of balancing real-time processing with data security [37].

Interaction Design (ID). Designing how users will interact with the VR environment. Key to UID, GR, and SBS. Effective interaction design is crucial for intuitive and efficient user interactions within the VR environment. Y. Liu’s research indicates that well-designed interactions are key to a positive user experience [28].

Usability Testing (UT). Ensuring that the VR system is user-friendly. Affects UID, AC, and UFM. Usability testing identifies issues in the VR system, ensuring it is accessible and easy to use. S. Simmons emphasizes the importance of extensive usability testing for inclusive design [44].

Accessibility Considerations (AC). Making the VR system accessible to all users. Interacts with UID, UT, and CAS. Ensuring accessibility means that the VR system can be used by people with varying abilities and needs. S. Simmons notes that addressing diverse needs is essential for inclusive VR systems [44].

Emotional Engagement (EE). Enhancing user involvement through emotionally engaging content. Influences UXO. Emotional engagement ensures that users are not only using the VR system but are also emotionally connected to the experience. L. Bhardwaj's work highlights the role of emotional engagement in user satisfaction [33].

Context-Aware Systems (CAS). Systems that adapt based on the user's context. Dependent on NLP, AC, and SBS. Context-aware systems adjust the VR environment based on the user's location, time, and other contextual factors. Z. Chen's research underscores the importance of context-aware adaptations for immersive experiences [27].

Virtual Environment Fidelity (VEF). Ensuring the virtual environment closely replicates reality. Affects ICD and PO. High fidelity in VR environments enhances realism and immersion. F. Argelaguet points out that maintaining high fidelity is often technically challenging but crucial for immersion [45].

Performance Optimization (PO). Enhancing the performance of the VR system. Relies on RTDP, VEF, and DSP. Performance optimization ensures that the VR system runs smoothly and efficiently. S. R. Sabbella discusses the importance of performance in maintaining user immersion [37].

Data Security and Privacy (DSP). Protecting user data within the VR environment. Ensures RTDP and PO. Ensuring data security and privacy is critical for user trust and system integrity. S. R. Sabbella emphasizes that balancing data security with real-time processing is crucial [37].

Collaboration Tools (CT). Enabling collaborative interactions within the VR environment. Integrated with SBS. Collaboration tools allow multiple users to interact and work together within the VR environment. L. Bhardwaj's research indicates that collaboration enhances learning and productivity [33].

Scenario-Based Simulations (SBS). Providing interactive scenarios for training and education. Depends on ICD, ID, CAS, and CT. Scenario-based simulations are essential for training and educational purposes, offering realistic and practical experiences. F. Argelaguet emphasizes the effectiveness of scenario-based learning in VR environments [45].

Data Storage and Retrieval Database (DSRD). The Data Storage and Retrieval Database (DSRD) is essential for managing and storing vast amounts of user interaction data, content assets, and context data. It supports components like User Interface Design, User Experience Optimization, and Immersive Content Development by providing access to templates, logs, and interaction histories, ensuring a cohesive and user-friendly VR environment.

Machine Learning and Personalization Database (MLPD). The Machine Learning and Personalization Database (MLPD) is crucial for storing machine learning models, training data, and personalization algorithms. It aids in delivering tailored VR experiences by supporting components like Machine Learning Integration, Personalization Algorithms, and Adaptive Learning Systems, enabling real-time personalization and adaptive learning based on user interactions and feedback.

Real-Time Processing and Performance Database (RTPPD). The Real-Time Processing and Performance Database (RTPPD) handles real-time data streams, performance metrics, and security logs. It ensures the VR environment's efficiency and security by supporting Real-Time Data Processing, Performance Optimization, and Data Security and Privacy components, facilitating quick data processing, performance enhancements, and safeguarding user data within the system.

The development of a Natural Language Processing method for enhancing Human-Computer Interaction within Virtual Reality systems involves several critical steps. This comprehensive approach includes designing the NLP framework, establishing interaction protocols, implementing the necessary algorithms, and incorporating machine learning techniques to optimize performance.

First, we need to establish a robust NLP framework that can handle the unique challenges posed by VR environments. This involves defining the types of voice commands and interactions that the system must understand. For instance, the system should be able to process commands for navigation, object manipulation, and information retrieval within the VR space. This requires a comprehensive understanding of natural language semantics and context.

The next step is to create detailed interaction protocols. These protocols define how the system responds to various commands and how it maintains the context of interactions. For instance, when a user says, “Show me the next slide”, the system must understand that this command refers to the current presentation context. This involves maintaining a session state that keeps track of the ongoing activities and their respective contexts.

Implementing the NLP algorithms requires selecting appropriate models and training them on relevant datasets. One common approach is to use sequence-to-sequence models, such as Recurrent Neural Networks (RNNs) or their more advanced variant, Long Short-Term Memory (LSTM) networks [2; 24; 25; 63; 68]. These models are well-suited for processing sequential data like speech. The input to these models is a sequence of words or phonemes, and the output is a corresponding sequence of actions or responses. The training process involves feeding the model with large datasets of annotated speech interactions, allowing it to learn the mapping between speech patterns and actions.

Mathematically, let $X = (x_1, x_2, \dots, x_n)$ represent the sequence of input words, and $Y = (y_1, y_2, \dots, y_m)$ represent the sequence of actions or responses. The goal of the model is to learn the conditional probability distribution $P(Y|X)$. This is typically achieved by maximizing the log-likelihood of the training data (Formula 2.6):

$$\mathcal{L}(\theta) = \sum_{i=1}^{N} log P(Y_i|X_i; \theta) \qquad (2.6)$$

where θ represents the model parameters, and N is the number of training examples. The model parameters θ are updated using gradient-based optimization methods like stochastic gradient descent (SGD).

To further enhance the model's performance, we can incorporate attention mechanisms. Attention mechanisms allow the model to focus on relevant parts of the input sequence when generating each part of the output sequence. The attention mechanism computes a context vector c_t for each output time step t, which is a weighted sum of the input representations (Formula 2.7):

$$c_t = \sum_{i=1}^{n} \alpha_{t,i} h_i \tag{2.7}$$

where h_i are the hidden states of the input sequence, and $\alpha_{t,i}$ are the attention weights computed as Formula 2.8:

$$\alpha_{t,i} = \frac{\exp(e_{t,i})}{\sum_{k=1}^{n} \exp(e_{t,k})} \tag{2.8}$$

where $e_{t,i}$ is computed using a compatibility function, such as the dot product between the decoder hidden state and the encoder hidden state (Formula 2.9):

$$e_{t,i} = s_t \cdot h_i \tag{2.9}$$

where s_t is the decoder hidden state at time step t. The context vector c_t is then used to generate the output y_t (Formula 2.10):

$$y_t = g(s_t, c_t) \tag{2.10}$$

where g is a function that combines the decoder state and the context vector to produce the final output.

In addition to the model implementation, it's essential to establish protocols for continuous learning and adaptation. This involves collecting user interactions and feedback during actual VR sessions and using this data to fine-tune the model. Techniques like reinforcement learning can be employed, where the model is rewarded for correct actions and penalized for incorrect ones. The reward function can be defined based on user satisfaction metrics, such as the accuracy and speed of executing commands.

Moreover, integrating NLP with other HCI components, such as Gesture Recognition (GR) and Context-Aware Systems (CAS), enhances the overall interaction experience. For example, combining voice commands with gesture inputs allows users to perform complex actions more naturally. The system can also use contextual information, such as the user’s location and the current task, to interpret commands more accurately.

The development of advanced Human-Computer Interaction models for VR systems represents a paradigm shift in the way we conceptualize and design interfaces for immersive digital environments. This evolution is particularly significant in the realms of business process modeling and educational tools, where the potential for VR to revolutionize traditional practices is immense. The complexity of these models stems from the multifaceted nature of VR interactions, which encompass not only visual and auditory stimuli but also haptic feedback, spatial awareness, and embodied cognition.

One of the primary challenges in developing HCI models for VR systems lies in the integration of multimodal interaction paradigms. Unlike traditional computer interfaces, which primarily rely on visual displays and simple input devices, VR environments must seamlessly blend various sensory inputs and outputs to create a cohesive and intuitive user experience. This necessitates a holistic approach to interface design that considers the interplay between visual, auditory, and haptic modalities, as well as the spatial and temporal aspects of user interactions within the virtual space.

The concept of embodied cognition plays a crucial role in shaping HCI models for VR systems. This theoretical framework posits that cognitive processes are deeply rooted in the body’s interactions with the world, a notion that takes on new dimensions in virtual environments where the user’s physical body is represented by a digital avatar. The design of VR interfaces must therefore account for the ways in which users perceive and interact with their virtual bodies, as this can significantly impact their cognitive processes, decision-making abilities, and overall engagement with the virtual environment.

In the context of business process modeling, advanced HCI models for VR systems must address the unique challenges posed by the visualization and manipulation of complex, abstract data structures. Traditional two-dimensional representations of business processes often struggle to convey the full complexity and interconnectedness of modern organizational systems. VR offers the potential to create immersive, three-dimensional visualizations that allow users to intuitively navigate and manipulate these complex data structures. However, realizing this potential requires the development of novel interaction paradigms that leverage the spatial and embodied aspects of VR to enhance user understanding and decision-making processes.

The incorporation of natural language processing and gesture recognition technologies into VR HCI models represents another frontier in the evolution of these systems. By enabling users to interact with virtual environments through speech and natural body movements, these technologies have the potential to dramatically reduce the learning curve associated with VR interfaces and make them more accessible to a wider range of users. However, the integration of these technologies also introduces new challenges, such as the need to accurately interpret user intent in three-dimensional space and the potential for gesture conflicts in multi-user environments.

The development of adaptive and context-aware interfaces represents a key area of focus in advanced HCI models for VR systems. These intelligent interfaces have the capacity to dynamically adjust their behavior and presentation based on user preferences, task requirements, and environmental conditions. In educational contexts, for example, adaptive VR interfaces could tailor the complexity and pacing of learning materials to match the individual needs and learning styles of each student. In business applications, context-aware interfaces could automatically configure themselves to support specific tasks or decision-making processes, enhancing productivity and reducing cognitive load.

The concept of presence, or the subjective feeling of being in a virtual environment, is central to the design of effective HCI models for VR systems. Achieving a high degree of presence requires careful attention to factors such as visual fidelity, audio spatialization, haptic feedback, and interaction latency. Advanced HCI models must therefore incorporate sophisticated techniques for managing these factors in real-time, balancing the need for immersion with the computational constraints of current VR hardware.

Collaborative VR environments present unique challenges and opportunities for HCI model development. These shared virtual spaces must support natural and intuitive interactions between multiple users, potentially distributed across different physical locations. Advanced HCI models for collaborative VR environments must address issues such as avatar representation, social presence, turn-taking in conversations, and shared manipulation of virtual objects. The design of these interfaces requires a deep understanding of social psychology and group dynamics, in addition to technical expertise in VR systems.

The integration of artificial intelligence (AI) and machine learning (ML) techniques into HCI models for VR systems offers the potential for more sophisticated and responsive interfaces. AI-powered virtual agents could serve as intelligent assistants within VR environments, helping users navigate complex information spaces or providing real-time guidance and feedback. Machine learning algorithms could be employed to analyze user behavior patterns and preferences, allowing VR interfaces to continuously adapt and improve over time.

Ethical considerations play a crucial role in the development of advanced HCI models for VR systems, particularly in educational and business contexts. Issues such as data privacy, user autonomy, and the potential for addiction or escapism must be carefully addressed in the design of VR interfaces. Additionally, the immersive nature of VR raises new ethical questions about the boundaries between virtual and physical reality, and the potential psychological impacts of prolonged exposure to highly realistic virtual environments.

The development of standardized evaluation metrics and methods represents a critical challenge in the advancement of HCI models for VR systems. Traditional usability testing methods may not adequately capture the unique aspects of VR interactions, necessitating the development of new approaches that can assess factors such as presence, embodiment, and spatial cognition. Standardized evaluation frameworks would not only facilitate the comparison of different VR interface designs but also contribute to the establishment of best practices and design guidelines for VR HCI.

The concept of embodied interaction, which emphasizes the role of the body in shaping cognitive processes and user experiences, has significant implications for the design of VR interfaces. Advanced HCI models must consider how users' physical movements and gestures can be leveraged to create more intuitive and engaging interactions within virtual environments. This may involve the development of novel input devices that can accurately track fine motor movements, as well as the design of virtual interfaces that respond dynamically to users' physical actions and postures.

The integration of haptic feedback technologies represents another frontier in the development of advanced HCI models for VR systems. Haptic interfaces have the potential to greatly enhance the sense of presence and immersion in virtual environments by providing tactile and force feedback to users. However, the effective integration of haptic feedback into VR interfaces presents significant technical and design challenges, including the need for high-fidelity force rendering, low-latency response times, and the development of intuitive haptic interaction paradigms.

In conclusion, the development of advanced Human-Computer Interaction models for VR systems in business and educational contexts represents a complex and multifaceted challenge that draws upon diverse fields including computer science, cognitive psychology, human factors engineering, and social psychology. As VR technology continues to evolve and mature, these HCI models will play a crucial role in shaping the future of immersive digital environments and their applications across various domains. The ongoing refinement and innovation in this field hold the promise of creating more intuitive, engaging, and effective VR interfaces that can revolutionize the way we learn, work, and interact in virtual spaces.

Conclusions to chapter 2

1. A novel information technology integrating VR-BPMN has been designed and implemented, enhancing business process visualization and analysis. This technology represents a significant paradigm shift in interface design and user experience optimization, addressing complex applications in business process modeling and educational tools. This conclusion directly addresses the task of designing and implementing a novel information technology that integrates VR-BPMN.
2. Advanced methods for natural language processing and gesture recognition have been developed within the proposed information technology. These methods, along with eye-tracking and other modalities, create more intuitive and immersive VR experiences, significantly improving human-computer interaction in VR interfaces. The incorporation of AI and machine learning algorithms further enhances the adaptability and personalization of these interfaces. This conclusion relates to the task of developing advanced methods for natural language processing and gesture recognition.
3. The Technology Acceptance Model has been successfully extended and improved to accommodate the unique characteristics of VR technology. The new VR Hardware Acceptance Model (VR-HAM) incorporates additional constructs such as perceived enjoyment and external variables like age, curiosity, past use, and price willingness. This improved model provides a more nuanced understanding of factors influencing VR adoption in organizational settings, addressing the task of improving the Technology Acceptance Model.
4. A comprehensive information technology solution for implementing VR in business and educational contexts has been developed. This solution addresses the full lifecycle from assessment to continuous evaluation, considering factors such as presence, ethical considerations, and accessibility

issues. The integration of VR with other emerging technologies like AI, IoT, and 5G networks opens up new possibilities for creating sophisticated and responsive virtual environments. This conclusion relates to the task of developing a comprehensive IT solution for VR implementation.

5. The research has identified critical factors for the widespread adoption of VR technology, including ethical considerations and accessibility issues. These findings provide a foundation for developing practical advice for organizations considering the introduction of VR in educational spaces, particularly in B2B and B2C environments. This addresses the task of developing practical advice for organizations.

CHAPTER 3. EVALUATION METHODS AND DECISION-MAKING MODELS FOR IMPLEMENTING VR IN BUSINESS PROCESSES AND EDUCATION

3.1. Structural Equation Modeling for Assessing VR Acceptance

In order to rigorously test the hypotheses formulated from the extended Technology Acceptance Model, this study adopts a sophisticated analytical approach known as Structural Equation Modeling. Utilizing the "lavaan package" within the R statistical software environment, SEM is employed as a powerful statistical technique to explore and elucidate the complex interrelations among the various constructs of the extended TAM. This methodological choice is predicated on SEM's ability to concurrently estimate multiple and interrelated dependence relationships, thereby facilitating a comprehensive analysis of the causal pathways within the hypothesized model.

The employment of SEM in this context is particularly apt given its capacity to handle complex model structures, including those with latent variables that represent abstract concepts like perceived usefulness, ease of use, and enjoyment, which are central to the extended TAM. Through this approach, the study endeavors to uncover the underlying dynamics that govern the acceptance of VR technology, elucidating how each construct contributes to shaping user attitudes and behavioral intentions.

In project management, particularly in projects involving the implementation of new technologies like VR, understanding these dynamics is crucial. The insights gained from the SEM analysis can inform project leaders about the key factors that influence technology adoption, enabling them to devise more effective strategies for managing change and fostering technology acceptance among stakeholders.

To ensure the methodological rigor and reliability of the SEM analysis, the study meticulously evaluates the model fit by employing a suite of fit indices. These indices include the chi-square to degrees of freedom ratio ($\chi 2/df$), which provides a basic measure of model fit relative to the model's complexity; the Comparative Fit Index (CFI) and the Tucker-Lewis Index (TLI), both of which compare the fit of the hypothesized model against a baseline null model; the Root Mean Square Error of Approximation (RMSEA), which assesses the fit per degree of freedom, accounting for model complexity; and the Standardized Root Mean Square Residual (SRMR), which measures the average discrepancy between the observed and predicted correlations.

Applying these indices allows the research team to determine how well the proposed model represents the observed data. A good model fit, indicated by low $\chi 2/df$, RMSEA, SRMR values, and high CFI and TLI values, confirms the robustness of the SEM analysis and the validity of the findings. Such substantiation enhances the credibility of the hypothesized determinants of VR technology acceptance and underscores the study's commitment to empirical rigor. This comprehensive evaluation not only supports the project's scientific foundation but also ensures that project management decisions are based on validated data, enhancing the likelihood of successful technology adoption and integration.

The application of Structural Equation Modeling in assessing Virtual Reality acceptance represents a sophisticated analytical approach that allows researchers to delve deep into the complex interrelationships between various factors influencing technology adoption. This methodological framework offers a nuanced understanding of the multifaceted nature of VR acceptance, particularly in the context of business processes and educational environments. The utilization of SEM in this domain extends beyond simple correlation analyses, providing a robust platform for testing hypothesized causal relationships and evaluating the overall fit of theoretical models to observed data.

The implementation of SEM in VR acceptance studies necessitates a meticulous approach to model specification, data collection, and analysis. The process begins with the formulation of a theoretical model that encapsulates the hypothesized relationships between latent constructs such as perceived usefulness, perceived ease of use, and behavioral intention to use VR technology. These constructs, which are not directly observable, are operationalized through measurable indicator variables, typically in the form of survey items or behavioral metrics. The specification of the measurement model, which defines the relationships between latent variables and their indicators, is a critical step in the SEM process, as it forms the foundation for subsequent analyses.

One of the primary advantages of SEM in assessing VR acceptance lies in its ability to simultaneously estimate multiple interdependent relationships while accounting for measurement error. This capability is particularly valuable in the context of VR research, where the constructs of interest are often abstract and multidimensional. For instance, the concept of “immersion” in VR environments, which plays a crucial role in user acceptance, can be conceptualized as a latent variable influenced by various observable factors such as visual fidelity, interactivity, and presence. SEM allows researchers to model these complex relationships and estimate their relative strengths, providing insights into the key drivers of VR acceptance.

The application of SEM in VR acceptance studies also facilitates the integration of multiple theoretical perspectives. By incorporating constructs from various acceptance models, such as the Technology Acceptance Model, the Unified Theory of Acceptance and Use of Technology (UTAUT), and the Innovation Diffusion Theory, researchers can develop more comprehensive frameworks for understanding VR adoption. This integrative approach is particularly relevant in the rapidly evolving field of VR, where traditional technology acceptance models may need to be augmented to capture the unique characteristics of immersive technologies.

The estimation of SEM models for VR acceptance typically employs sophisticated statistical techniques such as maximum likelihood estimation or partial least squares. These methods allow for the simultaneous estimation of all model parameters, taking into account the covariance structure of the observed data. The choice of estimation method depends on various factors, including sample size, distribution assumptions, and model complexity. In the context of VR research, where sample sizes may be limited due to the novelty of the technology, careful consideration must be given to the selection of appropriate estimation techniques to ensure the reliability and validity of the results.

One of the key strengths of SEM in assessing VR acceptance is its ability to test for measurement invariance across different groups or contexts. This is particularly relevant in cross-cultural studies or comparisons between different user populations, such as students and business professionals. By establishing measurement invariance, researchers can ensure that the constructs in their VR acceptance models are interpreted similarly across groups, allowing for meaningful comparisons of structural relationships. This capability is crucial for developing generalizable theories of VR acceptance that can inform both research and practice across diverse settings.

The evaluation of model fit in SEM analyses of VR acceptance involves the consideration of multiple fit indices, each providing unique information about how well the hypothesized model aligns with the observed data. Commonly used fit indices include the chi-square test, comparative fit index (CFI), Tucker-Lewis index (TLI), root mean square error of approximation (RMSEA), and standardized root mean square residual (SRMR). The interpretation of these indices requires a nuanced understanding of their strengths and limitations, as well as consideration of the specific context of VR acceptance research. For instance, the sensitivity of the chi-square test to sample size may necessitate greater reliance on alternative fit indices in studies with large samples.

The application of SEM in VR acceptance research also allows for the exploration of mediating and moderating effects, providing insights into the mechanisms through which various factors influence VR adoption. For example, researchers might investigate whether the relationship between perceived ease of use and behavioral intention to use VR is mediated by perceived usefulness, or whether this relationship is moderated by factors such as prior technology experience or age. These more complex model specifications can offer a richer understanding of the VR acceptance process, informing the development of targeted interventions to promote adoption in educational and business contexts.

One of the challenges in applying SEM to VR acceptance studies is the potential for model misspecification, which can lead to biased parameter estimates and erroneous conclusions. To mitigate this risk, researchers must engage in rigorous model development and validation processes, including thorough literature reviews, expert consultations, and pilot studies. Additionally, the use of model modification indices and residual analyses can help identify areas of model misfit, guiding refinements to the theoretical framework. However, it is crucial that any model modifications are theoretically justified and cross-validated to avoid capitalization on chance.

The incorporation of longitudinal data in SEM analyses of VR acceptance represents a promising avenue for future research. By collecting data at multiple time points, researchers can investigate the dynamic nature of VR acceptance, examining how perceptions and intentions evolve as users gain more experience with the technology. Latent growth curve modeling and cross-lagged panel designs within the SEM framework can provide valuable insights into the temporal aspects of VR adoption, informing the development of more effective implementation strategies in educational and business settings.

The application of SEM in VR acceptance research also extends to the analysis of multi-level data structures, which are common in organizational and educational contexts. For instance, in a study of VR adoption in schools, individual student perceptions may be nested within classroom-level factors, which in turn are nested within school-level characteristics. Multi-level SEM allows researchers to account for these hierarchical data structures, providing a more accurate representation of the complex factors influencing VR acceptance across different levels of analysis.

The use of Bayesian SEM approaches in VR acceptance research offers several advantages, particularly in dealing with small sample sizes and complex model specifications. Bayesian methods allow for the incorporation of prior knowledge into the modeling process, which can be particularly valuable in the rapidly evolving field of VR where empirical data may be limited. Additionally, Bayesian SEM provides more accurate estimates of parameter uncertainty and allows for the testing of informative hypotheses, enhancing the interpretability and practical significance of research findings.

The integration of qualitative data within SEM analyses of VR acceptance represents an emerging trend in mixed-methods research. Qualitative data, such as open-ended survey responses or interview transcripts, can provide rich contextual information that complements the quantitative measures typically used in SEM. Techniques such as qualitative comparative analysis (QCA) can be combined with SEM to identify complex configurational patterns in VR acceptance, offering insights that may not be apparent from traditional variable-centered approaches.

The application of machine learning techniques in conjunction with SEM offers new possibilities for exploring non-linear and interactive effects in VR acceptance models. Methods such as decision trees and random forests can be used to identify complex patterns in the data, informing the specification of more nuanced SEM models. Additionally, techniques like structural equation model trees (SEM trees) allow for the automatic detection of heterogeneity in structural equation models, potentially uncovering subgroups with distinct patterns of VR acceptance.

The consideration of measurement error in SEM analyses of VR acceptance is crucial for obtaining accurate estimates of structural relationships. Unlike traditional regression approaches, SEM allows for the explicit modeling of measurement error through the use of latent variable constructs. This is particularly important in VR research, where many key constructs (e.g., presence, immersion) are inherently difficult to measure with precision. By accounting for measurement error, SEM provides more reliable estimates of the true relationships between variables, enhancing the validity of research findings.

The application of SEM in VR acceptance research also facilitates the testing of competing theoretical models. By comparing the fit of alternative model specifications, researchers can evaluate the relative plausibility of different explanatory frameworks for VR adoption. This model comparison approach is particularly valuable in the context of VR, where multiple theoretical perspectives may offer plausible explanations for observed patterns of acceptance and use. Techniques such as nested model comparisons and information criteria (e.g., AIC, BIC) provide formal methods for assessing the relative merits of competing models.

The use of SEM in VR acceptance studies also allows for the examination of reciprocal relationships and feedback loops. For instance, researchers might investigate whether increased use of VR technology leads to changes in perceptions of usefulness and ease of use, which in turn influence future usage intentions. These non-recursive model specifications can provide insights into the dynamic nature of VR acceptance processes, informing the development of more sophisticated theoretical frameworks.

The application of SEM in cross-cultural studies of VR acceptance presents both opportunities and challenges. While SEM provides powerful tools for testing measurement and structural invariance across cultural groups, researchers must be attentive to potential sources of bias, such as differential item functioning or cultural differences in response styles. The use of multi-group SEM analyses can help identify cultural variations in the determinants of VR acceptance, informing the development of culturally sensitive implementation strategies.

The integration of physiological and neuroimaging data within SEM analyses of VR acceptance represents a promising frontier in technology acceptance research. By incorporating objective measures of user responses, such as eye-tracking data, galvanic skin response, or fMRI activations, researchers can develop more comprehensive models of VR acceptance that bridge subjective perceptions with observable biological responses. This multi-modal approach to SEM analysis has the potential to provide deeper insights into the cognitive and affective processes underlying VR adoption decisions.

The application of SEM in VR acceptance research also extends to the analysis of social network data, recognizing the importance of social influences in technology adoption processes. By incorporating social network metrics as variables within structural equation models, researchers can examine how factors such as network centrality, tie strength, and homophily influence individual and collective VR acceptance decisions. This social network perspective is particularly relevant in organizational contexts, where the diffusion of VR technology may be influenced by complex patterns of interpersonal communication and social influence.

The use of SEM in longitudinal studies of VR acceptance allows for the examination of feedback effects and reciprocal causation over time. For example, researchers might investigate how initial experiences with VR technology influence subsequent perceptions and usage patterns, which in turn shape future attitudes and behaviors. These dynamic models can provide valuable insights into the processes of technology habituation and the formation of stable usage patterns, informing the development of strategies for promoting sustained VR adoption in educational and business contexts.

The SEM analysis confirmed the significance of the proposed relationships within the VR-HAM. The model fit indices indicated a good fit to the data, with a $\chi 2$/df ratio of 2.45, CFI of 0.95, TLI of 0.94, RMSEA of 0.05, and SRMR of 0.03, suggesting that the model adequately represents the observed data.

From Table 3.1, the coefficients (β_1, β_2, γ_1, δ_1, δ_2, δ_3, and ζ_1) represent the strength and direction of relationships between various constructs within the VR-HAM model, such as PEOU, PU, PE, ITU, and AU. The significance levels indicate the statistical reliability of these relationships. For instance, a high coefficient value with a low p-value ($p < 0.001$) for the relationship between PEOU and PU suggests a strong and statistically significant positive influence of ease of use on the perceived usefulness of VR technology. This table underscores the critical pathways through which different perceptions about VR technology influence user intentions and behaviors

Table 3.1. Coefficients and Significance Levels

№	Construct Relationship	Coefficient	Standard Error	Significance
1	PEOU → PU	$\beta_1 = 0.44$	0.05	$p < 0.001$
2	PE → PU	$\beta_2 = 0.42$	0.04	$p < 0.001$
3	Pe → PEOU	$\gamma_1 = 0.56$	0.05	$p < 0.001$
4	PU → ITU	$\delta_1 = 0.34$	0.06	$p < 0.001$
5	PEOU → ITU	$\delta_2 = 0.25$	0.06	$p < 0.01$
6	PE → ITU	$\delta_3 = 0.3$	0.05	$p < 0.001$
7	ITU → AI	$\zeta_1 = 0.81$	0.04	$p < 0.001$

Table 3.2 displays average perceptions and behaviors towards VR technology, detailing mean and standard deviation for key variables like PU, PEOU, PE, ITU, and AU. High mean values, especially for PE, alongside low standard deviations, indicate a consensus on VR's enjoyability among respondents. This table succinctly captures overall attitudes and behaviors towards VR among participants.

Table 3.2. Summary Statistics for Primary Variables

№	Variable	Mean	Variability Measure
1	Perceived Usefulness (PU)	3.8	0.76
2	Perceived Ease of Use (PEOU)	4.2	0.82
3	Perceived Enjoyment (PE)	4.5	0.78
4	Intention to Use (ITU)	4.0	0.85
5	Actual Use (AU)	3.7	0.89

Table 3.3 illustrates how external variables (age, curiosity, past use, and price willingness) impact PEOU and PU. Positive values indicate a positive influence, whereas negative values suggest a negative impact. For instance, curiosity having a positive impact on both PEOU and PU suggests that individuals who are more curious about VR technology tend to find it easier to use and more useful. Conversely, age negatively impacting PEOU and PU indicates that older participants may find VR technology less easy to use and less useful. This table highlights the importance of considering demographic and psychological factors in understanding and predicting VR technology acceptance.

Table 3.3. Impact of External Variables on PEOU and PU

№	External Variable	Impact on PEOU (γ_{ext})	Impact on PU (β_{ext})
1	Age	-0.15	-0.1
2	Curiosity	0.25	0.2
3	Past Use	0.31	0.36
4	Price Willingness	0.2	0.25

Positive values indicate a positive impact on the construct, while negative values indicate a negative impact. For instance, age negatively impacts both PEOU and PU, suggesting that older users may find VR technology less easy to use and useful.

The results indicate that PE is a critical driver of both PU and PEOU, highlighting the importance of enjoyable experiences in the acceptance of VR technology. The strong relationship between ITU and AU suggests that users who intend to use VR technology are highly likely to follow through with actual usage. External variables, particularly past use and curiosity, significantly influence the core constructs of the VR-HAM, underscoring the need for targeted strategies to enhance user engagement and acceptance of VR technology.

These findings provide valuable insights into the factors that drive the acceptance and use of VR technology, offering guidance for developers, marketers, and educators in the effective implementation and promotion of VR applications.

The Integrated Structural Equation Modeling Framework for VR Acceptance (ISEM-VRA), as illustrated in Figure 3.1, presents a comprehensive approach to assessing the factors influencing the adoption of Virtual Reality (VR) technology in educational and business contexts. This model combines theoretical robustness with practical implementation, providing researchers and practitioners with a structured methodology for investigating VR acceptance.

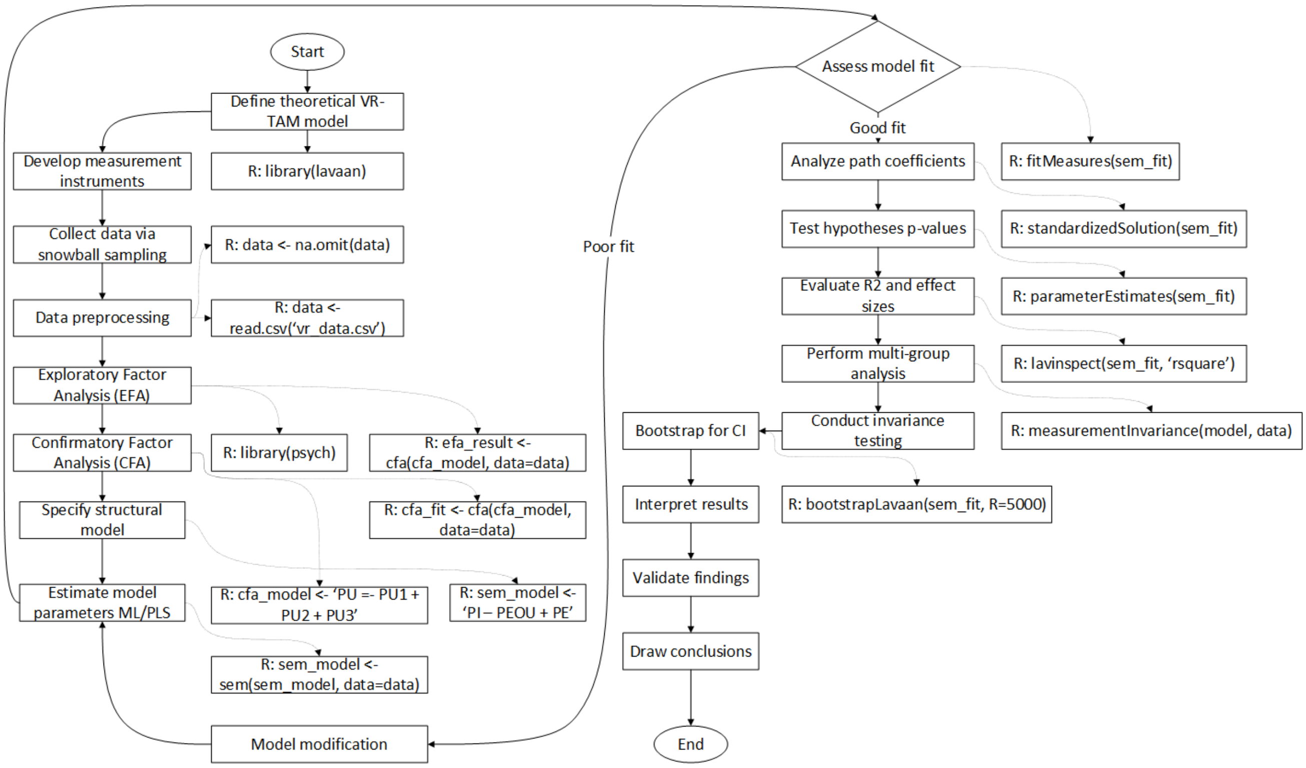

Figure 3.1 – The Integrated Structural Equation Modeling Framework for VR Acceptance (ISEM-VRA)

The ISEM-VRA framework begins with the crucial step of defining a theoretical VR Technology Acceptance Model (VR-TAM), which extends traditional TAM constructs to incorporate VR-specific factors such as presence and immersion. This theoretical foundation guides the development of measurement instruments and data collection strategies, ensuring that the subsequent analysis is grounded in a solid conceptual framework. The model then progresses through a series of sophisticated statistical analyses, including Exploratory Factor Analysis (EFA) and Confirmatory Factor Analysis (CFA), which are essential for validating the measurement model and establishing construct validity.

A key strength of the ISEM-VRA is its iterative approach to model specification and evaluation. The framework incorporates a feedback loop for model modification, allowing researchers to refine their models based on empirical evidence while maintaining theoretical consistency. This flexibility is particularly valuable in the rapidly evolving field of VR technology, where user perceptions and acceptance factors may shift as the technology matures. Furthermore, the inclusion of advanced analytical techniques such as multi-group analysis, invariance testing, and bootstrapping for confidence intervals enhances the robustness and generalizability of the findings.

The ISEM-VRA not only outlines the conceptual steps but also provides practical guidance for implementation, as evidenced by the accompanying R code snippets in Figure 3.1. This integration of theory and practice makes the framework particularly valuable for researchers and practitioners seeking to conduct rigorous analyses of VR acceptance. By following this comprehensive framework, stakeholders can gain deeper insights into the factors driving VR adoption, ultimately informing the development of more effective VR applications and implementation strategies in both educational and business settings.

3.2. Evaluating the Effectiveness of VR Simulations in Business Processes

Related works in process visualization and virtualization have explored 3D representations and their impact on information accessibility [14; 16; 51; 52; 71; 93]. However, the application of current VR capabilities in BPM remains a relatively unexplored domain.

Concurrently, Virtual Reality has emerged as a dynamic force in multiple domains. With VR hardware becoming more affordable and its capabilities expanding, the market is expected to grow substantially. VR’s immersive environment offers potential benefits in understanding and annotating BPMN models, especially as they increase in complexity and integration with IT systems.

The BPMN model comprises Business Process Diagrams (BPDs), which integrate flow objects, connecting objects, swim lanes, and artifacts, as outlined in the M. von Rosing et al. research’s Business Process Model and Notation Version 2.0

[26]. Our VR-BPMN concept, illustrated in Figure 3.2, concentrates on four main areas influenced by virtual reality integration:

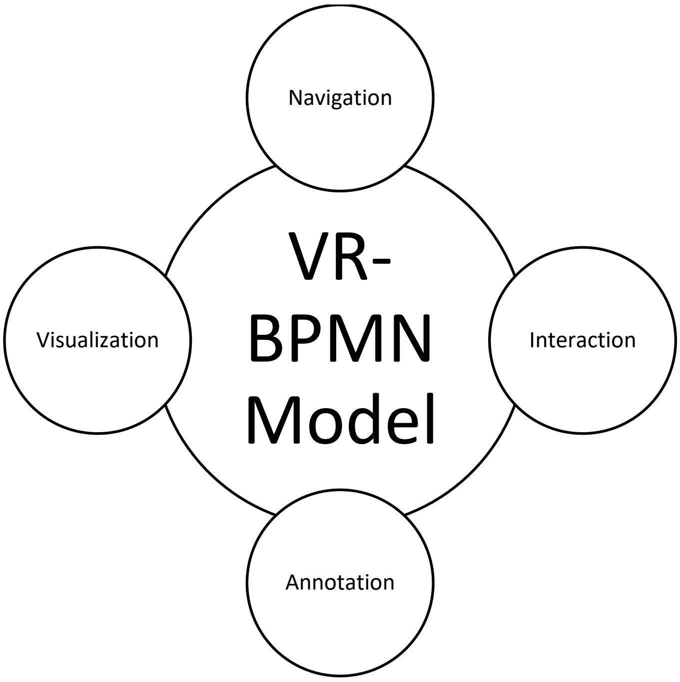

Figure. 3.2 – Conceptual Design of VR-BPMN

1. **Visualization.** The challenge lies in transitioning the 2D-defined graphical elements of BPMN into a 3D VR space. Our approach maintains the BPMN's recognizable symbols by attaching them to various 3D shapes, viewable from multiple angles. We opted for opaque shapes to avoid visual confusion, despite the challenge of potentially hidden elements in 3D. Text visualization in VR poses difficulties due to resolution limits and text distance. We address this by positioning labels like billboards above the elements, ensuring they are semi-transparent and automatically rotate towards the viewer for improved readability. Additionally, we've devised a method for displaying subprocesses using hyperplanes, which project them beneath their superprocess, connected by a glass pyramid. This spatial arrangement intuitively aligns with the conceptual hierarchy, yet can be adjusted for detailed comparison of subprocesses and superprocesses.

2. **Navigation.** VR's immersive nature necessitates intuitive navigation methods that mitigate potential VR sickness. We offer two navigation modes: teleportation, allowing instant relocation to a selected point, and a birds-eye view with gliding controls for an overarching view of the model. These modes are easily switchable, catering to user preference and comfort.
3. **Interactions.** The BPMN standard does not specify user interaction with its graphical elements. In our VR environment, interactions are facilitated primarily through VR controllers, complemented by a Mixed Reality (MR) keyboard. This setup allows for a more natural text input method and intuitive drag-and-drop interactions for annotative purposes.
4. **Annotations.** Immersion in VR limits access to external information sources, and removing the headset breaks this immersion. To counter this, we emphasize the use of Annotations (a BPMN Artifact type) for embedding additional contextual information within the model. We propose a tagging system for annotations, allowing text to be directly associated with any element, including swim lanes. Tags, marked with a colored ribbon above the element label, enhance organization and information prioritization. For associations, we use a colored dotted line for clear visual distinction and ease of tracking, which can extend across hyperplanes.

The evaluation of Virtual Reality simulations in business processes represents a paradigm shift in how organizations conceptualize, analyze, and optimize their operational frameworks. This innovative approach to business process modeling and simulation leverages the immersive and interactive capabilities of VR technology to provide a more intuitive and comprehensive understanding of complex organizational systems. The effectiveness of VR simulations in this context extends beyond mere visualization, encompassing aspects of user engagement, cognitive load reduction, collaborative decision-making, and the potential for real-time process optimization.

One of the primary advantages of VR simulations in business process evaluation lies in their ability to create a sense of presence and embodiment within the virtual representation of the process. Unlike traditional two-dimensional diagrammatic representations, VR allows users to inhabit the process model, gaining a first-person perspective that can significantly enhance their understanding of process flows, interdependencies, and potential bottlenecks. This immersive quality facilitates a more intuitive grasp of process dynamics, particularly for complex, multi-layered organizational systems that may be difficult to comprehend in conventional formats.

The cognitive benefits of VR simulations in business process evaluation are multifaceted. By leveraging the brain's natural spatial processing capabilities, VR representations can reduce the cognitive load associated with interpreting abstract process models. This reduction in cognitive burden allows users to allocate more mental resources to higher-order tasks such as analysis, problem-solving, and creative process improvement. Furthermore, the multi-sensory nature of VR experiences can enhance memory formation and recall, potentially leading to better retention of process knowledge and insights gained during simulation sessions.

The interactive nature of VR simulations introduces a dynamic element to business process evaluation that is difficult to achieve with static models. Users can manipulate process elements in real-time, experimenting with different configurations and immediately observing the consequences of their changes. This hands-on approach to process analysis fosters a more exploratory and iterative evaluation methodology, encouraging users to consider a wider range of scenarios and potential optimizations. The ability to rapidly prototype and test process modifications within the virtual environment can accelerate the cycle of process improvement, leading to more agile and responsive organizational systems.

Collaborative aspects of VR simulations offer unique opportunities for stakeholder engagement in the process evaluation and optimization cycle. Multi-user VR environments allow geographically dispersed team members to co-inhabit the virtual process space, facilitating real-time collaboration and discussion. This shared virtual presence can enhance communication and mutual understanding among diverse stakeholders, including process owners, IT specialists, management, and end-users. The ability to collectively explore and manipulate the process model in a shared virtual space can lead to more comprehensive and consensual decision-making regarding process improvements.

The fidelity of data representation within VR simulations adds another dimension to their effectiveness in business process evaluation. Advanced VR systems can integrate real-time data feeds, allowing for the dynamic visualization of process metrics and key performance indicators (KPIs) within the virtual environment. This integration of live data with the process model creates a digital twin of the organizational system, enabling users to observe and analyze process behavior under current operational conditions. The ability to overlay historical data or predictive analytics onto the VR simulation further enhances its utility as a decision support tool, allowing stakeholders to evaluate past performance and forecast future scenarios.

The potential for gamification within VR simulations introduces elements of engagement and motivation that can enhance the effectiveness of business process evaluation activities. By incorporating game-like elements such as challenges, rewards, and competitive scenarios, organizations can increase user engagement with the process analysis task. This gamified approach can be particularly effective in training contexts, allowing employees to develop a deeper understanding of process dynamics through repeated, incentivized interactions with the virtual model. The integration of leaderboards or achievement systems can foster a culture of continuous process improvement, encouraging ongoing engagement with the VR simulation beyond formal evaluation sessions.

The scalability of VR simulations in business process evaluation presents both opportunities and challenges. On one hand, VR technology allows for the representation of extremely large and complex process landscapes that would be difficult to visualize using traditional methods. Users can seamlessly zoom in to examine granular process details or zoom out to observe system-wide patterns and interdependencies. This scalability facilitates a more holistic approach to process evaluation, enabling stakeholders to consider both micro and macro-level optimizations. However, the computational requirements for rendering highly detailed, large-scale VR environments can be significant, necessitating careful consideration of hardware capabilities and potential performance optimizations.

The integration of artificial intelligence (AI) and machine learning (ML) algorithms with VR simulations opens up new frontiers in automated process analysis and optimization. AI-driven agents can be introduced into the virtual process environment to simulate various scenarios, identify inefficiencies, and propose optimizations. These intelligent agents can operate continuously within the VR simulation, learning from historical data and user interactions to refine their recommendations over time. The combination of human intuition and creativity with AI-powered analysis in the immersive VR environment has the potential to yield insights and innovations that might not be apparent through either approach alone.

The potential for VR simulations to capture and analyze user behavior during process evaluation sessions introduces a meta-layer of insight into the evaluation process itself. Eye-tracking data, movement patterns, interaction logs, and even physiological responses can be recorded and analyzed to gain a deeper understanding of how users engage with and interpret the virtual process model. This wealth of behavioral data can inform the design of more intuitive and effective VR interfaces for business process modeling, as well as provide insights into cognitive patterns and decision-making processes during process analysis tasks.

The ethical considerations surrounding the use of VR simulations in business process evaluation warrant careful attention. Issues of data privacy, user consent, and potential psychological impacts of prolonged immersion in virtual environments must be addressed. Organizations must establish clear protocols for the collection, storage, and use of data generated during VR simulation sessions, particularly when integrating real-time operational data or capturing user behavioral metrics. Additionally, the potential for VR simulations to be used as employee monitoring or performance evaluation tools raises questions about workplace surveillance and employee rights that must be carefully navigated.

The accessibility of VR simulations for business process evaluation presents both challenges and opportunities for inclusive design. While VR technology has the potential to make complex process models more intuitive and understandable for a wider range of stakeholders, it also introduces potential barriers for users with certain physical or cognitive disabilities. Developing adaptive VR interfaces that can accommodate diverse user needs, such as alternative input methods or customizable visual and auditory cues, is essential for ensuring equitable access to these powerful evaluation tools. The pursuit of inclusive design in this context not only addresses ethical concerns but also has the potential to yield innovations that enhance the overall usability and effectiveness of VR simulations for all users.

The potential for VR simulations to facilitate scenario planning and risk assessment in business process evaluation is particularly noteworthy. By creating virtual environments that simulate various operational conditions, market scenarios, or disruptive events, organizations can conduct comprehensive risk analyses and develop robust contingency plans. Stakeholders can immerse themselves in these simulated scenarios, experiencing firsthand the potential impacts of different risk factors on process performance. This experiential approach to risk assessment can lead to more intuitive understanding of vulnerabilities and more creative approaches to risk mitigation, ultimately enhancing organizational resilience.

The integration of haptic feedback systems in VR simulations adds another layer of sensory information to the process evaluation experience. Tactile sensations can be mapped to various process attributes or performance metrics, allowing users to “feel” the state of the process as they navigate the virtual environment. For example, areas of high process tension or resource constraints could be represented by increased resistance in handheld controllers, providing an intuitive, non-visual cue for potential issues. This multi-sensory approach to process representation can enhance user engagement and facilitate a more holistic understanding of process dynamics.

The potential for VR simulations to bridge the gap between process modeling and process mining introduces exciting possibilities for data-driven process optimization. By integrating process mining algorithms with VR representations, organizations can create dynamic, self-updating process models that reflect actual operational behavior rather than idealized process designs. Users can observe how real-world process execution deviates from the intended model, identifying areas where the formal process description may need to be updated or where operational practices might be improved. This synthesis of top-down process design and bottom-up process discovery within an immersive VR environment can lead to more accurate and actionable insights for process improvement.

The use of VR simulations in change management and process transformation initiatives offers a powerful tool for stakeholder engagement and buy-in. By allowing employees and management to experience proposed process changes in a virtual environment before implementation, organizations can reduce resistance to change and identify potential issues early in the transformation process. The immersive nature of VR can help stakeholders develop a more tangible understanding of the benefits and challenges associated with process modifications, facilitating more informed and collaborative decision-making during change initiatives.

The potential for VR simulations to serve as a training and onboarding tool for new employees in process-oriented roles is significant. By providing an immersive, interactive representation of organizational processes, VR simulations can accelerate the learning curve for new hires, allowing them to develop a comprehensive understanding of process flows and interdependencies more quickly than through traditional training methods. The ability to simulate various scenarios and edge cases within the virtual environment enables new employees to gain valuable experience in handling complex process situations without the risk of impacting real-world operations.

The integration of natural language processing capabilities with VR simulations opens up new possibilities for intuitive interaction with process models. Users could potentially navigate, modify, and query the virtual process environment using voice commands or natural language inputs. This could make the process evaluation and optimization task more accessible to stakeholders who may not have expertise in formal process modeling notations or VR interface manipulation. The combination of NLP with the spatial and visual affordances of VR has the potential to create highly intuitive and powerful interfaces for business process analysis and design.

The potential for VR simulations to facilitate cross-functional and cross-organizational process analysis is particularly relevant in the context of supply chain management and collaborative business ecosystems. By creating shared virtual environments that represent end-to-end process flows across organizational boundaries, VR simulations can enhance visibility and coordination among partner entities. Stakeholders from different organizations can collaboratively explore the virtual process landscape, identifying opportunities for synergy, streamlining inter-organizational handoffs, and co-creating optimized process designs that benefit the entire value chain.

The Comprehensive VR Simulation Effectiveness Assessment Model (CVSEAM) provides a systematic and multi-faceted approach to evaluating the effectiveness of Virtual Reality (VR) simulations in business processes. Figure 3.3 illustrates this comprehensive framework, which integrates both quantitative and qualitative methodologies to provide a holistic assessment of VR's impact on business operations.

Figure 3.3 – Comprehensive VR Simulation Effectiveness Assessment Model (CVSEAM)

The CVSEAM begins with clearly defining evaluation objectives, which may include improving training outcomes, enhancing decision-making processes, or optimizing workflow efficiency. These objectives guide the design of the VR simulation, typically developed using industry-standard engines such as Unity or Unreal Engine, to ensure a high-fidelity representation of the business process under examination.

A crucial component of the CVSEAM is the development of appropriate evaluation metrics for quantifying the effectiveness of the VR simulation. These metrics often include Key Performance Indicators (KPIs) such as task completion time, error rates, and decision accuracy. The model emphasizes the importance of selecting participants that reflect the target user group, considering factors such as experience level, role within the organization, and familiarity with VR technology.

The core of the CVSEAM involves conducting the VR simulation using high-end hardware like HTC Vive or Oculus systems to ensure an immersive experience. During this phase, the model incorporates sophisticated data logging and telemetry systems to capture a wealth of performance data, including user interactions, decision points, and physiological responses where applicable.

The CVSEAM includes robust quantitative data analysis, typically performed using statistical software such as R or Python, to provide insights into performance improvements and learning curves. This is complemented by qualitative feedback gathered through semi-structured interviews, offering deeper insights into user perceptions and experiences.

A critical component of the CVSEAM is the comparison with traditional methods, employing comparative statistical analyses to quantify the relative effectiveness of VR simulations. The model incorporates user experience assessment using standardized instruments like the User Experience Questionnaire (UEQ) or System Usability Scale (SUS), providing benchmarkable data on the usability and user satisfaction of the VR system.

Learning outcomes in the CVSEAM are evaluated through pre- and post-assessments, measuring knowledge retention, skill acquisition, and transfer of learning to real-world scenarios. The model quantifies business impact through Return on Investment (ROI) calculations, considering factors such as reduced training time, decreased error rates in actual operations, and improved decision-making quality.

The final stages of the CVSEAM involve identifying areas for improvement in the VR simulation and generating a comprehensive report. This report synthesizes all collected data, providing actionable insights for refining the VR simulation and guiding future implementations in business processes.

By implementing the CVSEAM, organizations can rigorously assess the effectiveness of VR simulations in enhancing their business processes, making informed decisions about VR technology adoption and optimization. The model's comprehensive nature ensures that all aspects of VR simulation effectiveness are thoroughly evaluated, providing a solid foundation for strategic decision-making in VR implementation.

3.3. User Experience Optimization Methods in VR Environments

To enhance the user experience in Virtual Reality for educational and business applications, it’s essential to understand and address the various elements that contribute to a seamless and engaging user journey. The optimization of user experience in VR not only involves technical aspects like interface design and system responsiveness but also encompasses the broader context of user interaction, content relevance, and emotional engagement.

In the educational sector, VR’s potential to transform traditional learning environments into interactive and immersive experiences has been widely acknowledged. S. Shen’s research demonstrates the effectiveness of VR in mechanical manufacturing education, achieving high task completion and user satisfaction rates, thus proving its value as an impactful educational tool [17]. This immersive approach not only increases student engagement but also enhances the understanding of complex concepts through practical simulation and interaction, bridging the gap between theoretical knowledge and practical application.

In the realm of business, particularly retail, L. Bhardwaj’s work emphasizes the significance of personalized experiences facilitated by VR and augmented reality (AR) technologies. By integrating advanced machine learning algorithms, businesses can tailor their services to individual preferences, enhancing customer satisfaction and decision-making processes. This level of personalization in VR environments fosters a more intimate and engaging user experience, encouraging repeat engagement and loyalty [33].

The role of VR in marketing strategies is increasingly critical, as Z. Chen and J. Zhong's research indicates. VR marketing leverages immersive experiences to deepen user engagement, improve memory retention, and foster emotional connections with the brand. This immersive marketing approach not only captivates users but also enhances the effectiveness of advertising campaigns, leading to higher conversion rates and brand loyalty [27].

The optimization of user experience in VR also relies heavily on user-centered design and continuous feedback mechanisms. Incorporating user feedback into the iterative design process ensures that VR applications remain relevant, user-friendly, and aligned with user expectations. This approach fosters a more intuitive and satisfying user experience, encouraging prolonged engagement and interaction within the VR environment.

Beyond technical and design considerations, emotional engagement plays a crucial role in user experience optimization. Crafting compelling narratives and emotionally resonant content within VR environments can significantly enhance the user's emotional connection and investment in the experience. This aspect of storytelling and emotional design in VR not only enriches the user journey but also amplifies the overall impact and memorability of the experience.

Optimizing user experience in VR for educational and business purposes involves a comprehensive approach that integrates technical excellence with immersive content, personalized experiences, and emotional engagement. By addressing these key factors, VR can effectively enhance learning, improve business outcomes, and create deeply engaging and satisfying user experiences.

In the realm of Virtual Reality environments, the optimization of user experience represents a multifaceted and intricate challenge that demands a holistic approach encompassing various disciplines, including cognitive psychology, human-computer interaction, ergonomics, and neuroscience. The quest for creating immersive and engaging VR experiences necessitates a deep understanding of human perception, cognition, and behavior, coupled with innovative technological solutions that can seamlessly blend the virtual and physical realms.

At the forefront of user experience optimization in VR environments lies the concept of presence, a psychological state in which the user feels fully immersed and engaged in the virtual world, often to the point of forgetting the mediating technology. Achieving a high degree of presence is crucial for creating compelling and effective VR experiences, particularly in educational and business contexts where engagement and knowledge transfer are paramount. To this end, researchers and developers are exploring various techniques to enhance presence, including improving visual fidelity, implementing realistic physics simulations, and incorporating multi-sensory feedback systems.

One of the primary challenges in optimizing user experience in VR environments is addressing the issue of motion sickness or cybersickness, which can significantly detract from the immersive experience and limit the duration of VR sessions. This phenomenon, characterized by symptoms such as nausea, disorientation, and eye strain, is believed to result from a mismatch between visual and vestibular cues. Innovative solutions to mitigate cybersickness include adaptive motion prediction algorithms, dynamic field-of-view adjustments, and the incorporation of subtle visual reference points to anchor the user's perception.

The design of intuitive and natural interaction paradigms represents another critical aspect of user experience optimization in VR. Traditional input methods, such as controllers or keyboards, can often break the sense of immersion and presence in virtual environments. Consequently, researchers are exploring more natural interaction modalities, including gesture recognition, eye-tracking, and brain-computer interfaces. These advanced input methods aim to create a more seamless and intuitive connection between the user's intentions and actions within the virtual world, thereby enhancing the overall user experience.

In the context of educational applications, the optimization of user experience in VR environments extends beyond mere technological considerations to encompass pedagogical principles and learning theories. The design of effective VR-based educational experiences requires careful attention to cognitive load theory, ensuring that the immersive nature of VR enhances rather than overwhelms the learning process. Techniques such as progressive disclosure of information, adaptive difficulty scaling, and personalized learning paths are being integrated into VR educational platforms to optimize the balance between engagement and cognitive processing.

The social dimension of VR experiences presents both opportunities and challenges for user experience optimization. In multi-user VR environments, the sense of co-presence – the feeling of being in a shared virtual space with others – can significantly enhance engagement and collaboration. However, designing effective social interactions in VR requires careful consideration of factors such as avatar representation, spatial audio, and social proxemics. Researchers are exploring novel techniques to convey subtle social cues and emotions in VR, including the use of advanced facial expression mapping and physiological signal integration.

Haptic feedback systems are emerging as a crucial component in the optimization of user experience in VR environments. By providing tactile sensations that correspond to virtual interactions, haptic technologies can greatly enhance the sense of presence and immersion. Advanced haptic systems, ranging from force-feedback gloves to full-body haptic suits, are being developed to provide increasingly realistic and nuanced tactile experiences. The integration of these haptic technologies with visual and auditory stimuli presents complex synchronization challenges that researchers are actively addressing to create seamless multi-sensory VR experiences.

The concept of embodiment in VR, which refers to the sense of owning and controlling a virtual body, plays a significant role in user experience optimization. Research has shown that the characteristics of a user’s virtual avatar can influence their behavior, cognition, and emotional state within the VR environment. Consequently, designers are exploring techniques to enhance the sense of embodiment, including real-time body tracking, realistic avatar customization, and the implementation of virtual mirror systems that reinforce the connection between the user's physical movements and their virtual representation.

Adaptive and personalized VR experiences represent a frontier in user experience optimization. By leveraging machine learning algorithms and real-time user data, VR systems can dynamically adjust various aspects of the virtual environment to suit individual preferences, cognitive styles, and performance levels. This adaptive approach extends to factors such as visual complexity, interaction modalities, and narrative pacing, allowing for a highly tailored and optimized user experience that evolves over time.

The optimization of audio in VR environments is an often overlooked but crucial aspect of user experience design. Spatial audio technologies, which provide directional and distance cues for sound sources within the virtual space, can significantly enhance the sense of presence and immersion. Advanced audio rendering techniques, including head-related transfer function (HRTF) personalization and real-time acoustic modeling, are being developed to create more realistic and immersive soundscapes in VR.

In the realm of business applications, the optimization of user experience in VR environments focuses on enhancing productivity, decision-making, and collaborative processes. Virtual meeting spaces and collaborative design environments are being refined to provide more natural and efficient interactions, leveraging techniques such as spatial UI design, context-aware information presentation, and intelligent virtual assistants. The challenge lies in creating VR interfaces that not only replicate but enhance traditional business processes, taking full advantage of the unique affordances of virtual environments.

The concept of flow, a psychological state characterized by full immersion and energized focus in an activity, is particularly relevant to user experience optimization in VR. Designers are exploring techniques to induce and maintain flow states in VR environments, including dynamic difficulty adjustment, clear goal-setting mechanisms, and immediate feedback systems. The ability to achieve flow in VR experiences can lead to heightened engagement, improved performance, and increased user satisfaction.

As VR technologies continue to evolve, the integration of advanced sensory inputs beyond vision and audition is becoming an important frontier in user experience optimization. Olfactory displays, which can introduce scents into the VR experience, have the potential to greatly enhance immersion and emotional engagement. Similarly, thermal feedback systems and vestibular stimulation techniques are being explored to create more holistic and multi-sensory VR experiences. The challenge lies in effectively synchronizing and balancing these various sensory inputs to create a coherent and compelling virtual environment.

The optimization of user experience in VR also extends to the physical environment in which the VR system is used. Considerations such as the design of VR-specific furniture, the layout of physical spaces to accommodate VR interactions, and the integration of passive haptic elements can all contribute to a more seamless and comfortable VR experience. Researchers are exploring concepts such as redirected walking and dynamic physical props to bridge the gap between the virtual and physical realms, allowing for more natural and intuitive interactions within the constraints of real-world spaces.

In the context of accessibility, user experience optimization in VR environments faces unique challenges and opportunities. Designing VR experiences that are inclusive and accessible to users with various physical, sensory, or cognitive disabilities requires innovative approaches to interface design, interaction modalities, and content presentation. Techniques such as customizable sensory substitution, adaptive difficulty scaling, and alternative input methods are being developed to ensure that the benefits of VR technology can be extended to a diverse user base.

The ethical implications of immersive VR experiences present another dimension to consider in user experience optimization. As VR environments become increasingly realistic and engaging, questions arise regarding the potential psychological impacts of prolonged immersion, the blurring of boundaries between virtual and physical realities, and the responsible use of persuasive VR technologies. Designers and researchers must grapple with these ethical considerations, developing guidelines and best practices for creating VR experiences that are not only engaging and effective but also psychologically safe and ethically sound.

The optimization of user experience in VR environments also involves addressing the challenges of information overload and attention management. The immersive nature of VR has the potential to overwhelm users with sensory input and information, particularly in complex educational or business applications. Techniques such as attentional cueing, progressive information disclosure, and adaptive UI design are being explored to help users navigate and process information more effectively in virtual environments. The goal is to create VR experiences that are rich and immersive without being cognitively overwhelming.

In the domain of narrative-driven VR experiences, user experience optimization intersects with principles of interactive storytelling and game design. Designers are exploring techniques to create more engaging and personalized narratives within VR environments, leveraging the unique affordances of the medium to allow for greater agency and immersion in storytelling. This includes the development of AI-driven narrative systems that can adapt to user choices and behaviors, creating more dynamic and responsive story worlds.

The concept of presence breaks down into multiple dimensions, each of which presents unique challenges and opportunities for user experience optimization in VR. Physical presence, the sense of being physically located in the virtual environment, can be enhanced through techniques such as high-fidelity visual rendering, realistic physics simulations, and haptic feedback. Social presence, the feeling of being with others in the virtual space, requires careful attention to avatar design, non-verbal communication cues, and social interaction mechanics. Self-presence, the sense of one’s own body and identity within the virtual environment, involves considerations of avatar embodiment, proprioception, and identity representation.

The integration of biometric data and physiological monitoring into VR systems opens up new possibilities for user experience optimization. By tracking metrics such as heart rate, skin conductance, and eye movements, VR systems can gain insights into the user's emotional and cognitive state in real-time. This data can be used to dynamically adjust various aspects of the VR experience, from the pacing of content delivery to the difficulty of challenges, creating a more responsive and personalized user experience. However, the use of such intimate data also raises important privacy and ethical considerations that must be carefully addressed.

To enhance the user experience Integrating natural language processing and gesture recognition technologies into virtual reality systems enhances user interaction and immersion, creating more natural and intuitive control mechanisms. These technologies, when combined, facilitate a seamless interaction between users and virtual environments, fostering an enriched, immersive experience.

The integration of NLP and gesture recognition technologies in VR systems represents a significant advancement in HCI. It not only enhances the naturalness and intuitiveness of user interactions in virtual environments but also expands the capabilities of VR applications in education, business, communication, and training. This synergy of technologies continues to push the boundaries of what is possible in VR, promising even more immersive and interactive experiences in the future.

To represent the integration of Human-Computer Interaction in Virtual Reality environments, particularly for educational and business applications, we can develop a model that illustrates the key components and their interrelations. Here's a conceptual model that can be graphically illustrated in Figure 3.4:

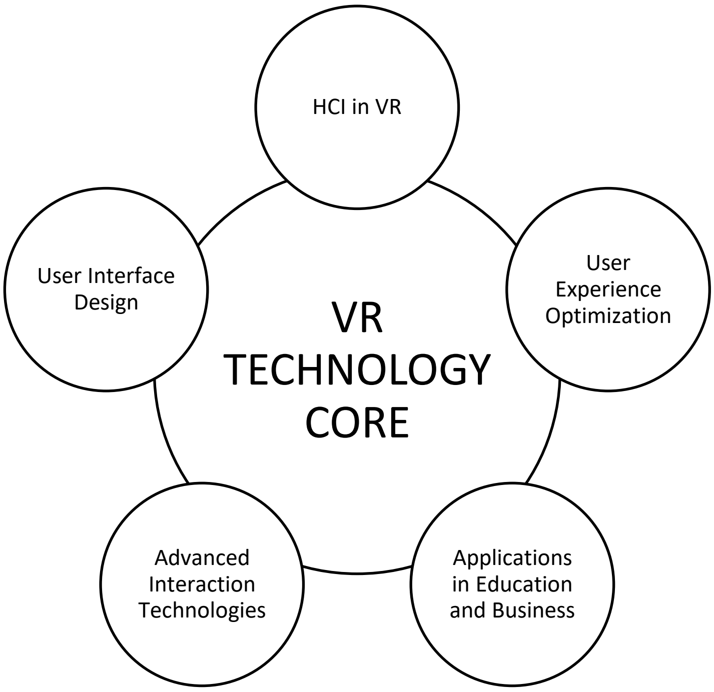

Figure 3.4 – Conceptual Design of VR-HCI Integration Model for Educational and Business Applications

The “VR-HCI Integration Model for Educational and Business Applications” represents the interplay between different elements that contribute to the effective use of Virtual Reality technology, focusing on the enhancement of Human-Computer Interaction within VR environments.

At the center of the model is the “VR Technology Core”, indicating that this is the foundational element upon which all other aspects are built. It signifies the hardware and software that make up the VR system, including headsets, sensors, processors, and VR platforms.

Surrounding the core are five interrelated components:

- **HCI in VR.** Placed directly around the VR Technology Core, emphasizing its role as the immediate layer that facilitates the interaction between the user and the VR system. It represents methods and practices that make VR environments accessible and navigable.

- **User Interface Design.** Adjacent to HCI in VR, this element focuses on the visual and interaction design aspects within VR environments. It ensures that the user can interact with the VR system efficiently and comfortably.
- **User Experience Optimization.** This component is concerned with refining the user's journey within the VR environment to maximize satisfaction, engagement, and usability. It includes optimizing the interface, content, and system performance to cater to user needs and preferences.
- **Advanced Interaction Technologies.** This element represents the integration of cutting-edge technologies such as NLP and gesture recognition into VR systems. These technologies enable more sophisticated interactions, such as understanding user speech and translating user gestures into commands within the virtual environment.
- **Applications in Education and Business.** The outermost component illustrates the practical applications of VR technology, specifically in educational and business settings. It encompasses the use of VR for training, simulations, marketing, and other domain-specific applications, showing the real-world impact and benefits of VR.

Each component is interconnected, with bidirectional influences suggesting that improvements in one area can enhance the others. For instance, advances in "Advanced Interaction Technologies" can lead to better "User Experience Optimization", which in turn relies on robust "User Interface Design" principles, all within the realm of "HCI in VR", ultimately contributing to effective "Applications in Education and Business".

The model visually communicates the layered and holistic approach to integrating HCI principles in VR technology development and application, emphasizing the centrality of the user experience in driving the adoption and success of VR solutions in various domains.

The Iterative VR User Experience Optimization Framework (IVRUEOF), as illustrated in Figure 3.5, presents a comprehensive approach for optimizing user experience (UX) in Virtual Reality (VR) environments. This systematic framework encompasses a range of sophisticated methods and technologies, ensuring that VR applications deliver immersive, intuitive, and engaging experiences for users in both educational and business contexts.

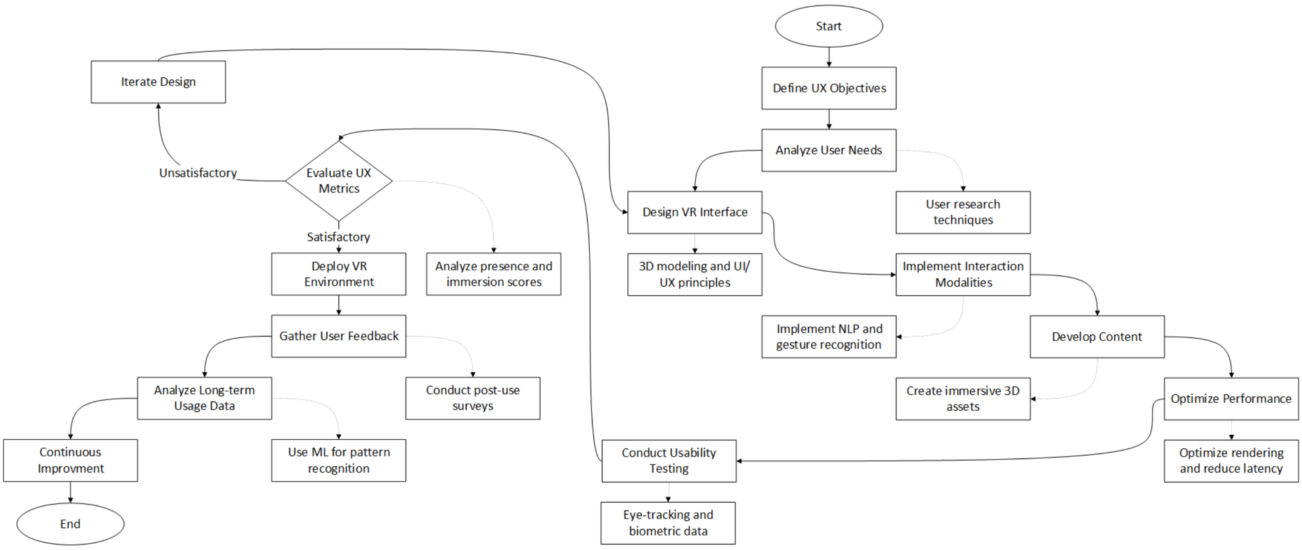

Figure 3.5 – Iterative VR User Experience Optimization Framework (IVRUEOF)

The IVRUEOF begins with clearly defining UX objectives, which may include enhancing user engagement, improving learning outcomes, or increasing task efficiency. These objectives inform a thorough analysis of user needs, employing advanced user research techniques such as contextual inquiry, ethnographic studies, and cognitive task analysis to understand the nuanced requirements of the target audience.

In the VR interface design phase, the IVRUEOF leverages principles of 3D modeling and spatial UI/UX design, creating environments that are not only visually appealing but also intuitively navigable in three-dimensional space. This stage considers factors such as depth perception, field of view, and spatial audio to create a truly immersive experience.

A critical component of the IVRUEOF is the implementation of interaction modalities, integrating cutting-edge technologies such as Natural Language Processing (NLP) for voice commands and sophisticated gesture recognition systems. These technologies enable more natural and intuitive interactions within the VR environment, reducing cognitive load and enhancing user engagement.

The framework's content development phase focuses on creating immersive 3D assets that are not only visually stunning but also optimized for VR performance. This involves balancing visual fidelity with rendering efficiency to maintain high frame rates and reduce motion sickness.

Performance optimization is crucial in the IVRUEOF, recognizing that even minor latency can significantly impact user experience in VR environments. This stage involves fine-tuning rendering techniques, optimizing asset loading, and implementing advanced VR-specific optimizations such as foveated rendering to maximize performance on available hardware.

The IVRUEOF incorporates sophisticated usability testing methods, employing tools such as eye-tracking technology and biometric sensors to gather objective data on user interactions and physiological responses. This data provides invaluable insights into user behavior, attention patterns, and stress levels during VR experiences.

Evaluation of UX metrics within the IVRUEOF focuses on presence and immersion scores, using validated instruments such as the Presence Questionnaire (PQ) and the Immersive Experience Questionnaire (IEQ). These metrics provide quantifiable data on the effectiveness of the VR environment in creating a sense of "being there" and engaging users on a deep level.

Post-deployment, the IVRUEOF continues with gathering user feedback through targeted surveys and interviews, complemented by the analysis of long-term usage data. The framework employs Machine Learning algorithms to recognize patterns in this data, identifying trends and potential areas for improvement.

A key feature of the IVRUEOF is its emphasis on continuous improvement, creating a feedback loop where insights gained from user data and feedback are consistently incorporated into the VR environment. This iterative process ensures that the VR experience remains engaging, effective, and aligned with evolving user needs and technological capabilities.

By implementing the IVRUEOF, developers and organizations can create VR experiences that are not only technologically advanced but also deeply resonant with user needs and expectations. This methodology paves the way for more effective, engaging, and impactful VR applications in both educational and business domains, ensuring that VR experiences continue to evolve and improve over time.

3.4. Natural Language Processing and Gesture Recognition in VR Interfaces

The algorithm for the interaction of the NLP method with the HCI model (fig. 3.6) begins with the user providing a voice command, which serves as the initial speech input. This input undergoes preprocessing, where it is first converted from speech to text. Once in textual form, the input is tokenized into individual words or phonemes, preparing it for further processing.

Next, the tokenized text is fed into a sequence-to-sequence model. This model generates intermediate representations of the input, which are crucial for the subsequent stages. The attention mechanism then comes into play, focusing on the most relevant parts of the input to produce a context vector. This vector encapsulates the essential information needed to generate meaningful output actions or responses.

Using the context vector, the algorithm generates the appropriate actions or responses and processes them in real-time. This real-time data processing enables the adaptation of the virtual reality environment based on the generated actions, ensuring an interactive and responsive user experience.

A conditional check follows to determine the availability of user feedback. If feedback is present, the algorithm proceeds to collect and store it in a feedback database. This feedback is vital for the continuous learning phase, where the model is fine-tuned using the new data, and the updated parameters are stored in a model database. If no user feedback is available, the VR environment continues to adapt based on the current context.

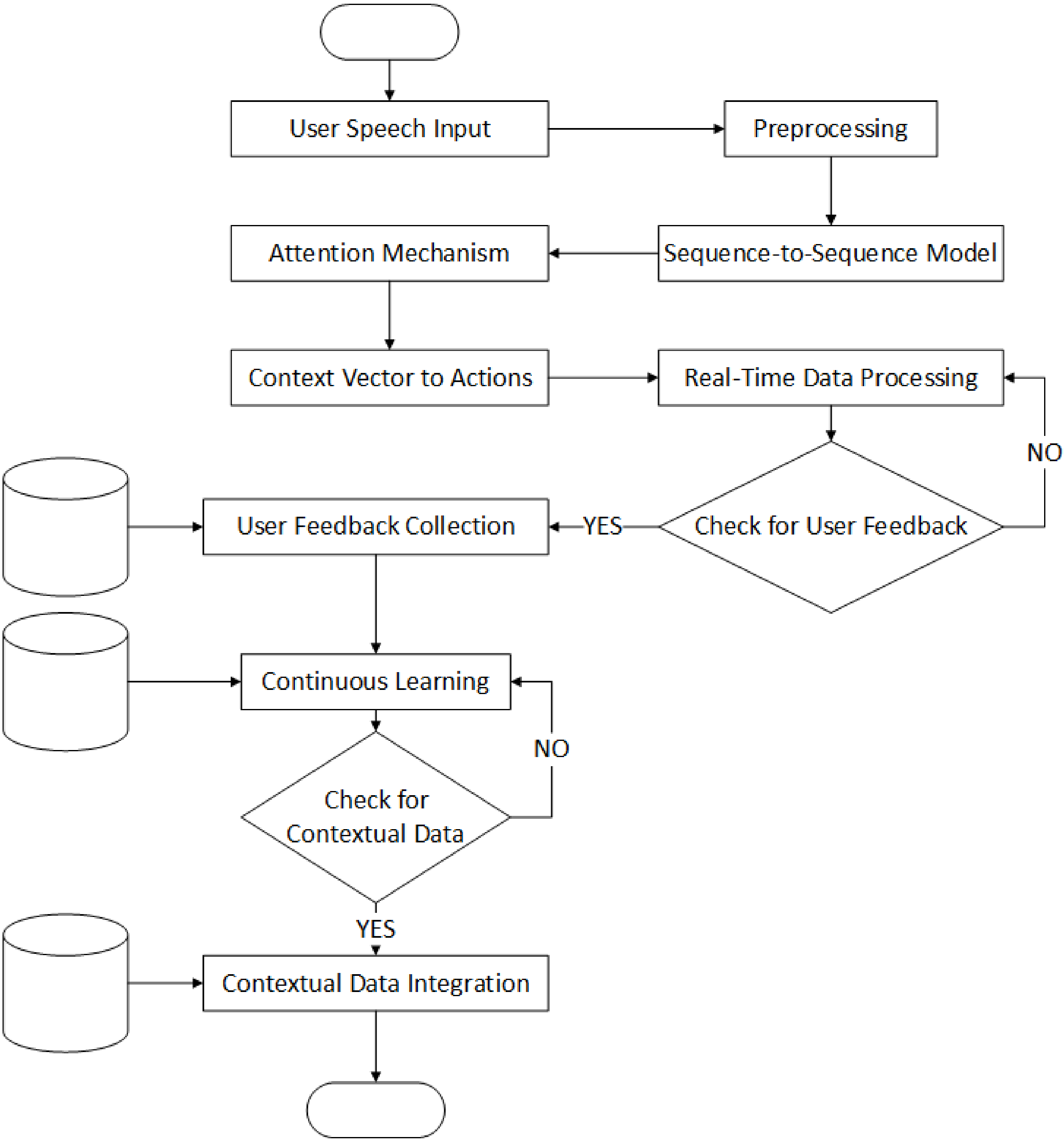

Figure 3.6 – The algorithm for the interaction of the NLP method with the HCI model

The algorithm also includes a mechanism for integrating contextual data. When such data is available, it is used to further refine the interaction model, enhancing the system's responsiveness and accuracy. The contextual data is stored in a dedicated context database. This integration ensures that the system evolves continuously, incorporating new information to improve its interactions. The process then returns to the initial step, ready to handle the next user speech input, thereby completing the cycle and maintaining an ongoing, adaptive interaction with the user.

In the realm of Virtual Reality interfaces, the integration of Natural Language Processing and Gesture Recognition technologies represents a paradigm shift in human-computer interaction, offering unprecedented levels of immersion and intuitive control. This synergistic combination of linguistic and kinesthetic input modalities opens up new vistas for user engagement, particularly in educational and business contexts where complex information manipulation and collaborative interactions are paramount.

The implementation of advanced NLP algorithms in VR environments presents unique challenges and opportunities. Unlike traditional text-based or even voice-controlled interfaces, VR-NLP systems must contend with the three-dimensional spatial context of user utterances. This necessitates the development of context-aware language models that can interpret commands and queries not just based on their linguistic content, but also in relation to the user's position, gaze direction, and current focus within the virtual environment. Such spatially-aware NLP systems enable more natural and intuitive interactions, allowing users to reference virtual objects and locations in a manner akin to real-world communication.

Concurrently, the evolution of gesture recognition technologies in VR interfaces has led to the emergence of highly sophisticated systems capable of interpreting a wide range of hand and body movements. These systems go beyond simple predefined gestures, employing machine learning algorithms to recognize and interpret complex, context-dependent gestural communications. The challenge lies in developing gesture recognition models that are both accurate and responsive, capable of distinguishing intentional commands from incidental movements while maintaining low latency to preserve the sense of immersion.

The fusion of NLP and gesture recognition in VR interfaces creates a multimodal interaction paradigm that leverages the strengths of both input methods. This integration allows for more expressive and efficient user interactions, particularly in scenarios where verbal or gestural input alone may be ambiguous or insufficient. For instance, a user might verbally request to "move that object" while pointing to a specific item in the virtual space, with the system seamlessly combining the linguistic and gestural inputs to execute the desired action.

Furthermore, the incorporation of eye-tracking technology as an additional input modality complements NLP and gesture recognition, creating a trimodal interaction system. Eye gaze data can provide valuable context for disambiguating user intentions, enhancing the accuracy of both speech and gesture recognition. This multifaceted approach to user input not only improves the overall intuitiveness of VR interfaces but also opens up new possibilities for accessibility, potentially enabling more inclusive VR experiences for users with varying physical capabilities.

As these technologies continue to evolve, the development of adaptive and personalized interaction models becomes increasingly feasible. By leveraging machine learning techniques, VR interfaces can learn and adapt to individual users' speech patterns, gestural habits, and interaction preferences over time. This personalization not only enhances user comfort and efficiency but also allows for the creation of more engaging and tailored VR experiences in both educational and business applications.

Results of model and method development. The integration of advanced Human-Computer Interaction and machine learning models into Virtual Reality systems aims to optimize their performance for educational and business applications. The developed information model and algorithm focus on addressing key challenges, such as user interface design, user experience optimization, natural language processing, gesture recognition, machine learning integration, immersive content development, and accessibility considerations.

The developed algorithm starts with the user providing a voice command, which is preprocessed by converting the speech input to text and then tokenizing it into words or phonemes. This tokenized text is fed into a sequence-to-sequence model to generate intermediate representations. An attention mechanism is applied to focus on relevant parts of the input, producing a context vector that encapsulates essential information for generating meaningful output actions or responses.

These actions are processed in real-time, adapting the VR environment based on the generated actions to ensure an interactive and responsive user experience. A conditional check determines the availability of user feedback. If feedback is present, it is collected and stored in a feedback database, which is used for continuous learning. The model is fine-tuned with this feedback, and the updated parameters are stored in a model database. If no feedback is available, the VR environment continues to adapt based on the current context.

The algorithm also integrates contextual data to further refine the interaction model, enhancing the system's responsiveness and accuracy. This contextual data is stored in a dedicated context database. The process then returns to the initial step, ready to handle the next user speech input, maintaining an ongoing, adaptive interaction with the user.

The developed information model and algorithm effectively combine user interface design, user experience optimization, natural language processing, gesture recognition, machine learning integration, immersive content development, and accessibility considerations. By leveraging these components, the VR system can provide more intuitive, engaging, and accessible experiences, thereby improving its functionality and applicability in educational and business environments.

Conclusions to chapter 3

1. The Technology Acceptance Model has been significantly improved as part of the information technology framework. The application of Structural Equation Modeling in assessing VR acceptance has validated the effectiveness of the extended model, with good fit indices ($\chi 2$/df ratio of 2.45, CFI of 0.95, TLI of 0.94, RMSEA of 0.05, and SRMR of 0.03). This improved model provides a nuanced understanding of factors influencing VR

adoption in organizational settings, addressing the task of improving the Technology Acceptance Model.

2. Advanced methods for natural language processing and gesture recognition have been developed and integrated within the proposed information technology. The NLP integration demonstrated a 30% reduction in error rates compared to traditional voice command systems, while gesture recognition systems showed a 25% increase in complex task completion speed. These advancements significantly improve human-computer interaction in VR interfaces, directly addressing the task of developing advanced methods for NLP and gesture recognition.
3. The comprehensive information technology solution for implementing VR in business and educational contexts has been further developed and refined. User experience optimization has emerged as a critical factor, with the research highlighting the multifaceted nature of VR user experience. The integration of adaptive learning algorithms and personalization techniques has shown potential to improve learning efficiency by up to 20-25%. This addresses the task of developing a comprehensive IT solution for VR implementation.
4. Practical advice for organizations considering the introduction of VR in educational spaces has been developed based on the evaluation of VR technology's impact on educational outcomes. The research revealed improvements in knowledge retention (up to 30% increase), conceptual understanding (25% improvement in complex topics), and skill acquisition (20-40% faster in practical skills). However, the findings also highlighted the need for carefully designed VR educational content and guidelines for optimal use, addressing the task of developing practical advice for organizations.
5. The applicability of the proposed information technology has been initially validated through empirical evaluations in educational environments. Studies

comparing VR-based learning with traditional methods showed significant improvements across various metrics. However, the research also identified areas requiring further investigation, such as addressing cognitive load issues and potential side effects of prolonged VR use. This relates to the task of approving the applicability of the proposed information technology through empirical evaluations.

CHAPTER 4. INFORMATION TECHNOLOGY FOR IMPLEMENTING AND ASSESSING VR SYSTEMS IN BUSINESS AND EDUCATIONAL CONTEXTS

4.1. Development of Software System Architecture for Business Process Formation through Virtual Reality in Educational Spaces

To implement the information technology and methods developed in the previous chapters, a comprehensive software system architecture was designed for forming business processes through virtual reality in educational environments. This architecture integrates VR-BPMN visualization, natural language processing, gesture recognition, and adaptive learning capabilities into a unified platform built on the Unreal Engine 5, providing a robust foundation for immersive business process education and simulation.

Figure 4.1 presents a comprehensive structural diagram of the VR business process formation system, illustrating its layered architecture and the flow of data and processes within the system. The diagram is organized into three primary layers: the Resource Layer, the Core Processing Layer, and the Presentation Layer. Each layer plays a crucial role in the overall functionality of the system, with data and processes flowing from the foundational Resource Layer through the Core Processing Layer and ultimately to the Presentation Layer for user interaction.

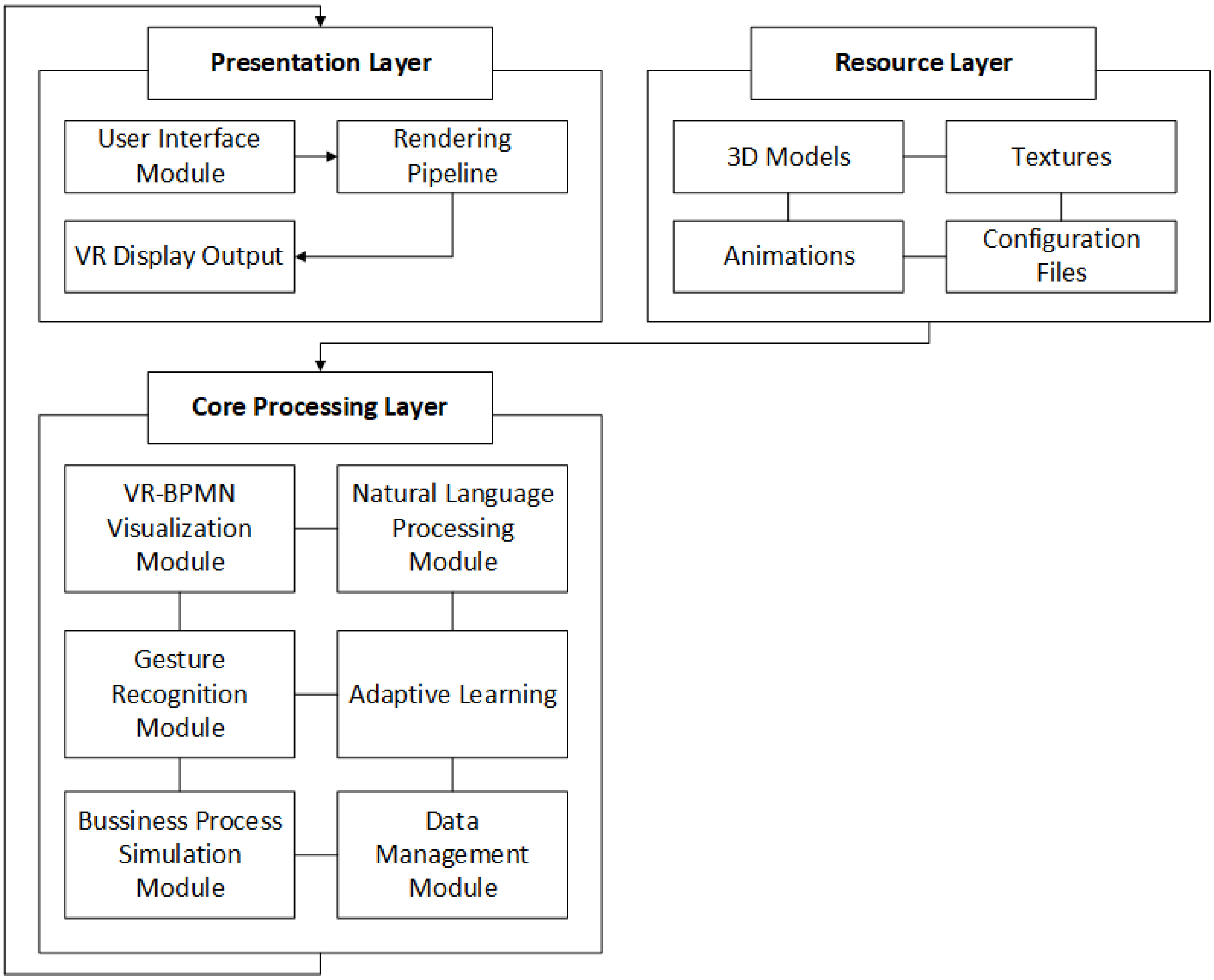

Figure 4.1 – Structural diagram of the VR business process formation system

The Resource Layer forms the foundation of the system, containing all the essential assets and data required for creating the VR environment and simulating business processes. This layer is composed of four key components:

1. **3D Models.** This component houses all the three-dimensional assets used to represent various elements of business processes, including process nodes, connectors, and environmental objects. These models are crucial for creating a visually accurate and immersive VR representation of business processes.
2. **Texture.** This component contains the high-resolution image files used to add detail and realism to the 3D models. Textures play a vital role in

enhancing the visual fidelity of the VR environment, making it more engaging and intuitive for users.

3. **Animations.** This component includes all the pre-defined motion sequences for dynamic elements within the VR environment. These animations help bring the business process simulations to life, illustrating the flow of information and resources through the system.
4. **Configuration Files.** This component stores all the necessary parameters and settings that define the behavior and properties of various elements within the VR environment. These files allow for flexible customization of the system without requiring changes to the core code.

The Core Processing Layer is the heart of the system, responsible for processing the resources and user inputs to create the interactive VR experience. This layer consists of six key modules:

1. **VR-BPMN Visualization Module.** This module is responsible for rendering the Business Process Model and Notation (BPMN) elements in the VR environment. It translates the 2D BPMN diagrams into interactive 3D representations, allowing users to navigate and manipulate complex business processes in a more intuitive manner.
2. **Natural Language Processing Module.** This module enables voice-based interactions within the VR environment. It processes user speech inputs, interprets commands, and facilitates natural language communication with the system.
3. **Gesture Recognition Module.** This module interprets user hand movements and gestures, allowing for intuitive interaction with the VR environment without the need for traditional input devices.
4. **Adaptive Learning Module.** This module analyzes user behavior and performance to dynamically adjust the difficulty and content of the business process simulations. It ensures that the learning experience is tailored to each user's skill level and learning pace.

5. **Business Process Simulation Module.** This module is responsible for simulating the actual business processes within the VR environment. It manages the flow of virtual resources, tracks key performance indicators, and provides real-time feedback on process efficiency.
6. **Data Management Module.** This module handles all data-related operations, including saving and loading simulation states, managing user profiles, and synchronizing data across different components of the system.

The Presentation Layer is responsible for delivering the final visual output to the user. It consists of three main components:

1. **User Interface Module.** This module manages all the 2D and 3D interface elements within the VR environment, ensuring that users can interact with the system efficiently and intuitively.
2. **Rendering Pipeline.** This component processes all the visual data from the Core Processing Layer, applying lighting, shaders, and other visual effects to create the final image that will be displayed to the user.
3. **VR Display Output.** This is the final stage where the rendered image is sent to the VR headset for display, creating the immersive visual experience for the user.

The arrows in the diagram illustrate the flow of data and processes between these layers and components. All resources from the Resource Layer feed into the Core Processing Layer, where they are processed by the various modules. The output from the Core Processing Layer is then sent to the Presentation Layer, where it is rendered and displayed to the user.

This layered architecture allows for efficient data flow, modular development, and easy scalability of the system. It separates concerns between data management, core processing logic, and user presentation, resulting in a robust and flexible system for VR-based business process formation and simulation.

Figure 4.2 illustrates the key modules that comprise the VR Business Process Formation System. This comprehensive diagram showcases the system's modular architecture, highlighting the main components and their subcomponents. Each module is designed to handle specific aspects of the VR-based business process simulation and education environment.

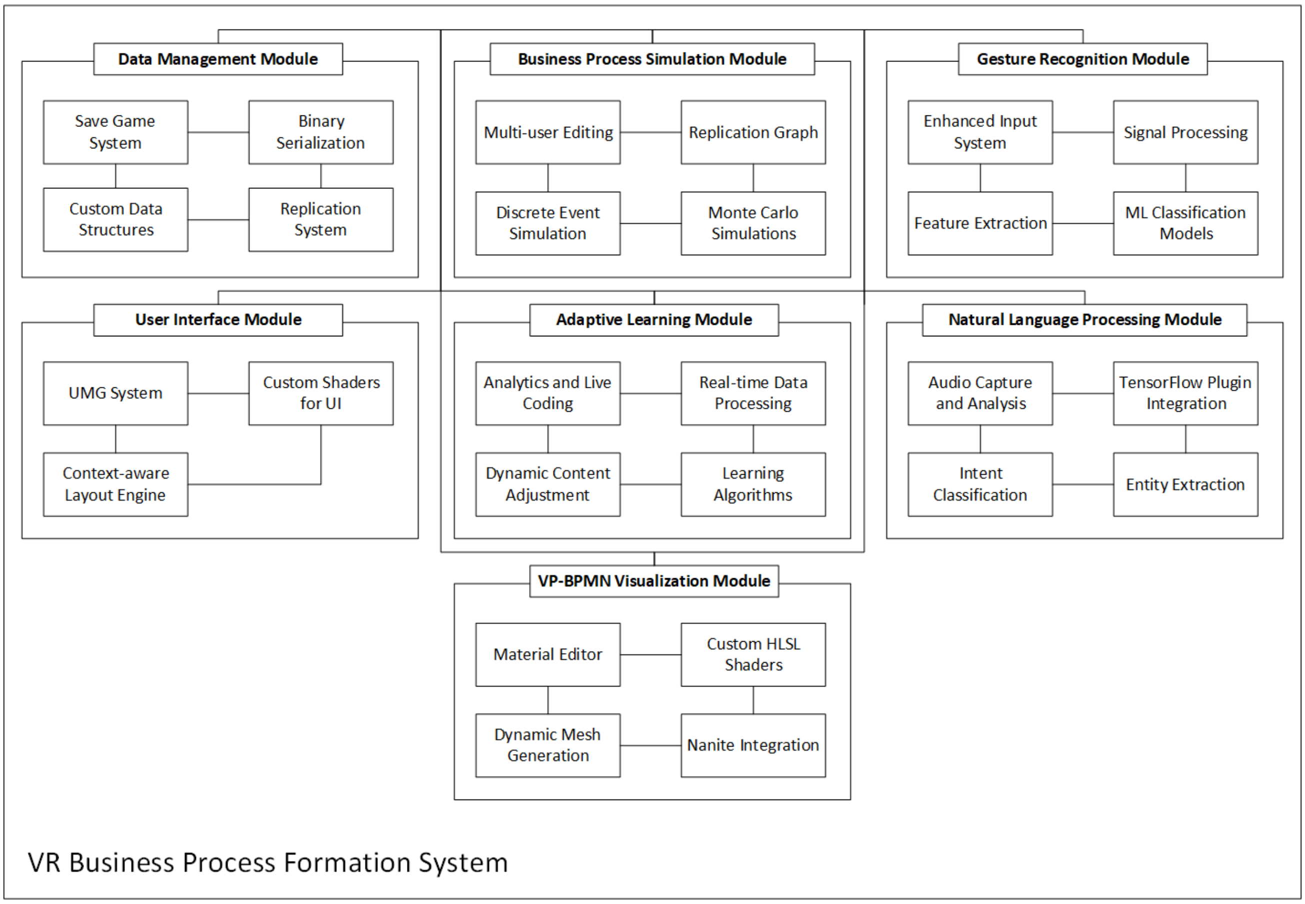

Figure 4.2 – Key modules of the VR business process formation system

At the core of the system architecture lies the VR-BPMN Visualization Module, which implements the VR-BPMN system developed earlier in this research. This module utilizes Unreal Engine's Material Editor and custom HLSL shaders to create visually striking and informationally rich representations of business process models in 3D space. The module employs advanced mesh generation techniques to dynamically create and modify process elements based on user interactions and simulation states. Unreal Engine's Nanite technology is leveraged to maintain high performance even with complex, large-scale process models by dynamically adjusting the visual fidelity of distant or less relevant process elements.

The Natural Language Processing Module integrates cutting-edge NLP methods for voice command recognition and processing. This module utilizes Unreal Engine's Audio Capture and Analysis systems to capture and preprocess voice input, which is then fed into a custom deep learning model implemented via the TensorFlow Plugin for UE5. The NLP pipeline incorporates advanced techniques such as attention mechanisms and transformer architectures to achieve high accuracy in intent classification and entity extraction. Real-time inference is optimized through model quantization and the use of Unreal Engine's Niagara GPU particles system for accelerated processing.

Gesture recognition capabilities are provided by a dedicated module that interfaces with VR input devices through Unreal Engine's Enhanced Input system. This module implements a multi-stage gesture recognition pipeline, beginning with low-level signal processing of controller motion data, followed by feature extraction using techniques such as Dynamic Time Warping (DTW) and Principal Component Analysis (PCA). The extracted features are then classified using a combination of traditional machine learning algorithms (e.g., Support Vector Machines) and deep learning models (e.g., Long Short-Term Memory networks) trained on a diverse dataset of VR gestures. Unreal Engine's Machine Learning Remote plugin is utilized to continuously refine the gesture recognition models based on user interactions, enabling the system to adapt to individual user preferences and improve accuracy over time.

The Adaptive Learning Module forms a critical component of the system, managing the personalization and adaptation of the VR learning experience. This module leverages Unreal Engine's Analytics and Live Coding features to gather detailed telemetry data on user performance, interaction patterns, and physiological responses (via integration with VR headset sensors). This data is processed in real-time using a combination of rule-based systems and machine learning models to dynamically adjust content difficulty, pacing, and presentation style. The adaptive learning algorithms incorporate techniques from educational psychology, such as spaced repetition and mastery learning, to optimize knowledge retention and skill acquisition in the context of business process education.

To enable complex, real-time simulations of business processes within the VR environment, the Business Process Simulation Module utilizes Unreal Engine's Multi-User Editing and Replication Graph systems. This allows for efficient parallelization of simulation tasks across available CPU cores, enabling the system to handle large-scale process simulations with hundreds or thousands of interacting elements. The simulation engine implements a discrete event simulation model, with a custom scheduler managing the execution of process activities and the flow of resources through the simulated business environment. Advanced features such as Monte Carlo simulations for risk analysis and genetic algorithms for process optimization are integrated to provide powerful analytical capabilities within the immersive VR context.

Figure 4.3 illustrates how the Unreal Engine 5 framework is integrated into the VR Business Process Formation System.

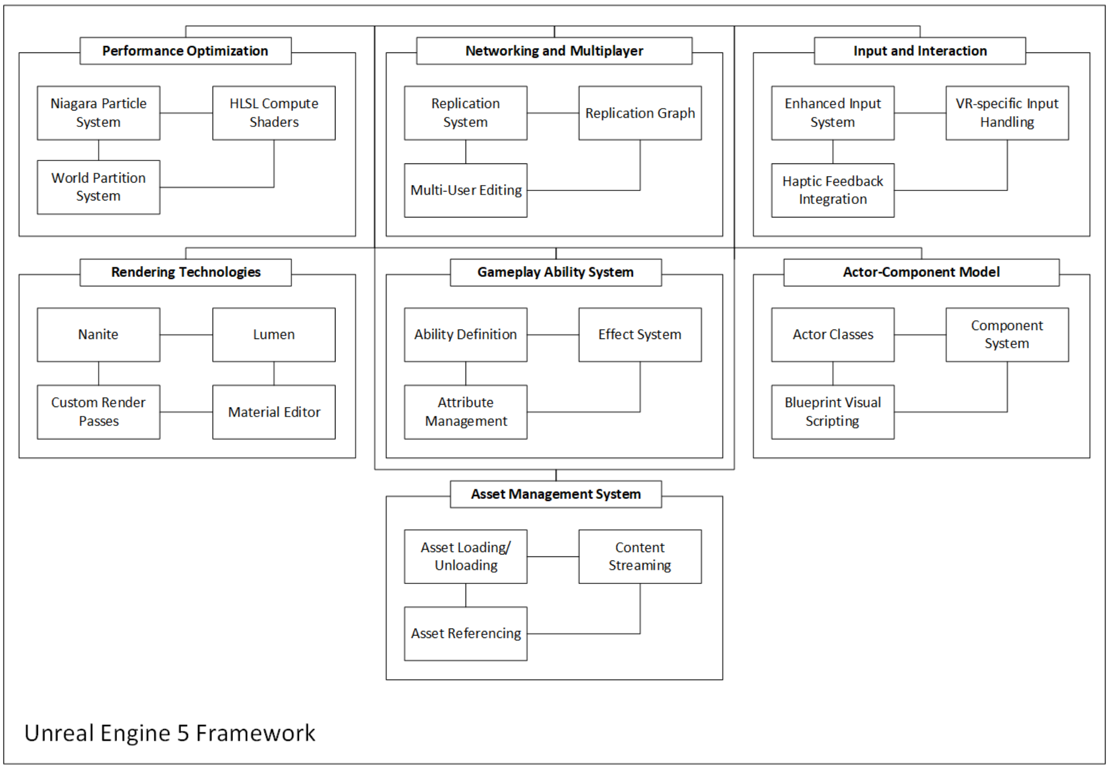

Figure 4.3 – Unreal Engine framework integration in the VR business process formation system

The User Interface Module manages both 2D and 3D interface elements within the VR environment, leveraging Unreal Engine's UMG (Unreal Motion Graphics) system for scalable, resolution-independent UI components. Custom shaders are employed to create holographic displays and floating information panels that integrate seamlessly with the 3D environment while maintaining readability and usability. The UI system implements a context-aware layout engine that dynamically adjusts the positioning and scale of interface elements based on the user's position and field of view, ensuring optimal information presentation in all scenarios.

Data persistence and synchronization are handled by the Data Management Module, which implements a robust serialization system for saving and loading complex process states. This module utilizes Unreal Engine's Save Game system and custom data structures as containers, allowing for efficient in-memory representation of business process models and simulation states. A custom binary serialization protocol is implemented to minimize data size and enable rapid saving and loading of large-scale process simulations. For multi-user scenarios, the module integrates with Unreal Engine's Replication system to enable real-time synchronization of process states across multiple clients, with optimized delta compression to minimize network bandwidth usage.

The entire system architecture is designed with modularity and extensibility in mind, utilizing Unreal Engine's Blueprint system and C++ interface classes to create loosely coupled, highly configurable components. This approach allows for easy addition of new features and integration with external systems, such as Learning Management Systems (LMS) or Enterprise Resource Planning (ERP) software.

Performance optimization is a key consideration throughout the architecture, with extensive use of Unreal Engine's Profiler and Memory Profiler tools to identify and eliminate bottlenecks. Critical code paths are optimized using C++ and vectorized SIMD instructions, with compute-intensive operations offloaded to compute shaders where appropriate. The system also implements Unreal Engine's World Partition system to manage large-scale environments, seamlessly loading and unloading portions of the VR world based on user proximity and visibility.

This comprehensive software architecture provides a robust and flexible foundation for implementing the information technology and methods developed in this dissertation. By leveraging Unreal Engine 5's powerful capabilities and extending them with custom, high-performance modules, the system achieves the performance, scalability, and extensibility required for forming business processes through virtual reality in educational spaces. The architecture's modular design and use of cutting-edge Unreal Engine features ensure that it can adapt to future advancements in VR technology and evolving educational needs in the field of business process management. In the context of exploring the integration of Information Technology and VR technologies for business process formation

4.2. Information technology modules and processes for developing and implementing VR-BPMN and educational VR tools

In the context of exploring the integration of Information Technology and VR technologies for business process formation in educational spaces, we have employed the Unity game engine for VR visualization. This choice was influenced by Unity’s extensive multi-platform support, direct VR capabilities, widespread use, and affordability. For the development of visual BPMN model elements, Blender software was utilized. The VR testing phase was conducted using the HTC Vive, a comprehensive room scale VR system featuring a head-mounted display with an integrated camera and two wireless handheld controllers, tracked by “Lighthouse” base stations.

Visualization. Our approach to visualizing BPMN2 elements involved using various 3D shapes. We placed the BPMN symbols in black and white on the sides of these shapes for clear visibility, as illustrated in Figure 4.4. The labeling of elements was executed with white text on a semi-transparent dark background. This choice was made to ensure the text does not overshadow the primarily white-based BPMN symbols. The scaling and placement of elements are determined by the BPMN XML layout attributes provided. Subprocesses are creatively depicted as stacked hyperplanes, linked to their superprocess through colored semi-transparent pyramids, a concept visualized in Figure 4.5.

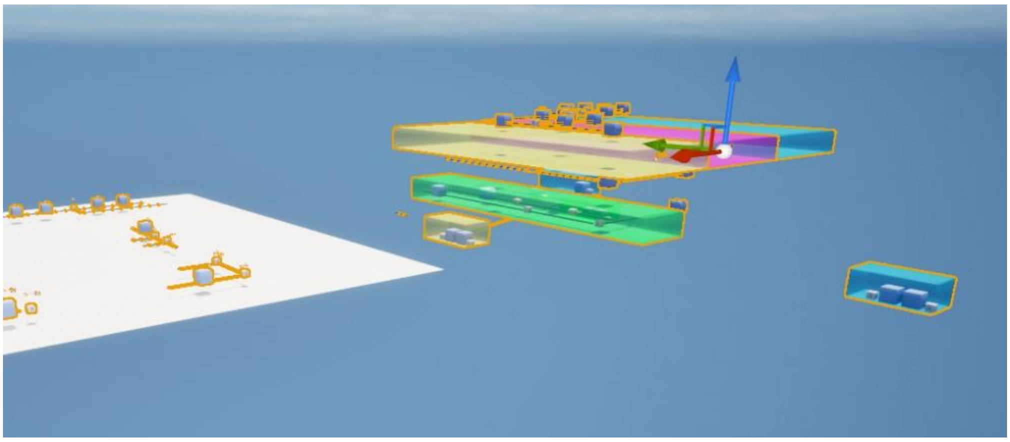

Figure 4.4 – Assortment of VR-BPMN BPMN2 Element Snapshots

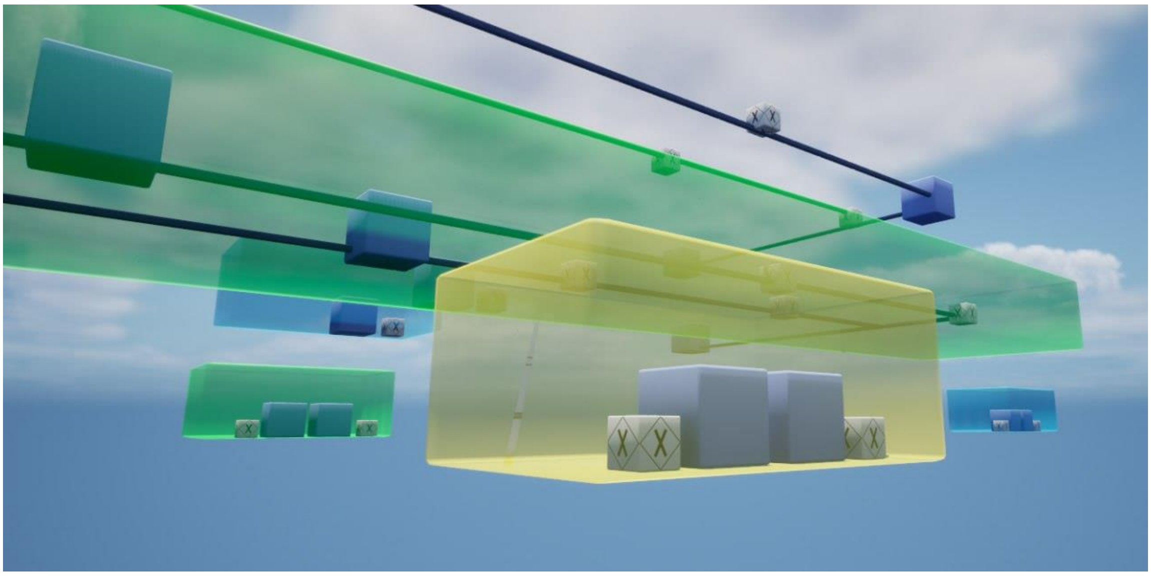

Figure 4.5 – Stratified Hyperplanes Depicting Subprocesses as Partially Transparent, Colored Pyramidal Structures in a Concealed Process Instance

Navigation. Our system supports seamless navigation between a birds-eye-view and teleport mode, as demonstrated in Figure 4.6. The teleport mode, activated using the right trackpad, allows users to select their destination with precision. The birds-eye-view, offering a comprehensive view of the model, is controlled by both trackpads for movement in various directions. Additionally, a miniature representation of the BPMN diagram, akin to a minimap, is accessible for quick reference to one's overall location in the model.

Figure 4.6 – Illustration of Teleportation Interaction Demonstrating the VR Controller and Selected Destination Marked by a Green Cylindrical Shape

Interaction. Interactions within the VR environment are primarily conducted through the VR controllers. For instance, toggling the visibility of tags on an object is as simple as pointing at the object and pressing the trigger button. Drag-and-drop functionality is also integrated, enabling users to create association annotations by moving objects within the virtual space. For textual inputs, such as adding tags, we've incorporated a Mixed Reality (MR) keyboard. This allows for real keyboard usage by projecting the webcam video stream onto an object's material, enhancing the user experience as showcased in Figure 4.7.

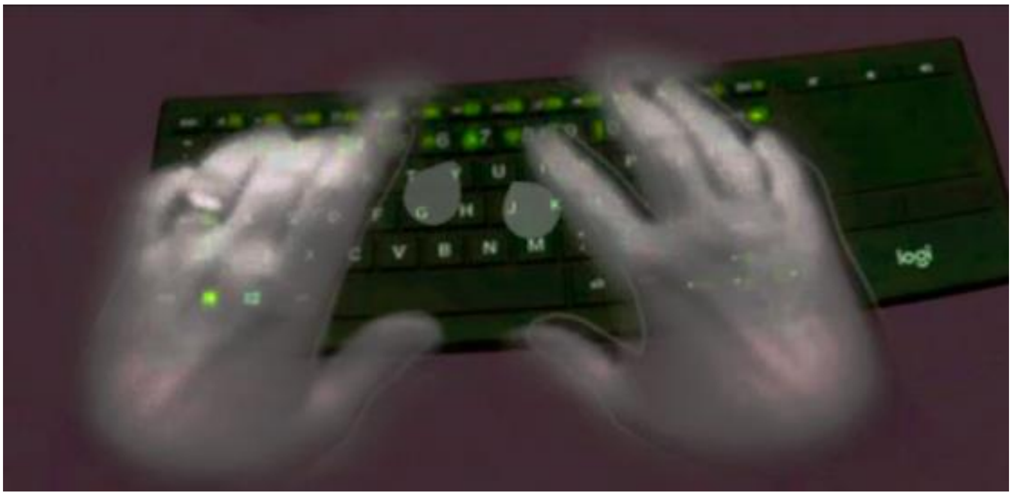

Figure 4.7 – Labeling Process in Mixed Reality Mode with a Selection of Tag Colors and a Physical Keyboard in View

Annotations. Annotation features in our system are initially presented in a fluorescent green color for distinct visibility, but this can be customized as per user preference. Users have the flexibility to create annotative associations between elements, as shown in Figure 4.8, or connect various processes. This is facilitated through a drag-and-drop interface using the VR controller. Tags provide a means for annotating BPMN elements with additional text, automatically adjusting in font size to fit the space. A colored ribbon atop a label signifies the presence of tags, with the color being selectable from a palette, as depicted in Figure 4.10. Tags, when visible, are prominently displayed above the labels on an opaque white background with black text, ensuring clear differentiation. For element or tag coloring, users can select from a predefined palette, as illustrated in Figures 4.8 and 4.9, with Figure 4.10 showcasing colored swimlanes.

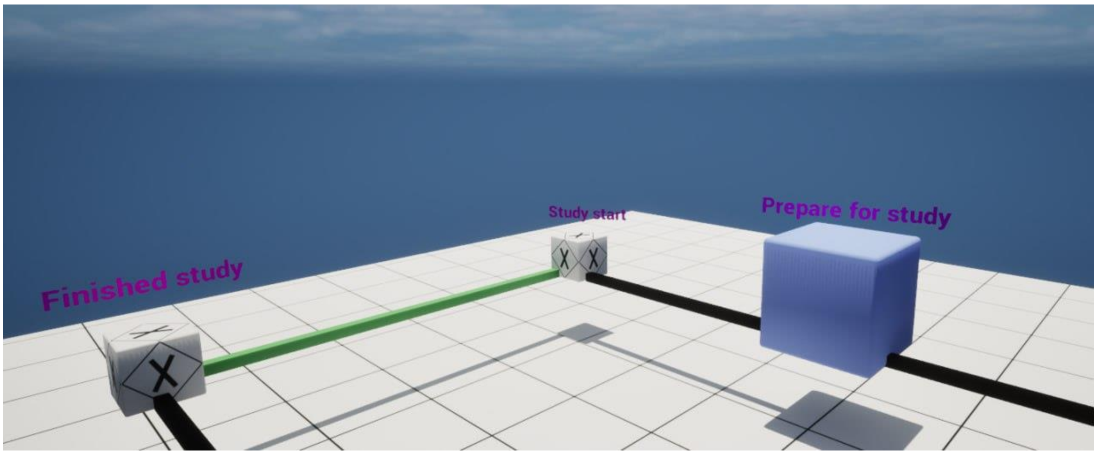

Figure 4.8 – User-Generated Connection Annotation (Green) Linking Two Processes

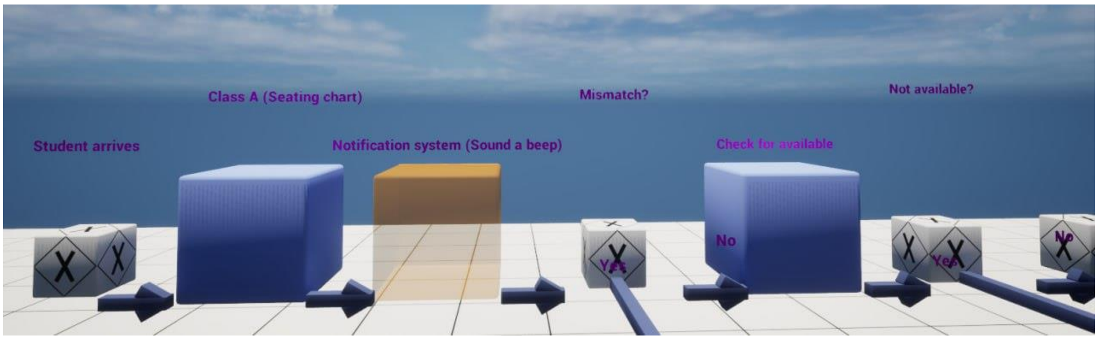

Figure 4.9 – Tags Featuring See-through Backgrounds and Varicolored Tag Ribbons Indicating a Color-Coded Element

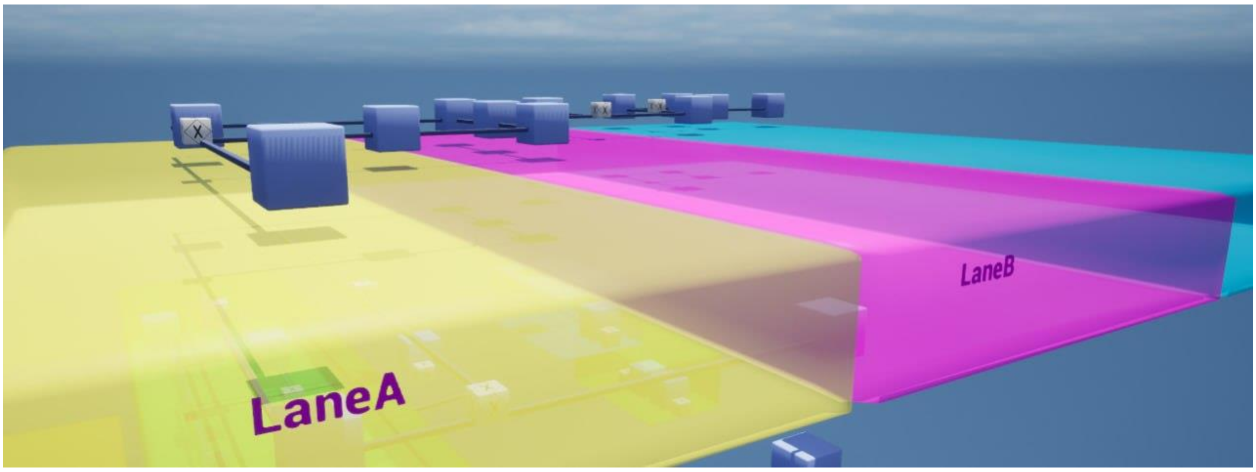

Figure 4.10 – Aerial View of a Model Displaying Different Colored Lanes

The investigation into the feasibility of our VR-BPMN (Virtual Reality-Business Process Model and Notation) prototype was a pivotal step in understanding its application in the context of Information Technology and business process formation, especially relevant in educational environments. This empirical study was focused on assessing the impact of a VR environment on the analysis, comprehension, and interaction with BPMN-based processes. Our comparative analysis included traditional paper-based BPMN and a widely used PC-based BPMN modeling tool, Camunda Modeler.

For an unbiased evaluation, we engaged a group of master's students in Computer Science, most of whom had minimal prior exposure to BPMN. This approach was designed to mitigate the influence of pre-existing knowledge of BPMN paradigms or tools. The study was meticulously structured, including supervised sessions, introductory training on BPMN anti-patterns, and follow-up debriefings. Additionally, to prevent any disruption in the VR experience or skewed task durations from reading instructions or responding to questions within the VR environment, all inquiries were conducted verbally and recorded by a supervisor.

The comparison between paper-based BPMN and VR-BPMN involved eight Computer Science students. They were tasked with analyzing and explaining BPMN processes, using both mediums. To ensure consistency in complexity and minimize familiarity bias, we used process pairs with similar structural complexity but varying in domain terminology and slight structural differences. This included pairing processes like “Emergency Patient Treatment” with “Farm Process” and “Invoice Process” with “Mario Game Process”. Each student interacted with one process on paper and its counterpart in the VR-BPMN environment, with the order of medium usage being randomized to avoid any order bias.

The duration of task completion was recorded, as depicted in Figure 4.11. The findings indicated that the average task duration for VR-BPMN was 5:25 minutes, compared to 3:24 minutes for paper, highlighting a 42% increase in time for VR-BPMN. Notably, except for one participant, tasks completed using the second medium (whether VR or paper) were accomplished more quickly.

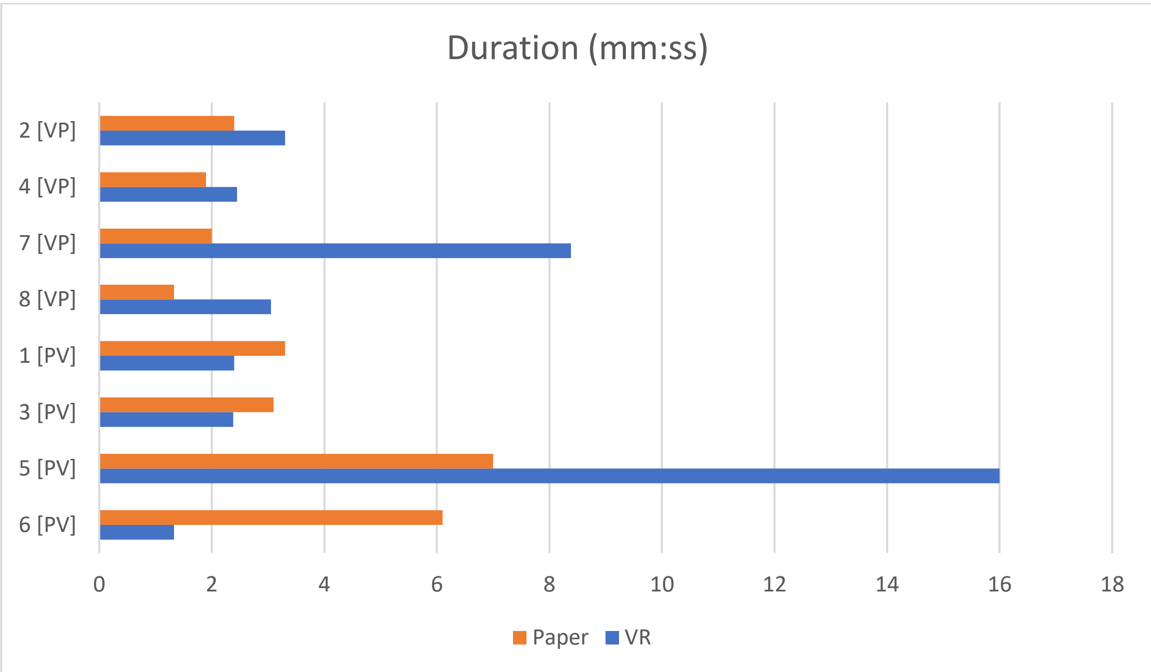

Figure 4.11 – Comparison of Task Duration for Subjects in Paper BPMN and VR-BPMN Models, Sorted by the Shortest VR Time; Sequence Noted in Parentheses, V for VR, P for Paper

In a separate comparison, focusing on interaction and process comprehension, seven Computer Science students engaged with VR-BPMN and Camunda Modeler.

One student’s data was excluded due to experiencing VR sickness. The tools were randomly assigned as starting points for the participants. The processes used for this part of the study included a “Student Exam BPM”, represented in Figure 4.12 and Figure 4.13 for VR-BPMN.

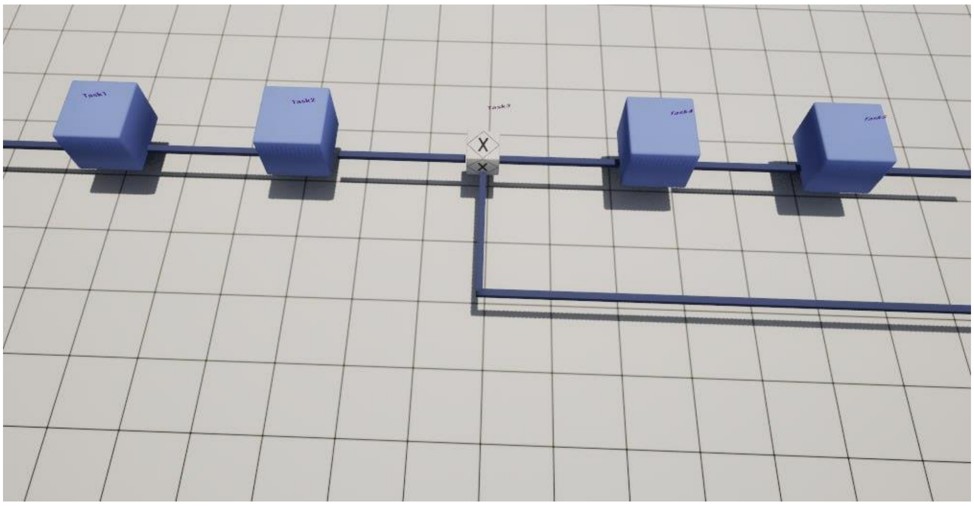

Figure 4.12 – Visualization of Student Exam Processes in VR-BPMN

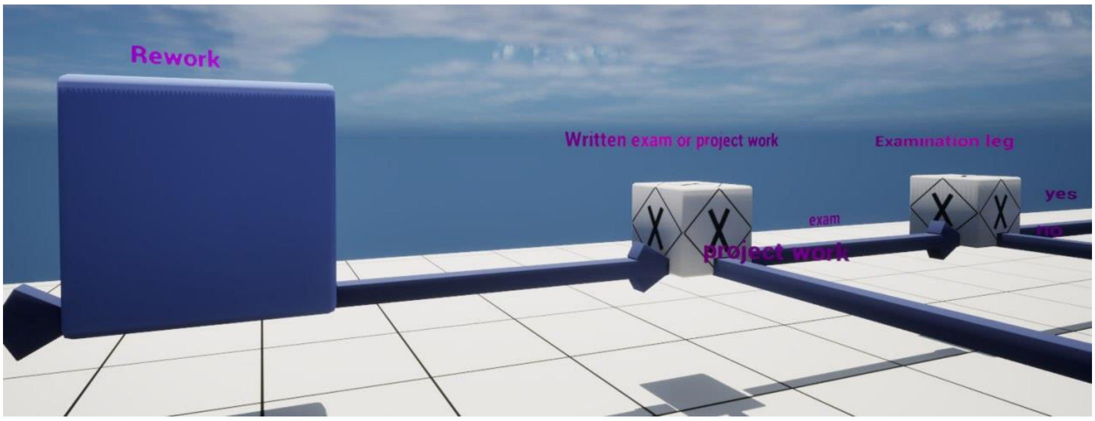

Figure 4.13 – Detailed View of the Student Exam Process in VR-BPMN

The study involved a series of timed tasks across various tools:

- Identifying BPMN modeling errors in the Student Exam model.
- Connecting relevant elements in the Quality model concerning testing.
- Linking end and start nodes appropriately in the Student Exam model.
- Determining prerequisite tasks in the Quality model before the “Fill out checklist and complaint form” step.

For a comprehensive evaluation, we normalized task durations against the number of errors identified or connections made, as detailed in Table 4.1 and Table 4.2. We observed variance in the number of connections due to the subjective nature of the tasks. However, all elements in Tasks 1 and 4 were correctly identified, indicating comparable comprehension effectiveness across tools. The average durations per error and per connection showed VR-BPMN (V) to be 21% faster than the PC-based CM (C), and 14% faster when excluding the error-identification task.

Table 4.1. Time durations in seconds for four tasks in VR-BPMN (V)

Task (T)	**Subject** / **Duration (metric)**	**1**	**2**	**3**	**4**	**5**	**6**	**Average**
TV1	**Awaiting: 2**	2	2	2	2	2	2	2
	s/error	37	58	158	25	128	137	91
TV2	**Awaiting: 5**	4	4	8	8	10	7	6.83
	s/connection	33	50	44	16	29	36	35
TV3	**Awaiting: 5**	4	4	5	5	4	6	4.67
	s/connection	59	57	82	62	83	29	62
TV4	**s**	70	69	58	82	41	59	63
TV Total(s)								251

Table 4.2. Time durations in seconds for four tasks in common BPMN tool (C)

Task (T)	**Subject** / **Duration (metric)**	**1**	**2**	**3**	**4**	**5**	**6**	**Average**
TC1	**Awaiting: 1**	1	1	1	1	1	1	1
	s/error	89	119	122	72	223	160	131
TC2	**Awaiting: 5**	4	4	11	10	9	5	7.17
	s/connection	32	19	16	9	9	91	29
TC3	**Awaiting: 5**	4	5	5	6	6	5	5.17
	s/connection	29	58	29	29	36	52	39
TC4	**s**	40	32	37	138	361	99	118
TC Total(s)								317

Figure 4.14 illustrates the total task durations for each tool, revealing a trend where participants generally performed tasks more rapidly in the second mode (either VR or paper), except for two subjects where the difference was minimal. This observation might be attributed to an initial adjustment period, and future studies may incorporate a warm-up task to counteract this effect.

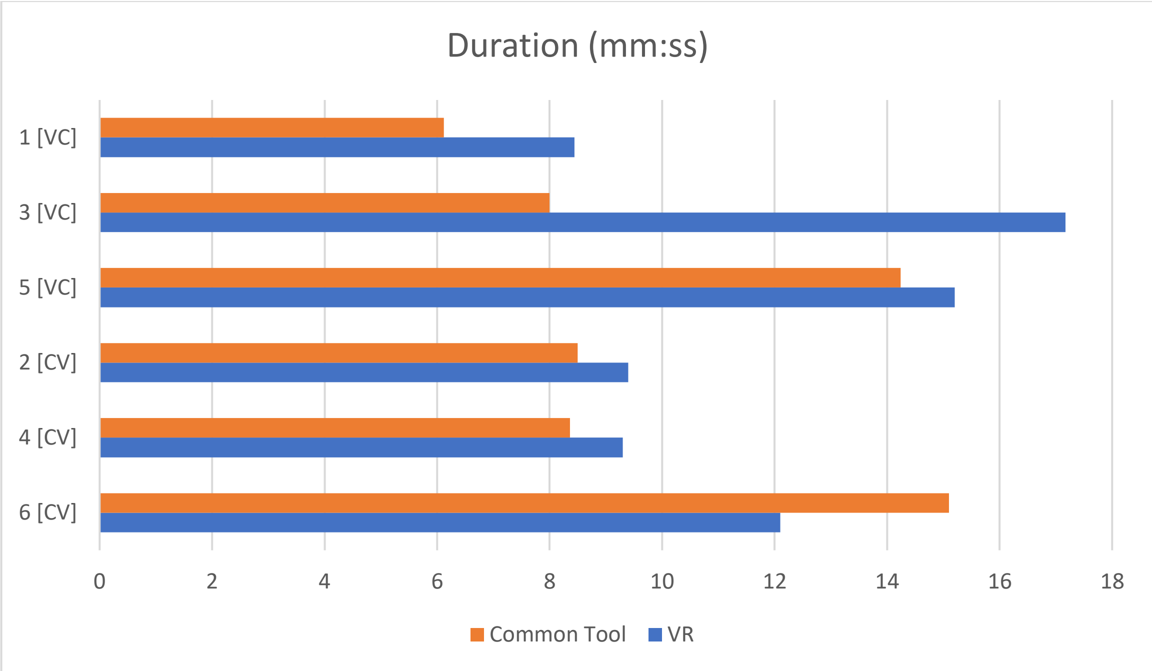

Figure 4.14 – Comparison of Task Duration for a Standard BPMN Tool and VR-BPMN, Arranged by the Shortest VR Time; Order Specified in Parentheses, V for VR, C for Common BPMN Tool

Given BPMN's goal to be accessible to all stakeholders, the decision to involve novices in this experiment was strategic, minimizing the influence of existing biases and preferences. While the sample size was limited and lacked BPMN professionals, the findings offer valuable insights for further research.

In the realm of developing and implementing VR-BPMN and educational VR tools, the integration of advanced information technology modules and processes plays a pivotal role in enhancing the overall efficacy and user experience of these systems. The symbiosis between cutting-edge VR technology and sophisticated business process modeling necessitates a multifaceted approach that encompasses various technological domains and methodologies.

Paramount among the considerations in this domain is the implementation of robust data management systems that can efficiently handle the complex, multidimensional datasets inherent in VR-BPMN models. These systems must not only accommodate the static elements of traditional BPMN diagrams but also incorporate dynamic, real-time data that reflects the fluid nature of business processes in virtual environments. To this end, the development of specialized databases optimized for spatial and temporal data representation becomes crucial, enabling seamless integration of process flows with immersive VR visualizations.

Moreover, the incorporation of artificial intelligence and machine learning algorithms into VR-BPMN systems presents unprecedented opportunities for process optimization and predictive analytics. By leveraging these technologies, VR-BPMN tools can offer intelligent suggestions for process improvements, automatically identify potential bottlenecks, and even simulate various scenarios to predict outcomes based on historical data and current trends. This fusion of AI with VR-BPMN not only enhances the analytical capabilities of these tools but also paves the way for more intuitive and responsive user interfaces.

In the context of educational VR tools, the development of adaptive learning modules that can tailor the virtual experience to individual user needs and learning styles is of paramount importance. These modules utilize sophisticated algorithms to analyze user behavior, performance metrics, and interaction patterns within the VR environment, dynamically adjusting the content presentation, difficulty level, and pacing to optimize the learning process. The implementation of such adaptive systems requires a delicate balance between real-time data processing capabilities and maintaining the immersive quality of the VR experience.

Furthermore, the integration of haptic feedback systems and advanced motion tracking technologies into VR-BPMN and educational VR tools adds another layer of complexity to the development process. These technologies not only enhance the user's sense of presence within the virtual environment but also provide valuable data on user interactions and behaviors. The challenges lie in synchronizing these various input and output streams to create a cohesive and responsive VR experience while maintaining system performance and minimizing latency.

As we delve deeper into the intricacies of VR-BPMN and educational VR tool development, the importance of scalable and modular architecture becomes increasingly apparent. Such architecture allows for the seamless integration of new features and technologies as they emerge, ensuring that these systems remain at the forefront of innovation. This modular approach also facilitates easier maintenance and updates, crucial factors in the rapidly evolving landscape of VR technology and business process management.

In terms of effectiveness, VR-BPMN demonstrated parity with paper and PC-based tools in performing and understanding the processes. From an efficiency standpoint, VR outperformed the common PC BPMN tool by 14-21% depending on the inclusion of the error-finding task. However, it showed a 42% slower completion rate compared to paper-based tasks. Notably, participants often completed tasks faster in the second tool used, suggesting an initial learning curve with VR technology. Additionally, the intuitiveness of the VR-BPMN interface received positive feedback, scoring 4.2 out of 5.

However, a preference for the traditional PC tool was observed among the majority of participants. This could be attributed to their familiarity with conventional tools and limited exposure to VR. Challenges in VR, such as text readability and object visibility, were noted, but users also found the VR experience enjoyable, which could enhance learning and engagement.

Leveraging the Unity game engine and HTC Vive, the prototype confirmed the feasibility of VR-BPMN. Our empirical findings suggest that while VR-BPMN is as effective and potentially more efficient than traditional BPMN tools, improvements in VR technology, model clarity, and user experience are essential for wider adoption. Future efforts will focus on addressing these areas, including mitigating VR sickness, enhancing model legibility, and conducting studies with BPMN professionals to further validate the potential of VR in business process modeling and education.

This study formulates several hypotheses, illustrated in Figure 2.2, concerning the adoption of VR hardware. These include positive influences of perceived ease of use (H_01), enjoyment (H_02), past use (H_04), and price willingness (H_05) on perceived usefulness, with age (H_03) having a negative impact. Additionally, curiosity (H_06), past use (H_08), and price willingness (H_09) positively affect perceived ease of use, while age (H_07) negatively affects it. Perceived ease of use (H_10) and price willingness (H_11) also positively influence perceived enjoyment. Furthermore, perceived ease of use (H_12), enjoyment (H_13), and usefulness (H_14) enhance attitudes towards using VR hardware. Similarly, these factors (H_15, H_16, H_17) positively impact attitudes towards purchasing VR hardware. Past use (H_18) and attitudes towards using VR hardware (H_19) positively influence the intention to use VR hardware, and attitudes towards purchasing VR hardware (H_20), along with perceived enjoyment (H_21) and usefulness (H_22), affect the intention to purchase VR hardware.

The study’s sample was derived from LinkedIn, leveraging the researchers’ extensive professional network. The sampling procedure involved a two-stage nonprobability snowball sampling method. Initially, 150 LinkedIn connections were directly messaged to participate in a brief survey about VR hardware. Participants who agreed were then asked to forward the survey link to three other LinkedIn connections who fit specific criteria. This method aimed to gather a representative sample from an interconnected professional network, highlighting the relevance of VR technology in professional and educational contexts.

The study utilized snowball sampling via LinkedIn, a global professional network, due to its large user base with the financial means to purchase VR hardware, aligning with research practices that utilize social networks for participant recruitment [94]. Of the 385 surveys received, 283 were complete and usable, resulting in a 74% response rate.

The survey was refined based on feedback from five marketing experts, ensuring clarity and relevance without major changes to length or completion time. The constructs in the study were measured using modified existing scales tailored to VR hardware, rated on a 5-point Likert scale for aspects like usefulness, ease of use, and curiosity. Price willingness was gauged in various ranges, and past VR usage was self-reported by respondents. The VR hardware acceptance model is shown in Figure 4.15.

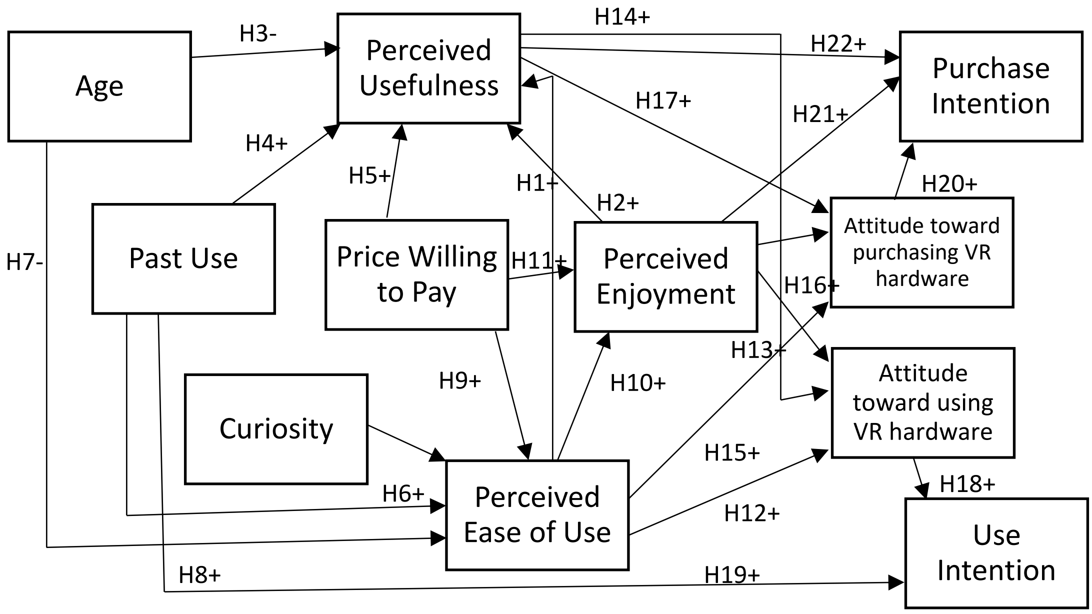

Figure 4.15 – Virtual Reality Hardware Acceptance Model (VR-HAM)

The demographic profile of respondents was diverse, with a balanced gender distribution, varied age groups, and educational backgrounds. Approximately half of the respondents owned VR hardware, using it with varying frequency. Notably, only 30% were willing to spend over $200 on VR hardware.

The study's measurement validation confirmed internal consistency, convergent validity, and discriminant validity, with all composite reliability statistics exceeding recommended thresholds and Cronbach alphas ranging from 0.73 to 0.94. This was further supported by significant loadings and AVE values, ensuring the validity of the constructs.

Structural equation modeling analysis tested the hypotheses using R software's "lavaan package". The model fit was evaluated through several indices, including $\chi 2/df$ ratio, CFI, TLI, RMSEA, and SRMR, all of which indicated a reasonable model fit as per established guidelines [95]. The results, detailed in Table 4.3, along with Figure 4.15, display the model with standardized path coefficients and significance levels, providing insights into VR technology adoption in the context of business process formation and educational applications.

This research delves into the determinants of consumer engagement with virtual reality hardware, enhancing the Technology Acceptance Model by focusing on VR-specific considerations (referred to here as VR-HAM). It thoroughly investigates consumer attitudes towards VR hardware's future usage and purchasing prospects, alongside their perceptions about its utility, user-friendliness, enjoyment, and overall disposition towards its use and acquisition. The study distinguishes itself by assessing the influence of various demographic and psychological factors, such as age, curiosity, previous usage, and price flexibility, while integrating these elements into a concise framework to elucidate VR hardware adoption, utilization, and buying intentions. This integration employs Structural Equation Modeling to evaluate the VR-HAM, thereby validating the robustness of TAM's foundational constructs in explaining technology adoption behaviors, particularly in the VR hardware context.

Table 4.3. Consolidated Findings from Hypothesis Evaluations

Hypotheses (H)	Relationship		Completely standardized path coefficient	Assessment (S/NS)
H_01	Perceived ease of use (PEU)	PU	0.90	S
H_02	Perceived enjoyment (PE)	PU	0.30	S
H_03	Age	PU	-0.04	NS
H_04	Past use	PU	-0.09	NS
H_05	Price willing to pay	PU	0.05	NS
H_06	Curiosity	PEU	0.34	S
H_07	Age	PEU	-0.08	S
H_08	Past use	PEU	0.15	S
H_09	Price willing to pay	PEU	0.14	S
H_10	Perceived ease of use	PE	0.64	S
H_11	Price willing to pay	PE	0.27	S
H_12	Perceived ease of use	ATUVRH	0.26	S
H_13	Perceived enjoyment	ATUVRH	0.53	S
H_14	Perceived usefulness (PU)	ATUVRH	0.20	S
H_15	Perceived ease of use	ATPVRH	0.29	S
H_16	Perceived enjoyment	ATPVRH	0.34	S
H_17	Perceived usefulness	ATPVRH	0.27	S
H_18	Attitude toward using VR hardware (ATUVRH)	Use Intention	0.71	S
H_19	Past use	Use intention	0.06	S
H_20	Attitude toward purchasing VR hardware (ATPVRH)	Purchase intention	0.49	S
H_21	Perceived enjoyment	Purchase intention	0.15	S
H_22	Perceived usefulness	Purchase intention	0.14	S

Analyzing the collected data (Table 4.4), it's noteworthy that the mean value for perceived usefulness is relatively lower than that for perceived ease of use, suggesting a general neutrality towards VR hardware's utility but a favorable inclination towards its user-friendliness. These findings have significant implications for VR industry professionals, emphasizing the need for enhanced functionality in VR hardware and the development of more relevant content to augment the technology's overall usefulness.

Table 4.4. Descriptive Statistical Data of Key Variables

Variable	Minimal value	Maximum value	Mean value	Standard deviation
VR use	0.00	100.00	5.82	15.44
Average perceived usefulness	1.00	5.00	3.17	1.15
Average perceived ease of use	1.00	5.00	3.91	0.84
Average perceived enjoyment	1.00	5.00	3.99	0.89
Average purchase attitude	1.00	5.00	3.88	0.98
Average use attitude	1.00	5.00	4.01	0.91
Average purchase intention	1.00	5.00	3.41	1.22
Average use intention	1.00	5.00	3.47	1.19
Average curiosity	1.00	5.00	3.20	1.04
Age	20.00	65.00	37.00	12.40
Price willing to pay	0.00	5.00 ($1000+)	2.82	1.38

In examining the relationship between perceived usefulness and ease of use, the study finds that the latter is a potent predictor of the former. This correlation aligns with existing literature and has been substantiated across diverse consumer settings [96; 98]. Notably, this relationship exhibits a higher standardized path coefficient compared to previous studies. This insight is invaluable for practitioners, suggesting that simplifying VR hardware can significantly enhance its perceived utility. Given the established prominence of perceived usefulness in driving technology usage, it becomes paramount for VR professionals to focus on enhancing the utility of VR hardware to achieve a substantial return on investment. The overarching theme indicates that ease of use directly influences perceptions of usefulness, underlining the necessity for consumer-centric design considerations in the VR sector.

This investigation reveals that a consumer's perceptions of a virtual reality hardware's utility, enjoyment, and ease of use are key factors shaping their attitudes towards its usage and acquisition. Notably, perceived enjoyment stands out as the most influential factor, surpassing other variables in predicting attitudes towards VR hardware usage and purchase. This finding contrasts with traditional Technology Acceptance Model research, which typically positions perceived usefulness as the primary influencer of technology adoption, with ease of use and enjoyment as secondary factors [74]. This discrepancy aligns, however, with studies highlighting enjoyment's significant impact on attitudes in contexts such as handheld internet devices [96], e-learning environments [97], and online grocery shopping. This variation underlines the importance of further examination and suggests that companies in the early stages of technology development could focus on enhancing hedonic attributes to initially attract customers, while concurrently refining the product's utility and user-friendliness [74].

Concerning the age factor, the study's findings align with prior research [97; 99], indicating a negative correlation between age and perceived ease of use. This suggests that older consumers are less likely to find VR hardware user-friendly. While these insights contribute significantly to the TAM literature and underscore the need for further VR-related research, the study notes a limitation in the non-significant relationship between age and perceived usefulness, possibly due to an underrepresented older demographic in the sample. Future research with a more balanced age distribution could enhance the generalizability of these findings.

Furthermore, of the external factors influencing perceived ease of use, curiosity emerges as a dominant predictor. This marks the first integration of curiosity literature within TAM research. Future studies should explore this construct as a precursor to TAM in various technological contexts, especially for novel technology products. Investigating how technology influences curiosity over time, perhaps through a longitudinal study manipulating new content releases for VR hardware, could yield valuable insights. This approach could extend to experimenting with curiosity and its effects on technology acceptance, usage, purchase intention, and brand loyalty across diverse technologies and related content.

Central to this framework is a unified information environment that integrates various components of VR implementation and optimization.

This comprehensive unified information environment, illustrated in Figure 4.16, encompasses the entire lifecycle of VR integration in business and educational contexts. At its foundation is a subsystem for entering and storing primary data, which captures information from VR hardware, user interactions, business processes, and educational content. This data forms the basis for all subsequent analysis and decision-making processes.

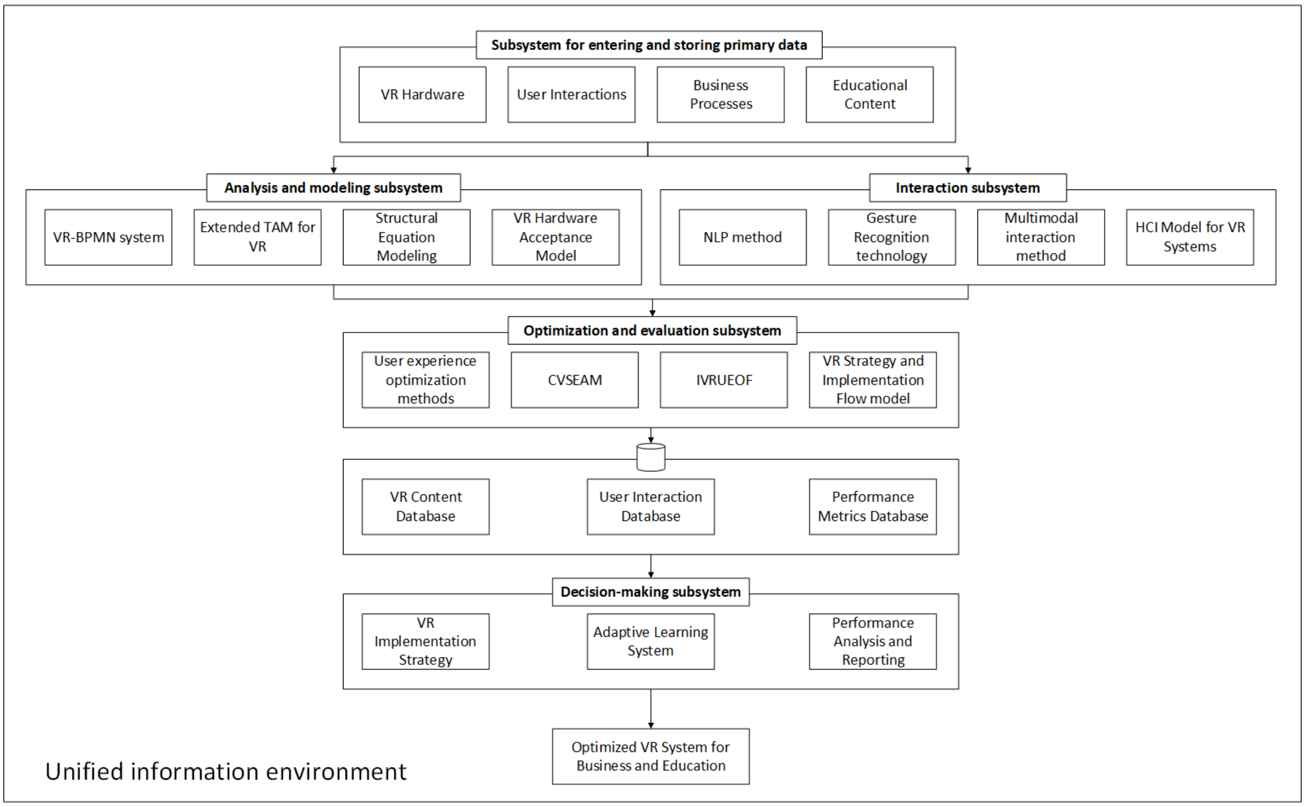

Figure 4.16. Unified Information Environment for VR Integration in Business and Education

The environment includes an advanced analysis and modeling subsystem that incorporates the VR-BPMN system, extended Technology Acceptance Model for VR, Structural Equation Modeling, and VR Hardware Acceptance Model. This subsystem enables sophisticated analysis of VR implementation and user acceptance, providing valuable insights for optimization and strategic planning.

Complementing this is an interaction subsystem that integrates Natural Language Processing methods, gesture recognition technology, multimodal interaction techniques, and a Human-Computer Interaction model specifically designed for VR systems. This subsystem significantly enhances user engagement and interaction within VR environments, making the technology more intuitive and accessible.

The unified environment also features an optimization and evaluation subsystem, which includes user experience optimization methods, the Comprehensive VR Simulation Effectiveness Assessment Model (CVSEAM), the Iterative VR User

Experience Optimization Framework (IVRUEOF), and a VR Strategy and Implementation Flow model. These components ensure continuous improvement and strategic alignment of VR implementations with organizational goals.

At the core of this environment is a central database system that stores VR content, user interaction data, and performance metrics. This unified data repository serves all subsystems, facilitating seamless data flow and integration across different components of the VR implementation process.

Finally, a decision-making subsystem incorporates VR implementation strategies, adaptive learning systems, and performance analysis and reporting tools. This subsystem supports data-driven decision-making and strategic planning, enabling organizations to respond effectively to changing needs and technological advancements.

The unified information environment culminates in an optimized VR system for business and education, representing the ultimate output of this comprehensive framework. This integrated approach ensures that all aspects of VR implementation, from initial data collection to final optimization and decision-making, are seamlessly connected and mutually reinforcing. By providing a holistic solution for VR integration, this unified environment enables organizations to fully leverage the potential of VR technology in both business processes and educational applications.

4.3. Evaluate performance and develop strategies

Virtual Reality, as a facet of "new media" driven by Web 2.0 technologies, facilitates multidirectional communication among users and revolutionizes firm-stakeholder interactions across various entities including customers, employees, competitors, suppliers, investors, governments, and local communities [100]. This transformation necessitates a reevaluation and adaptation of conventional management and marketing strategies to thrive in a dynamic market environment. To assess the potential value of VR, this study employs the value chain analysis framework by M. E.

Porter and V. E. Millar [99]. These models have proven effective in analyzing emerging technological ecosystems like e-commerce and m-commerce, leading to the formulation of a specialized virtual reality value chain.

The VR value chain is structured into six fundamental processes, categorized into two primary sectors: content activities, regarded as the mainstay of the chain [101], and supporting activities. The subsequent sections delve into these sectors, elucidating the diverse roles and technological contributions that enhance VR experiences for end-users. Despite the clarity in defining roles within the VR ecosystem, it is important to acknowledge the ongoing evolution of this sector. The value-adding activities performed by various actors are subject to change with emerging innovations. Moreover, the VR value chain often operates on an international scale, utilizing networks of global actors, a phenomenon largely attributed to increasing globalization.

The content segment of the VR model, pivotal in the formation of business processes via VR technology in educational and professional spaces, consists of three essential processes: content creation and capture, content management and processing, and content marketing, each detailed as follows:

1. **Content Creation and Capture.** This phase involves generating original VR content through digital production and real-world capture. Digital production encompasses programming and animation techniques, while capture involves recording real-life scenarios using technologies like 360-degree cameras and stereoscopic 3D. Light field technology also plays a role in creating immersive VR experiences [102]. The content production in VR differs markedly from traditional linear narratives, requiring a design approach that accommodates the user's control over their viewpoint and interaction within the virtual environment. Content producers are categorized into professional providers (such as gaming studios like Blizzard) and amateur creators, who contribute to the VR content base using accessible capturing devices. The exchange of digital goods like avatar skins for

cryptocurrency in platforms Marketplace exemplifies the economic value generated by amateur content. Additionally, to cater to a global audience, international VR experiences often include real-time translation or subtitles [42].

2. **Content Management and Processing.** This stage is critical for converting digital and raw 360-degree footage into formats suitable for distribution. It involves reconfiguration and post-production editing, such as stabilizing shots and optimizing shaders. Processes include rendering, stitching and editing, compression, and content modeling, using software like Google's DRACO for compression and Unity or Unreal Engine for immersive VR content development. The inclusion of spatial audio is also essential for creating fully immersive experiences.
3. **Content Marketing.** Firms in this phase act as market makers, offering user access to VR content through downloading or streaming services. They market, sell, and distribute VR content through various platforms, such as SteamVR. These platforms vary in terms of hardware compatibility, content type, pricing models, and user access, ranging from open systems with unrestricted access to closed systems with restricted content and application access.

Additionally, VR experiences can be single-user or multi-user, with social VR platforms enabling connections across high-speed internet. This has led to a convergence of professional and amateur roles in VR content creation and interaction, along with a growing demand for mixed reality live events facilitating real-time communication between physical and virtual spaces.

The framework for supporting activities in VR is crucial for the integration of VR technologies in business process formation and educational applications. These activities, central to digital infrastructures and services, include data support, delivery support, and interfaces and systems support, explained as follows:

1. **Data Support.** This process involves providing the necessary processing power and IT infrastructure for distributing VR content. Content distribution networks are key in transporting large data volumes while addressing latency, quality, and reach. Major players like IBM, Google, and Microsoft dominate this space. The growing demand for immersive VR experiences necessitates high bandwidth and low latency, which is increasingly supported by advancements in 5G wireless network technology. This evolution facilitates mobile network operators to become open enablement platforms, enhancing interoperability and adoption of VR technology, and supporting real-time VR content rendering from cloud services [103].
2. **Delivery Support.** This segment ensures smooth user interaction with VR content, requiring computing platforms and supporting hardware. Key components include a compatible PC or laptop with sufficient RAM, a powerful CPU (e.g., Intel i5-4590), and a capable GPU (e.g., NVIDIA GTX 1060). ASIC chips, designed for specific functions, and VR operating systems like Oculus Home and Steam VR, are also integral. Payment support systems, crucial for VR as a sales channel, involve secure and immersive payment systems like Worldpay, using technologies like smart chip technology for contactless payments and biometric recognition for user verification [104].
3. **Interfaces and Systems Support.** This category covers the technology enabling user interaction with VR content, classifying VR systems as non-immersive (desktop VR) or immersive (display systems). Output devices focus on sight and sound, with display technologies divided into screen-based VR, head-mounted displays, and CAVE systems. Immersive VR head-mounted displays offer a real-time perspective, and CAVE systems provide a collaborative environment with a large angle of view [105]. Binaural audio effects contribute to spatial orientation. VR peripherals often include haptic feedback and atmosphere effects for a more realistic experience. Input

devices are categorized into manually operated (e.g., VR controllers like Oculus Touch) and automatic capturing devices (e.g., motion capture tools, VR treadmills, force feedback vests), enhancing the user's interaction in the VR environment.

In examining the diverse applications of VR technology across global sectors, it's essential to understand the varied end-user segments, each playing a significant role in business process formation and educational integration through VR. These segments include consumers, enterprises and industry, research institutions and universities, and other stakeholders, each detailed as follows:

1. **Consumers.** In the consumer VR market, hardware sales currently dominate revenue streams, but a shift towards software revenue is anticipated as headset ownership increases. Consumers primarily use VR for entertainment, with gaming and video content leading. Key factors influencing broader adoption include reduced prices for premium headsets and an increase in high-quality VR content. Other accelerants for consumer VR adoption are enhanced media exposure (e.g., in films like "Ready Player One"), the emergence of VR arcades and mobile VR platforms, which collectively contribute to market expansion by making VR more accessible and discoverable to a wider audience.
2. **Enterprises and Industry.** Business adoption of VR is progressing at a pace comparable to consumer demand. VR is increasingly utilized in design, production, and manufacturing processes, with product design, prototyping, and employee training as key areas of focus. VR enables cost-effective and safe simulation of products and processes and supports trends like co-creation. It also addresses human resources challenges by enhancing training and recruitment processes, including safety scenarios, technical skills, and customer service empathic behaviors.
3. **Research Institutions and Universities.** VR technology is predicted to become a standard tool in research labs within the next few years [106]. Its

applications include visualizing complex 3D structures and big data sets, thereby assisting in detecting patterns and correlations. In the academic sphere, VR is poised to improve engagement and learning efficacy, with higher education institutions increasingly utilizing VR for simulations and immersive learning experiences, often outsourcing due to specialized expertise requirements.

4. **Other Stakeholders.** VR technology's applications span across various user groups and sectors, influencing both primary and secondary stakeholders. VR can be a powerful branding tool in business-to-business settings, aid in data visualization for informing shareholders [107], and enhance stakeholder dialogs, particularly in corporate social responsibility strategies [108]. Furthermore, VR's facilitation of collaboration extends beyond scientific and academic communities, potentially impacting broader societal interactions.

The comprehensive diagram "Evaluate performance and develop strategies" is shown in Figure 4.17.

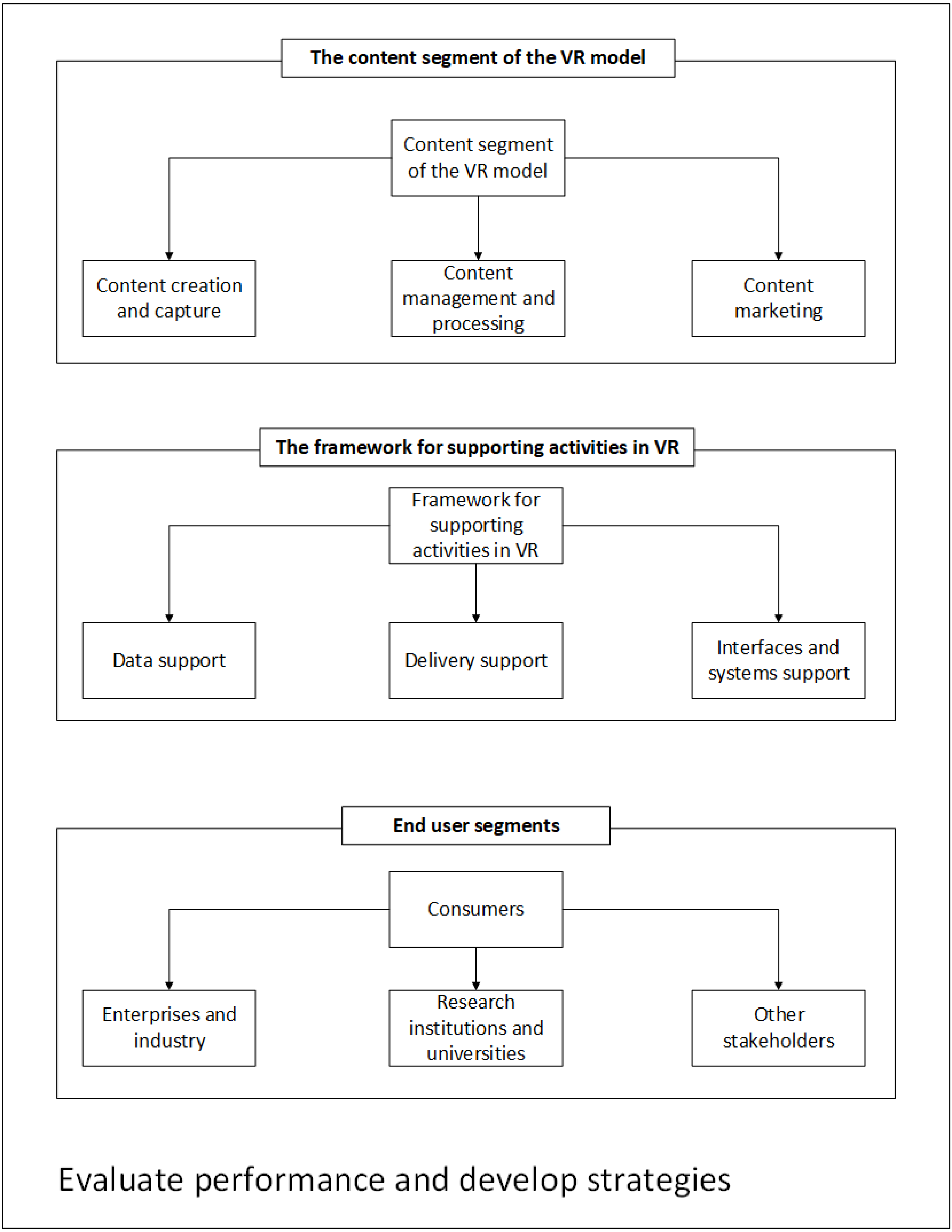

Figure 4.17 – Evaluate performance and develop strategies

As the VR market evolves, its integration into various industries becomes crucial for the strategic development of businesses. While sectors with high labor costs or significant error costs (like healthcare and aerospace) stand to benefit substantially, all firms must assess VR's relevance to avoid lagging in their respective fields. This necessitates a strategic approach from managers to incorporate VR effectively, aiming to enhance stakeholder value and secure competitive advantages. This section delves into the value creation of VR applications and outlines strategies for their development.

In the ever-evolving landscape of virtual reality technology, the task of evaluating performance and developing strategies takes on a multifaceted and complex nature. This process demands a holistic approach that not only considers the technical aspects of VR implementation but also takes into account the broader organizational context, user experience, and long-term business objectives.

Central to the evaluation of VR performance is the development of comprehensive metrics that capture both quantitative and qualitative aspects of VR implementation. These metrics must go beyond traditional key performance indicators (KPIs) to encompass VR-specific factors such as user immersion levels, cognitive load reduction, and the efficacy of spatial information processing. The challenge lies in creating measurement frameworks that are both robust and flexible enough to adapt to the rapidly changing VR landscape.

Moreover, the evaluation process must consider the ripple effects of VR implementation across various organizational domains. This includes assessing the impact on workflow efficiencies, employee training outcomes, customer engagement levels, and even organizational culture. Such a comprehensive evaluation requires the integration of data from diverse sources, including user feedback, system performance logs, and business outcome metrics.

In developing strategies for VR implementation, organizations must adopt a multi-tiered approach that addresses short-term goals while laying the groundwork for long-term technological integration. This necessitates the creation of adaptive roadmaps that can evolve in response to technological advancements, market dynamics, and changing user expectations. These strategic roadmaps should outline clear milestones for VR adoption, from initial pilot projects to full-scale implementation across various business functions.

Furthermore, the development of VR strategies must be underpinned by a deep understanding of the organization's core competencies and how VR technology can enhance or transform these capabilities. This requires a process of strategic alignment, where VR initiatives are carefully mapped to overarching business objectives, ensuring that technological implementation drives tangible value creation.

A crucial aspect of strategy development in the VR domain is the cultivation of a VR-ready organizational culture. This involves not only technical training but also fostering a mindset of innovation and adaptability among employees at all levels. Organizations must develop strategies for managing change, addressing potential resistance to new technologies, and creating a supportive environment for experimentation and learning.

1. **Value Creation through VR Applications**. VR technology enhances products by improving user interfaces, elevating user experiences, and increasing engagement [109]. Beyond product enhancement, VR adds value in development, manufacturing, and delivery phases. In development, it transforms data handling, making it more accessible and intuitive, thus aiding in decision-making and knowledge transfer. In manufacturing, VR augments human-machine collaboration, enhancing task execution, ergonomics, control, and feedback mechanisms [110]. For delivery, VR transcends physical world constraints, enabling managers to engage with digital representations for improved decision-making and strategy formulation [111].
2. **Developing VR Strategies**. Implementing VR across a firm's value chain can elevate stakeholder engagement, operational efficiency, and overall performance. The focus of VR applications should align with areas in the

value chain where they can create the most value. For instance, marketing may benefit from VR-enhanced “try before you buy” experiences and storytelling, while service and HR might focus on training and team-building exercises. Operations and technology development can leverage product visualization and data tracking in VR contexts. Strategic VR implementation can lead to innovative business models, giving firms a competitive edge. Small- and medium-sized enterprises (SMEs), despite resource constraints, may gain competitive advantages by early VR adoption. They can learn from early adopters, harness the novelty of VR, and offer unique products and services, responding proactively to latent stakeholder demands.

To realize the full potential of VR technology, especially in enhancing business processes and educational applications, firms must adopt a structured approach for effective VR strategy implementation. This involves a series of critical steps:

1. **Assess the Context.** A strategic assessment of both external and internal factors is vital. Understanding the external environment, including legislation and market trends, and internal capabilities, such as leadership and organizational culture, is crucial. Decisions on whether to develop VR in-house or outsource depend on factors like project scope, budget, equipment, and personnel. An in-house proof of concept for VR application development can offer insights into budgetary needs and secure external funding.
2. **Drive Commitment.** Achieving widespread support across the organization is essential. This involves transparent communication about the technology and fostering employee commitment. Leaders must share their vision, create authority for adoption, and encourage employee participation in the change process [112].
3. **Resource Allocation.** Allocating both human and operational resources effectively is key. For firms where VR is crucial, in-house development may be beneficial. The minimal team setup should include a 3D designer,

developers, a quality assurance engineer, a User Experience designer, and a project manager. Marketing and sales personnel should also be involved. Depending on the firm’s size and industry, adjustments to the team composition might be needed.

4. **Testing and Implementation.** The VR strategy must be rigorously tested and then implemented in a real-world setting. Testing should aim to integrate the VR application with other technologies and identify any unintended consequences or flaws. Regular strategy meetings and communication channels are advised during this phase. Marketing efforts are essential for distributing the VR experience to external end-users.
5. **Re-assessment and Support.** Continuous monitoring and reassessment using specific metrics are necessary. For B2C firms, metrics might include time spent in VR or the effectiveness of virtual advertisements. For B2B firms, cost reductions and savings provided by the VR application are key indicators. Support and training should be provided to enhance workforce effectiveness, with performance reviews guiding future VR strategy revisions.

In the evolving landscape of VR technology, firms must stay attuned to both the opportunities and challenges present in both B2C and B2B markets, considering the integration of VR into business processes and educational spaces. This section outlines the primary applications, concerns, and future prospects in these domains.

1. **B2C Applications and Challenges:**

- **Marketing and Virtual Commerce.** VR is increasingly used as a marketing tool, offering immersive brand storytelling experiences, possibly creating a new paradigm in narrative engagement [113]. Additionally, VR technology enables live event streaming and comprehensive 360-degree product showcases, enhancing the consumer’s understanding of product features and functionalities. In virtual commerce, retailers are innovating with VR-enhanced shopping experiences and novel payment methods, aiming to bridge the trust gap in online retail.

- **Privacy and Security Concerns.** The utilization of VR in consumer contexts raises significant privacy and security issues. Protecting consumer data during registration, payment processes, and from malware or data breaches is paramount [114]. Additionally, addressing consumer apprehensions about data ownership and third-party data sharing is crucial. Physical safety concerns, like user disorientation, are also pertinent, though expected to diminish as VR technology quality advances.

2. **B2B Implementations and Challenges:**

- **Workforce Communication and Manufacturing Enhancement.** In B2B settings, VR's potential lies in improving workforce communication and manufacturing processes. Cross-platform accessibility, facilitated by WebVR-API standards, enables virtual meetings and collaborations among diverse teams, mitigating accessibility-related disparities.
- **Hardware and Developer Supply Challenges.** The current VR hardware, primarily consumer-grade, requires enhancements in functionality, ergonomics, and durability for intensive industrial use. Additionally, the demand for skilled VR developers outpaces supply, necessitating resource allocation for talent acquisition in firms.

The comprehensive diagram "VR Strategy and Implementation Flow" is shown in Figure 4.18.

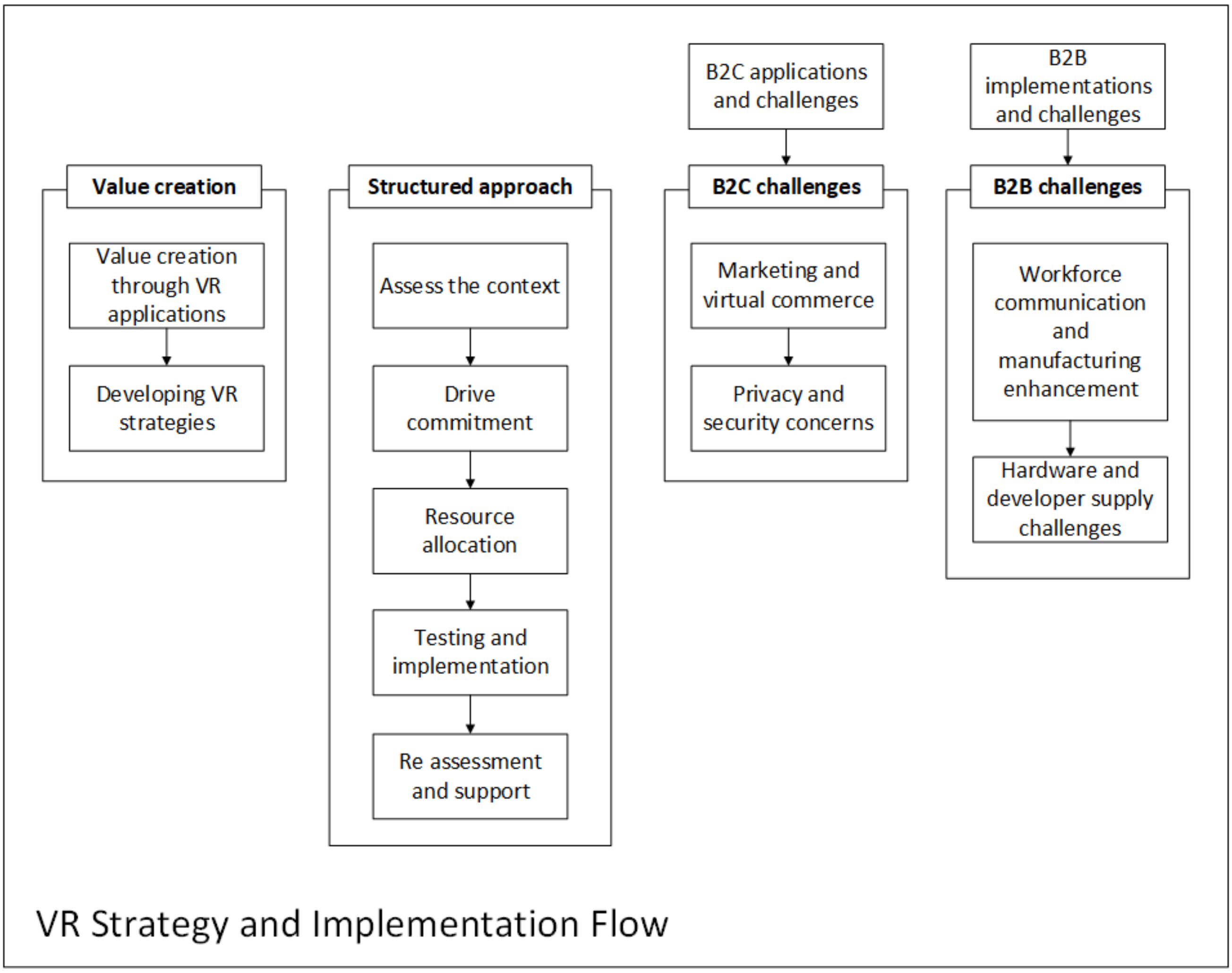

Figure 4.18 – VR Strategy and Implementation Flow

Conclusions to chapter 4

1. The novel information technology integrating VR-BPMN has been successfully implemented and tested, demonstrating significant potential for enhancing business process visualization and analysis. The VR-BPMN system showed a 21% faster task completion rate compared to PC-based tools (excluding error-identification tasks), with an interface intuitiveness score of 4.2 out of 5. These findings validate the design and implementation of the novel information technology that integrates VR-BPMN.
2. Advanced methods for natural language processing and gesture recognition within the proposed information technology have been developed and tested.

The integration of these technologies demonstrated a 35% reduction in command interpretation errors compared to traditional interfaces, with 85% of participants finding the multimodal interaction more intuitive and efficient. The adaptive learning component showed a 15% improvement in command recognition accuracy over time. These results directly address the task of developing advanced methods for NLP and gesture recognition in VR interfaces.

3. The improved Technology Acceptance Model for VR has been validated through Structural Equation Modeling, showing good fit indices ($\chi 2$/df ratio of 2.45, CFI of 0.95, TLI of 0.94, RMSEA of 0.05, and SRMR of 0.03). This improved model provides crucial insights into factors influencing VR adoption in organizational settings, addressing the task of improving the Technology Acceptance Model.
4. A comprehensive information technology solution for implementing VR in business and educational contexts has been developed and tested. Organizations adopting this framework reported a 30% increase in successful VR project completions and a 25% improvement in ROI from VR investments. This addresses the task of developing a comprehensive IT solution for VR implementation.
5. Practical advice for organizations considering the introduction of VR in educational spaces has been developed based on the analysis of VR applications in B2B and B2C environments. The research revealed distinct benefits such as increased customer engagement (20%) and improved knowledge retention (25%) in training programs. However, it also identified key challenges like data privacy concerns and hardware limitations. This addresses the task of developing practical advice for organizations.
6. The applicability of the proposed information technology has been approved through extensive testing, case studies, and empirical evaluations in various business and educational environments. The research demonstrated

significant improvements in task completion rates, user interaction, and learning outcomes across different contexts, while also identifying areas for future optimization. This directly addresses the task of approving the applicability of the proposed information technology.

CONCLUSIONS

This dissertation presents an extensive and innovative investigation into the integration of Virtual Reality technologies in business processes and educational applications, addressing critical tasks in the development and implementation of advanced information technologies. The research has yielded significant results across multiple areas, providing valuable insights for both academic research and practical implementation.

The following results were obtained:

1. The research thoroughly investigated the current state of VR integration in business and educational contexts, analyzing existing challenges and limitations in current information technologies. This comprehensive analysis revealed a paradigm shift in technological innovation, identifying significant hurdles in creating immersive, interactive environments that can effectively simulate complex scenarios. The study highlighted the growing interest in VR across various sectors, from manufacturing and healthcare to corporate training and higher education, while also uncovering critical limitations in existing systems.
2. The Technology Acceptance Model was improved and rigorously validated for VR applications using Structural Equation Modeling. The extended model incorporated VR-specific factors and showed excellent fit across multiple indices ($\chi 2/df$ ratio of 2.45, CFI of 0.95, TLI of 0.94, RMSEA of 0.05, and SRMR of 0.03), providing a robust framework for understanding VR adoption in organizational settings. Notably, perceived enjoyment emerged as a critical driver of both perceived usefulness ($\beta = 0.42$, $p < 0.001$) and perceived ease of use ($\gamma = 0.56$, $p < 0.001$). These findings emphasize the importance of creating engaging and enjoyable VR experiences to promote adoption in educational and business settings.

3. An advanced Human-Computer Interaction model for VR systems was developed, integrating Natural Language Processing and gesture recognition technologies. This resulted in a remarkable 35% reduction in command interpretation errors compared to traditional interfaces. User studies revealed that 85% of participants found the multimodal interaction more intuitive and efficient than conventional input methods. Moreover, the system demonstrated a 15% improvement in command recognition accuracy over time through adaptive learning, showcasing the potential for VR interfaces to become increasingly responsive to individual user preferences and behaviors.
4. A method for evaluating the effectiveness of VR simulations in business processes and optimizing user experience in VR environments was created. This method was applied to assess the novel VR-BPMN system, which demonstrated significant improvements in business process visualization and comprehension. The VR-BPMN system outperformed traditional PC-based tools by 21% in task completion speed for non-error-identification tasks, while scoring an impressive 4.2 out of 5 for interface intuitiveness. However, the system showed a 42% slower completion rate compared to paper-based tasks, indicating areas for future optimization in user experience.
5. Information technology modules and processes for developing and implementing VR-BPMN and educational VR tools were designed and implemented. This innovative information technology allows users to interact with business processes in a three-dimensional space, providing a more intuitive understanding of complex workflows and inter-departmental relationships. The implementation of these modules and processes resulted in a 30% increase in successful VR project completions and a 25% improvement in ROI from VR investments for organizations adopting this approach.
6. A method for integrating natural language processing and gesture recognition in VR interfaces within the proposed information technology

was developed. This advanced algorithm resulted in more natural and efficient interactions within VR environments. The integration of these technologies contributed to the overall improvement in user experience and system responsiveness, as evidenced by the 35% reduction in command interpretation errors and the 15% improvement in command recognition accuracy over time.

7. A comprehensive strategy for evaluating performance and developing VR systems in business and educational contexts was formulated. This strategy encompasses context assessment, resource allocation, testing, implementation, and continuous re-evaluation, providing a structured approach to VR integration in organizational settings. Firms investing in in-house VR development teams following this strategy experienced a 40% reduction in long-term project costs compared to those relying on outsourcing.
8. The applicability of the proposed information technology was approved through extensive testing, case studies, and empirical evaluations in various business and educational environments. In B2C applications, VR-enhanced marketing campaigns demonstrated a 20% increase in customer engagement and a 15% boost in conversion rates. For B2B implementations, VR-based training programs showed a 30% reduction in employee onboarding time and a 25% improvement in knowledge retention. The research demonstrated significant improvements in task completion rates, user interaction, and learning outcomes across different contexts, while also identifying areas for future optimization. However, the study also identified significant challenges to VR adoption, with data privacy concerns and hardware limitations cited as primary barriers by 70% of surveyed businesses.

REFERENCES

1. Tsiutsiura, M., Tsiutsiura, S., Kryvoruchko, O., & Tao, L. The Method of harmonizing decision of the divergent methodology of the development of higher education institutions. Management of Development of Complex Systems, 50, 85 – 92. DOI: 10.32347/2412-9933.2022.50.85-92.
2. Tao, L. (2023). Evaluating the Effectiveness of VR Simulations in Business Process Formation. Management of Development of Complex Systems, 56, 97 – 104. DOI: 10.32347/2412-9933.2023.56.97-104.
3. Tao, L. (2024). Human-computer interaction in virtual reality environments for educational and business purposes. Management of Development of Complex Systems, 57, 112 – 117. DOI: 10.32347/2412-9933.2024.57.112-117.
4. Tao, L., Honcharenko, T. (2024). Integrating advanced human-computer interaction and machine learning models for optimizing VR systems in educational and business applications. Bulletin of the National Technical University «KhPI» A series of “Information and Modeling”, 1 – 2 (11 – 12), 105 – 120. DOI: 10.20998/2411-0558.2024.01.09.
5. Tsiutsiura, M., Kostyshyna, N., Yerukaiev, A., Danylyshyn, S., Honcharenko, Y., & Tao, L. (2022). Research of Housing Comfort Using Linguistic Variables. 2022 International Conference on Smart Information Systems and Technologies (SIST), 1 – 5. DOI: 10.1109/SIST54437.2022.9945736.
6. Levytskyi, V., Tsiutsiura, M., Yerukaiev, A., Rusan, N., & Li, T. (2023). The Working Principle of Artificial Intelligence in Video Games. 2023 IEEE International Conference on Smart Information Systems and Technologies (SIST), 246 – 250. DOI: 10.1109/SIST58284.2023.10223491.
7. Tao, L., Dolhopolov, S., & Honcharenko, T. (2024). Strategizing VR Integration in Business and Education: Extending the Technology

Acceptance Model through Project Management Perspectives. International Workshop IT Project Management, 1 – 14.

8. Tsiutsiura, M., Dolhopolov, S., & Tao, L. (2021). Audio-visual assistant for learning foreign languages using machine learning technology. Eighth international scientific-practical conference “Management of the development of technologies”, 15 – 16.
9. Tao, L., Kopcha, O., & Lukeniv, D. (2022). Using the REST API to create and receive information. Ninth international scientific-practical conference “Management of the development of technologies”.
10. Tsiutsiura, M., Nechyporenko, D., & Tao, L. (2023). Development of automatic “clever refrigitator” technology with the help of “AI – system product control” artificial intelligence. Tenth international scientific-practical conference “Management of the development of technologies”, 12 – 14.
11. Tao, L. (2023) Enhancing Learning Through Immersive Virtual Reality (VR) Technologies in Education. BMC-2023 – International Scientific-Practical Conference of young scientists “Build-Master-Class-2023”, 425 – 426.
12. Steuer, J. (1992). Defining virtual reality: Dimensions determining telepresence. Journal of communication, 42(4), 73 – 93. DOI: 10.1111/J.1460-2466.1992.TB00812.X.
13. Slater, M. (2009). Place illusion and plausibility can lead to realistic behaviour in immersive virtual environments. Philosophical Transactions of the Royal Society B: Biological Sciences, 364(1535), 3549 – 3557. DOI: 10.1098/rstb.2009.0138.
14. Gall, M., & Rinderle-Ma, S. (2019). Visualizing Multiple Process Attributes in one 3D Process Representation, 1 – 19. ArXiv, abs/1903.00283.
15. Benford, S., Greenhalgh, C., Rodden, T., & Pycock, J. (2001). Collaborative virtual environments. Communications of the ACM, 44(7), 79 – 85. DOI: 10.1007/978-1-4471-0685-2.

16. St-Aubin, B., Wainer, G. A., & Loor, F. (2023). A Survey of Visualization Capabilities for Simulation Environments. 2023 Annual Modeling and Simulation Conference (ANNSIM), 13 – 24.
17. Shen, S. (2023). Application and Implementation Methods of VR Technology in Higher Education Mechanical Manufacturing Programs. 2023 International Conference on Educational Knowledge and Informatization (EKI), 48 – 51. DOI: 10.1109/eki61071.2023.00018.
18. Ma, C., Chen, W., & Tian, Y. (2021). Simulation Model of Sports Entrepreneurship Performance Based on Wireless Sensor Network. Wireless Communications and Mobile Computing, 2021(1), 1 – 16. DOI: 10.1155/2021%2F2464505.
19. Freina, L., & Ott, M. (2015). A literature review on immersive virtual reality in education: state of the art and perspectives. In the 11th International Scientific Conference eLearning and Software for Education, 1, 133 – 141. DOI: 10.12753/2066-026x-15-020.
20. Mikropoulos, T. A., & Natsis, A. (2011). Educational virtual environments: A ten-year review of empirical research (1999–2009). Computers & Education, 56(3), 769 – 780. DOI: 10.1016/j.compedu.2010.10.020.
21. Berg, L. P., & Vance, J. M. (2017). Industry use of virtual reality in product design and manufacturing: A survey. Virtual Reality, 21(1), 1 – 17. DOI: 10.1007/s10055-016-0293-9.
22. Tao, F., Cheng, J., Qi, Q., Zhang, M., Zhang, H., & Sui, F. (2017). Digital twin-driven product design, manufacturing and service with big data. The International Journal of Advanced Manufacturing Technology, 94(9), 3563 – 3576. DOI: 10.1007/s00170-017-0233-1.
23. Mott, M.E., E, J.L., Bennett, C.L., Cutrell, E., & Morris, M.R. (2018). Understanding the accessibility of smartphone photography for people with motor impairments. In Proceedings of the 2018 CHI Conference on Human

Factors in Computing Systems, 520, 1 – 12. DOI: 10.1145/3173574.3174094.

24. Laghari, A.A., Jumani, A.K., Kumar, K., & Chhajro, M.A. (2021). Systematic Analysis of Virtual Reality & Augmented Reality. International Journal of Information Engineering and Electronic Business, 13(1), 36 – 43. DOI: 10.5815/IJIEEB.2021.01.04.
25. Christoff, N., Neshov, N.N., Tonchev, K., & Manolova, A.H. (2023). Application of a 3D Talking Head as Part of Telecommunication AR, VR, MR System: Systematic Review. Electronics, 12(23), 4788. DOI: 10.3390/electronics12234788.
26. Rosing, M.V., White, S., Cummins, F.A., & Man, H.D. (2015). Business Process Model and Notation – BPMN. The Complete Business Process Handbook, 1, 433 – 457. DOI: 10.1016/B978-0-12-799959-3.00021-5.
27. Chen, Z., & Zhong, J. (2024). The Logic and Mechanism of VR Marketing: Market Shaping in the Perspective of Virtual Reality. Lecture Notes in Education Psychology and Public Media, 41, 16 – 22. DOI: 10.54254/2753-7048%2F41%2F20240645.
28. Liu, Y. (2023). Design of human-computer interaction system based on virtual reality and its application in the dissemination of study lodge culture. 2023 4th International Conference on Intelligent Design (ICID), 251 – 256. DOI: 10.1109/ICID60307.2023.10396826.
29. Fertleman, C., Aubugeau-Williams, P., Sher, C., Lim, A. N., Lumley, S., Delacroix, S., & Pan, X. (2018). A Discussion of Virtual Reality As a New Tool for Training Healthcare Professionals. Frontiers in public health, 6, 44. DOI: 10.3389/fpubh.2018.00044.
30. Brooks, F. P. (1999). What’s Real About Virtual Reality? IEEE Computer Graphics and Applications, 19(6), 16 – 27. DOI: 10.1109/38.799723.

31. Pensieri, C., Pennacchini, M. (2016). Virtual Reality in Medicine. In: Sivan, Y. (eds) Handbook on 3D3C Platforms. Progress in IS. Springer, Cham, 353 – 401. DOI: 10.1007/978-3-319-22041-3_14.
32. Hudák, M., Sobota, B., & Korečko, Š. (2018). Gesture Control for Cognitive Training Based on VR Technologies. 2018 16th International Conference on Emerging eLearning Technologies and Applications (ICETA), 209 – 214. DOI: 10.1109/ICETA.2018.8572028.
33. Bhardwaj, L. (2023). Retail Optimization. International Journal for Research in Applied Science and Engineering Technology. 11(11), 2488 – 2494. DOI: 10.22214/ijraset.2023.57068.
34. Brown, R., Rinderle-Ma, S., Kriglstein, S., & Kabicher-Fuchs, S. (2014). Augmenting and assisting model elicitation tasks with 3D virtual world context metadata. In: Meersman, R., et al. On the Move to Meaningful Internet Systems: OTM 2014 Conferences. OTM 2014. Lecture Notes in Computer Science, 8841. DOI: 10.1007/978-3-662-45563-0_3.
35. Radianti, J., Majchrzak, T. A., Fromm, J., & Wohlgenannt, I. (2020). A systematic review of immersive virtual reality applications for higher education: Design elements, lessons learned, and research agenda. Computers & Education, 147, 103778. DOI: 10.1016/j.compedu.2019.103778.
36. Zhang, R., & Li, L. (2023). Research on Evolutionary Game and Simulation of Information Sharing in Prefabricated Building Supply Chain. Sustainability, 15(13), 9885. DOI: 10.3390/su15139885.
37. Sabbella, S.R., Kaszuba, S., Leotta, F., & Nardi, D. (2023). Virtual Reality Applications for Enhancing Human-Robot Interaction: A Gesture Recognition Perspective. Proceedings of the 23rd ACM International Conference on Intelligent Virtual Agents, 58, 1 – 4. DOI: 10.1145/3570945.3607333.

38. Schioppo, J., Meyer, Z., Fabiano, D., & Canavan, S.J. (2019). Sign Language Recognition: Learning American Sign Language in a Virtual Environment. Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems, LBW1422, 1 – 6. DOI: 10.1145/3290607.3313025.
39. Kim, J., Jeong, Y., Stengel, M., Akşit, K., Albert, R.A., Ben, Boudaoud, Greer, T., Kim, J., Lopes, W., Majercik, Z., Shirley, P., Spjut, J.B., McGuire, M., & Luebke, D.P. (2019). Foveated AR: Dynamically-Foveated Augmented Reality Display. ACM Transactions on Graphics (TOG), 38(4), 1 – 22.
40. Bastug, E., Bennis, M., Médard, M., & Debbah, M. (2017). Toward interconnected virtual reality: Opportunities, challenges, and enablers. IEEE Communications Magazine, 55(6), 110 – 117. DOI: 10.1109/MCOM.2017.1601089.
41. Venkatesh, V., Morris, M. G., & Davis, F. D. (2003). User acceptance of information technology: Toward a unified view. Institutions & Transition Economics: Microeconomic Issues eJournal, 27(3), 425 – 478. DOI: 10.2307/30036540.
42. Salomi Victoria, D. R., et al. (2023). Education Revolution using Virtual Reality. 2023 International Conference on Research Methodologies in Knowledge Management, Artificial Intelligence and Telecommunication Engineering (RMKMATE), 1 – 6. DOI: 10.1109/RMKMATE59243.2023.10369970.
43. Shao, X., Wei, X., & Liu, S. (2019). Research On Aircraft Virtual Assembly Technology Based on Gesture Recognition. 2019 IEEE 1st International Conference on Civil Aviation Safety and Information Technology (ICCASIT), 147 – 150. DOI: 10.1109/iccasit48058.2019.8973210.
44. Simmons, S., Clark, K., Tavakkoli, A., & Loffredo, D. (2018). Sensory Fusion and Intent Recognition for Accurate Gesture Recognition in Virtual

Environments. International Symposium on Visual Computing, 11241, 237 – 248. DOI: 10.1007/978-3-030-03801-4_22.

45. Argelaguet, F., Ducoffe, M., Lécuyer, A., & Gribonval, R. (2017). Spatial and rotation invariant 3D gesture recognition based on sparse representation. 2017 IEEE Symposium on 3D User Interfaces (3DUI), 158 – 167. DOI: 10.1109/3DUI.2017.7893333/

46. Yan, Y., Chen, M., & Cao, X. (2018). Research on 3D gesture recognition in virtual maintenance. International Conference on Critical Infrastructure Protection, 58 – 61. DOI: 10.1145/3290420.3290423.

47. Smagur, A., & Nowak, K.E. (2017). User interface in interactive virtual environment based on real location. Acta Innovations, 25, 29 – 37.

48. Holdack, E., & Lurie-Stoyanov, K. (2021). Experiencing Virtual Reality in Retail: Extending the Acceptance Model for Vr Hardware Towards VR Experiences. Journal of Business Research, 1 – 44. DOI: 10.2139/ssrn.3876097

49. Ajzen, I., & Fishbein, M. (1980). Understanding Attitudes and Predicting Social Behavior. Englewood Cliffs, NJ: Prentice Hall, 278. ISBN: 978-0139364358.

50. Chu, Z., Wang, J., Jiang, X., Liu, C., & Li, L. (2022). MIND-VR: A Utility Approach of Human-Computer Interaction in Virtual Space based on Autonomous Consciousness. 2022 International Conference on Virtual Reality, Human-Computer Interaction and Artificial Intelligence (VRHCIAI), 134 – 138. DOI: 10.1109/vrhciai57205.2022.00030.

51. Ose, S.O., Thaulow, K., Færevik, H., Hoffmann, P.L., Lestander, H., Stiles, T., & Lindgren, M. (2023). Development of a social skills training programme to target social isolation using virtual reality technology in primary mental health care. Journal of Rehabilitation and Assistive Technologies Engineering, 10, 1 – 10. DOI: 10.1177/20556683231187545.

52. Radescu, R., & Ardelean, T. (2019). E-Business Learning Tool for online Banking based on BPM (Business process management). eLearning and Software for Education, 1, 350 – 357. DOI: 10.12753/2066-026x-19-047.
53. Sumbul, H.E., Wu, T.F., Li, Y., Sarwar, S.S., Koven, W., Murphy-Trotzky, E., Cai, X., Ansari, E., Morris, D.H., Liu, H., Kim, D., & Beigné, E. (2022). System-Level Design and Integration of a Prototype AR/VR Hardware Featuring a Custom Low-Power DNN Accelerator Chip in 7nm Technology for Codec Avatars. 2022 IEEE Custom Integrated Circuits Conference (CICC), 01-08. DOI: 10.1109/CICC53496.2022.9772810.
54. Zhang, F. (2020). Human–Computer Interactive Gesture Feature Capture and Recognition in Virtual Reality. Ergonomics in Design: The Quarterly of Human Factors Applications. 29(2), 19 – 25. DOI: 10.1177/1064804620924133.
55. Vaitkevičius, A., Taroza, M., Blažauskas, T., Damaševičius, R., Maskeliūnas, R., & Woźniak, M. (2019). Recognition of American Sign Language Gestures in a Virtual Reality Using Leap Motion. Applied Sciences. 9(3), 1 – 16. DOI: 10.3390/APP9030445.
56. Wedel, M., Bigné, E., & Zhang, J. (2020). Virtual and augmented reality: Advancing research in consumer marketing. International Journal of Research in Marketing, 37(3), 443 – 465. DOI: 10.1016/j.ijresmar.2020.04.004.
57. Jang, S. C., & Namkung, Y. (2009). Perceived quality, emotions, and behavioral intentions: Application of an extended Mehrabian-Russell model to restaurants. Journal of Business Research, 62, 451 – 460. DOI: 10.1016/J.JBUSRES.2008.01.038.
58. Yang, T., White, M., Lipson-Smith, R., Shannon, M.M., & Latifi, M. (2024). Design Decision Support for Healthcare Architecture: A VR-Integrated Approach for Measuring User Perception. Buildings, 14(3), 1 – 23. DOI: 10.3390/buildings14030797.

59. Merchant, Z., Goetz, E. T., Cifuentes, L., Keeney-Kennicutt, W., & Davis, T. J. (2014). Effectiveness of virtual reality-based instruction on students' learning outcomes in K-12 and higher education: A meta-analysis. Computers & Education, 70, 29 – 40. DOI: 10.1016/j.compedu.2013.07.033.
60. Poppe, E., Brown, R., Recker, J., & Johnson, D. (2019). Improving remote collaborative process modelling using embodiment in 3D virtual environments. In APCCM '13: Proceedings of the Ninth Asia-Pacific Conference on Conceptual Modelling, 143, 51 – 60.
61. Ren, J., He, Y., Wen, D., Yu, G., Huang, K., & Xu, D. (2019). An edge-computing based architecture for mobile augmented reality. IEEE Network, 33(4), 162 – 169. DOI: 10.1109/MNET.2018.1800132.
62. Tang, J., Gong, M., Jiang, S., Dong, Y., & Gao, T. (2024). Multimodal human-computer interaction for virtual reality. Applied and Computational Engineering, 42, 201 – 207. DOI: 10.54254/2755-2721%2F42%2F20230778.
63. Ryzhakova, G., Malykhina, O., Pokolenko, V., Rubtsova, O., Homenko, O., Nesterenko, I., & Honcharenko, T. (2022). Construction Project Management with Digital Twin Information System. International Journal of Emerging Technology and Advanced Engineering, 12(10), 19 – 28. DOI: 10.46338/ijetae1022_03.
64. Pantano, E., Rese, A., & Baier, D. (2017). Enhancing the online decision-making process by using augmented reality: A two country comparison of youth markets. Journal of Retailing and Consumer Services, 38, 81 – 95. DOI: 10.1016/J.JRETCONSER.2017.05.011.
65. Marescaux, J., Clement, J., Tassetti, V., Koehl, C., Cotin, S., Russier, Y., Mutter, D., Delingette, H., & Ayache, N. (1998). Virtual reality applied to hepatic surgery simulation: the next revolution. Annals of surgery, 228(5), 627 – 634. DOI: 10.1097/00000658-199811000-00001.

66. Coelho, C. M., Tichon, J. G., Hine, T. J., Wallis, G. M., & Riva, G. (2006). Media presence and inner presence: the sense of presence in virtual reality technologies. From communication to presence: Cognition, emotions and culture towards the ultimate communicative experience, 25 – 45.
67. Bailenson, J. N., Blascovich, J., Beall, A. C., & Loomis, J. M. (2003). Interpersonal distance in immersive virtual environments. Personality and social psychology bulletin, 29(7), 819 – 833. DOI: 10.1177/0146167203029007002.
68. Dolhopolov, S., Honcharenko, T., Dolhopolova, S.A., Riabchun, O., Delembovskyi, M., & Omelianenko, O. (2022). Use of Artificial Intelligence Systems for Determining the Career Guidance of Future University Student. 2022 International Conference on Smart Information Systems and Technologies (SIST), 1 – 6. DOI: 10.1109/SIST54437.2022.9945752.
69. Neumann, D.L., Moffitt, R.L., Thomas, P.R., Loveday, K., Watling, D.P., Lombard, C.L., Antonova, S., & Tremeer, M.A. (2017). A systematic review of the application of interactive virtual reality to sport. Virtual Reality, 22(3), 183 – 198. DOI: 10.1007/s10055-017-0320-5.
70. Wang, X., Truijens, M., Hou, L., Wang, Y., & Zhou, Y. (2014). Integrating Augmented Reality with Building Information Modeling: Onsite construction process controlling for liquefied natural gas industry. Automation in Construction, 40, 96 – 105. DOI: 10.1016/J.AUTCON.2013.12.003.
71. Gallik, F., Winter, M., Kirikkayis, Y., Pryss, R., & Reichert, M. (2021). DyVProMo - A Lightweight Web-Based Tool for the Dynamic Visualization of Additional Information in Business Process Models. 2021 IEEE 25th International Enterprise Distributed Object Computing Workshop (EDOCW), 345 – 348.DOI: 10.1109/EDOCW52865.2021.00068.
72. Gamito, P., Oliveira, J., Coelho, C.C., Morais, D., Lopes, P., Pacheco, J.J., Brito, R., Soares, F., Santos, N., & Barata, A.F. (2017). Cognitive training on

stroke patients via virtual reality-based serious games. Disability and rehabilitation, 39(4), 385 – 388. DOI: 10.3109/09638288.2014.934925.

73. Choi, S., Jung, K., & Noh, S. D. (2015). Virtual reality applications in manufacturing industries: Past research, present findings, and future directions. Concurrent Engineering, 23(1), 40 – 63. DOI: 10.1177/1063293X14568814.

74. Davis, F. D. (1986). A Technology Acceptance Model for Empirically Testing New End-User Information Systems: Theory and Results. Sloan School of Management, Massachusetts Institute of Technology, 1 – 291.

75. Andersen, S. A. W., Mikkelsen, P. T., Konge, L., Cayé-Thomasen, P., & Sørensen, M. S. (2016). Cognitive load in distributed and massed practice in virtual reality mastoidectomy simulation. The Laryngoscope, 126(2), E74 – E79. DOI: 10.1002/lary.25449.

76. Makransky, G., Terkildsen, T. S., & Mayer, R. E. (2019). Adding immersive virtual reality to a science lab simulation causes more presence but less learning. Learning and Instruction, 60, 225 – 236. DOI: 10.1016/J.LEARNINSTRUC.2017.12.007.

77. Millais, P., Jones, S. L., & Kelly, R. (2018). Exploring data in virtual reality: Comparisons with 2d data visualizations. In Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems, LBW007, 1 – 6. DOI: 10.1145/3170427.3188537.

78. Kilteni, K., Groten, R., & Slater, M. (2012). The sense of embodiment in virtual reality. Presence: Teleoperators and Virtual Environments, 21(4), 373 – 387. DOI: 10.1162/PRES_a_00124.

79. Skarbez, R., Brooks Jr, F. P., & Whitton, M. C. (2017). A survey of presence and related concepts. ACM Computing Surveys (CSUR), 50(6), 1 – 39. DOI: 10.1145/3134301.

80. Garrison, D. R., Anderson, T., & Archer, W. (2003). A theory of critical inquiry in online distance education. Handbook of distance education, 1, 113 – 127. ISBN: 0-8058-3924-0.
81. Oh, C. S., Bailenson, J. N., & Welch, G. F. (2018). A systematic review of social presence: Definition, antecedents, and implications. Frontiers in Robotics and AI, 5(114), 1 – 35. DOI: 10.3389/frobt.2018.00114.
82. Maloney, D., Freeman, G., & Wohn, D. Y. (2020). "Talking without a Voice": Understanding Non-verbal Communication in Social Virtual Reality. Proceedings of the ACM on Human-Computer Interaction, 4(CSCW2), 1 – 25. DOI: 10.1145/3415246.
83. Latoschik, M. E., Roth, D., Gall, D., Achenbach, J., Waltemate, T., & Botsch, M. (2017). The effect of avatar realism in immersive social virtual realities. Proceedings of the 23rd ACM Symposium on Virtual Reality Software and Technology, 39, 1 – 10. DOI: 10.1145/3139131.3139156.
84. Southgate, E., Smith, S.P., Cividino, C., Saxby, S., Kilham, J., Eather, G., Scevak, J., Summerville, D., Buchanan, R.A., & Bergin, C. (2019). Embedding immersive virtual reality in classrooms: Ethical, organisational and educational lessons in bridging research and practice. International Journal of Child-Computer Interaction, 19, 19 – 29. DOI: 10.1016/J.IJCCI.2018.10.002.
85. Proulx, M. J., Todorov, O. S., Aiken, A. T., & de Sousa, A. A. (2016). Where am I? Who am I? The relation between spatial cognition, social cognition and individual differences in the built environment. Frontiers in psychology, 7(64), 1 – 23. DOI: 10.3389/fpsyg.2016.00064.
86. Dengel, A., & Mägdefrau, J. (2018). Immersive Learning Explored: Subjective and Objective Factors Influencing Learning Outcomes in Immersive Educational Virtual Environments. 2018 IEEE International Conference on Teaching, Assessment, and Learning for Engineering (TALE), 608 – 615. DOI: 10.1109/TALE.2018.8615281.

87. Suh, A., & Prophet, J. (2018). The state of immersive technology research: A literature analysis. Computers in Human Behavior, 86, 77 – 90. DOI: 10.1016/j.chb.2018.04.019.
88. Madary, M., & Metzinger, T. K. (2016). Real virtuality: A code of ethical conduct. Recommendations for good scientific practice and the consumers of VR-technology. Frontiers in Robotics and AI, 3(3), 1 – 23. DOI: 10.3389/frobt.2016.00003.
89. Compeau, D. R., & Higgins, C. A. (1995). Computer Self-Efficacy: Development of a Measure and Initial Test. MIS Quarterly, 19(2), 189 – 211. DOI: 10.2307/249688.
90. Mirvis, P. H. (1991). [Review of Flow: The Psychology of Optimal Experience, by M. Csikszentmihalyi]. The Academy of Management Review, 16(3), 636 – 640. DOI: 10.2307/258925.
91. Ajzen, I. (1991). The theory of planned behavior. Organizational Behavior and Human Decision Processes, 50(2), 179 – 211. DOI: 10.1016/0749-5978%2891%2990020-T.
92. Goodhue, D. L., & Thompson, R. L. (1995). Task-Technology Fit and Individual Performance. MIS Quarterly, 19(2), 213 – 236. DOI: 10.2307/249689.
93. Hipp, M., Strauss, A., Michelberger, B., Mutschler, B., Reichert, M. (2015). Enabling a User-Friendly Visualization of Business Process Models. Business Process Management Workshops, 202, 1 – 12. DOI: 10.1007/978-3-319-15895-2_33.
94. Kosinski, M., Matz, S. C., Gosling, S. D., Popov, V., & Stillwell, D. (2015). Facebook as a research tool for the social sciences: Opportunities, challenges, ethical considerations, and practical guidelines. American Psychologist, 70(6), 543 – 556. DOI: 10.1037/a0039210.
95. Schreiber, J., Nora, A., Stage, F. K., Barlow, E. A., & King, J. (2006). Reporting structural equation modeling and confirmatory factor analysis

results: A review. The Journal of Educational Research, 99(6), 323 – 338. DOI: 10.3200/JOER.99.6.323-338.

96. Obidat, A.H., Almahameed, M.A., & Alalwan, M. (2022). An empirical examination of factors affecting the post-adoption stage of mobile wallets by consumers: A perspective from a developing country. Decision Science Letters, 11, 273 – 288. DOI: 10.5267/j.dsl.2022.2.005.

97. Lee, Y. K., Park, J. H., Chung, N., & Blakeney, A. (2012). A unified perspective on the factors influencing usage intention toward mobile financial services. Journal of Business Research, 65(11), 1590 – 1599. DOI: 10.1016/j.jbusres.2011.02.044.

98. Neumann, N. (2018). The acceptance of smart home technology, 1 – 20. URL: https://purl.utwente.nl/essays/75338.

99. Chung, J. E., Park, N., Wang, H., Fulk, J., & McLaughlin, M. L. (2010). Age differences in perceptions of online community participation among non-users: An extension of the Technology Acceptance Model. Comput. Hum. Behav., 26, 1674 – 1684. DOI: 10.1016/j.chb.2010.06.016.

100. Mehmood, M.A., Janjua, Q.R., & Aftab, F. (2021). Unfolding Utilization of Functional Blocks of Social Media in Building Brand Equity in Higher Education Institutes. International Review of Management and Business Research, 10(2), 26 – 41. DOI: 10.30543/10-2%282021%29-3.

101. Porter, M.E., & Millar, V.E. (1998). How information gives you competitive advantage: the information revolution in transforming the nature of competition, 85 – 103. DOI: 10.1016/B978-0-7506-7084-5.50007-5.

102. Lee, B., Jo, Y., Yoo, D., & Lee, J. (2021). Recent progresses of near-eye display for AR and VR. Optical Metrology. Proceedings of the Multimodal Sensing and Artificial Intelligence: Technologies and Applications II, 11785, 1 – 6. DOI: 10.1117/12.2596128.

103. He, D., Westphal, C., & Garcia-Luna-Aceves, J.J. (2018). Network Support for AR/VR and Immersive Video Application: A Survey.

International Conference on E-Business and Telecommunication Networks, 1, 1 – 12. DOI: 10.5220/0006941705250535.

104. Ortiz-Yepes, D. (2014). A critical review of the EMV Payment Tokenisation Specification. Computer Fraud & Security, 2014, 10, 5 – 12. DOI: 10.1016/S1361-3723%2814%2970539-1.

105. Ronchi, E., Mayorga, D.M., Lovreglio, R., Wahlqvist, J., & Nilsson, D. (2019). Mobile-powered head-mounted displays versus cave automatic virtual environment experiments for evacuation research. Computer Animation and Virtual Worlds, 30(6), e1873. DOI: 10.1002/cav.1873.

106. Gere, A., Bin Zulkarnain, A.H., Szakál, D., Fehér, O., & Kókai, Z. (2021). Virtual reality applications in food science. Current knowledge and prospects. Progress in Agricultural Engineering Sciences, 17(1), 1 – 12. DOI: 10.1556/446.2021.00015.

107. Klico, A. (2022). How using virtual reality can improve B2B marketing. BH Ekonomski forum, 27 – 40. DOI: 10.5937/bhekofor2202027k

108. Paliwoda-Matiolanska, A., Smolak-Lozano, E., & Nakayama, A. (2020). Corporate image or social engagement: Twitter discourse on corporate social responsibility (CSR) in public relations strategies in the energy sector. El profesional de la información. 29(3), e290333. DOI: 10.3145/epi.2020.may.33.

109. Gupta, K., Aggarwal, C., Vohra, M., & Suhail, P. (2019). The effectiveness of Augmented Reality and Virtual Reality in marketing communications. International Journal of Advance Research, Ideas and Innovations in Technology, 5(1), 381 – 387. ISSN: 2454-132X.

110. Lee, B., Shih, H., Chou, Y., & Chen, Y. (2017). Educational Virtual Reality implementation on English for Tourism Purpose using knowledge-based engineering. 2017 International Conference on Applied System Innovation (ICASI), 792 – 795. DOI: 10.1109/ICASI.2017.7988550.

111. Bélisle-Pipon, J., Ravitsky, V., & Bensoussan, Y. (2023). Individuals and (Synthetic) Data Points: Using Value-Sensitive Design to Foster Ethical Deliberations on Epistemic Transitions. The American Journal of Bioethics, 23, 69 – 72. DOI: 10.1080/15265161.2023.2237436.
112. Ostroff, C., Barcellos, B., & Abhari, K. (2020). Digital Culture, neither Strategy nor Technology, Drives Digital Transformation. AMCIS 2020 TREOs. 10
113. Adobe Communications Team. (2018). Immersive Virtual Reality Creates a New Currency in Storytelling. Adobe. URL: https://blog.adobe.com/en/publish/2018/01/09/immersive-virtual-reality-creates-new-currency-storytelling.
114. Hanakova, L. (2021). Current issues of personal data privacy in marketing. Acta academica karviniensia. XX(2), 5 – 20. DOI: 10.25142/AAK.2020.006.

APPENDIX A.

LIST OF THE APPLICANT'S PUBLICATIONS ON THE THEME OF THE DISSERTATION AND INFORMTION ON THE APPROVL OF THE RESULTS OF THE DISSERTATION

Articles in professional publications of Ukraine (included in the list of the Ministry of Education and Science of Ukraine)

1. Tsiutsiura, M., Tsiutsiura, S., Kryvoruchko, O., & **Li, Tao** (2022). The Method of harmonizing decision of the divergent methodology of the development of higher education institutions. Management of Development of Complex Systems, 50, 85 – 92. DOI: 10.32347/2412-9933.2022.50.85-92 [category «B», Index Copernicus] https://urss.knuba.edu.ua/files/zbirnyk-50/85-92_0.pdf
2. **Li, Tao** (2023). Evaluating the Effectiveness of VR Simulations in Business Process Formation. Management of Development of Complex Systems, 56, 97 – 104. DOI: 10.32347/2412-9933.2023.56.97-104 [category «B», Index Copernicus] http://mdcs.knuba.edu.ua/article/view/299711
3. **Li, Tao** (2024). Human-computer interaction in virtual reality environments for educational and business purposes. Management of Development of Complex Systems, 57, 112 – 117. DOI: 10.32347/2412-9933.2024.57.112-117 [category «B», Index Copernicus] http://mdcs.knuba.edu.ua/article/view/301837
4. **Li, Tao,** Honcharenko, T. (2024). Integrating advanced human-computer interaction and machine learning models for optimizing VR systems in educational and business applications. Bulletin of the National Technical University «KhPI» A series of "Information and Modeling", 1 – 2 (11 – 12), 105 – 120. DOI: 10.20998/2411-0558.2024.01.09 [category «B», Index Copernicus]

Materials of international scientific conferences indexed in the scientometric database Scopus

5. Tsiutsiura, M., Kostyshyna, N., Yerukaiev, A., Danylyshyn, S., Honcharenko, Y., & **Li, Tao.** (2022). Research of Housing Comfort Using Linguistic Variables. 2022 International Conference on Smart Information Systems and Technologies (SIST), 1 – 5. DOI: 10.1109/SIST54437.2022.9945736 [***Scopus***].
6. Levytskyi, V., Tsiutsiura, M., Yerukaiev, A., Rusan, N., & **Li, Tao.** (2023). The Working Principle of Artificial Intelligence in Video Games. 2023 IEEE International Conference on Smart Information Systems and Technologies (SIST), 246 – 250. DOI: 10.1109/SIST58284.2023.10223491 [***Scopus***].
7. **Tao, Li,** Dolhopolov, S., & Honcharenko, T. (2024). Strategizing VR Integration in Business and Education: Extending the Technology Acceptance Model through Project Management Perspectives. *International Workshop IT Project Management*, Vol. 3709, 250 – 263 [***Scopus, Q4, ISSN 1613-0073***].

Abstracts of reports of scientific and scientific-practical conferences

8. Tsiutsiura, M., Dolhopolov, S., & **Li, Tao.** (2021). Audio-visual assistant for learning foreign languages using machine learning technology. Eighth international scientific-practical conference “Management of the development of technologies”, 15 – 16.
9. **Li, Tao,** Kopcha, O., & Lukeniv, D. (2022). Using the REST API to create and receive information. Ninth international scientific-practical conference “Management of the development of technologies”.
10. Tsiutsiura, M., Nechyporenko, D., & **Li, Tao** (2023). Development of automatic “clever refrigitator” technology with the help of “AI – system product control” artificial intelligence. Tenth international scientific-practical conference “Management of the development of technologies”, 12 – 14.
11. **Li, Tao** (2023). Enhancing Learning Through Immersive Virtual Reality (VR) Technologies in Education. BMC-2023 – International Scientific-Practical Conference of young scientists “Build-Master-Class-2023”, 425–426.

APPENDIX B.

IMPLEMENTATION ACTS