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PHD THESIS

DEVELOPMENT OF AN ECONOMIC-DIGITAL MODEL FOR CONSTRUCTION ENTERPRISES IN A TRANSFORMATIONAL ENVIRONMENT

Specialty: 051 – Economics

Area of knowledge: 05 – “Social and Behavioral Sciences”

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

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ABSTRACT

Jing Qian. **Development of an economic-digital model for construction enterprises in a transformational environment** – Qualification research thesis (manuscript form). Dissertation for the degree of Doctor of Philosophy in the specialty 051 "Economics". – Kyiv National University of Construction and Architecture, Ministry of Education and Science of Ukraine, Kyiv, 2025.

The dissertation is devoted to solving the scientific and practical task of forming an economic-digital model for the development of construction enterprises, which integrates modern approaches of economic diagnostics with digital management technologies to ensure adaptability, innovation activity, and sustainable functioning of business entities in the transformational environment of contemporary construction development.

The relevance of the research is driven by the urgent need to reconsider the theoretical-methodological foundations and applied approaches to managing the development of construction enterprises under the conditions of deep transformations in the socio-economic environment, economic digitalization, and growing instability of market factors. Today, the construction sector of Ukraine operates under intensified dynamics of regulatory changes, resource constraints, technological renewal, and challenges caused by both internal and global factors (including the consequences of military aggression, rising costs of construction resources, and changes in the structure of demand for construction services). In this context, the need to form an integrated economic-digital model becomes increasingly important. Such a model would provide strategic resilience for enterprises, their adaptability to change, enhanced competitiveness, and effective management of innovation and investment potential.

The absence of an established methodology for formalizing such models, the insufficient substantiation of digital approaches in the context of economic development

of construction enterprises, as well as the fragmented nature of digital transformation practices in the industry, highlight the need for a comprehensive scientific study. The results of such research may be applied both in the practical activities of enterprises and in the development and implementation of managerial decisions related to the introduction of digital innovations at the level of individual construction companies.

The *object* of the study is the economic processes of development of construction enterprises in the context of the transformation of their functional environment.

The *subject* of the study is the set of theoretical, methodological, and applied principles for the formation of an economic-digital model for the development of construction enterprises, which ensures their adaptability, innovativeness, and effective management in the conditions of a digital economy.

The *purpose* of the study is to develop a theoretical and methodological framework and applied toolkit for forming an economic-digital model of construction enterprise development, taking into account the specific features of the transformational environment and the need to ensure their competitiveness and sustainable economic growth.

To achieve this purpose, the research addresses a set of interrelated tasks aimed at investigating fundamental theoretical concepts, diagnosing existing barriers to digitalization, formalizing the key structural and functional components of the model, and justifying the mechanisms for its practical implementation:

- to conduct a critical analysis of the evolution of scientific approaches to the construction of digitally-oriented economic models in the construction sector, taking into account the current challenges of the transformational environment;
- to identify institutional and economic prerequisites and key technological factors influencing the formation of the digital architecture of construction enterprises, particularly in the context of foreign experience (based on the example of the PRC);

- to identify financial and resource constraints of digitalization and analyze the cost parameters of implementing BIM technologies into the structure of an enterprise's economic-digital model;
- to develop a methodology for assessing the digital readiness and economic adaptability of a construction enterprise to operate under conditions of digital transformation;
- to substantiate approaches to evaluating the effectiveness of functional process transformation based on economic-digital indicators;
- to design a structural and functional model for the development of a construction enterprise, adapted to the conditions of the digital economy and transformational challenges;
- to substantiate directions and tools for adapting the economic-digital model into the strategic and operational contours of construction enterprise development management;
- to formulate analytical principles for ensuring alignment between strategic vision and tactical management actions in a digitally-oriented environment;
- to develop an economic-analytical toolkit for evaluating the effectiveness of implementing digital solutions in construction enterprise activities and to confirm its practical applicability through testing on enterprises operating in a transformational development environment.

Research Methods. The study employs a comprehensive set of general scientific and specialized methods, including: *analysis and synthesis* – to generalize theoretical approaches to the digitalization of the economy and the development of economic models for enterprise growth; the *system approach* – to identify interconnections between digital, organizational, and economic elements of the model; *economic and statistical methods* – to assess the level of digital readiness, adaptability, and the effectiveness of transformational processes; *modeling* – to construct the structural and functional architecture of the economic-digital model for the development of construction enterprises; and *expert evaluation* – to verify the applied tools of the model and substantiate managerial decisions in the transformational environment of development.

The core hypothesis of the study is that solving the identified scientific tasks will contribute to the formation of an effective economic-digital model for the development of construction enterprises, which will ensure the adaptation of their management processes to transformational changes in the external environment, improve operational performance, and support sustainable strategic growth within the digital economy.

The scientific novelty of the research lies in the following:

Improved:

– the methodology for assessing the level of digital readiness and economic adaptability of construction enterprises has been improved. Compared to existing digital maturity models, the proposed approach integrates economic indicators of adaptability to transformational changes and enables a comprehensive diagnosis of an enterprise's potential for innovative development;

– the structural and functional model of construction enterprise development has been enhanced**.** Unlike existing static management models, the study proposes a flexible model architecture that considers digital transformation vectors, the level of resource provision, and institutional conditions;

– applied approaches to integrating the economic-digital model into the enterprise management system have been developed**.** Tools for adapting the model to both strategic and operational decision-making levels have been substantiated, which enhances the effectiveness of managerial influence under the conditions of environmental instability;

– mechanisms for aligning strategic and tactical parameters of enterprise development in a digital environment have been substantiated**.** Tools have been developed to harmonize goals at various management levels, minimizing organizational and managerial imbalances during the implementation of digital solutions;

– an economic and analytical toolkit for evaluating the effectiveness of digital solutions has been created**.** A combination of qualitative and quantitative approaches to assessing the performance of digital projects in construction is proposed, contributing to more grounded managerial analysis and planning.

Have been further developed:

– the evolution of scientific approaches to the construction of digitally-oriented economic models in the construction sector has been systematized and refined**.** Unlike existing approaches, where digitalization is often considered fragmentarily (mainly at the level of technological solutions), this study analyzes the integration of digital tools into the overall economic model of enterprise development at the micro level;

– the understanding of institutional-economic and technological factors of digital transformation in construction enterprises has been deepened through a comparative analysis of China’s experience in forming a digital enterprise architecture, and the feasibility of adapting selected elements with a focus on the construction industry has been substantiated;

– financial and resource barriers to digitalization and the economic characteristics of BIM implementation have been clarified**.** Unlike existing approaches that emphasize the technical aspect of digital innovations, this research focuses on cost structure, regulatory and institutional barriers, and the evaluation of the cost-effectiveness of digital transformation of an enterprise’s operating system;

– analytical support for evaluating the effectiveness of digital transformation of enterprise functional processes has been further developed**.** The proposed system of digital-economic indicators integrates financial, process, and strategic parameters in a volatile environment, which distinguishes it from most existing models that are primarily focused on technical and technological indicators.

Chapter One substantiates the theoretical and methodological foundations of the economic-digital development of construction enterprises in the transformational development environment. The conceptual and categorical apparatus has been clarified, including the author’s definition of the term *"transformational development environment."* A critical analysis of the current state of construction enterprises has been conducted, identifying barriers to digital transformation and assessing their innovative and managerial potential. Strategic directions for digitalization have been defined, a conceptual research map has been developed, and the necessity of transitioning to integrated economic-digital solutions has been justified.

Chapter Two focuses on the development of tools and methodological solutions for the practical formation of an economic-digital model for the development of a construction enterprise. An original methodology for assessing digital readiness and economic adaptability has been proposed, based on the combination of quantitative and qualitative indicators, enabling a comprehensive assessment of an enterprise's capacity to implement digital technologies in a transformational environment. The methodology includes a differentiated system of indicators covering digital infrastructure level, flexibility of management processes, human capital potential, and investment openness to digital solutions. An approach has been developed for evaluating the effectiveness of functional process transformation, based on a system of economic-digital indicators. Key business processes that are most affected by digitalization—such as procurement logistics, production planning, work performance monitoring, and cost management—have been structured. Performance evaluation indicators have been defined, including productivity, energy efficiency, and digital integration, allowing for the tracking of changes within the functional units of the enterprise. A structural and functional model of economic-digital development has been proposed, which takes into account the organizational structure of the construction enterprise, the specifics of digital processes, and the requirements for adaptive management. The model is presented as an integrated system of interrelated components: digital analysis, strategic planning, resource management, risk management, and feedback monitoring. Its architecture allows for flexible adaptation to market changes and open integration with sectoral information platforms, enabling the clear definition of model parameters for subsequent testing and analytical support at later stages of the research.

Chapter Three presents the practical results of implementing the developed economic-digital model into the system of managing the development of a construction enterprise. A systematic approach to integrating the model into the architecture of managerial decisions is proposed, which involves its step-by-step incorporation into the existing management contours of the enterprise. Based on scenario modeling, the study demonstrates how the economic-digital model can be adapted to the organizational specifics of the enterprise, taking into account the level of digital maturity, resource availability, type of construction activity, and strategic goals. A methodology for the formation of coordinated managerial decisions in a digital environment has been developed. It is based on the principles of dynamically balancing short- and long-term development priorities, the application of KPI indicators, and the use of adaptive planning tools. An algorithm for synchronizing strategic orientations with operational performance indicators has been proposed, enabling controllability of transformation processes and flexibility in decision-making. Particular attention is given to the creation of an economic-analytical toolkit for assessing the effectiveness of digital solution implementation, which allows for the quantitative measurement of digital transformation results. The toolkit includes a system of comparative indicators *"before"* and *"after"* the implementation of digital solutions and accounts for economic feasibility, the level of process automation, productivity improvement, cost reduction, shortening of project timelines, and other operational effects. The proposed model has been tested on actual construction enterprises, confirming its effectiveness and practical relevance under current industry conditions.

Theoretical significance of the results lies in deepening scientific understanding of the economic-digital transformation of construction enterprises through the refinement of definitions, the development of a structural-functional model of digital development, and the substantiation of principles for aligning management decisions in a changing development environment. A conceptual basis has been formed for further research in the field of the digital economy in construction.

Practical significance of the results consists in the development and implementation of an economic-digital model that enhances the effectiveness of managing the development of construction enterprises in a transformational environment. The proposed methodologies for assessing digital readiness, adaptability, and the effectiveness of transformational processes have been tested on real enterprises and can be used to improve strategic and operational management, reduce costs, increase productivity, and strengthen resilience to risks.

Keywords: construction enterprise, development, development project, economic-digital model, digital transformation, building information modeling (BIM), innovative development, development management, formalized indicators, enterprise operating system, digital environment, development strategy, performance evaluation, integrated administration, enterprise management.

АНОТАЦІЯ

Цянь Цзін **Формування економіко-цифрової моделі розвитку будівельних підприємств в умовах трансформаційного середовища** – Кваліфікаційна наукова праця на правах рукопису. Дисертація на здобуття наукового ступеня доктора філософії за спеціальністю 051 «Економіка». – Київський національний університет будівництва і архітектури, МОН України, Київ, 2025.

Дисертація присвячена вирішенню науково-практичної задачі формування економіко-цифрової моделі розвитку будівельних підприємств, яка поєднує сучасні підходи економічної діагностики з цифровими технологіями управління для забезпечення адаптивності, інноваційної активності та стійкого функціонування суб'єктів господарювання в умовах трансформаційного середовища сучасного будівельного девелопменту.

Актуальність дослідження зумовлена нагальною потребою переосмислення теоретико-методологічних засад і прикладних підходів до управління розвитком будівельних підприємств в умовах глибоких трансформацій соціально-економічного середовища, цифровізації економіки та посилення нестабільності ринкових чинників. Сучасна будівельна галузь України функціонує в умовах підвищеної динаміки нормативно-правових змін, ресурсних обмежень, технологічного оновлення та викликів, спричинених як внутрішніми, так і глобальними факторами (зокрема, наслідками воєнної агресії, зростанням вартості будівельних ресурсів, зміною структури попиту на будівельні послуги). У цьому контексті актуалізується потреба у формуванні інтегрованої економіко-цифрової моделі, яка б дозволила забезпечити стратегічну стійкість підприємств, їх адаптивність до змін, підвищення конкурентоспроможності та ефективне управління інноваційно-інвестиційним потенціалом.

Відсутність усталеної методології формалізації таких моделей, недостатній рівень обґрунтованості цифрових підходів у контексті економічного розвитку будівельних підприємств, а також фрагментарність практик цифрової трансформації у галузі зумовлюють потребу в комплексному науковому дослідженні, результати якого можуть бути використані як у практичній діяльності підприємств, так і у розробленні та реалізації управлінських рішень щодо впровадження цифрових інновацій на рівні окремих будівельних підприємств.

Об'єктом дослідження є економічні процеси розвитку будівельних підприємств у контексті трансформації їхнього функціонального середовища.

Предметом дослідження є сукупність теоретичних, методичних та прикладних засад формування економіко-цифрової моделі розвитку будівельних підприємств, що забезпечує їх адаптивність, інноваційність та ефективність управління в умовах цифрової економіки.

Метою дослідження є розроблення теоретико-методологічного підґрунтя та прикладного інструментарію формування економіко-цифрової моделі розвитку будівельних підприємств з урахуванням особливостей трансформаційного середовища та необхідності забезпечення їх конкурентоспроможності й стійкого економічного зростання.

Для досягнення поставленої мети, у роботі було вирішено низку взаємопов'язаних *завдань,* спрямованих на дослідження фундаментальних теоретичних положень, діагностику існуючих бар'єрів цифровізації, формалізацію ключових структурно-функціональних компонентів моделі, а також обґрунтування механізмів її практичної реалізації:

- здійснити критичний аналіз еволюції наукових підходів до побудови цифрово-орієнтованих економічних моделей у сфері будівництва, з урахуванням сучасних викликів трансформаційного середовища;
- визначити інституційно-економічні передумови та ключові технологічні чинники, що впливають на формування цифрової архітектури будівельних підприємств, зокрема в контексті зарубіжного досвіду (на прикладі КНР);

- ідентифікувати фінансово-ресурсні обмеження цифровізації та проаналізувати вартісні параметри впровадження BIM-технологій у структуру економіко-цифрової моделі підприємства;
- розробити методику оцінювання цифрової готовності та економічної адаптивності будівельного підприємства до функціонування в умовах цифрової трансформації;
- обґрунтувати підходи до оцінювання ефективності трансформації функціональних процесів підприємства на основі економіко-цифрових індикаторів;
- сформувати структурно-функціональну модель розвитку будівельного підприємства, адаптовану до умов цифрової економіки та трансформаційних викликів;
- обгрунтувати напрями та інструменти адаптації економіко-цифрової моделі у стратегічні та оперативні контури управління розвитком будівельного підприємства;
- сформувати аналітичні засади забезпечення узгодженості між стратегічним баченням і тактичними управлінськими діями в цифрово-орієнтованому середовищі;
- розробити економіко-аналітичний інструментарій оцінки ефективності впровадження цифрових рішень у діяльність будівельних підприємств і підтвердити його прикладною результативністю через апробацію на підприємствах, що функціонують в умовах трансформаційного середовища девелопменту.

Методи дослідження. У дослідженні використано комплекс загальнонаукових і спеціальних методів, зокрема: аналіз і синтез – для узагальнення теоретичних підходів до цифровізації економіки та побудови економічних моделей розвитку підприємств; системний підхід – для визначення взаємозв’язків між цифровими, організаційними та економічними елементами моделі; економіко-статистичні методи – для оцінювання рівня цифрової готовності, адаптивності та ефективності трансформаційних процесів; моделювання – для побудови структурно-функціональної архітектури економіко-цифрової моделі розвитку будівельного підприємства; експертне оцінювання – для верифікації прикладних інструментів моделі та обґрунтування управлінських рішень у трансформаційному середовищі девелопменту.

Основна гіпотеза дослідження полягає в тому, що завдяки вирішенню поставлених наукових завдань результати дослідження сприятимуть формуванню ефективної економіко-цифрової моделі розвитку будівельних підприємств, яка забезпечить адаптацію їх управлінських процесів до трансформаційних змін зовнішнього середовища, підвищить результативність операційної діяльності та забезпечить стійке стратегічне зростання в умовах цифрової економіки.

Наукова новизна *одержаних результатів* полягає в наступному:

удосконалено

– методику оцінювання рівня цифрової готовності та економічної адаптивності будівельного підприємства. У порівнянні з існуючими моделями цифрової зрілості, запропонований підхід інтегрує економічні індикатори адаптивності до трансформаційних змін і дозволяє комплексно діагностувати потенціал підприємства до інноваційного розвитку;

– структурно-функціональну модель розвитку будівельного підприємства. На відміну від існуючих статичних моделей управління, у дослідженні запропоновано гнучку архітектуру моделі, що враховує цифрові вектори трансформації, рівень ресурсної забезпеченості та інституційні умови;

– прикладні підходи до інтеграції економіко-цифрової моделі в систему управління підприємством. Обґрунтовано інструменти адаптації моделі до стратегічного та оперативного рівнів прийняття рішень, що підвищує ефективність управлінського впливу в умовах нестабільності середовища функціонування будівельного підприємства;

– механізми узгодження стратегічних і тактичних параметрів розвитку підприємства в цифровому середовищі. Розроблено інструменти гармонізації цілей на різних рівнях управління, що дозволяють мінімізувати організаційно-управлінські дисбаланси у процесі впровадження цифрових рішень;

– економіко-аналітичний інструментарій оцінки ефективності цифрових рішень. Запропоновано поєднання якісних і кількісних підходів до оцінювання результативності цифрових проєктів у будівництві, що сприяє більш обґрунтованому управлінському аналізу та плануванню.

набули подальшого розвитку:

– систематизовано та уточнено еволюцію наукових підходів до побудови цифрово-орієнтованих економічних моделей у будівництві. на відміну від наявних підходів, де цифровізація розглядається фрагментарно (на рівні технологічних рішень), у роботі здійснено аналіз інтеграції цифрових інструментів у загальну економічну модель розвитку підприємств на мікрорівні;

– поглиблено розуміння інституційно-економічних та технологічних чинників цифрової трансформації будівельних підприємств шляхом порівняльного аналізу досвіду КНР щодо формування цифрової архітектури підприємства та обґрунтовано доцільність адаптації окремих елементів з фокусом на будівельну галузь;

– уточнено фінансово-ресурсні бар’єри цифровізації та економічні характеристики впровадження BIM-технології. На відміну від наявних підходів, що акцентують на технічному аспекті цифрових інновацій, у роботі акцент зроблено на витратній структурі, нормативно-інституційних перепонах і оцінці вартісної ефективності цифрової трансформації операційної системи підприємства;

– набуло подальшого розвитку аналітичне забезпечення оцінки ефективності цифрової трансформації функціональних процесів підприємства. Запропонована система цифрово-економічних індикаторів інтегрує фінансові, процесні та стратегічні параметри в умовах змінного середовища, що відрізняє її від більшості існуючих моделей, орієнтованих на облік лише техніко-технологічних показників.

У першому розділі обґрунтовано теоретико-методологічні засади економіко-цифрового розвитку будівельних підприємств у трансформаційному середовищі девелопменту. Уточнено понятійно-категоріальний апарат, зокрема введено авторське визначення "трансформаційне середовище девелопменту". Здійснено критичний аналіз сучасного стану будівельних підприємств, виявлено бар'єри цифрової трансформації та оцінено їх інноваційно-управлінський потенціал. Визначено стратегічні орієнтири цифровізації, сформовано концептуальну карту дослідження та обґрунтовано необхідність переходу до інтегрованих економіко-цифрових рішень.

У другому розділі дисертації зосереджено увагу на розробленні інструментів та методичних рішень для практичного формування економіко-цифрової моделі розвитку будівельного підприємства. Розроблено авторську методику оцінювання рівня цифрової готовності та економічної адаптивності, яка базується на поєднанні кількісних та якісних показників і дозволяє комплексно оцінити спроможність підприємства до впровадження цифрових технологій в умовах трансформаційного середовища. Методика включає диференційовану систему індикаторів, що охоплює рівень цифрової інфраструктури, гнучкість управлінських процесів, кадровий потенціал та інвестиційну відкритість до цифрових рішень. Розроблено підхід до оцінювання ефективності трансформації функціональних процесів, що базується на системі економіко-цифрових індикаторів. Здійснено структуризацію ключових процесів діяльності будівельного підприємства, які зазнають найбільшого впливу внаслідок цифровізації (зокрема, закупівельна логістика, виробниче планування, моніторинг виконання робіт, управління витратами). Визначено показники оцінки результативності трансформації, зокрема продуктивність, енергоефективність, цифрова інтегрованість, що дозволяє відстежувати динаміку змін у функціональних блоках підприємства. Запропоновано структурно-функціональну модель економіко-цифрового розвитку, яка враховує особливості організаційної будови будівельного підприємства, специфіку цифрових процесів і вимоги до адаптивного управління. Модель представлено як інтегровану систему взаємопов’язаних компонентів: цифрового аналізу, стратегічного планування, управління ресурсами, ризик-менеджменту та зворотного моніторингу. Її архітектура передбачає гнучкість адаптації до змін ринкового середовища, а також відкрите підключення до галузевих інформаційних платформ, що дало змогу задати чіткі параметри моделі для подальшого її апробування та аналітичного супроводу на подальших етапах дослідження.

У третьому розділі дисертації представлено практичні результати щодо впровадження розробленої економіко-цифрової моделі в систему управління розвитком будівельного підприємства. Запропоновано підхід до системної інтеграції моделі в архітектуру управлінських рішень, що передбачає її поетапне включення в існуючі управлінські контури підприємства. На основі моделювання сценаріїв розвитку продемонстровано, як економіко-цифрова модель може бути адаптована до організаційної специфіки підприємства, з урахуванням рівня цифрової зрілості, доступності ресурсів, типу будівельної діяльності та стратегічних цілей. Розроблено методику формування узгоджених управлінських рішень у цифровому середовищі. Вона базується на принципах динамічного балансування коротко- і довгострокових пріоритетів розвитку, застосування KPI-індикаторів, а також інструментів адаптивного планування. Запропоновано алгоритм синхронізації стратегічних орієнтирів із оперативними показниками функціонування, що дозволяє забезпечити керованість процесами трансформації та гнучкість у прийнятті управлінських рішень. Особливу увагу приділено створенню економіко-аналітичного інструментарію оцінки ефективності впровадження цифрових рішень, який дає змогу кількісно вимірювати результати цифрової трансформації. Інструментарій включає систему порівняльних індикаторів «до» і «після» впровадження цифрових рішень, враховує економічну доцільність, рівень автоматизації процесів, підвищення продуктивності, зменшення витрат, скорочення термінів виконання робіт та інші операційні ефекти. Проведено апробацію запропонованої моделі на прикладі конкретних будівельних підприємств, що підтвердило її ефективність і практичну цінність у сучасних умовах функціонування будівельної галузі.

Теоретичне значення отриманих результатів полягає в поглибленні наукових уявлень про економіко-цифрову трансформацію будівельних підприємств шляхом уточнення понять, формування структурно-функціональної моделі цифрового розвитку та обґрунтування принципів узгодження управлінських рішень у змінному середовищі девелопменту. Сформовано концептуальну основу для подальших досліджень у сфері цифрової економіки будівництва.

Практичне значення отриманих результатів полягає у розробленні та впровадженні економіко-цифрової моделі, що забезпечує підвищення ефективності управління розвитком будівельних підприємств у трансформаційному середовищі. Запропоновані методики оцінювання цифрової готовності, адаптивності та ефективності трансформаційних процесів апробовані на реальних підприємствах і можуть бути використані для вдосконалення стратегічного та оперативного управління, зниження витрат, підвищення продуктивності та стійкості до ризиків.

Ключові слова: будівельне підприємство, девелопмент, девелоперський проєкт, економіко-цифрова модель, цифрова трансформація, інноваційний розвиток, операційна система підприємства, стратегія розвитку, оцінювання ефективності, інформаційне моделювання бізнес-процесів, інформаційне моделювання (BIM), управління підприємством.

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ABBREVIATIONS

BIM – Building Information Model

IT – Information Technologies

DEA – Data Envelopment Analysis

DT – Digital Technologies

DTF – Digital TransFormation

ICP – Investment and Construction Project

CCPs – Capital Construction Projects

IMT – Information modeling technology

CDE – Common Data Environment

UIS – Unified Information System

EDMS – Electronic Document Management System

INTRODUCTION

Relevance of the topic of the dissertation. The current stage of economic development is characterized by profound transformational shifts, which are due to the influence of global digital trends, increased uncertainty of the external environment, increased requirements for competitiveness and innovation of enterprises, especially in the construction sector. Construction enterprises play a strategic role in the socio-economic development of states, ensuring the implementation of infrastructure, housing and industrial projects.The relevance of the dissertation topic is due to the rapid growth of the role of digital technologies in the formation of new models of economic development, especially in the construction industry, which is at the same time one of the most resource-intensive and dynamically changing spheres of the economy. In the conditions of digital transformation and the constant complication of the external environment, construction enterprises are faced with the need for rapid updating of management approaches, increased adaptability to changes and the implementation of innovative digital solutions. However, the lack of comprehensive economic and digital models capable of ensuring sustainable development and strategic stability of enterprises in such conditions makes it necessary to scientifically understand new methodological principles and applied mechanisms for managing the development of construction development entities.

The scientific problem is to form an integrated economic and digital model that would not only coordinate digital tools with traditional management processes, but also ensure the effectiveness of transformational changes and innovative activity of enterprises. Scientific works by Ukrainian and foreign authors examine individual aspects of the digitalization of the construction industry, economic adaptation of enterprises, the use of BIM technologies, and the formation of digital infrastructure.

The issues of forming economic and digital models of enterprise development, digital transformation of management processes and adaptation of construction companies to the challenges of the digital economy have been reflected in the scientific works of many foreign researchers. In particular, an important contribution to the development of theoretical and methodological foundations of digitalization and economic adaptation of enterprises was made by such scientists as K. Schwab, M. Porter, H. Chesbrough, T. Davenport, M. Fischer, R. Bolton, A. Hartmann, F. Haase, K.Graft, P. Schumann, R. Grundemann, Shi Zhijun. Their works highlight aspects of strategic management of digital innovations, the formation of digital architecture of enterprises, the cost-effectiveness of implementing BIM technologies, the use of digital platforms in construction, as well as approaches to harmonizing management decisions in a changing environment.

In the context of the transformation of the modern economic environment and the challenges of digitalization of the construction industry, leading Ukrainian scientists focus on the issues of forming economic and digital models of development, improving management processes and increasing the efficiency of the functioning of enterprises. A significant contribution to the development of scientific and methodological approaches to the modernization of management systems in the digital environment was made by O. Amosha, S. Bushuyev, T. Goncharenko, G. Ryzhakova, A. Shpakov, N. Petrukha, O. Khomenko, L. Zgalat-Lozynska, I. Novikova, D. Prykhodko, V. Pokolenko, O. Tugay, R. Trach. At the same time, the issues of a comprehensive assessment of the digital readiness of enterprises, the formalization of structural and functional models of development in a transformational environment, as well as the assessment of the efficiency of digital solutions taking into account economic indicators, remain insufficiently studied. The lack of an established methodology for formalizing such models, the insufficient level of justification of digital approaches in the context of the economic development of construction enterprises, as well as the fragmentation of digital transformation practices in the industry determine the need for comprehensive scientific research, the results of which can be used both in the practical activities of enterprises and in the development and implementation of management decisions regarding the implementation of digital innovations at the level of individual construction enterprises. Thus, the study devoted to the formation of an economic and digital model of development of construction enterprises has important scientific and practical significance, as it is aimed at improving management tools in the context of profound changes in the external and internal environment of the industry.

The connection of the work with scientific programs, plans, topics. The dissertation was completed within the framework of scientific research and scientific search work, which was carried out with the participation of the author of the work at the Department of Construction Economics of the Kyiv National University of Construction and Architecture, namely: within the framework of the implementation of the topic "Development of modern economic and analytical tools for development management of contract construction" (state registration number 0115U000860) the author improved the methodology for assessing the level of digital readiness and economic adaptability of enterprises, proposed a system of economic and digital indicators for assessing the effectiveness of the transformation of functional processes, and also developed an analytical tool for implementing digital solutions in the development project management system.;

The author's contribution to the implementation of the research topic "Digital Transformation of Administration Processes in Construction Development: Organizational, Technological and Economic-Analytical Approaches to Multi-Project Activities of Enterprises" (state registration number 0124U005168) consists in the formation of an applied model for integrating digital tools into the management system of the multi-project environment of a construction enterprise. The author substantiated the economic and analytical tools of digital transformation, which include assessing adaptability, resource consistency and efficiency of the implementation of development projects. Approaches to synchronizing strategic and tactical management decisions in a digital environment have been developed, which allows increasing operational flexibility, reducing the risks of project uncertainty and ensuring transparency of administration in the conditions of a transformational economy. The results obtained can be used to improve digital models of administration of development projects with a multi-project structure.

The purpose of the study is to develop a theoretical and methodological basis and applied tools for the formation of an economic and digital model of the development of construction enterprises, taking into account the peculiarities of the transformational environment and the need to ensure their competitiveness and sustainable economic growth.

To achieve this purpose, the work solved a number of interrelated **tasks** aimed at studying fundamental theoretical provisions, diagnosing existing barriers to digitalization, formalizing key structural and functional components of the model, as well as substantiating the mechanisms for its practical implementation:

1. To carry out a critical analysis of the evolution of scientific approaches to building digitally-oriented economic models in the construction sector, taking into account modern challenges of the transformational environment;
2. To identify institutional and economic prerequisites and key technological factors that influence the formation of the digital architecture of construction enterprises, in particular in the context of foreign experience (on the example of the PRC);
3. To identify financial and resource limitations of digitalization and analyze the cost parameters of implementing BIM technologies into the structure of the economic and digital model of the enterprise;
4. To develop a methodology for assessing the digital readiness and economic adaptability of a construction enterprise to operate in the conditions of digital transformation;
5. To substantiate approaches to assessing the effectiveness of the transformation of the functional processes of the enterprise based on economic and digital indicators;

6. To form a structural and functional model of the development of a construction enterprise, adapted to the conditions of the digital economy and transformation challenges;

7. To substantiate the directions and tools for adapting the economic and digital model into the strategic and operational contours of managing the development of a construction enterprise;

8. To form analytical principles for ensuring consistency between the strategic vision and tactical management actions in a digitally oriented environment;

9. To develop an economic and analytical toolkit for assessing the effectiveness of implementing digital solutions in the activities of construction enterprises and confirm its applied effectiveness through testing at enterprises operating in a transformational development environment.

Research methods. The study used a set of general scientific and special methods, in particular: analysis and synthesis - to generalize theoretical approaches to the digitalization of the economy and the construction of economic models of enterprise development; a systemic approach - to determine the relationships between digital, organizational and economic elements of the model; economic and statistical methods - to assess the level of digital readiness, adaptability and efficiency of transformation processes; modeling - to build a structural and functional architecture of the economic and digital model of the development of a construction enterprise; expert evaluation - to verify the applied tools of the model and justify management decisions in a transformational development environment.

The scientific novelty of the results obtained is as follows:

Improved:

— the methodology for assessing the level of digital readiness and economic adaptability of a construction enterprise. Compared with existing models of digital maturity, the proposed approach integrates economic indicators of adaptability to transformational changes and allows for a comprehensive diagnosis of the enterprise's potential for innovative development;

— a structural and functional model of the development of a construction enterprise. Unlike existing static management models, the study proposes a flexible architecture of the model that takes into account digital vectors of transformation, the level of resource availability and institutional conditions;

— applied approaches to integrating the economic and digital model into the enterprise management system. The tools for adapting the model to the strategic and operational levels of decision-making are substantiated, which increases the effectiveness of managerial influence in the conditions of instability of the construction enterprise's operating environment;

— mechanisms for coordinating strategic and tactical parameters of enterprise development in the digital environment. Tools for harmonizing goals at different levels of management have been developed, allowing to minimize organizational and managerial imbalances in the process of implementing digital solutions;

— economic and analytical tools for assessing the effectiveness of digital solutions. A combination of qualitative and quantitative approaches to assessing the effectiveness of digital projects in construction has been proposed, which contributes to more substantiated management analysis and planning.

have been further developed:

— the evolution of scientific approaches to building digitally-oriented economic models in construction has been systematized and clarified. Unlike existing approaches, where digitalization is considered fragmentarily (at the level of technological solutions), the work has analyzed the integration of digital tools into the general economic model of enterprise development at the micro level;

— the understanding of institutional, economic and technological factors of digital transformation of construction enterprises has been deepened through a comparative analysis of the experience of the PRC in forming the digital architecture of the enterprise and the feasibility of adapting individual elements with a focus on the construction industry has been substantiated;

— the financial and resource barriers to digitalization and the economic characteristics of the implementation of BIM technology have been clarified. Unlike existing approaches that emphasize the technical aspect of digital innovations, the work focuses on the cost structure, regulatory and institutional barriers and assessment of the cost-effectiveness of the digital transformation of the enterprise's operating system;

— analytical support for assessing the effectiveness of digital transformation of functional processes of an enterprise has been further developed. The proposed system of digital economic indicators integrates financial, process and strategic parameters in a changing environment, which distinguishes it from most existing models focused on accounting only technical and technological indicators.

The theoretical significance of the dissertation work lies in the deepening, systematization and further development of scientific provisions on the formation of digitally oriented economic models of enterprise development in the construction sector. The work first proposes a comprehensive interpretation of the "economic-digital model" as a dynamic management circuit that combines economic development mechanisms with digital tools, technologies and analytical platforms. Significant scientific improvement has been made in conceptual approaches to structuring the digital architecture of construction enterprises, taking into account the institutional and economic environment; theoretical principles for assessing the digital maturity and adaptability of enterprises; methodology for transforming functional processes in construction through the integration of economic and digital indicators; understanding the balance between strategic vision and tactical actions in the digital environment; classification and typology of financial and resource barriers to digitalization in the context of implementing BIM technologies.

The practical significance of the results obtained lies in the development and testing of effective methodological approaches, tools, and applied solutions that can be used by construction industry enterprises in the process of transitioning to a digital development management model. The research results have significant practical value for managers, consultants, digital strategists, and developers of innovative solutions working in the field of construction development and related industries.

The practical value of the entire study and its individual conclusions and results are confirmed by their implementation in the practical activities of construction enterprises, in particular in the form of experimental use of the economic-digital model in the processes of digitalization of production and management processes (Alfa-Service LLC, Fomalhaut-Polymin LLC). In addition, some provisions of the work were used in the development of KNUCA training courses in specialties 051 "Economics" and 073 "Management".

The object of the study is the economic processes of development of construction enterprises in the context of the transformation of their functional environment.

The subject of the study is a set of theoretical, methodological and applied principles for the formation of an economic and digital model of development of construction enterprises, which ensures their adaptability, innovation and management efficiency in the digital economy.

Personal contribution of the applicant. All provisions, results and conclusions of the dissertation are substantiated by the author independently, based on her own theoretical generalizations, critical analysis of sources, as well as empirical research. The materials submitted for defense do not violate the copyrights of other persons and do not contain unfair practices of scientific borrowing. The results of the verification confirm that the applicant completed the dissertation work in compliance with the principles of academic integrity, ensuring the appropriate level of scientific ethics, reliability, originality and lawful use of information sources.

Publications. According to the results of the research, 18 scientific papers were published, including: 9 articles in scientific specialized publications of category "B" of

Ukraine; 2 - in periodical scientific professional publications of other states that are members of the EU; 7 publications of an approbatory nature in the form of abstracts of reports at international and domestic scientific and practical conferences.

Structure and scope of the dissertation. The dissertation consists of an introduction, three chapters, conclusions, appendices and a list of sources used. The full volume of the dissertation is 197 pages of printed text. The total list of sources used is 175 names. The work was carried out at the Department of Management in Construction of the Kyiv National University of Civil Engineering and Architecture.

CHAPTER 1. THEORETICAL FRAMEWORK FOR SHAPING THE ECONOMIC AND DIGITAL DEVELOPMENT MODEL OF CONSTRUCTION ENTERPRISES

1.1. Evolution of conceptual approaches to the creation of digitally-oriented economic models in construction

The active displacement of traditional forms of doing business by new formats based on the widespread use of information technologies (IT), knowledge and data in digital form, indicates the high competitiveness of digital business models in modern conditions. In this regard, the digital transformation (DTF) of construction enterprises using traditional business models becomes a question of their survival in the new conditions dictated by digital technologies (DT). (Figure 1.1).

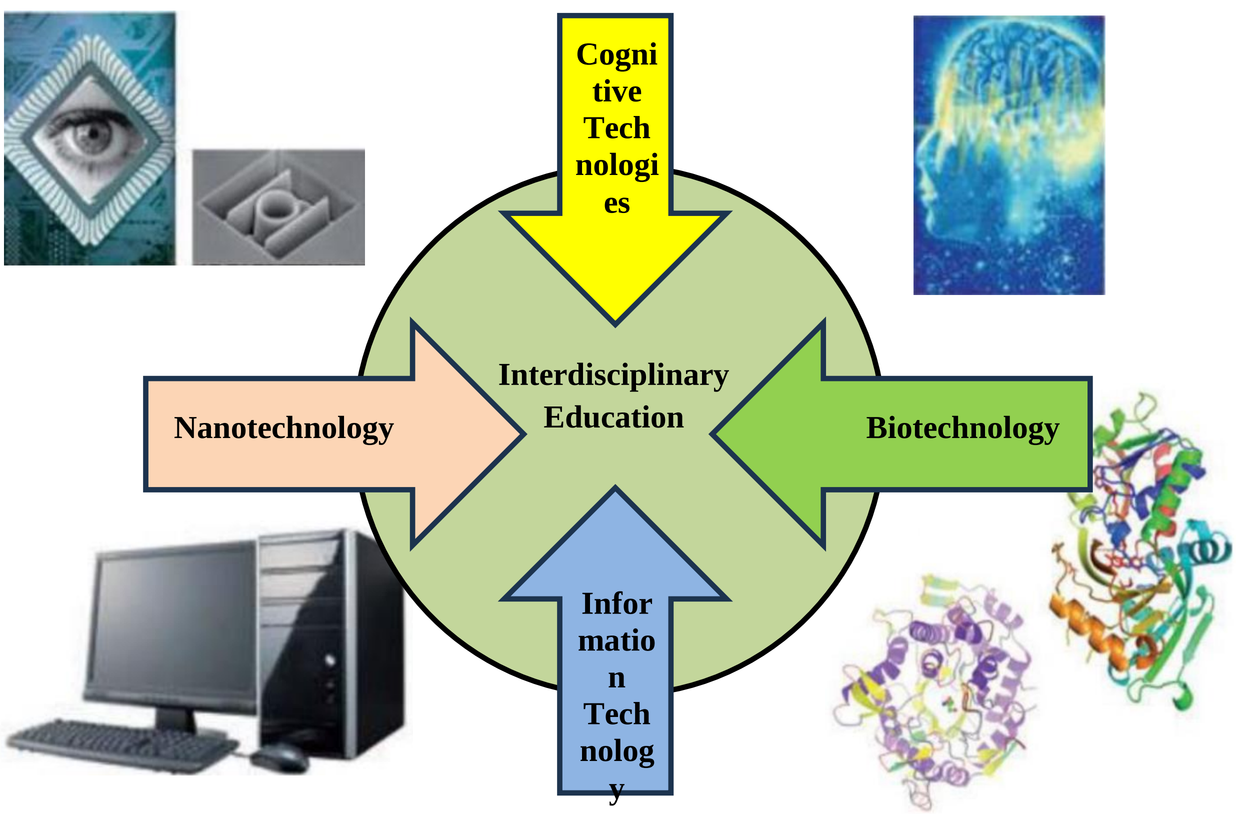


Figure 1.1 – Convergence of technologies and spheres.

The information, service, individual and «digitized» economy of the future must be oriented towards satisfying the needs of each person. The creation of new value should be based on an innovative mechanism for increasing the intellectual potential of society to ensure the transition to sustainable development

The main task is to study the «structure» and capabilities of a person and copy them in the form of model technical systems. A new stage of technological development is the reproduction of living nature systems. Based on atoms and bioorganic molecules, the creation of technologies for atomic-molecular construction and self-organization. The result of which should be biorobotic systems (Figure 1.2).

For the formation and effective functioning of the new economy, society itself must be ready. There is a concept according to which the social layer must have the characteristics of society 5.0 in order to effectively internalize the digital mentality (Table 1.1).

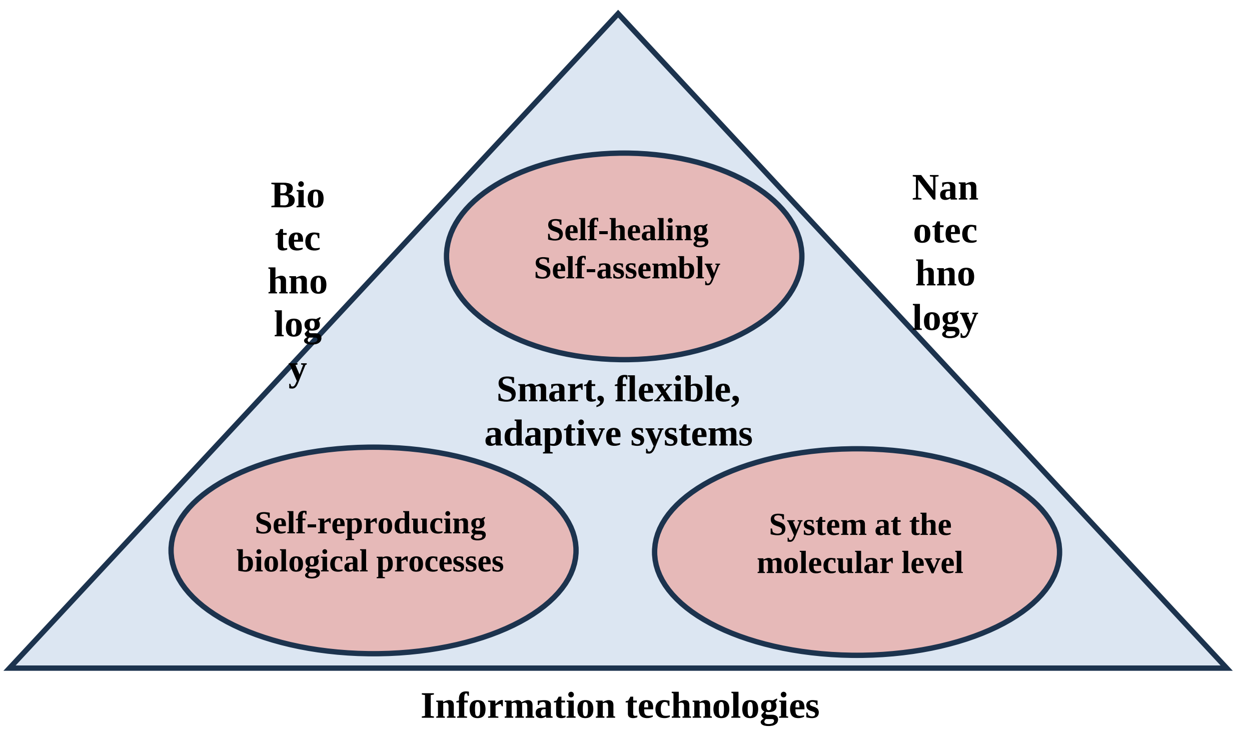


Figure 1.2 – Evolution of systems in the new economy.

Table 1.1 – The essence, features and scientific and technological foundations of the concept of «Society 5.0» in the context of the digital economy

Society 4.0	**Society 5.0**
From individual optimization to optimization of society as a whole. Removal of various restrictions to solve social problems and ensure the well-being of society and its citizens.	
Information society. Invention of the computer. Beginning of the dissemination of information.	Super Smart Society. Internet of Things and Artificial Intelligence (AI). Progress in Biotechnology.
Individual optimization.	Optimization of society as a whole through the convergence of physical and cyber structures (general optimization).
Optimal consumption of resources.	Effective handling of new resources – data.
A world bound by various restrictions (temporal, spatial, etc.).	A world free from restrictions.
Solving individual problems.	Finding solutions to complex social problems.
Focus on increasing industry efficiency.	The main focus is the well-being of citizens and society as a whole.
Reduction in the number of people. Reduction in industrial competitiveness.	Increasing the intelligence of a society that develops resilience in the context of population reduction to emerging restrictions, which contributes to doubling the gross product per unit of population.
Rapid aging of the population. Infringement of women's rights in the social world order.	Formation of a social order in which, among others, older people and women take full part, maximizing the development of each person's abilities. Gender and age freedom from any restrictions.
Terrorist attacks. Natural disasters. Old infrastructure base.	Cybersecurity of society. Minimizing physical damage due to cyber attacks, criminal acts, man-made threats. Relief from anxiety.
Uneven regional development. Predominance of urban agglomerations.	Ensuring a high quality of life regardless of territorial location. Leveling the quality gap between regions, cities and megacities
Environmental issues. Resource deficit.	Ensuring harmonious economic development linked to the state of the environment. Reducing associated waste when consuming resources/energy. Overcoming environmental/resource constraints.

At the same time, a qualitative transition to a new format of industry is also observed (Table 1.2).

Table 1.2 – Qualitative features of the new format industry

Activity aspects	**Traditional industrial structure**	**Industry of a new format**
Transformational factors	Globalization processes, increasing competition in industrial segments, increasing financial leverage over organizations, widespread commoditization of goods.	Digital economy, principles of sustainable development.
Raw materials	Consumption of renewable raw materials and natural gas.	Ubiquitous use of data, focus on maximum waste recycling, hydrogen energy.
Technological solutions	Use of gene and biotechnology in production processes, individualization of production.	DTF of management and business processes.
Research aspect	Convergent approximation of fundamental educational and applied corporate research.	Focusing research on industry-specific market conditions, big data practices, joint projects.
Organizational structure	Internationalization, specialization and localization of production, development of small and medium-sized businesses, consolidation of markets through mergers and acquisitions.	Development of flexible network economic structures, digital cooperation.
Product portfolio	Increasing the product selection and range through highly specialized goods, taking into account the individual specifics of the consumer, developing the generics market, replacing traditional materials with synthesized structures.	Creation of new value in the economy, prevalence of complex solutions in the market.
Safety and security of activities, ecology	Taking into account the environmental component in the production process, food safety ensured by eco-materials.	Prospective development based on the triad model: economy, ecology, society.

The transition of society to a global digital economy and the development of IT also carry certain risks that should be taken into account when forming a digital ecosystem in a particular country:

- the ability to control private life (movements, actions, purchases, preferences, personal life);
- the use of personal data in fraudulent schemes (biometrics, card data, etc.);

- global competition and the absence of barriers - national economic systems are becoming open to competitors from all over the world, which increases the aggressiveness of competition, including the use of dumping;
- a threat to the country's "digital sovereignty" - the possibility of electronic espionage, cyber attacks;
- commercial (industrial) espionage – with the development of information technology, it is becoming an increasingly popular tool among unscrupulous companies (states);
- reduction in tax revenues – if goods purchased online from other countries are not taxed, this actually contributes to an indirect outflow of money from the country;
- automation of labor using new technologies – frees up a large number of labor personnel, whose place is taken by a digital algorithm or machine, thereby increasing structural unemployment, reducing labor liquidity.

Thus, the transition of society to a digital economy will help reduce the above-mentioned risks.

In this regard, it is proposed to supplement the system of indicators of the company's digital maturity with the indicators presented in Table 1.3.

An assessment of the holding's level of digital maturity based on this system of indicators is presented in Figure 1.3.

It should be noted that the above methods for assessing the level of digitalization of industries and enterprises are applicable, first of all, for a qualitative analysis of digitalization processes.

At the same time, an important element in developing DTF programs is obtaining cost estimates of benefits and costs. One of the key indicators characterizing the impact of digitalization on the efficiency of industrial enterprises is the change in productivity [11].

Table 1.3 – Additional indicators of a company's digital maturity

Indicator	**Purpose of the indicator**	**The indicator includes performance indicators**
DTF Management System	The indicator is designed to quantitatively assess the state of the DTF management system.	Cost of implemented projects Expert assessment of the work of the DTF management system
Data	The indicator is designed to quantitatively assess the state of DTF in the direction of improving the quality of Holding management through working with data and supporting decision-making based on data.	Share of documents converted to electronic form Share of employees entering data into the corporate system Share of production resources providing data
Digital products	The indicator is designed to quantitatively assess the state of DTF in the direction of ensuring the Holding's competitive advantages through the introduction of DT into innovative products and services.	Share of digital products/digital services in total sales
Digital processes	The indicator is designed to quantitatively assess the state of DTF in the direction of increasing the Holding's efficiency through optimization and automation of business processes.	Share of optimized business processes Share of automated business processes
Personnel and Culture	The indicator is designed to quantitatively assess the state of DTF in the direction of preparing and involving managers and leaders in DTF.	Share of executives engaged in DTF Share of employees trained in digital skills Share of employees engaged in DTF
IT infrastructure	The indicator is designed to quantitatively assess the state of DTF in the direction of introducing end-to-end DT into the functioning of the Holding, as well as the sustainable operation of management tools.	Share of production resources connected to the system Automation and communication equipment utilization rate Control equipment correct operation rate

In modern scientific literature, there is no clear attitude towards the issue of increasing the productivity of production processes as a result of DTF. In particular, the question of whether digitalization has a direct impact on increasing productivity and accelerating economic growth remains open.

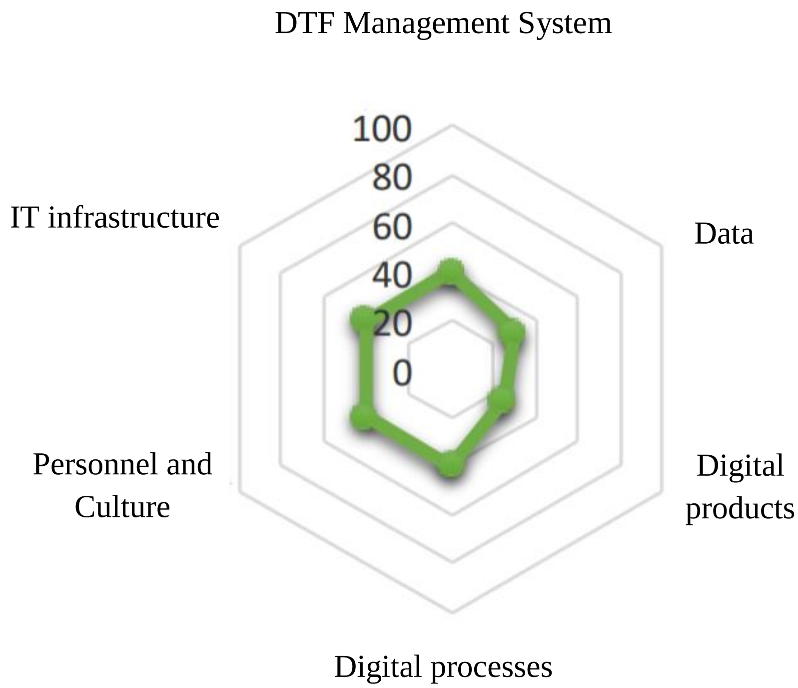


Figure 1.3 – Assessment of the level of digitalization based on additional indicators

The work [28] showed that investments in digital technology development are a significant factor in economic growth in all OECD countries, although to varying degrees. The positive impact of DT on economic growth was also confirmed in [34].

According to the China Academy of Information and Communications Technology (CAICT), digital technology has become a key factor driving the country's economic development in recent years.

Since 2003, China's digital economy has grown at a faster rate than its overall GDP, and since 2011, the growth gap has widened. As a result, DT contributed an estimated 67.9% to the country's GDP growth in 2018 [20]. According to CAICT's forecast, the integration of DT into other sectors of the economy will further increase this influence in the coming decade.

At the same time, an analysis of statistical data for OECD countries, conducted in [24], showed that aggregate productivity growth in many countries has slowed down over the past decade, which contradicts the hypothesis of a positive impact of digital technology development on productivity and economic well-being.

At the same time, an analysis of statistical data for OECD countries, conducted in [24], showed that aggregate productivity growth in many countries has slowed down over the past decade, which contradicts the hypothesis of a positive impact of digital technology development on productivity and economic well-being.

In the work [161], the concept of the productivity paradox for a post-industrial economy was introduced, according to which the introduction of individual technologies in itself does not lead to an increase in the productivity of enterprises. Proponents of this position argue that the impact of investments in DT on production is not as clear as claimed, due to the fact that statistical methods for their assessment are not yet sufficiently developed to accurately calculate such an impact. At the present stage, DT are not yet mature enough to be effectively included in every stage of production and its organization, as a result of which their impact on productivity will manifest itself with a time lag [34].

Since the formulation of the productivity paradox, a number of studies have emerged examining the relationship between the adoption of DT and productivity. M. Porter [8] points out that investing in ICT development is not necessarily strategically beneficial and can lead to a decrease in the competitiveness of enterprises. A positive effect will be achieved only if the enterprise's digital development strategy is consistent with the overall business strategy.

In work [29], the explanation of the productivity paradox in relation to information and communication technologies is based on the time lag between the development of the technology and its practical implementation. In particular, it is pointed out that the basic technologies of previous industrial revolutions (the steam engine in the 18th century, electricity in the 19th century) took more than a century to have a significant impact on economic growth. Therefore, assessing the relationship between technological developments and economic growth based only on current observable data may lead to an underestimation of the impact on productivity.

In work [3], the productivity paradox is explained by the S-shaped curves of the development of new technologies (Figure 1.4). While overall productivity as a result of successive changes in technological paradigms is characterized by an exponential growth trend, each new technology goes through several stages in its development: slow growth, rapid growth, and termination.

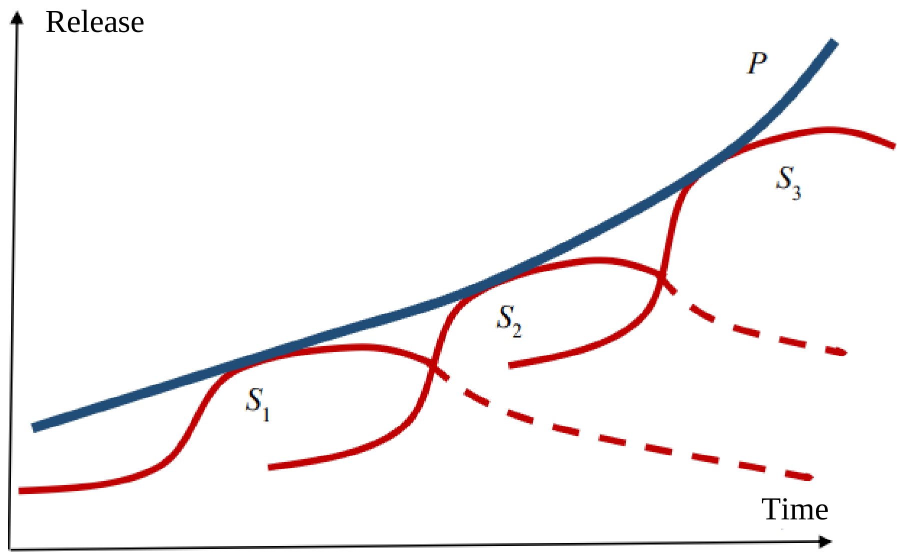


Figure 1.4 – Exponential productivity growth driven by S-shaped curves of new technology development

As a result, when the technological paradigm changes, productivity may not only fail to increase, but also, apparently, decrease in the initial period of the technological revolution.

The work [34] presents the theory of «creative destruction» of innovations, which suggests that each technological innovation becomes the basis for the next one.

Although the next technological innovation begins when the first one reaches its peak, it is characterized by a latent period during which its effects on the industry or the economy as a whole do not become apparent.

In this case, the observed impact of the new technology in its initial stage on productivity improvement may be significantly smaller than that of the existing one.

According to this theory, it is acceptable that the introduction of digital economy technologies at the initial stage is accompanied by a decrease in productivity compared to the technologies of the previous generation.

The work [24] indicates that the long-term benefits of investments in DT represent not only the profit obtained directly from the growth of productivity, but also the indirect ones associated with changes in technological systems and organization. The accumulation of new technologies may eventually lead to disruptive innovations in terminology [137] that yield significant productivity gains. However, this process may be accompanied by implementation delays, additional costs for redesigning business processes, and the need for expensive investments in intangible assets. Thus, even if digitalization of production cannot improve current productivity, it should nevertheless lead to productivity growth in the long term. This is illustrated, in particular, by the widespread introduction of computer technologies into production processes in the 1990s, which resulted in a sharp increase in productivity in industrialized countries in the 2000s [33]. Thus, during the relatively short «transition period», a positive relationship between the development of computer technology and economic growth was not observed.

In the work [94] a model of the innovation function was proposed, which describes, by analogy with the production function, the dependence of the volume of innovative products on the costs incurred by the enterprise on product innovations. The possibility of alternating in this function sections characterized by decreasing and increasing profitability from costs on innovations was shown, and a point of technological optimum was identified, which characterizes the maximum average productivity of innovative resources.

Summarizing the above concepts, it can be stated that the observed decrease in returns in the digital economy at the initial stage is a natural part of its development, since the production function with accelerating growth rates implies a slow growth rate in the initial phase. This situation is almost identical to that which took place in the initial period of the formation of industrial society. Skepticism about the industrial revolution was widespread due to the low rates of production growth in the initial stages of industrial society, but it later turned out that this was due to a lack of understanding of the features of accelerating economic growth in industrial society.

An alternative approach to analysing the impact of DT on productivity is to use microeconomic data. This is supported by earlier studies of ICT adoption in manufacturing, which have shown that productivity gains are not uniform across firms and depend on additional investments in skills, management and organisation [30].

An analysis of micro-level data on the impact of DT on the productivity of individual firms suggests that their adoption may be associated with a widening productivity gap between highly productive firms («digital champions») and other firms with lower productivity growth rates. This situation is illustrated by Figure 1.5, which shows the dependence of the increase in firm productivity upon the introduction of various DT on the already achieved level of productivity [32]. The diagrams are constructed on the basis of a sample containing more than 1.5 million observations on the productivity of firms from 20 OECD countries operating in 22 industries in the period 2010–2015. Here, the abscissa axis shows the quartile into which the company falls according to its productivity level (the first is the least productive, the fourth is the most productive), and the ordinate axis shows the increase in productivity when implementing the corresponding digital technology in relation to the average level (in percentage points).

It is clear that productivity gains are not evenly distributed. Highly productive firms benefit significantly more from technologies such as broadband Internet access, ERP and CRM systems.

At the same time, the implementation of cloud computing provides a greater increase in productivity primarily for low-productivity firms, while for the other quartiles it is approximately the same and below average.

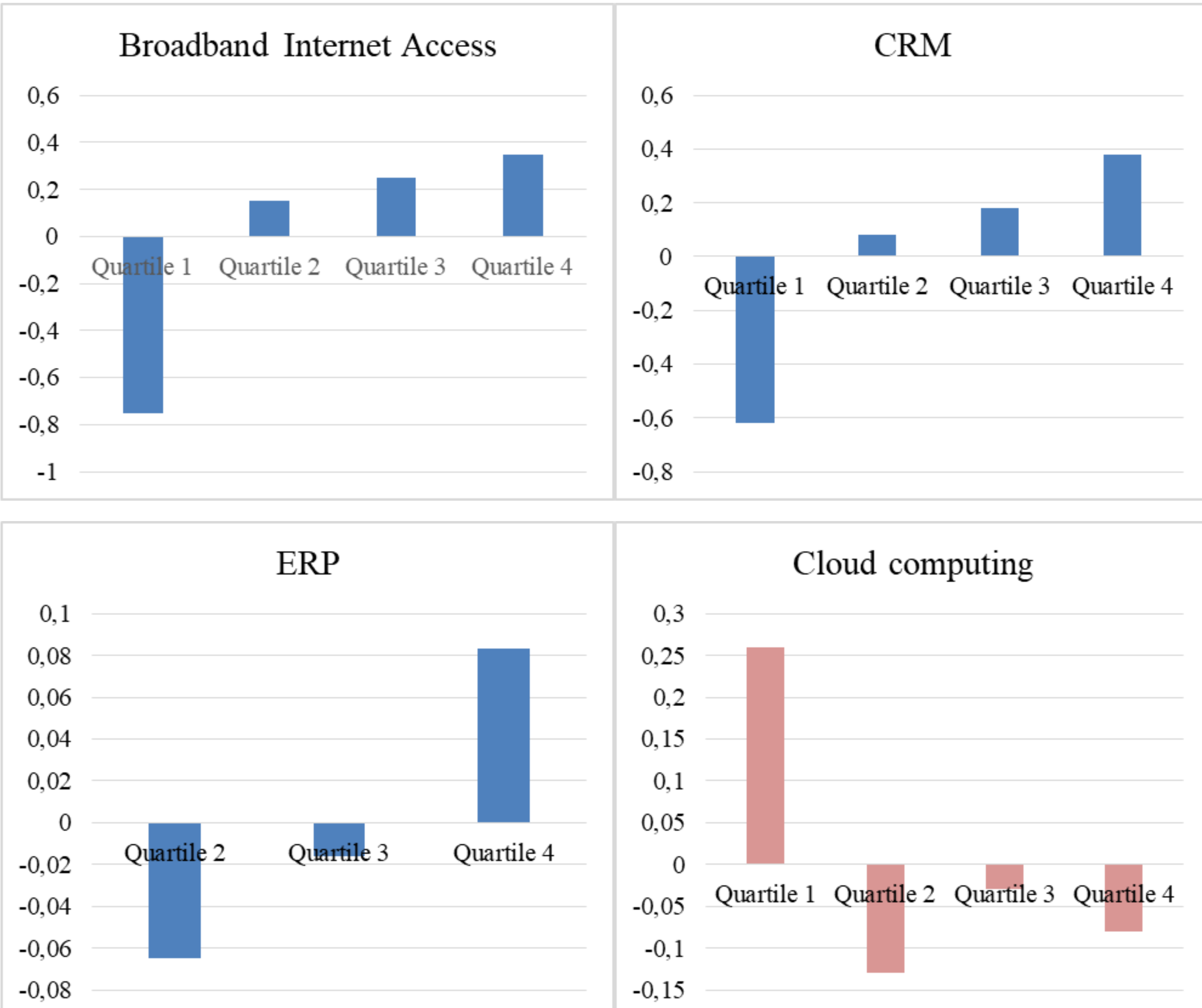


Figure 1.5 – Increase in firm productivity from the introduction of DT relative to the average level (pp)

A possible explanation for these dependencies is that in order to benefit from the implementation of DT, a fairly large amount of preparatory work is required, related to the reorganization of production and management processes, and the development of digital skills among personnel, which is more likely to be done in high-performance firms.

At the same time, the benefits of digitalisation are also unevenly distributed across sectors. In particular, the efficiency of digitalisation is generally higher in the services sector than in industry (Figure 1.6).

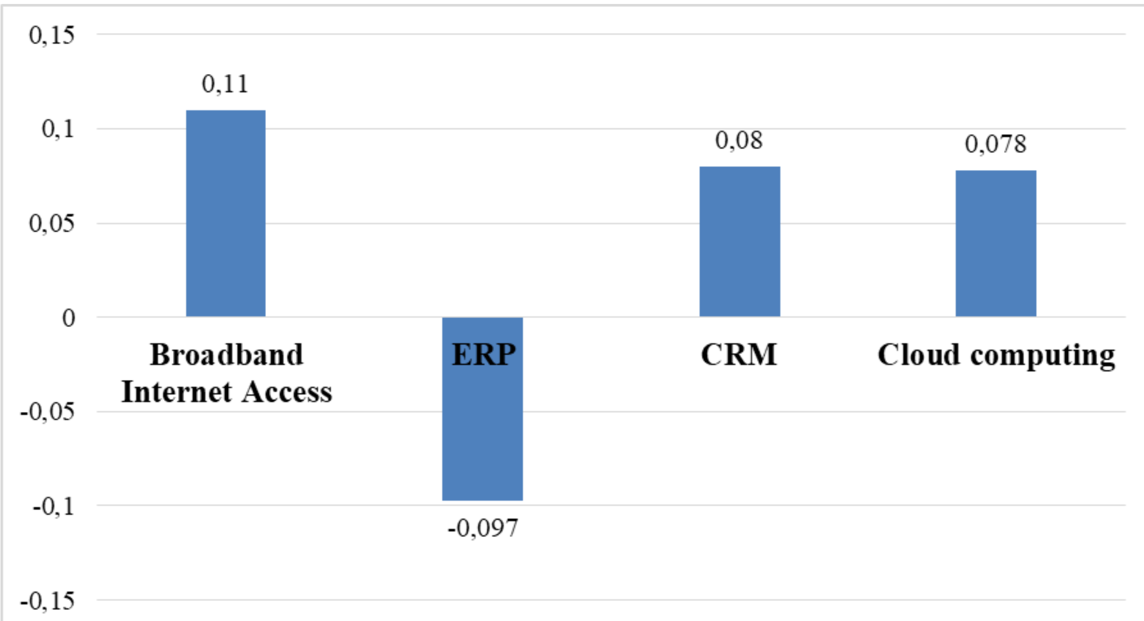


Figure 1.6 – Comparison of firm productivity gains (pp) from digital adoption in the services and industrial sectors

These results are consistent with the hypothesis formulated above that the impact of digital technology implementation is largely determined by the type of activity of the firm and the characteristics of its organization.

By raising average productivity in industry, digitalization has led to increased productivity inequality between firms and a slowdown in the growth of catch-up firms in advanced economies in industries with higher skill levels and a higher proportion of ICT specialists.

Overall, the analysis shows that the effects of DT implementation do not apply to all industries at the same time. The readiness of companies to perceive them is a multifaceted indicator, largely determined, along with technological and organizational factors, by the development of digital competencies of employees. As a result, traditionally organized firms, which often have less capacity to absorb new technologies, may have greater difficulty catching up in sectors where technology and knowledge matter most.

1.2. Institutional -economic foundations and technological determinants for building the digital architecture of construction enterprises in China

A different concept for the development of the digital economy is determined by the state policy of the People's Republic of China (PRC). Over the past decade, a number of state plans and programs have been developed in the PRC covering all aspects of the development of the digital economy, including: the Basic Plan-Strategy for the Development of Information Technology, the State Strategy for Working with Big Data, the State Strategy for Ensuring Information Security, the Program for the Development of New Generation Artificial Intelligence, infrastructure development strategies «Broadband China», «Internet Plus» and a number of others.

In accordance with them, the priority direction of scientific and applied research in the coming years is the development and implementation of new generation digital technologies in business and public administration, including cloud computing, the Internet of Things, big data, and artificial intelligence. The Internet Plus strategy, developed in 2015, aims to improve the efficiency of traditional industries in China by integrating Internet solutions into their activities.

To this end, digital infrastructure is being intensively developed, forming the basis of modern intelligent production, including new-generation information networks, fifth-generation mobile communication technologies, cloud technologies, data processing and storage centers.

Government support for digital technology and innovation development projects has made it possible to significantly increase the size of the digital economy, which reached 35.8 trillion yuan (5.5 trillion dollars) in 2019, which is more than a third of the country's GDP.

In accordance with the State Strategy for Working with Big Data, digital data is positioned as a strategic resource, the intensification of the use of which will contribute to the further development of the country's economy, increasing the efficiency of business and public administration.

The work [23] indicates that state regulation of digital industries in the PRC is aimed at organizing the collection and extraction of maximum value from data. In the PRC, a centralized system for collecting, extracting, processing and using big data is currently being actively formed. In 2009, the PRC government established Global Tone Communication Technology Co., Ltd. (GTCOM) to provide infrastructure for collecting, processing and storing big data. GTCOM serves as the primary contractor for the Chinese government and major Chinese private and public companies in the construction and operation of digital big data platforms. According to experts, it is currently one of the world's largest agencies working with big data [165].

The presence of a single platform for storing and processing big data creates the preconditions for the formation of a monopolistic structure of power of the state and large corporations in relation to the technical potential of big data [48]. The government is creating institutional conditions for collecting data from individuals and legal entities. Technical support for the infrastructure for collecting and processing data is provided by leading Internet companies, which, in addition to their own data collection mechanisms, have the ability to use public sets of big data owned by the state. According to the researchers, the implementation of this strategy opens up broad opportunities for the introduction of data-driven management into public administration and business models, and the transition to algorithmic responses to various problems and situations in the future.

On the other hand, the monopolization of the use of the potential of big data and other digital technologies by a relatively small number of large companies may lead to an increase in the gap in operational efficiency with the rest of the market, which will ultimately negatively affect the competitive environment and consumers of digital products [25]. In this regard, an important element of public policy is to increase the openness of the process of implementation and dissemination of digital technologies to ensure an equal distribution of the benefits they provide.

A necessary condition for ensuring equal access to digital benefits is improving the quality of human capital both within individual organizations and on the scale of the economy as a whole. This can be achieved by implementing state educational programs and professional retraining programs. The issue of developing digital competencies is especially relevant for workers in economic sectors with a low level of digitalization.

In addition to specific measures aimed at stimulating the development of the digital sector of the economy, industrial policy aimed at increasing the competitiveness of markets continues to play a significant role, including developing access to capital for innovative firms [79], reducing administrative barriers [46], increasing the efficiency of the public sector and expanding the range of e-government services [53].

The work [108] identifies six aspects of effective public policy that contribute to increasing competition in markets related to digital products and technologies:

– improving education and training in order to increase the supply and quality of specialists in these fields;

– development of financing instruments for innovative firms at the initial stages of their activities;

– incentive measures to ensure the potential return on entrepreneurial activity when introducing innovative products and services to the market;

– reducing regulatory barriers and administrative burdens for startups;

– pro-competitive regulation of business activities, ensuring equal conditions for doing business for firms entering and operating in the market;

– ensuring hedging of risks of innovative entrepreneurship, including the effectiveness of bankruptcy procedures.

The development of competition in the markets is closely linked to state innovation policy, which creates incentives for the development and implementation of new technologies, and therefore its improvement can lead to positive effects in the development of the digital economy.

One of the most important prerequisites for increasing the level of digitalization in construction is the use of the most common digital technologies in organizations.

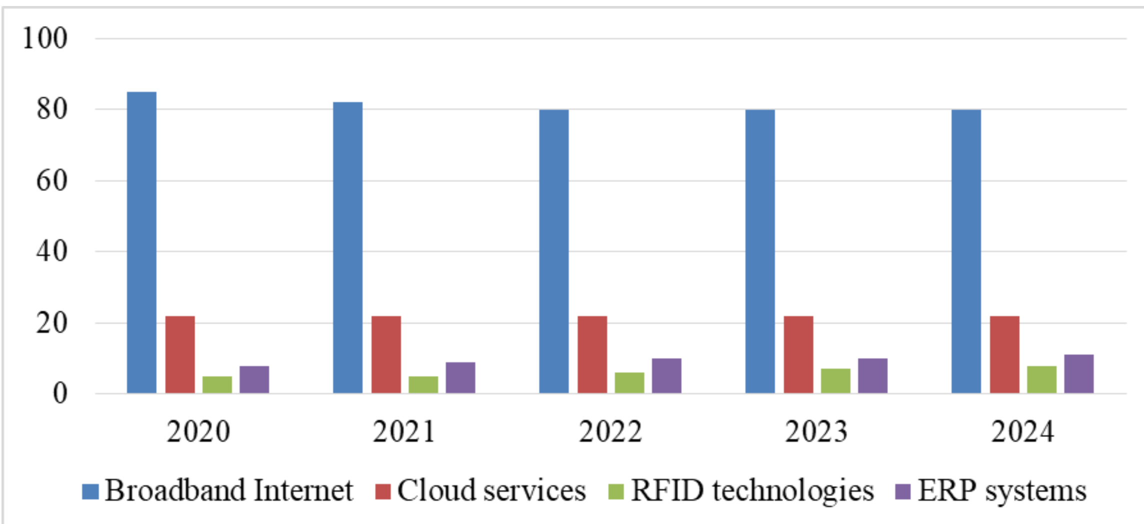


Figure 1.7 – Index of digitalization and intensity of use of digital technologies in organizations (as a percentage of the total number of organizations in the business sector) (compiled according to [34])

Based on the results of the analysis, it can be concluded that there is a smooth but fairly stable growth in the use of digital technologies.

The number of technologies today has created a certain critical mass that will enable the digital transformation of the industry. These technologies include information modeling, 3D printing, robotics and artificial intelligence, the creation of digital twins and analytics.

The combination of these technologies initiates the digital transformation of construction companies, as well as investment and construction design.

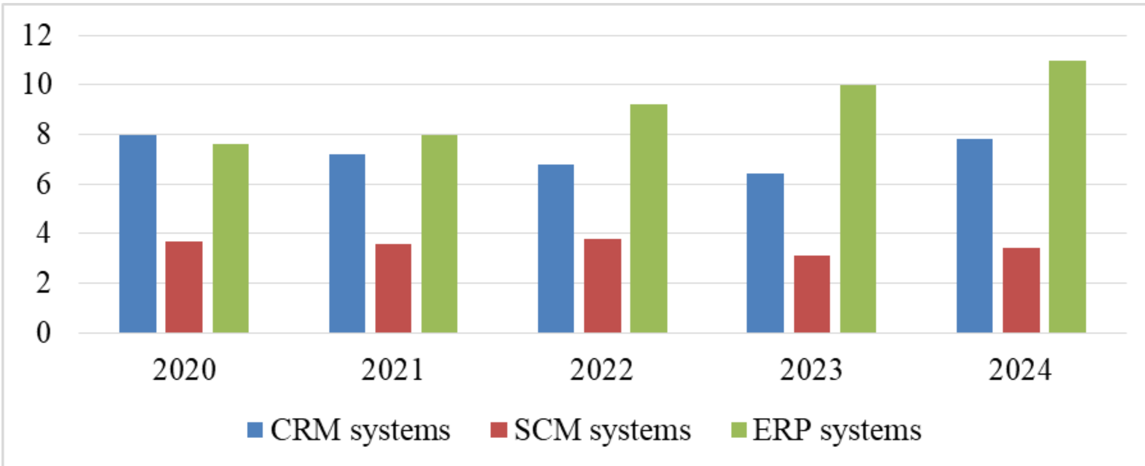


Figure 1.8 – Construction industry organizations using CRM, ERP, SCM systems (compiled based on data from [30])

It is necessary to highlight the following factors that influence the dynamics of the level of digitalization in construction. These are the stage of the life cycle of the facility, the availability of basic digital solutions, the number of options for using the technology, and end-to-end technologies.

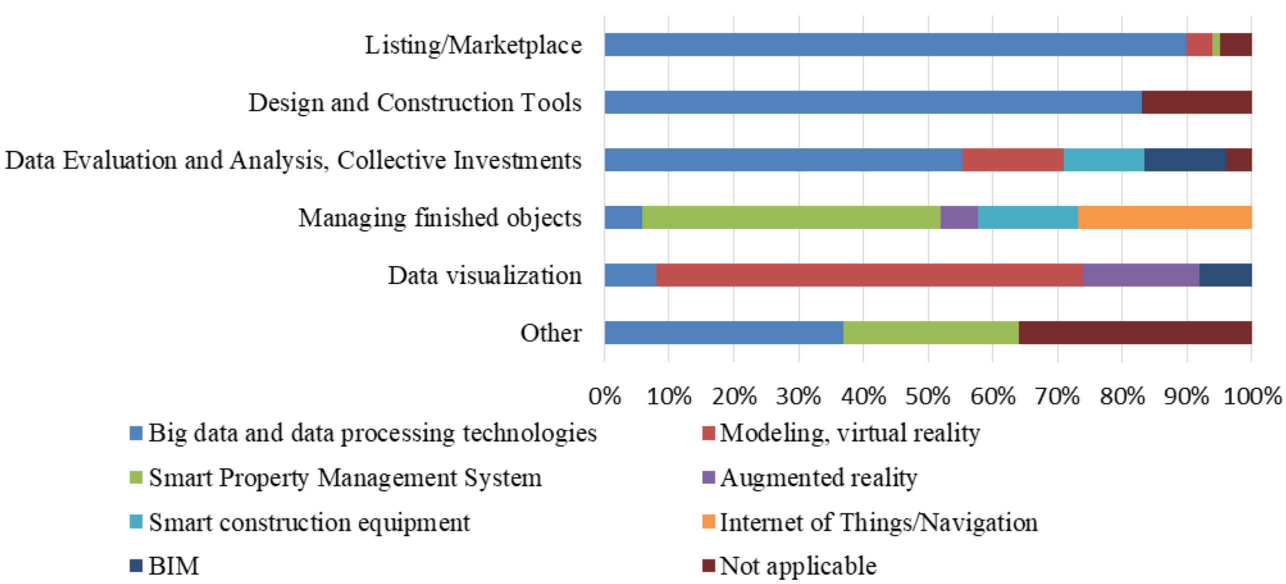


Figure 1.9 – Areas of activity and technologies used (compiled based on data from [30])

Overall, according to The National Association of Builders, 20% of companies use BIM (Fig. 1.10)

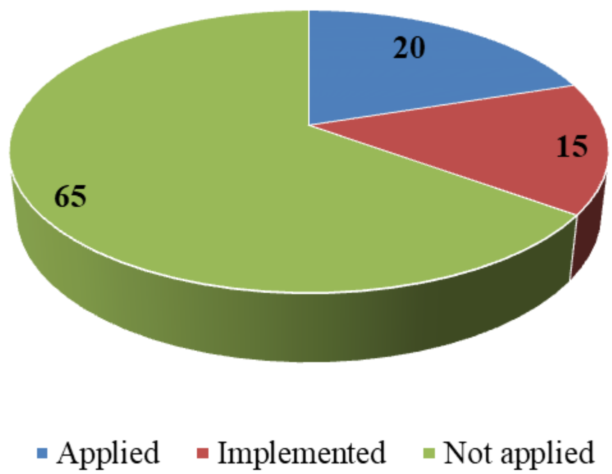


Figure 1.10 – Implementation of BIM in organizations [3]

The corresponding object structure for the application of BIM is presented in Figure 1.11.

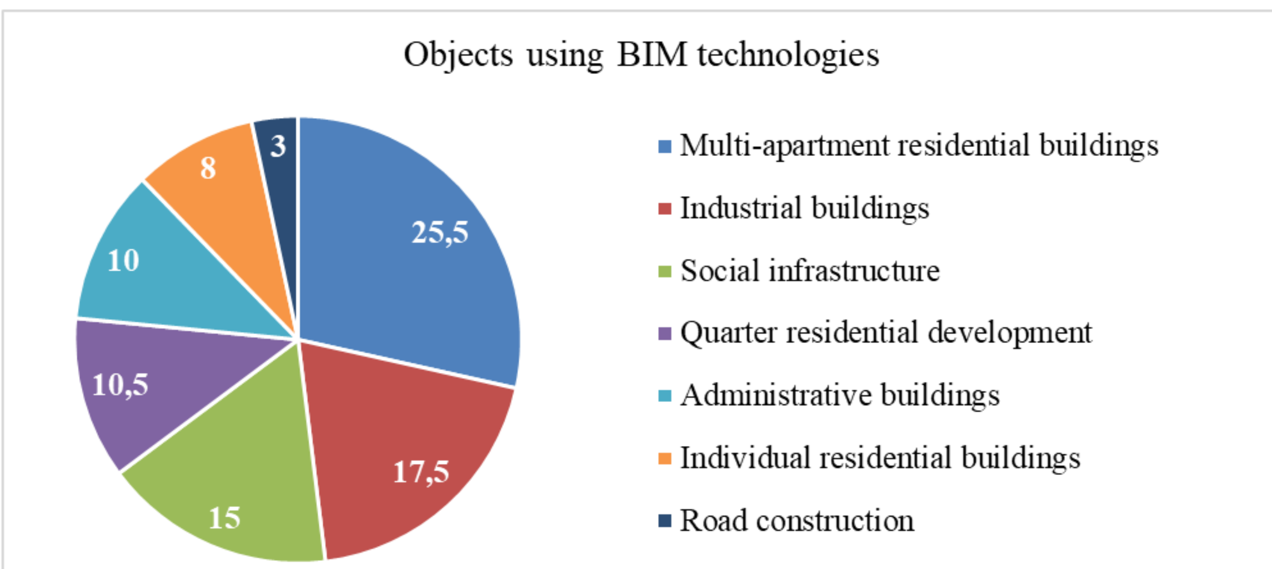


Figure 1.11 – Structure of the use of BIM technologies by type of objects (compiled based on [16,17]

BIM technologies are most effective at the design stage due to the visualization of design solutions, detailing, the possibility of multi-variant development and analysis, reducing the number and likelihood of errors. There is also an indirect impact on the cost of the construction investment project due to the minimization of errors and optimization of design solutions, which in turn reduces unforeseen expenses and loss of rhythm at the construction stage. These provisions confirm the results (Figure 1.12).

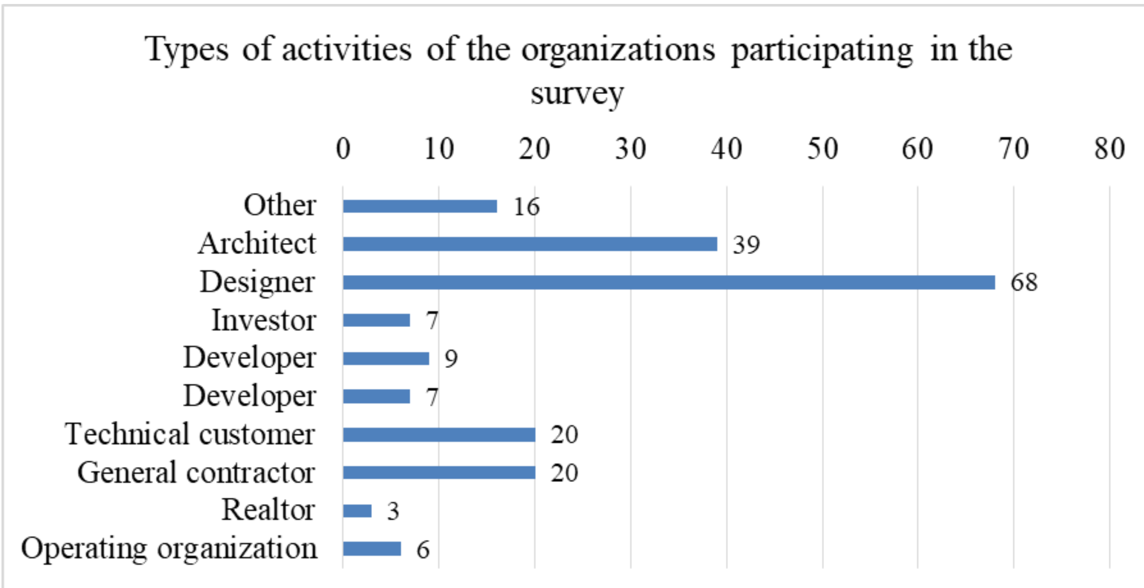


Figure 1.12 – Distribution by types of activities of organizations using BIM [17]

The fairly active use of BIM technologies in the design of construction projects is practically interrupted at subsequent stages of the life cycle of the facility due to the lack of relevant state standards and classifiers, an outdated regulatory framework, and the specifics of legal regulation of contractual relations between numerous stakeholders of a construction investment project. It should be noted that the key target stakeholder of BIM is the customer due to the ability to manage the complex multi-aspect process of design, construction and operation of facilities with maximum efficiency, taking into account the optimization of inter-subject relationships.

Based on the conducted analysis of statistics and the results of expert surveys, we systematize the factors and results of digitalization of construction at the current time.

Table 1.4 – Systematization and assessment of the environment of the directions of digitalization of construction

Direction of digitalization	Prerequisites for digitalization	Conditions of digitalization	Importance for digital transformation	Factors affecting the effectiveness of digital transformation
Information modeling of a construction object	CAD, 3D modeling, BIM design	Institutional risks, diverse interests of stakeholders, low density of the institutional environment	Key direction	External economic (dynamics of investments in construction and installation works, dynamics of construction and installation works volumes), internal economic (profitability of enterprises, resources), external institutional (regulatory support, state regulation)
Creation and operation of information systems	Availability of a number of IS	Fragmentation of information systems, low density of the institutional environment, small quantity, low availability and low quality of information	Key direction	external institutional (regulatory support, government regulation)
Use of automated equipment	Fragmentary use of automated equipment	Innovative inertia of the industry, low solvency of actors	Providing direction	External economic (dynamics of investments in construction and installation works, dynamics of construction and installation works volumes), internal economic (profitability of enterprises, resources)
Information technology and software	Fragmented use of IT and software	Fragmentation of IT and software, innovative inertia of the industry, low solvency of actors	Providing direction	External economic (dynamics of investments in construction and installation works, dynamics of construction and installation works volumes), internal economic (profitability of enterprises, resources)

Additive technologies in construction	R&D	Innovative risks, diverse interests of stakeholders, low density of the institutional environment	Providing direction	Institutional (regulatory support, government regulation)
Cloud data management platforms	Fragmented use of cloud systems	High level of costs, risks, resistance to change, multidirectional interests of stakeholders, low density of the institutional environment	Providing direction	External economic (dynamics of investments in construction and installation works, dynamics of construction and installation works volumes), internal economic (profitability of enterprises, resources), external institutional (regulatory support, government regulation)
internet of things	Fragmented use of IoT	High level of costs, risks, resistance to change, multidirectional interests of stakeholders, low density of the institutional environment	Providing direction	External economic (dynamics of investments in construction and installation works, dynamics of construction and installation works volumes), internal economic (profitability of enterprises, resources), external institutional (regulatory support, government regulation)
Government programs and projects	Implementation of a number of programs and projects	Low level of readiness, regional differentiation, presence of growth points	Stimulating direction	External institutional (regulatory support, government regulation)
Digital environment and digital platform	Lack of an industry digital platform, low density of the digital environment, its unevenness	Lack of a unified information environment, multidirectional interests of stakeholders, low density of the institutional environment	Target direction	External institutional (regulatory support, government regulation)

Based on the results of the analysis and systematization of the environment of digitalization directions in construction, we conducted a PESTLE analysis of the implementation of digital platforms based on BIM (table 1.5).

Table 1.5 – PESTLE analysis of the implementation of digital platforms based on BIM

POLITICIAN: • Stability of political power and the existing government • Tax policy (tariffs and benefits) • Support for IT technologies • Trends towards regulation or deregulation of the industry • Probability of military action in the country • Desire for protectionism of the industry • Future and current legislation regulating work in the industry	**ECONOMICAL:** • Terms of remuneration • Level of disposable income of companies in the industry • Credit-monetary and fiscal-budgetary policy of the country • Level of development and competitiveness of products
SOCIO-CULTURAL: • Requirements for product quality and service level • Education, availability of qualified personnel • Trends in society • Attitude to imported goods and services • Attitude to work, career, leisure and retirement • Striving for sustainable development	**TECHNOLOGICAL:** • Level of innovation and technological development of the industry • Development and penetration of the Internet, development of mobile devices • Expenditures on research and development • Access to the latest technologies • Legislation in the field of technological equipment of the industry • Degree of use, implementation and transfer of technologies
LEGAL: • Elaboration of the legislative sphere • Antitrust laws • Laws regulating the sector	**ECOLOGICAL:** • Energy Costs • Moving Away from Paper • Resource Consumption Management

Accordingly, a SWOT analysis was also conducted (Table 1.6).

Table 1.6 – SWOT analysis of the implementation of digital platforms based on BIM

STRENGTHS: • All interactions via the Internet (wide geography, minimum documents, no need for physical meetings) • Speed of decision-making and work execution • Mobility of work places • Access to products from any device via the Internet • Innovative solutions • State support	**WEAKNESSES:** • Lack of qualified specialists • Misunderstanding of the benefits of the transition by construction process participants • Internet dependence • Lack of a bright image
OPPORTUNITIES: • Weak competition in the market. • Prospects for rapid market development. • Increased availability of the Internet and development of digital infrastructure. • Emergence of new devices. • Support and development of the technologies used. • Possibility of introducing new technologies. • Attracting investors. • Expansion of competencies. • Preferential tax system.	**THREATS:** • Tightening of legislation on issues related to IT business. • Risk of data loss. • Possibility of new competitors. • Risk of cyber attacks. • Aggressive actions of large competitors in the industry. • Unfavorable political situation. • Tightening of fiscal policy (increase in tax rates, introduction of new taxes)

Based on the results of the analysis and the conducted PESTLE and SWOT analysis of digitalization in construction, it should be concluded that digitalization of construction has a low rate of development. At the same time, the necessity and feasibility of its activation is determined, and the target direction of digitalization is the creation of a single digital environment and a digital platform that allows participants in an investment and construction project to work together online in real time through electronic document management.

1.3. Financial-resource constraints of process digitalization and value-based aspects of BIM integration into the economic-digital model of the enterprise

The problem of high costs for the implementation of BIM technology seems to be quite significant (Figure 1.13)

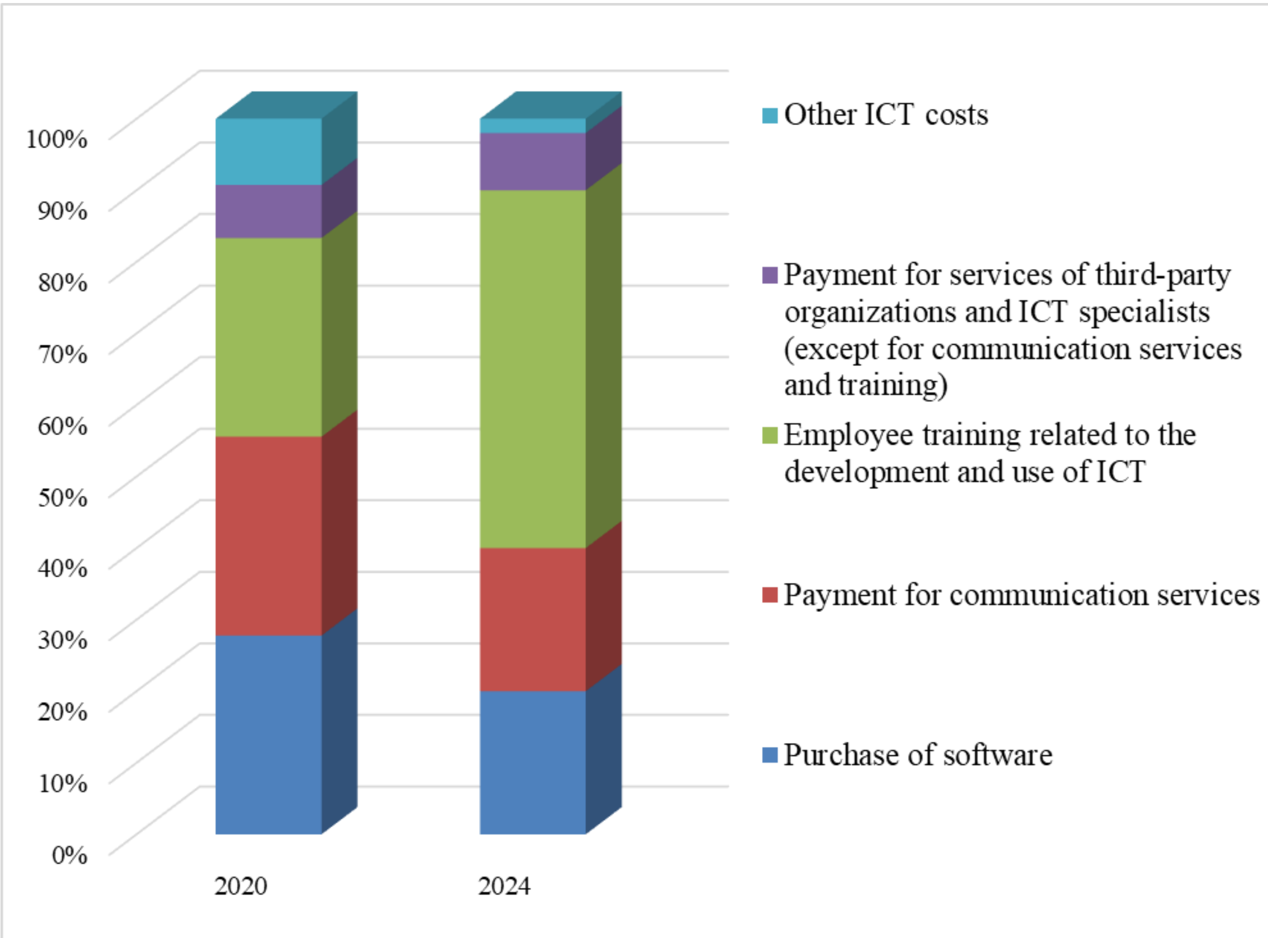


Figure 1.13 – Structure of ICT costs, % (compiled based on data from [9])

The purpose of our marketing research is to assess the effectiveness of the use of information modeling technologies by construction and design organizations based on the identification of economic and non-economic effects for different stages of the life cycle of a construction project. The study was conducted using the survey method (questionnaire) and structured interviews with representatives of the construction industry using BIM in their activities. Marketing analysis was conducted by means of an expert survey of representatives of a number of construction complex organizations listed in Appendix 2.

To assess the internal factors influencing the digitalization of construction enterprises and organizations, an expert assessment was carried out (Appendix 2).

Table 1.7 – Analysis of the results of the expert assessment of the factors of digitalization of construction enterprises

Digital technology factor	Average rating	Level of consistency
Field of activity	4,2	0,74
Enterprise size	3,8	0,65
Duration of digital tool usage	4,6	0,76
Number of implemented digital solutions	4,2	0,69
Customer requirements	3,7	0,81
Project complexity	4,7	0,94
Availability of a digital environment	4,5	0,88

The vast majority of companies using information modeling in their activities are in the field of design, engineering surveys and construction. It should also be noted that information modeling technologies are mainly used by companies with experience in a fairly large number of projects. A positive correlation is also observed between the use of information modeling and the number of employees involved in the implementation of projects. The use of information modeling is mainly used to implement projects for the construction of administrative buildings and industrial buildings.

It is also necessary to note the positive correlation between the period of use of BIM technologies and the magnitude of the effect.

The results of the expert survey on the issue of determining the advantages and disadvantages of implementing information modeling are summarized in Table 1.8.

Table 1.8 – Results of the expert survey of ICP participants on the advantages and disadvantages of using BIM [32]

	Advantage	Percentage of those who identified an advantage in the questionnaire				Average importance	Coherence
		1	2	3	4	5	6
1	Improved understanding of the project by all participants	72,00	70,40	65,00	67,70	68,78	0,04
2	Availability of information, fast data transfer and information exchange	61,00	63,00	57,00	60,00	60,25	0,04
3	Эффективнее расходование ресурсов	25,00	22,00	27,00	24,50	24,63	0,08
4	3D and 4D visualization of the construction site	36,00	74,10	54,50	64,30	57,23	0,28
5	High quality of the project	74,00	70,40	59,30	64,85	67,14	0,10
6	Reducing design time	46,00	74,10	53,70	63,90	59,43	0,21
7	Reduction of construction time	24,00	22,20	20,70	21,45	22,09	0,06
8	Cost reduction	33,00	18,50	22,80	20,65	23,74	0,27
9	Increase profits and profitability	32,00	35,00	28,00	31,50	31,63	0,09
10	Reducing design costs	41,95	48,10	35,80	41,95	41,95	0,12
11	Ability to detect collisions in projects	69,15	74,10	64,20	69,15	69,15	0,06
12	Reduction of the overall project implementation period	30,85	29,60	32,10	30,85	30,85	0,03
13	Improving the quality of construction	25,95	22,20	29,70	25,95	25,95	0,12
14	Reducing risks associated with supply chains during construction	18,20	18,50	17,90	18,20	18,20	0,01
15	Reducing the timeframe for engineering surveys	11,85	14,80	8,90	11,85	11,85	0,20
16	Reducing operating costs	10,65	11,10	10,20	10,65	10,65	0,03
17	Reducing the cost of engineering surveys	9,40	11,10	7,70	9,40	9,40	0,15
18	Reducing the timeframe for designing demolition and disposal of buildings	7,75	7,40	8,10	7,75	7,75	0,04
19	Reducing costs during demolition and disposal of a building	4,00	3,70	3,70	3,70	3,78	0,04
20	Reducing risks in investment justification for CCPs	4,45	0,00	8,90	4,45	4,45	0,82
21	Other	6,00	0,00	2,80	1,40	2,55	1,01

The study revealed that the use of BIM technology helps to increase the economic efficiency of investment and construction projects, including:

Based on the analysis of empirical research data, it can be concluded that there are three groups of key effects of digital transformation of construction at the micro level. The first group should include indicators of growth in the quality of work, including due to the coordination of organizations and specialists participating in the investment construction project, leading to a reduction in the number of collisions and an increase in labor productivity both due to automation and due to coordination. The second group of effects consists of increasing production efficiency, which includes a number of key aspects, including reducing lead times, reducing costs, increasing profitability and increasing the competitiveness of works and construction products. The third group of effects focuses on reducing risks by reducing transaction costs, increasing the accuracy of cost calculations and timing calculations. It should be noted that the reason for reducing risks is also the automation of processes, leading to increased productivity, as well as the possibility of collaboration, leading to increased coordination between organizations and specialists involved in the project.

The possibility of joint work and the corresponding increase in the coordination of the participants of the ICP is realized during the development and use of a single digital construction platform, created on the basis of a common data environment for electronic document management and online interaction between all participants of the construction market at all stages of the life cycle of the CCPs.

In order to analyze and evaluate the qualitative and economic indicators of the use of digital platforms at all stages of the life cycle of the CCPs, we conducted an expert survey [24]. The structure of the survey participants by type of activity of the organization is presented in Figure 1.14.

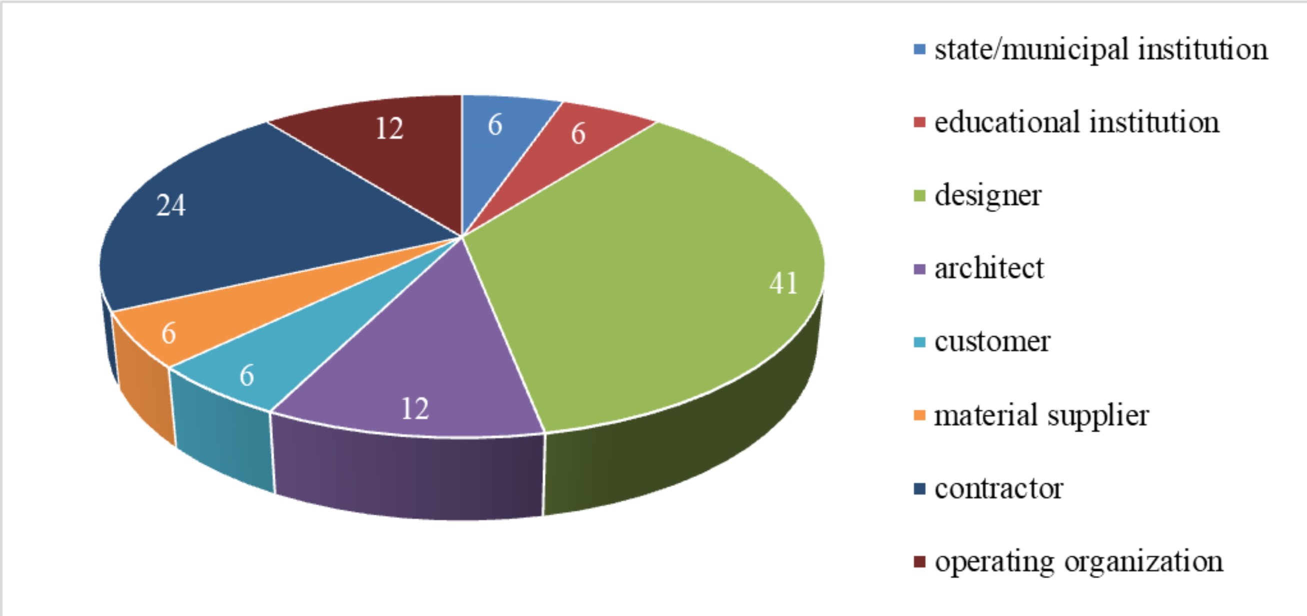


Figure 1.14 – Structure of survey participants by type of organization activity, % (compiled based on the results of [24])

The respondents’ answers regarding the digital tools used in their practice were distributed as follows (Figure 1.15).

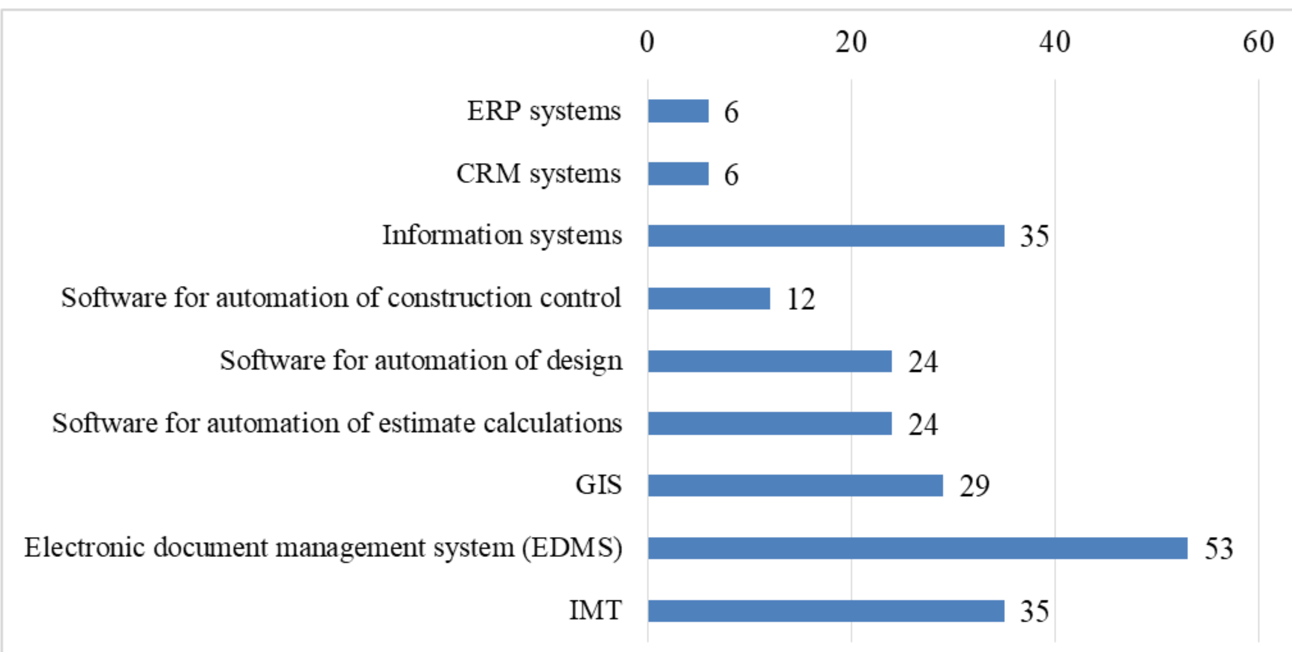


Figure 1.15 – Use of digital tools in the practice of construction participants, % (compiled based on the results of [24])

Based on the data in the figure, one can conclude that electronic document management systems are used quite widely by organizations. At the same time, a high share of IMT use is noted, not only by design organizations, but also by contractors and operators. The high proportion of organizations using information systems in the process of investment and construction activities is explained by the diversity of such systems and the multiplicity of functions implemented with their help.

On the issue of the main problems of interaction in the process of implementing investment and construction projects, the following results were obtained (Fig. 1.16)

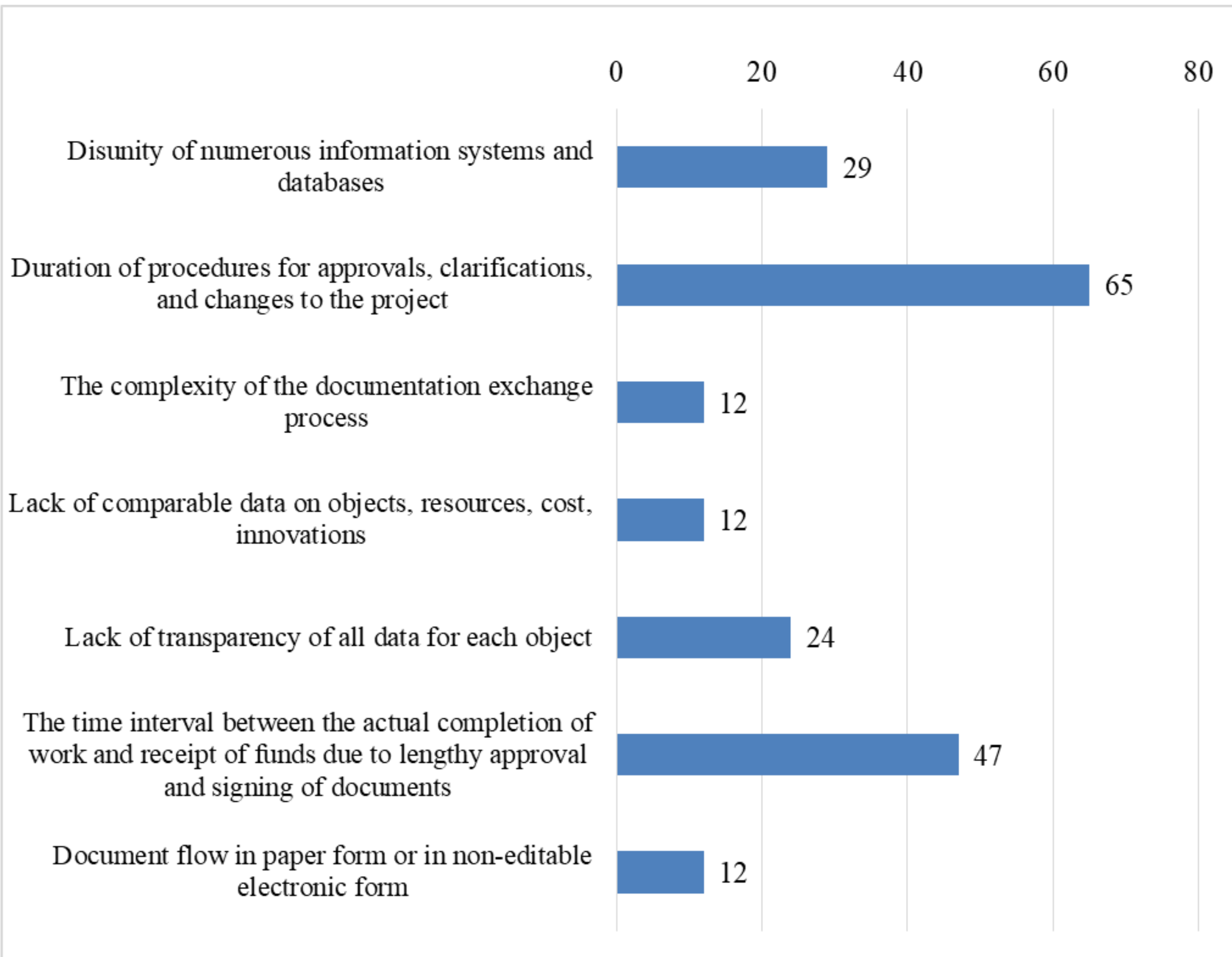


Figure 1.16 – Problems of interaction in the process of implementing investment and construction projects, % of respondents (compiled based on the results of [24])

Based on the results of the expert survey, the main problems of interaction between participants in the implementation of investment and construction projects are the duration of the procedures for coordinating and signing documentation, which leads to delays in making changes to the project, and also leads to an increase in the time lag between the actual performance of work and the receipt of financial resources. In turn, these facts increase the time for correcting comments and, ultimately, the construction time. Failure to meet construction deadlines is not only fraught with increased financial costs, but also with failure to implement investment programs.

The fragmentation of existing information systems and databases, along with the lack of transparency of data on objects, also negatively affects interactions in the investment and construction process, as stated by more than 20% of respondents.

Thus, the main problem of interaction in the process of implementing investment and construction projects was identified as the duration of the approval procedures, project changes and document signing.

Accordingly, the effectiveness of introducing digital document management between all participants in the construction market at all stages of the CCPs life cycle was estimated at 7 points out of 10 possible.

However, there are a number of obstacles to the implementation of a digital construction platform based on a common data environment for electronic document management and online interaction between all participants in the construction market at all stages of the CCPs life cycle (Fig. 1.17)

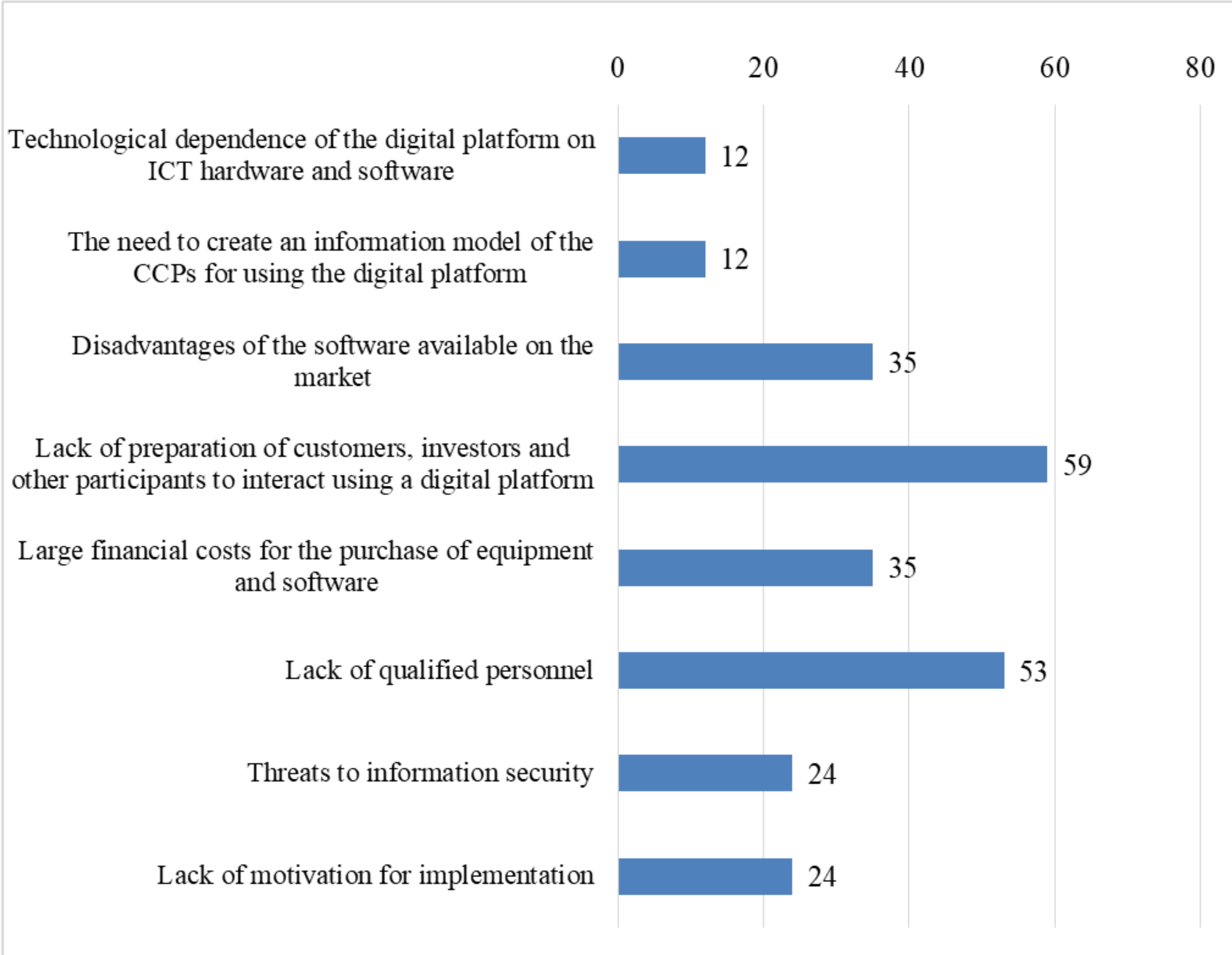


Figure 1.17 – Results of the assessment of the main obstacles to the implementation of a digital construction platform, % of respondents (compiled based on the results of [24])

The main obstacles to the implementation of a single digital construction platform are the lack of preparedness of participants for digital interaction, insufficient software, and the high cost of equipment and software. The problem of a shortage of qualified personnel, which is relevant for any area of digitalization, also attracts attention.

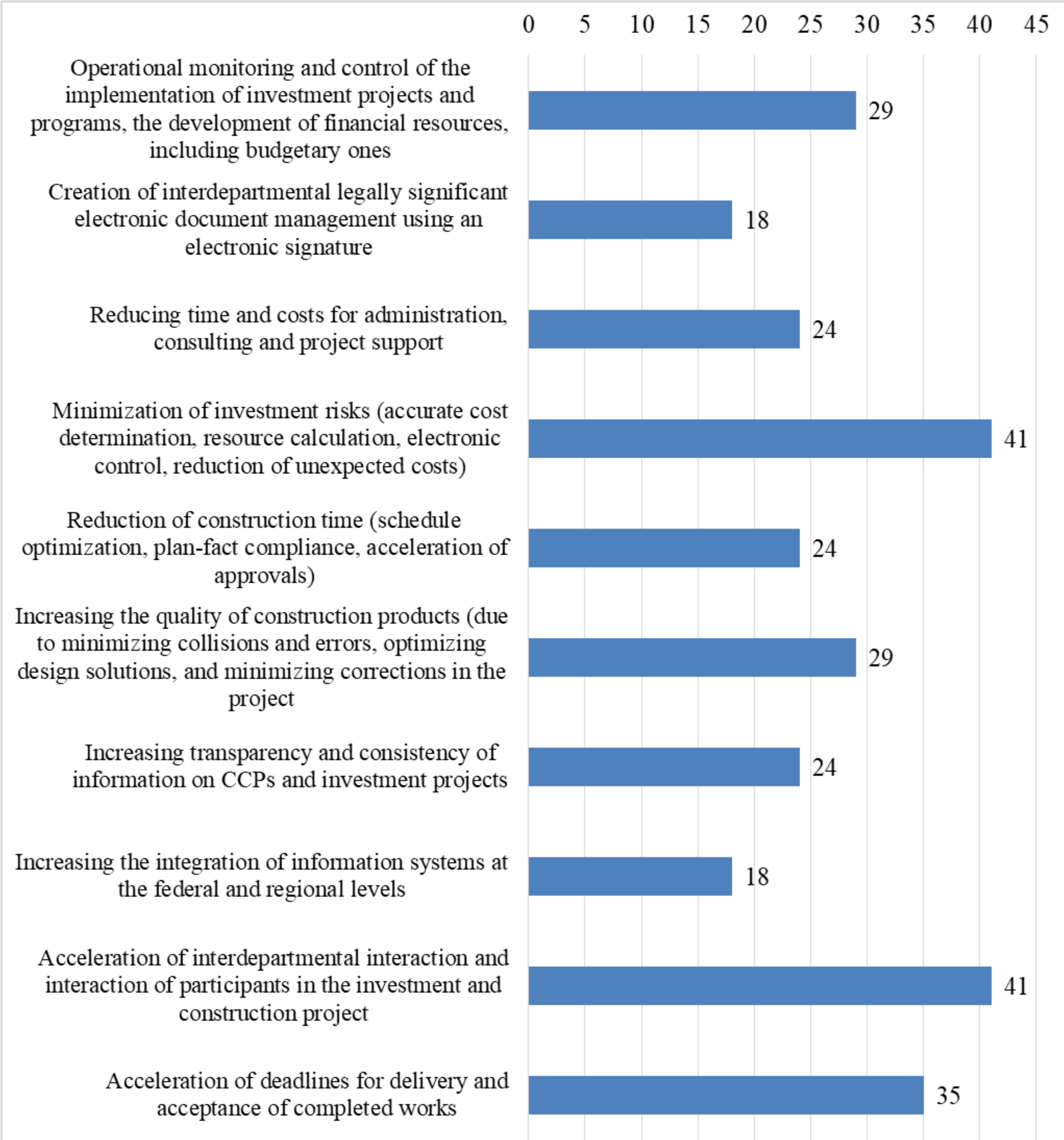


Figure 1.18 – Results of the assessment of the main effects of the implementation of the digital construction platform, % of respondents (compiled based on the results of [24])

The main effects of the implementation of the digital construction platform (based on the environment of common data for electronic document management and online interaction between all participants in the construction market at all stages of the life cycle of the construction project) are the acceleration of interdepartmental interaction and interaction of participants in the investment construction project, the corresponding acceleration of the deadlines for the acceptance of completed work and further growth in the pace of construction, as well as the minimization of investment risks due to the accurate determination of the cost of the ISP, the correct calculation of resources, the implementation of construction control in electronic form, and the reduction of unforeseen costs.

The main effects of the implementation of the digital construction platform (based on the environment of common data for electronic document management and online interaction between all participants in the construction market at all stages of the life cycle of the construction project) are the acceleration of interdepartmental interaction and interaction of participants in the investment construction project, the corresponding acceleration of the deadlines for the acceptance of completed work and further growth in the pace of construction, as well as the minimization of investment risks due to the accurate determination of the cost of the ICP, the correct calculation of resources, the implementation of construction control in electronic form, and the reduction of unforeseen costs.

Also, according to about 30% of respondents, the introduction of a digital platform based on the CDE with the possibility of electronic document management will allow for prompt monitoring and control of the implementation of investment projects and programs, the development of financial resources, including budgetary ones, which will lead not only to an increase in the efficiency of the implementation of the ICP, but also to an increase in the transparency of investment and construction activities in general and an increase in the efficiency of state investment policy. Also, almost 30% of respondents expect an increase in the quality of construction products due to the minimization of collisions and errors, optimization of design solutions, and minimization of corrections in the project when implementing a digital platform.

Another group of effects from the implementation of BIM is connected to a greater extent with the implementation of electronic document management through the CDE of the project participants. As a result of the conducted marketing analysis for this type of effect, the following results were obtained (Appendix 2).

Currently, the process of preparing executive documentation (from the formation of a set of documentation to its signing) takes on average more than 30 days. For the rhythmic flow of the process of implementing an investment construction project, it is necessary to fill out and sign a total of more than 160 forms of documentation. The problems of traditional paper document flow in construction include (according to the results of expert assessment):

– unstructured technical archives, storing them in paper form;

– maintaining operational documentation in paper form;

– a significant portion of staff time is spent searching for technical documentation;

– high probability of loss of documentation (about 20% of documentation, clarified and corrected during the process of corrections and approvals, is lost).

According to the survey, the average costs of paper document management are UAH 23,527 per 100 m^2 of investment and construction project. Accordingly, the amount of savings from switching to electronic document management will be at least UAH 20,000 per 100 m^2, not including logistics costs for delivery and forwarding of a set of documents, time spent on approvals, changes, etc.

The main way to solve the above-mentioned problems is the implementation of an electronic document management system based on the CDE.

The common data environment (CDE) is a hardware and software complex consisting of communication channels, server and software solutions, allowing for the management of data and processes during the life cycle of a capital construction project, and used by all participants as a single source of information.

The CDE is designed to coordinate the work of interorganizational teams, synchronize their activities, and exchange data in the common digital space of the project. The purpose of using the CDE is to reduce the time and costs of capital construction projects.

Tasks that can be solved with the help of the CDE [3]:

- Formation and maintenance of an information model;
- Organization of engineering and technical document flow between project participants in electronic form;
- Reduction of timeframes for the exchange of documents and information, timeframes for approval and communication;
- Increasing transparency and controllability of processes;
- Reducing the number of errors in projects and collisions on construction sites, reducing downtime;
- Assessment of the current state of the object and its compliance with the plan;
- Control of construction processes and execution of works.

Within the construction industry as a whole, such an opportunity arises with the creation of a single information space based on the creation of a digital platform that ensures not only inter-company but also inter-departmental interaction.

Conclusions to chapter 1

The analysis of the impact of digital technology development on the efficiency of construction companies carried out in this chapter allows to draw the following conclusions.

1. The application of scientific approaches to building digitally-oriented economic models in the construction sector, taking into account the modern challenges of the transformational environment, is relevant. Although the development of digital technologies leads to an increase in average productivity, its impact on the construction industry and enterprises is uneven and is determined by a set of technological and organizational factors, as well as employee competencies, which together describe the readiness for their implementation.

2. The mechanisms of influence of digital technologies on the efficiency of construction production are diverse and multifaceted. In addition to the automation of business processes, they increase the flexibility and adaptability of a construction enterprise, change the structure of relationships and the nature of interaction of the enterprise with other stakeholders, the methods of competition of firms and functioning of markets, the characteristics of resources used in the production process, and also form new competitive advantages of the final product due to its intellectualization. As a result, the methods and techniques of using digital technologies adapted to their main production processes acquire a priority role in ensuring the efficiency of construction enterprises.

3. The process of digital transformation of a construction enterprise is multifaceted, and its effectiveness can only be assessed using a comprehensive system of indicators that characterize its various aspects. The dissertation proposes using an economic and digital model of the enterprise as such a system. It has been revealed that the introduction of digital technologies into the production activities of construction

companies can lead to a qualitative change in the nature of business and provide significant advantages in the competitive struggle.

4. It has been established that a negative factor accompanying the introduction of digital technologies is inter-industry competition for highly qualified labor resources. Due to the fact that traditional industries are characterized, as a rule, by less attractive working conditions than the IT industry, there is a migration of professional personnel from industry to the IT sphere. An important factor stimulating the digital transformation of business is the implementation by the state of policies aimed at supporting the introduction of innovative digital technologies, which is confirmed by the experience of implementing relevant programs in foreign countries.

5. It is necessary to create a single digital platform based on a common data environment and digitalization of document flow between all stakeholders of the investment and construction project to eliminate conflicts in the business processes of construction project participants and to improve the efficiency of a construction company. Such a digital eco-platform can ensure:

- prompt receipt of data on risks and the status of investment project implementation in online mode, based on objective, verified and machine-readable data obtained through electronic document flow;
- reduction of communication times between construction participants during investment project implementation due to digital information exchange on a single platform;
- creation of a BIM model of an object at the construction stage in order to completely switch to a digital format;
- elimination of excessive administrative burden on all participants in the investment and construction process due to the digitalization of most procedures, documents and data;

6.

CHAPTER 2. STRUCTURAL-FUNCTIONAL ELEMENTS OF THE ECONOMIC-DIGITAL MODEL AND METHODOLOGICAL APPROACHES TO ITS DEVELOPMENT

2.1. 1. Methodological approach to evaluating digital maturity and economic flexibility of construction enterprises in a dynamic environment

Based on the basic management scheme based on the process approach (Figure 2.1), the following significant elements of the management system are highlighted:

1. Conceptual model of the management system (MS) of a construction enterprise (CE), corresponding to the elements in the diagram:
   - "Management Process";
   - "Managed Subsystem".
2. A balanced scorecard for database management efficiency, which corresponds to the element in the "performance indicators" diagram.

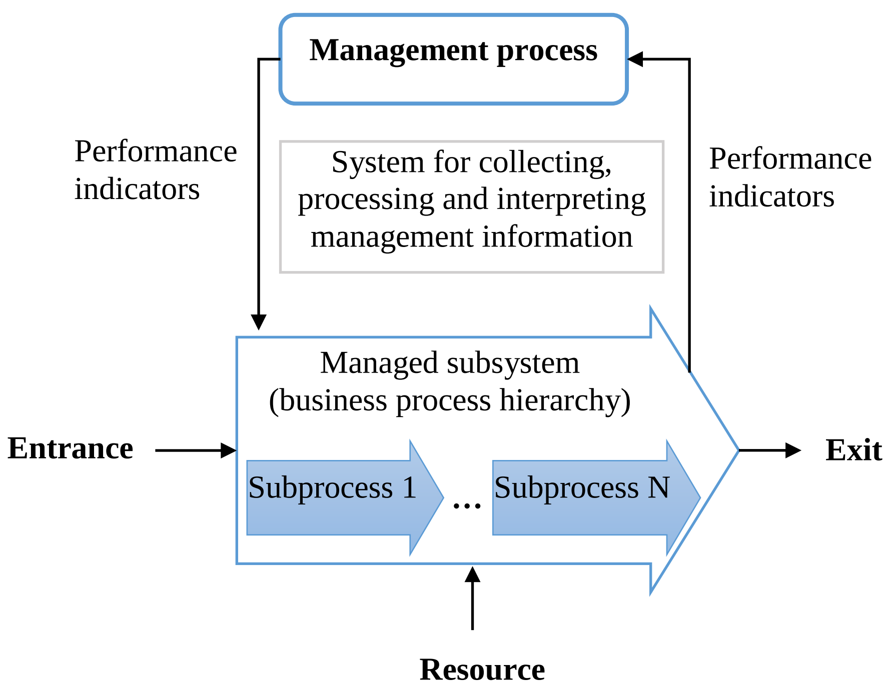


Figure 2.1 – Schematic diagram of management based on a process approach

Thus, it is a development of the methodological basis of process-oriented management in relation to construction development company (CDC).

Within the framework of the conceptual model (Figure 2.2), the relationship between the controlling and controlled elements of the MS CDC is formed, logically justified, and also revealed. The area of conceptual design of the MS is defined through the hierarchy and characteristics of organizational units.

The hierarchical ladder (Figure 2.3) in the MS CDC is divided into three levels in two main management categories:

– strategic:
  - level I – general management;
  - level II – middle management;

– operational:
  - level III – line management.

It is advisable to provide a description (Table 2.1, Table 2.2, Table 2.3) and provide a characteristic of the conceptual model of the MS CDC.

Table 2.1 – Main attributes of level I management

№	**Attributes of an organizational management unit**			
	Area of responsibility	**Powers/tasks**	**Management objects**	**Performance indicators**
1.	*«President»*			
	All business activities of the enterprise.	According to the company's charter	▪ Vice Presidents by area; ▪ financial reporting.	Consolidated financial statements indicators
2.	*«Vice President of Construction enterprise (CE) Main Activity»*			
	Project portfolio parameters and its status (core activity).	▪ Supervision of project implementation at the portfolio level; ▪ project supervision (sponsor function);	▪ Project managers; ▪ project metrics.	Project portfolio indicators.

		▪ design and strategic development of major CE, ensuring their implementatio.		
3.	*«Vice President of Construction enterprise (CE) auxiliary activities»*			
	Auxiliary activities.	▪ Administration of functions supporting the main activity; ▪ design and strategic development of auxiliary construction enterprises, ensuring their implementation.	▪ Functional managers; ▪ indicators of the level of service of individual structural units that support the main activity	Aggregated service level indicators of all structural units supporting the core business
4.	*«Vice President of Centers of Advanced Competence»*			
	Technologies and competencies in general, personnel development of the main activity.	▪ Organizing and administering knowledge exchange processes, improving work methods; ▪ Monitors employee performance.	▪ Functional manager for a specific competency; ▪ processes, procedures for enriching and sharing knowledge in groups.	▪ Aggregated indicators of personnel employment; ▪ indicators of professional assessment of personnel by types of competencies.
5.	*«Project Management Expert»*			
	Technologies and competencies within the framework of core activities.	▪ Transfer of information about linking processes between projects; ▪ assisting the process owner with the operations director in daily tasks of optimizing business processes (projects).	▪ Processes for documenting project progress and results.	▪ Expert assessments of the state of information regarding projects.

It should be noted:

– Vice Presidents coordinate their policies through the Board of Directors, the governing body of the organization, supplemented by a Business Process Management Board; the Business Process Management Board consists of employees from different levels of the hierarchy and serves as an advisory committee, which discusses issues related to processes and the effectiveness of their management at the highest strategic level.

Table 2.2 – Main attributes of level II management

№	Attributes of an organizational management unit			
	Area of responsibility	**Powers/tasks**	**Management objects**	**Performance indicators**
1.	*«Project Manager»*			
	Project results as an end-to-end business process or group of business processes.	1.Management of all project processes; ▪ Negotiations and coordination of the activities of employees at 3 levels of the management subsystem; 2. Coordination of the allocation of employees to the project, their effective workload.	▪ Business process managers; ▪ business process metrics.	System of aggregated project indicators.
2.	*«Functional manager»*			
	Activities of an auxiliary structural unit.	▪ Administration (control) of the work of the entrusted auxiliary structural unit; ▪ management of material resources, personnel.	▪ Activities of experts and function specialists; ▪ indicators of individual functional procedures.	Service level indicators of the structural unit (SLA).
3.	*«Leader by function»*			
	Human resource development, staffing of core	▪ Activities (processes, procedures) for the development and	Employees of core business process groups	Indicators of professional assessment of personnel by competence;

	activities	exchange of professional competencies; ▪ decision-making on the allocation of employees to projects (agreement of priorities).		assessment of employee efficiency.

It should be noted:

– An essential condition for the successful implementation of a process approach to CDC is the appointment of competent and authoritative employees as project managers (investment and construction processes). By appointing the most qualified employees to these positions, management emphasizes the high priority and importance of the role of the owner of the entire process. The project manager is a middle manager who is responsible for all processes within the project, but this does not necessarily mean that all employees involved in the project are subordinate to him alone. It only means that one manager is responsible and accountable for the implementation of the processes within the project; that the assessment of the manager's performance and the size of his incentive compensation depend on the successful implementation of the project;

– The position of project manager combines 2 management roles: owner of the investment and construction business process (within the framework of the process approach), project manager (within the framework of the project approach);

– Since the position of project manager and the position of leader by function are not held by the same employee, conflicts may develop. This is due to the fact that project managers are deprived of the opportunity to exercise resource management, they can try to shape management actions only due to their informal influence and authority. In such cases, in order to avoid conflicts between project managers and leaders by function, both parties must be inclined to compromise, especially project managers who have:

- provide regular feedback, assessing the effectiveness of processes involving accountable employees;
- regularly discuss with functional leaders and among themselves the prioritization of necessary employees for the project.

Table 2.3 – Main attributes of level III management

№	Attributes of an organizational management unit			
	Area of responsibility	**Powers/tasks**	**Management objects**	**Performance indicators**
1.	*«Process or CE group owner»*			
	Business Process(es) of the core business.	▪ Ensuring continuous integration of sub-processes and the functioning of the core business process system; ▪ improving the business process(es) through redesign.	Employees who are part of business process management groups; performance indicators of employees in business process management groups.	Business process performance indicators.

It should be noted:

– Process groups are not groups of employees who hold specific positions, but groups of employees who perform specific roles (functions) within the relevant business processes. Groups can be formal or informal, with the former being recommended;

– for CDC, in accordance with the specifics of the main activity identified by the results of management diagnostics, it is necessary to differentiate the elements of the MS for the production and non-production subsystems at the third level of the management hierarchy of the conceptual model - at the level of operational management of business processes within groups. This is due to the fact that the methods of process management of these subsystems are different, which requires an appropriate distribution of powers and responsibilities between the management links of these subsystems.

For each of the subsystems described above, the following subsections reflect the integration of the process approach from the perspective of two aspects:

– the role composition of members of groups responsible for business processes;

– the duties of members of these groups based on the hierarchy of process roles and job positions.

It should be noted that a role does not necessarily correspond to a group member on a 1:1 basis. The same group member may be assigned multiple "roles", and vice versa.

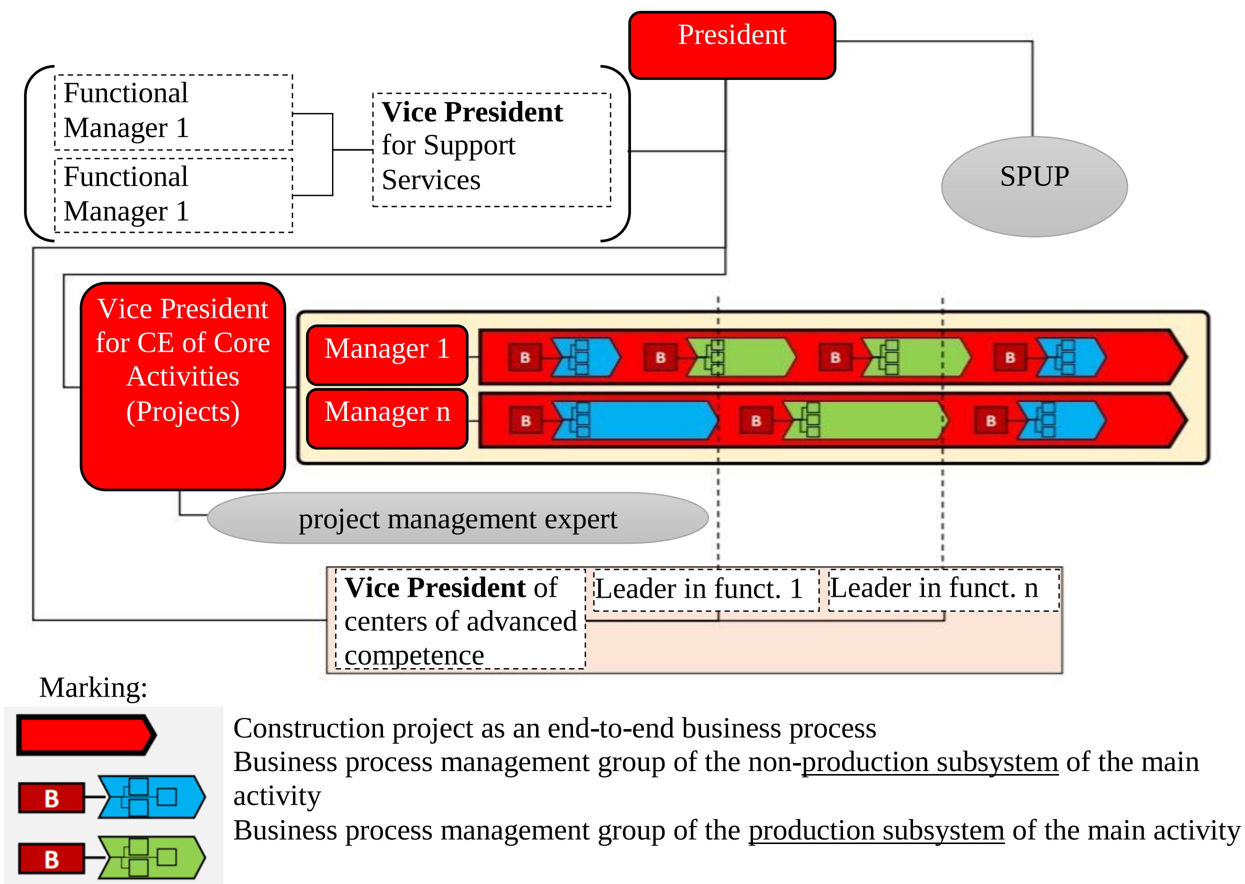


Figure 2.2 – Conceptual model of the MS CDC

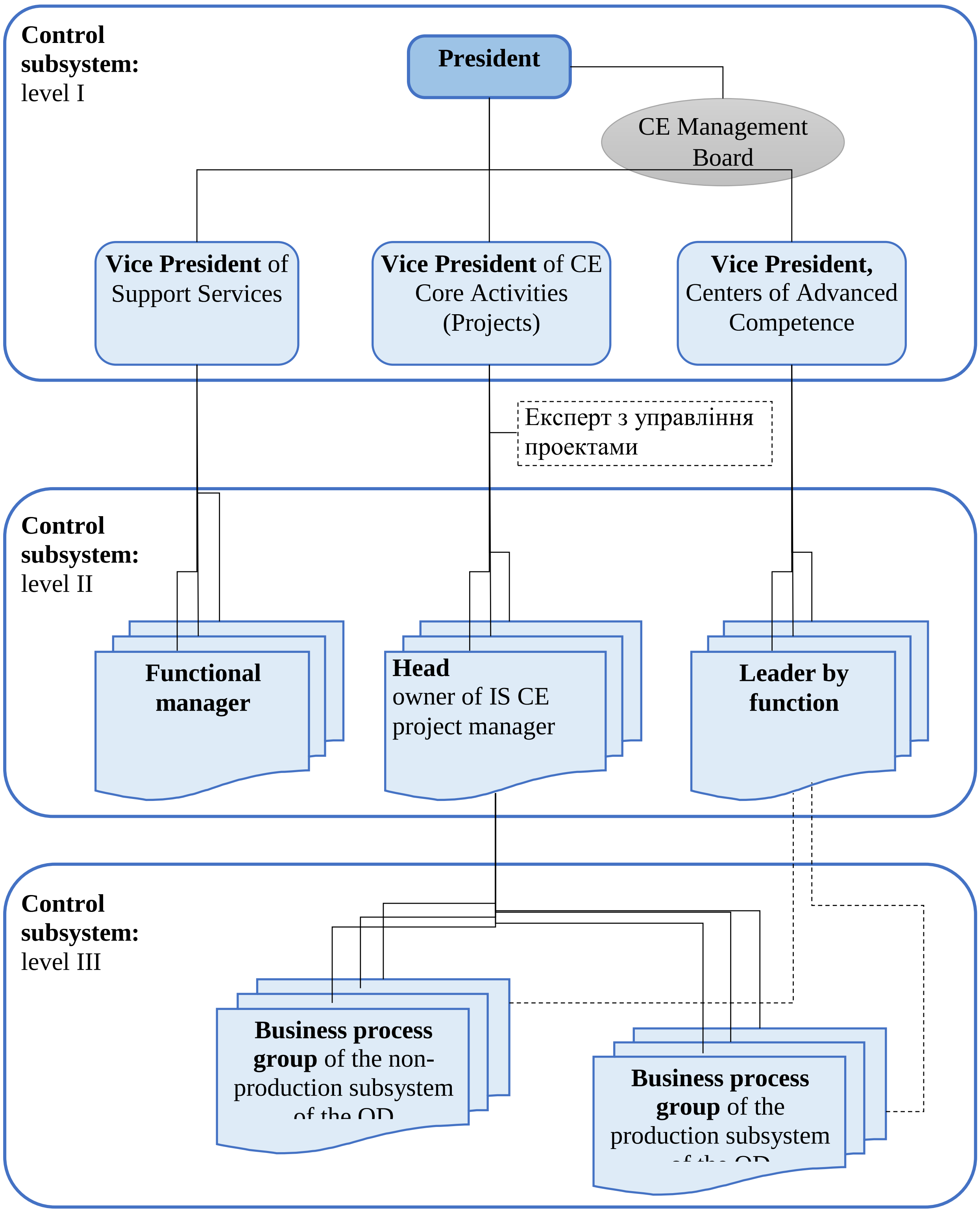


Figure 2.3 – Levels of the hierarchy of the conceptual model of the MS CDC

Let us consider in detail the theoretical and methodological basis of fuzzy sets (fuzzy logic). The fuzzy set approach was first presented and outlined by Zede [157] in 1965, and this approach was subsequently supplemented by various applications of fuzzy set theory. This theory describes how variables involved in the analytical description of a model can take on linguistic values. Thus, any linguistic variable can be characterized by a set of components $\Omega = [x, T, D]$ (where: x is the name of the variable; T is a term set or a set of values; D is the domain of definition).

The use of fuzzy descriptions means the following [80]:

1. The expert constructs a linguistic variable with its term-set of values (T). For example, on a scale: very low, low, average, high, very high.

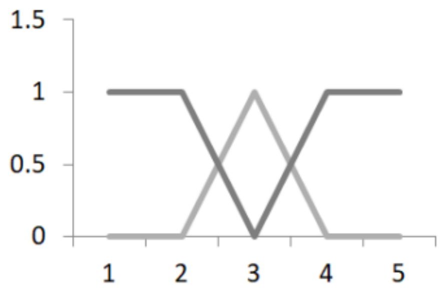
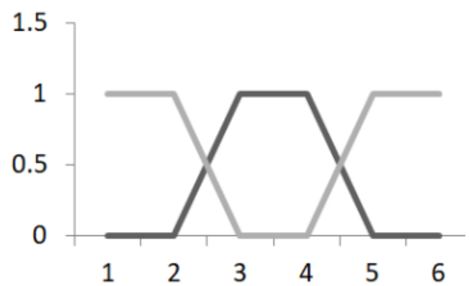
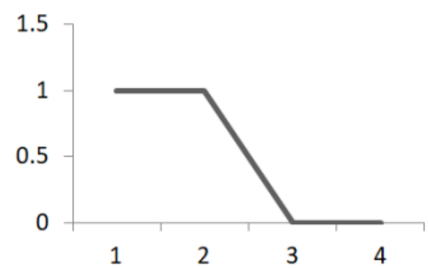
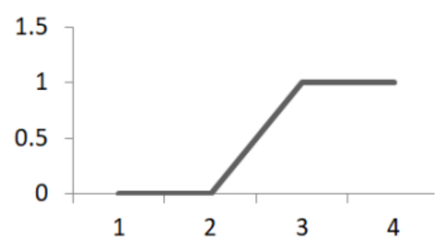
2. In order to constructively describe a linguistic variable, the expert selects the quantitative feature corresponding to it.

3. For each value of a linguistic variable, the expert associates a membership function with a particular fuzzy subset.

Membership functions can be represented as piecewise linear functions, which are convenient to use in practice, since they have an analytical representation in the form of a mathematical function. These membership functions include triangular functions (I), trapezoidal functions (II), Z-shaped functions (III), and S-shaped functions (IV) (Table 2.4).

To solve the economic problem, this paper uses a triangular membership function, which allows us to describe how certain processes influence the formation of digitalization processes in the construction complex of the region. Triangular membership functions are quite accurate in describing economic processes. Thus, for the purposes of a compact description, triangular membership functions $\mu(x)$ are conveniently described by triangular numbers of the following form (a_1, a_2, a_3) (where: a_1 and a_3 are the abscissas of the lower base; a_2 is the abscissa of the upper point of the triangle, defining $\mu(x)$ in the region with non-zero membership of the support x to the corresponding fuzzy subset).

Table 2.4 – Methodological basis of fuzzy logic

№	Function	Description
I		$f\Delta(x;a,b,c)=\begin{cases}0, if x\le a\\ \frac{x-a}{b-a}, if\ a<x\le b\\ \frac{c-x}{c-b}, if\ b<x\le c\\ 0, if\ c<x\end{cases}$ where a, b, c are some numerical parameters that take arbitrary real values and are ordered by the relation $a \le b \le c$
II		$f_m(x;a,b,c,d)=\begin{cases}0, if\ x\le a\\ \frac{x-a}{b-a}, if\ a<x\le b\\ \frac{d-x}{d-c}, if\ c<x\le d\\ 0, if\ d<x\end{cases}$ where a, b, c, d are some numerical parameters that take arbitrary real values and are ordered by the relation $a \le b \le c \le d$
III		$f_z(x;a,b)=\begin{cases}1, if\ x\le a\\ \frac{b-x}{b-a}, if\ a<x<b\\ 0, if\ b\le x\end{cases}$ where a and b are some numerical parameters that take arbitrary real values and are ordered by the relation $a < b$
IV		$f_s(x;a,b)=\begin{cases}0, if\ x\le a\\ \frac{x-a}{b-a}, if\ a<x<b\\ 1, if\ b\le x\end{cases}$ where a and b are some numerical parameters

		that take arbitrary real values and are ordered by the relation $a < b$

Designations: I – triangular membership function; II – trapezoidal membership function; III – Z-shaped membership function; IV – S-shaped membership function.

Having described a linguistic variable as discussed earlier, it can be applied in the appropriate methods and operations.

Using 6 steps, it is possible to form an aggregated assessment indicator, namely:

Stage 1.1. Determination of the composition of quantitative and qualitative indicators (factors) $X_1, \ldots, X_n$, which characterize the aggregate indicator Y.

Stage 1.2. Introduction of the linguistic variable Y and formation of scales for assessing the level of the indicator.

Step 1.3. Designation of the domain of definition of factors, set of values and triangular numbers in the summary table.

Stage 1.4. Standardization of factors X_i and formation of the matrix of factor values. It is advisable to standardize factors using the formula:

$$X_{norm} = \frac{X_i - \bar{X}}{\bar{X}} \tag{2.1}$$

Stage 1.5. Formation of a matrix table of factor values based on the obtained normalized levels with determination of the significance level. Factors are classified according to Table 2.5.

Table 2.5 – Classification of factor levels

y-value interval	Level Classification	Membership Function
$-1{,}000 \le X_{norm} \le -0{,}667$	X_1 (low)	1
$-0{,}667 < X_{norm} < -0{,}333$	X_1 (low)	$\lambda_1 = (-0{,}333 - x)/0{,}667$
	X_2 (below average)	$1 - \lambda_1 = \lambda_2$
$-0{,}333 \le X_{norm} < 0{,}000$	X_2 (below average)	$\lambda_2 = (0 - x)/0{,}667$

	X_3 (medium)	$1 - \lambda_2 = \lambda_3$
$0.000 \le X_{norm} < 0.333$	X_3 (medium)	$\lambda_3 = (0{,}333 - x)/0{,}667$
	X_4 (above average)	$1 - \lambda_3 = \lambda_4$
$0.333 \le X_{norm} < 0.667$	X_4 (above average)	$\lambda_4 = (0{,}667 - x)/0{,}667$
	X_5 (high)	$1 - \lambda_4 = \lambda_5$
$0.667 \le X_{norm} \le 1.000$	X_5 (high)	1

Stage 1.6. Calculation of the aggregated indicator Y. The value of the integrated variable can be calculated by moving from a set of individual factors $X_1, \ldots, X_n$ to a single aggregated indicator Y, the value of which can be recognized using the formed scale for assessing the level of variables (stage 2). To calculate this indicator, use the formula:

$$Y = \sum_{j=1}^{5} y_j \sum_{i=1}^{N} r_i \lambda_{ij} \tag{2.2}$$

Where: λ_{ij} – is determined from the matrix table of factor values (stage 5); y_j – nodal points of triangular numbers, which are calculated using the formula:

$$y_j = 0.833 - 0.167 * (j - 1) \tag{2.3}$$

Where: j is the column number λ.

To classify the aggregate indicator into groups, it is necessary to use Table 2.6

Table 2.6 – Risk profile level classification

y-value interval	Level Classification	Membership Function
$0{,}000 \le Y \le -0{,}167$	Y_1 (very low)	1
$0{,}167 < Y < 0{,}333$	Y_1 (very low)	$\lambda_1 = \dfrac{0{,}333 - y}{0{,}167}$
	Y_2 (low)	$1 - \lambda_1 = \lambda_2$

0.333≤Y<0.500	Y_2 (low)	$\lambda_2 = \dfrac{0,500 - x}{0,167}$
	X_3 (medium)	$1 - \lambda_2 = \lambda_3$
0,500≤Y<0,667	Y_3 (medium)	$\lambda_3 = \dfrac{0,667 - x}{0,167}$
	Y_4 (high)	$1 - \lambda_3 = \lambda_4$
0,667≤Y<0,833	Y_4 (high)	$\lambda_4 = \dfrac{0,833 - x}{0,167}$
	Y_5 (very high)	$1 - \lambda_4 = \lambda_5$
0,833≤Y≤1,000	Y_5 (very high)	1

The fuzzy set method allows for evaluating models and can be used to form a consolidated aggregate indicator of «the level of readiness of a region for the digital transformation of the construction complex», as well as to form a rating of subjects according to this indicator. The method will allow for an assessment of the regional construction complex using indicators of different properties and units of measurement, which will simplify the analysis procedure, as well as classify the subjects of the federation according to their level of readiness in accordance with the developed recommended scale for assessing fuzzy values of variables.

The algorithm for calculating the rating when adjusting data depending on the population size and area of the territory will be as follows:

Stage 2.1. Determine the groups (Y) of parameters that form the rating, collect quantitative and qualitative parameters (X) in accordance with the groups. Collect additional parameters: 1) area of the territory, thousand km^2; 2) average annual population, thousand people.

Stage 2.2. Perform normalization of the basic sample of parameters (X) of the rating (according to stage 1.1) in the range [0; 1], as well as additional parameters specified in stage 2.1 in accordance with formula 2.4:

$$N = \frac{X - X_{min}}{X_{max} - X_{min}} \quad (2.4)$$

де: X – параметр регіону; X_{min} – мінімальний параметр із вибірки по регіонах; X_{max} – максимальний параметр із вибірки по регіонах.

For correct subsequent calculation it is necessary that a unit be added to the calculated standardized value of each parameter X, since at the next step the calculation for the «zero» region will be impossible. Consequently, formula 2.4 will take the form 2.5:

$$N = \frac{X - X_{min}}{X_{max} - X_{min}} + 1 \quad (2.5)$$

Step 2.3. Calculate the ratio of the basic rating parameters to the additionally entered parameters (see step 2.1).

Stage 2.4. Perform normalization of the results of the obtained ratios in stage 2.3.

Repeat steps 1.3-1.6 used to calculate the base rating.

To classify the aggregate indicator Y being formed, it is proposed to use a 5-level scale (see Table 2.7), in which level 1 is very low [0.000; 0.333], level 5 is very high [0.667; 1.000].

Table 2.7 – Recommended scale of fuzzy values of the generated variable Y (compiled by the author)

№	Multiple meanings	Level	Name
1	0.000-0.333	Very low	The region's weak readiness for digital transformation of the construction complex is more than 50% below the average level
2	0.167-0.500	Low	The region's readiness for digital transformation of the construction complex is more than 25% below the average level.

3	0,333-0,667	Medium	Average level of readiness of the region for digital transformation of the construction complex.
4	0.500-0.833	High	The region's readiness for digital transformation of the construction complex is more than 25% higher than the average level.
5	0.667-1.000	Very high	The region is highly prepared for the digital transformation of the construction industry, more than 50% higher than average.

Each proposed level in Table 2.7 can be characterized as follows:

First level. In the region under study, the level of socio-economic development is low, scientific, technological and innovative development is practically absent, therefore, the basis for industry digital transformation has not been formed. The current state and development of the region's construction complex is considered a threat to its further socio-economic development. New construction is virtually non-existent, the flow of investment inflows into the industry does not allow for the proper development of the industry, and employment in the industry is low. Infrastructure development is practically absent. Information technologies in construction production (BIM) are not used. Regions from this group are not ready for the digital transformation of the construction complex.

Second level. In the region under study, the level of socio-economic development is below average compared to other regions. There is scientific technological and innovative development, but it is weak. The level of the current state and development of the construction complex of the region is considered satisfactory, therefore, it is difficult to maintain the existing level of socio-economic development. There is virtually no new construction, the flow of investment into the industry does not allow for the proper development of the industry, and employment in the industry is low.

Infrastructure development is limited. Information technologies in construction production (BIM) are practically not used. Regions from this group are not ready for the digital transformation of the construction complex.

Third level. In the region under study, the level of socio-economic development is at an average level compared to other regions. There is scientific, technological and innovative development in the region, but at an average level. The level of the current state and development of the construction complex of the region is considered average. There is new construction in the region, the flow of investment inflows into the industry allows for partial provision of the industry's development, the employment in the industry is average. Infrastructure development remains at the same level. Information technologies in construction production (BIM) are used by a small number of construction organizations. Regions from this group can be considered as potentially ready for digital transformation of the construction complex.

Fourth level. In the region under study, the level of socioeconomic development is above average compared to other regions. Scientific, technological and innovative development in the region is quite high. The level of the current state and development of the construction complex of the region is considered as above average. There is new construction in the region, the flow of investment inflows into the industry allows for the development of the industry, the employment in the industry is above average. Infrastructure development is possible. Information technologies in construction production (BIM) are used by a small number of construction organizations. Regions from this group can be considered as potentially ready for digital transformation of the construction complex.

Fifth level. In the region under study, the level of socio-economic development is high compared to other regions. Scientific, technological and innovative development in the region is high. The current state and development level of the construction complex of the region is considered high. There is new construction in the region, the flow of investment inflows into the industry allows for the development of the industry, and employment in the industry is high. Infrastructure development at a high level. Information technologies in construction production (BIM) are used by many construction organizations. Regions from this group are considered as potentially ready for digital transformation of the construction complex.

2.2. Assessment of the effectiveness of functional process transformation through economic and digital indicators

DEA (Data Envelopment Analysis) is a multivariate statistical analysis method used to evaluate the performance of regions, companies, organizations and other organizational units. The method was proposed in [147] and is based on the work [162]. DEA analysis is used to determine which units are using their resources most efficiently and can be useful in making decisions about improving productivity.

In DEA analysis, each unit is valued using several parameters, which can be either outputs (such as sales volume or revenue) or inputs (such as number of employees or production volumes). The method allows one to determine how well each unit uses its resources and to identify optimal resource management strategies.

DEA (Data Envelopment Analysis) is a nonparametric technique used to estimate the relative efficiency of decision making units (DMU) that have the same inputs and outputs. In other words, DEA analysis is used to determine which DMUs are performing well and which are not, compared to their peers.

DEA analysis involves the use of linear programming to compare the performance of each DMU with a «frontier» of the best DMUs. The inputs and outputs used for each DMU may include metrics such as costs, production volumes, and quality ratings. DEA analysis takes into account any trade-offs between inputs and outputs, such as the fact that increased production may require more input or less quality.

The output of DEA analysis is a set of efficiency ratios for each DMU, allowing managers to compare their performance with others in their industry or sector. DEA analysis can be used to identify areas where DMUs can improve their performance, for example by reducing costs or increasing production volumes. It can also be used to determine how resources can be allocated more efficiently.

DEA analysis has a wide range of applications, including finance, health care, education, and manufacturing. It is especially useful when traditional productivity measures based on a single input or output are insufficient or inapplicable. DEA analysis is becoming increasingly popular as firms and organizations seek to improve productivity and reduce costs.

DEA analysis can be used to evaluate productivity in various sectors, including regional economies. Using DEA analysis to compare regions helps to understand which regions are performing more efficiently and to optimize resource allocation between regions to improve overall efficiency.

When using DEA analysis for regions, input parameters may include factors such as tax rates, investment levels, availability of skilled labor, and education levels of the population. Output parameters can be factors such as economic growth, employment, quality of life, and infrastructure. DEA analysis for regional economies can help determine which regions are managing resources better and which aspects should be improved to increase productivity.

The advantages and disadvantages of the DEA method are presented in Table 2.8.

Overall, DEA analysis is a useful tool for assessing performance and finding best practices in a wide range of areas, from healthcare and education to finance and manufacturing. Despite the limitations of DEA analysis, its advantages and usefulness in assessing the performance of organizations and regions make it popular. The method continues to be a useful tool for assessing performance, optimizing resource allocation, and finding best practices across a wide range of sectors and industries.

As mentioned earlier, DEA analysis is a multiplicative mathematical optimization method for measuring the relative efficiency of a DMU (Decision Making Unit). The

DEA method allows comparing the performance of several DMUs using similar input and output parameters.

Table 2.8 – Advantages and disadvantages of DEA analysis

№	Advantages	Flaws
1	Relative Evaluation: DEA analysis allows for comparison of the relative performance of multiple decision making units (DMUs) and identification of best practices without the use of established standards, making it more flexible and adaptable to different sectors and industries.	Sensitivity to model choice: DEA analysis may yield different results depending on how the model is set up. Model choice may influence the assessment of the relative efficiency of decision making units (DMUs).
2	Insensitive to outliers: DEA analysis is robust to outliers and can account for outliers that can significantly affect other statistical methods.	Ranking Distribution: Sometimes DEA analysis can produce ambiguous results when two decision making units (DMUs) have the same ranking (i.e., they can be considered better). This can be problematic when making decisions based on the results of DEA analysis.
3	Consideration of multiple input and output parameters: DEA analysis allows consideration of multiple input and output parameters, which is especially useful in areas where it is difficult to measure performance using a single metric.	Limitations in defining input and output parameters: DEA analysis may be limited in the selection of input and output parameters for performance evaluation. Some parameters may be difficult to measure or estimate, which may lead to distorted results.
4	Using networks: DEA analysis can be used to evaluate performance in complex systems, including networks and groups of organizations.	Noise removal issues: DEA analysis may not always properly account for noise and errors in the data, which can also lead to distorted results.
5	Simplicity: DEA analysis does not require knowledge of unnecessary statistical methods, making it accessible and easy to use.	Low interpretability of results: DEA analysis can be difficult to interpret and explain, especially for those unfamiliar with the method.

The steps of DEA analysis include [147]:

1. Definition of DMU (Decision Making Unit): DMU is the unit of analysis that needs to be assessed. It can be a company, a firm, a branch, or an individual employee.

2. Identifying Input and Output Parameters: Input parameters are the resources that are used by the DMU to produce outputs. Output parameters are the results that the DMU produces. Identifying the correct input and output parameters and their levels is very important for calculating DEA.

3. Selecting a DEA model: There are several DEA models, including CCR (Charnes-Cooper-Rhodes) and BCC (Banker-Charnes-Cooper). The choice of DEA model depends on the purpose of the study and the characteristics of the data.

4. Defining the weighting matrix: The weighting matrix is used to evaluate the relative performance of each DMU by determining what portion of each input and output parameter of each URI can be attributed to efficiency and what portion cannot.

5. Solving the optimization problem: DEA analysis can be represented as a mathematical optimization problem, which is solved using linear programming.

6. Evaluating DEA Results: DEA analysis provides results in terms of the relative efficiency of each DMU. Typically, efficiency is expressed in terms of output and input parameters. DEA can also be used to identify best practices by identifying DMUs that are on the efficient frontier.

7. Interpretation of Results: The results of DEA analysis can be used to optimize resource allocation and identify best practices.

In general, DEA analysis can be useful when there is a need to evaluate the relative performance of several DMUs. One of the advantages of DEA is the relative nature of the assessment, which allows comparison of DMU performance without the use of established standards. However, as mentioned earlier, DEA has some limitations and disadvantages, such as sensitivity to model choice and difficulty in interpreting results.

The DEA method is a useful performance assessment tool that can be used across a wide range of sectors and industries to optimize resource allocation and identify best practices.

The CCR model is a widely used DEA model proposed by Charnes, Cooper, and Rhodes. It assumes that all DMUs operate at constant returns to scale (CRS) and measures technical and scale efficiency through an optimal value in the form of a ratio. In the CCR model, efficiency scores range from 0 to 1, where a score of 1 indicates a fully efficient DMU, while a score less than 1 represents an inefficient DMU. However, the CCR model assumes that all DMUs have the same efficiency frontier and does not take into account the impact of outliers or extreme values on efficiency estimates, which may lead to biased results.

The CCR model is an input-driven model and seeks to find the optimal input parameter weights for each DMU to use the minimum number of inputs to achieve a given output level while remaining efficient compared to other DMUs in the same set.

To build a CCR model in DEA, these steps are typically followed [147]:

Define inputs and outputs: Define the input and output parameters that will be used for evaluation. Inputs are the resources used in the production process, and outputs are the products or services produced.

Data Collection: Collect data on inputs and outputs for each decision making unit (DMU) in the sample. A DMU is a unit that produces outputs using inputs.

Data normalization: Scaling data so that each input and output is expressed in the same units of measurement. This allows data to be compared on a common basis.

Formulating a Linear Programming (LP) problem: Using normalized data to formulate an LP problem that will determine the optimal weights for the inputs.

Solving the LP problem: Solving the LP problem to determine the optimal weights for each input.

Calculating Performance Scores: Calculating performance scores for each DMU based on the ratio of its actual outputs to its weighted inputs.

Results Analysis: Results analysis to identify inefficient DMUs that could benefit from changes in their production processes.

The CCR (Charnes-Cooper-Rhodes) and BCC (Banker Charnes-Cooper) models are types of data efficiency analysis (DEA) models used to compare the relative efficiency of decision making units (DMUs) based on the use of inputs to produce outputs. The main difference between the CCR and BCC models is their treatment of redundant outputs.

In the CCR model, excess outputs are not allowed, and excess inputs can be calculated without taking output levels into account. This can lead to overestimation of efficiency, since the model assumes that all output targets are achieved. On the other hand, the BCC model takes into account both input and output excesses simultaneously, which makes it more flexible and realistic, leading to more accurate efficiency assessment. In addition, the BCC model allows for variable returns to scale, which means that the relationship between inputs and outputs is not assumed to be constant, and the model can better capture the actual production process. Table 2.9 presents the advantages and disadvantages of the two models.

The BCC model is generally considered a more accurate and rigorous version of the CCR model. However, the choice of model depends on the specific requirements of the analysis, such as the nature of the input and output parameters, the availability of reserves, and the scale of the operation.

In addition, the BCC model allows for the use of variable scales of production, which can take into account the possibility of changing the relationship between inputs and outputs with increasing funding.

Table 2.9 – Advantages and Disadvantages

Model	Advantages	Flaws
Charnes-Cooper-Rhodes	– the ability to take into account various input and output parameters; – performance assessment based on all available data sets; – the ability to use modern information technologies for reliable performance assessment.	– limiting the maximum efficiency to 1, which may lead to underestimation of regions that may exceed this value; – limitations related to the estimation parameters; – sensitivity to the choice of input and output parameters, which can greatly affect the results of the performance estimation; – limitations on the shape of the model (e.g. convexity conditions), which can cause problems in the estimation of the efficiency.
Banker-Charnes-Cooper	– the ability to more accurately assess the productivity of regions that are not on the edge of the production function; – the ability to assess the efficiency of regions with nonlinear production functions; – assessing the efficiency of regions based on more realistic and accurate data.	– the calculation of the maximum efficiency of the output parameter may be biased towards the assessed regions that have a large number of input parameters; – the model may be less user-friendly than the DEA CCR model, since it has a more complex mathematical formula; – restrictions on the shape of the model may lead to some limitations in assessing the efficiency of regions.

Overall, the flexibility of the BCC model, its ability to handle multiple input and output parameters, and the ability to account for variable production scales make it a more suitable choice for assessing the effectiveness of using public subsidies to develop digital and innovative processes in regions.

In the case of constant production scale, the output parameter changes proportionally to the input factor. However, when the scale effect is variable, a change in the input factor may lead to a disproportionate change in the output parameter.

This definition has an impact on the efficiency values. The variable scale effect can be mathematically represented by adding a new variable u_0 to the objective function of the original model (formulas 2.6-2.7).

$$e_0 = \frac{\sum_{j=1}^{s} u_j y_{j0} + u_0}{\sum_{i=1}^{r} v_i x_{i0}} \rightarrow max! \tag{2.6}$$

Considering that:

$$e_0 = \frac{\sum_{j=1}^{s} u_j y_{jm} + u_0}{\sum_{i=1}^{r} v_i x_{im}} \leq 1, \tag{2.7}$$

$u_j, v_i \geq 0$

where u_0 is the scale effect, if $u_0 < 0$ – decreasing scale of production,

if $u_0 > 0$ – increasing scale of production, if $u_0 = 0$ – constant scale of production.

Mathematically, the input-oriented BCC model is represented as follows (Table 2.10):

Table 2.10 – Input-oriented BCC model

Direct Input-Oriented BCC Model (BCCP-Input) with Backup Variable	Dual Input-Oriented Model BCCmodel (BCCD-Input) with Backup Variable
$min\theta_0, \lambda_j - \varepsilon(\sum_{j=1}^{s} s_j^{+} + \sum_{i=1}^{r} s_i^{-})$ under the following conditions: $\sum_{m=1}^{n} y_{jm}\lambda_m - s_j^{+} = y_{j0}$ for all regions j=1,..., s $x_{i0}\theta_0 - \sum_{m=1}^{n} x_{im}\lambda_m - s_i^{-} = 0$ for all regions i=1,…., r $\sum_{m=1}^{n} \lambda_m = 1$ $\lambda_m, s_j^{+}, s_i^{-} \geq 0, m = 1,2,\dots,n$	$max \sum_{j=1}^{s} \mu_j y_{j0} + u_0$ under the following conditions: $\sum_{i=1}^{r} t_j x_{i0} = 1$ $\sum_{j=1}^{s} \mu_j y_{jm} - \sum_{i=1}^{r} t_i x_{jm} + \sum_{m=1}^{n} \mu_0 \leq 0$ for all regions m=1, …, n $\mu_j, t_i \geq 0$ u_0 free

Source: Compiled by the author based on [147]

A comparison of the dual and direct methods in the BCC model is shown in Table 2.11.

Table 2.11 – Comparison of Dual and Direct Methods in the BCC Model

Linear programming form			
Enclosing shape Restrictions	Multiplicative form Variables	Multiplicative form Restrictions	sh
$\sum_{m=1}^{n} y_{jm} \lambda_m - s_j^{+} = y_{j0}$ $x_{i0}\theta_0 - \sum_{m=1}^{n} x_{im}\lambda_m - s_i^{-} = 0$ $\sum_{m=1}^{n} \lambda_m = 1$	$\mu_j, t_i \geq \varepsilon > 0$ u_0	$\sum_{i=1}^{r} t_j x_{i0} = 1$ $\sum_{j=1}^{s} \mu_j y_{jm} - \sum_{i=1}^{r} t_i x_{jm} + \sum_{m=1}^{n} \mu_0 \leq 0$	θ λ

Source: Compiled by the author based on [147]

In addition to the limitations of the formulation $min\theta_0, \lambda_j - \varepsilon(\sum_{j=1}^{s} s_j^{+} + \sum_{i=1}^{r} s_i^{-})$, condition is added $\sum_{m=1}^{n} \lambda_m = 1$, due to which the convexity of the production function is achieved. It follows directly from this that one region in the BCC model cannot be compared to other regions in the form of multipliers or shares, but only as weighted sums of regions if the sum of the evaluation coefficients is equal to 1 [147].

2.3. Formation of an economically justified structure of the enterprise development model in the new digital environment

Assessing the level of readiness is the basis for sustainable development of regions, since it allows for the creation of a basis for the formation and development of the concept of digital transformation of the economic activities of subjects of the construction complex of regions. In the long term, the level of readiness of the region for the digital transformation of the construction complex can act as a driver for the development of the RIS, which will have a positive impact on the overall innovative and digital development of the subject. Therefore, considering the approach to assessing the level of readiness within the framework of industry digital transformation, it will be possible to determine the current state of the regions, as well as understand which strategic initiative needs to be chosen when developing a particular territory.

Table 2.12 shows a selection of parameters (X) for the rating. The selection takes into account both quantitative and qualitative parameters. When selecting parameters (X), priority was given to availability, as well as annual updating of data. The sample is based on groups (Y), which are components of the level of readiness (see paragraph 1.2.3): 1) socio-economic conditions for the implementation of industry digitalization of regions; 2) development of science and innovation in the regions; 3) development of the construction complex of the regions; 4) development of digital technologies of the regions. The formation of groups in this way determines the set of parameters included in them, as well as the subsequent calculation by forming aggregated indicators of several levels - by groups and general, since determining the level of readiness of the industry for digital transformation is possible by forming an aggregated indicator of the rating of subjects – an index. When selecting parameters, the existing ratings analyzed in section 2.1.1 were taken into account. In the part of the group “development of science and innovation in the regions”, studies aimed at assessing the development of RIS were taken into account in order to take into account frequently used indicators.

Table 2.12 – Indicators for assessing the level of readiness of regions for the digital transformation of the construction complex (compiled by the author)

Group	Indicator		Indicator type
1. Socioeconomic conditions for the implementation of industry digitalization of regions (Y1)	X1	Human Development Index by Region	Qualitative
2. Development of science and innovation in the regions (Y2)	X2	Share of GRP by type of activity – professional, scientific and technical, % (in current basic prices; in % of the total)	Quantitative
	X3	Number of personnel engaged in scientific research and development, people	Quantitative
	X4	Volume of innovative goods, works and services, % of the total volume of shipped goods, completed works and services	Quantitative
	X5	Patent applications filed, units	Quantitative
	X6	Number of patents issued, units	Quantitative
	X7	Developed advanced production technologies, units.	Quantitative
	X8	Advanced production technologies used, units	Quantitative
	X9	The share of organizations implementing technological innovations in the total number of surveyed organizations, % of the total number of organizations	Quantitative
	X10	Level of innovative activity of organizations	Qualitative
3. Development of the construction complex of the regions (Y3)	X11	Commissioning of residential and non-residential buildings, total area of buildings, thousand m^2	Quantitative
	X12	Share of GRP by type of economic activity «Construction», % (in current	Quantitative

		basic prices; in % of the total)	
	X13	Distribution of the number of enterprises and organizations by type of economic activity Construction, units	Quantitative
	X14	Average annual number of people employed by type of economic activity Construction, thousand people	Quantitative
4. Development of digital technologies (Y4)	X15	Level of digital literacy of the population	Qualitative
	X16	The share of organizations using design programs, % of the total number of organizations	Quantitative
	X17	Share of GRP by type of activity in the field of information and communication, % (in current basic prices; in % of the total)	Quantitative
	X18	The proportion of organizations using broadband Internet, % of the total number of surveyed organizations	Quantitative
	X19	Use of digital technologies in organizations – Local area networks, in % of the total number of surveyed organizations	Quantitative
	X20	Use of digital technologies in organizations – «cloud» services, in % of the total number of surveyed organizations	Quantitative

Each group of factors allows us to assess the region in accordance with certain factors that form the basis for assessing the level of readiness of the region for the digital transformation of the construction complex, including determining the presence of digital potential in the subject for the development of technologies. Digital potential is a set of factors that contribute to the development of digital technologies in a region/municipality: personnel, scientific and technical equipment, innovation, general socio-economic development, industry development. Parameters X2-X14 and X16-X20 are collected by the Federal State Statistics Service [21], which is quite convenient for further calculation of the rating, since the parameters are accessible. Please note that the rating is formed for the period 2021, since parameters X2, X12 and X17 are not currently published for 2022.

Let us consider the group Y1 in detail. This group is filled with one parameter X1. Parameter X1 reflects the socio-economic conditions of the regions from the side of key characteristics of human potential. The integral indicator of the human development index was chosen as a parameter, which reflects the ability of people to lead a long and healthy life, receive an education and achieve an acceptable standard of living, therefore, it allows us to assess the level of development of a particular subject of the federation from the point of view of socio-economic development. The parameter is calculated by the Analytical Center [69] using the adjusted methodology as the geometric mean of three components: the income index, the education index, and the longevity index. Each component is an index calculated in the range from 0 to 1, where 1 reflects a better situation in a particular area.

The second group (Y2) contains indicators reflecting the level of development of science and innovation in the subjects of the federation. The indicators also form the basis for assessing the level of development of RIS:

– X2 allows us to assess the contribution of professional, scientific and technical activities to the total volume of GRP. The indicator is expressed as a percentage of the total volume of GRP and shows what part of the economy is associated with these types of activities.

– X3 reflects the number of people engaged in scientific research and development. The indicator allows us to assess the scale of scientific activity in the country and its impact on the economy and innovation potential.

– X4 allows to estimate the share of innovative products and services in the total volume of shipped goods, performed works and services. The indicator reflects the degree of innovation of the economy and its ability to create and implement new products and services.

– X5 reflects the number of patent applications filed and is an indicator of innovative activity and interest in protecting intellectual property.

– X6 shows the number of patents issued, reflects success in protecting intellectual property and innovative activity in the country.

– X7 reflects the number of developed advanced production technologies and allows us to assess the innovative potential and the country’s ability to create new technologies.

– X8 shows the number of advanced production technologies used, reflects the degree of innovation in production and the efficiency of using advanced technologies.

– X9 allows us to estimate the share of organizations engaged in technological innovations in the total number of surveyed organizations. The indicator reflects the scale and prevalence of technological innovations in the country's economy.

– X10 reflects the degree of use and development of new technologies, products and services in organizations. The indicator is important for assessing the level of development and competitiveness of the economy of a region or country, as well as for determining the growth potential and modernity of enterprises.

The third group (Y3) contains indicators characterizing the development of the region’s construction complex, namely:

– X11 reflects the number of new buildings that were constructed or put into operation in a given period of time, taking into account the total area. The indicator is important for measuring the volume of construction activity in a region or country.

– X12 reflects the percentage contribution of the construction industry to the total Gross Regional Product (GRP) of the region. It shows how significant the construction industry is for the economy and what percentage of its contribution is from the total production volume.

– X13 indicates the number of enterprises and organizations engaged in the construction industry. Allows you to assess the scale and competition in this industry, and also gives an idea of the number of jobs created in construction.

– X14 reflects the average number of workers employed in the construction industry during the year. Allows to assess the level of employment and the contribution of the construction industry to job creation. This indicator can also serve as an indicator for analyzing trends in the change in the number of workers in construction.

The fourth group of factors includes indicators of the development of digital technologies in the territories of the constituent entities of the federation:

– X15 is a calculated indicator measured on a ten-point scale. Data collection is carried out as part of the Digital Dictation campaign.

– X16 reflects the share of organizations that use design programs in their activities. The indicator allows you to assess the degree of penetration and use of modern technologies in design.

– X17 reflects the share of GRP in the field of information and communication in the total volume of GRP. The indicator allows us to assess the contribution of the information and communication industry to the economy of a region or country.

– X18 reflects the share of organizations that have access to broadband Internet. The indicator allows us to assess the degree of availability and use of high-speed Internet in the business sector.

– X19 reflects the share of organizations that use local area networks for their work. The indicator allows us to assess the degree of use of network technologies to ensure internal communication and information exchange in organizations.

– X20 reflects the share of organizations that use cloud services to store data and perform various tasks. The indicator allows you to assess the degree of penetration and use of cloud technologies in the business sector

It is assumed that the selected groups of indicators have a relationship, which is presented in Figure 2.4.

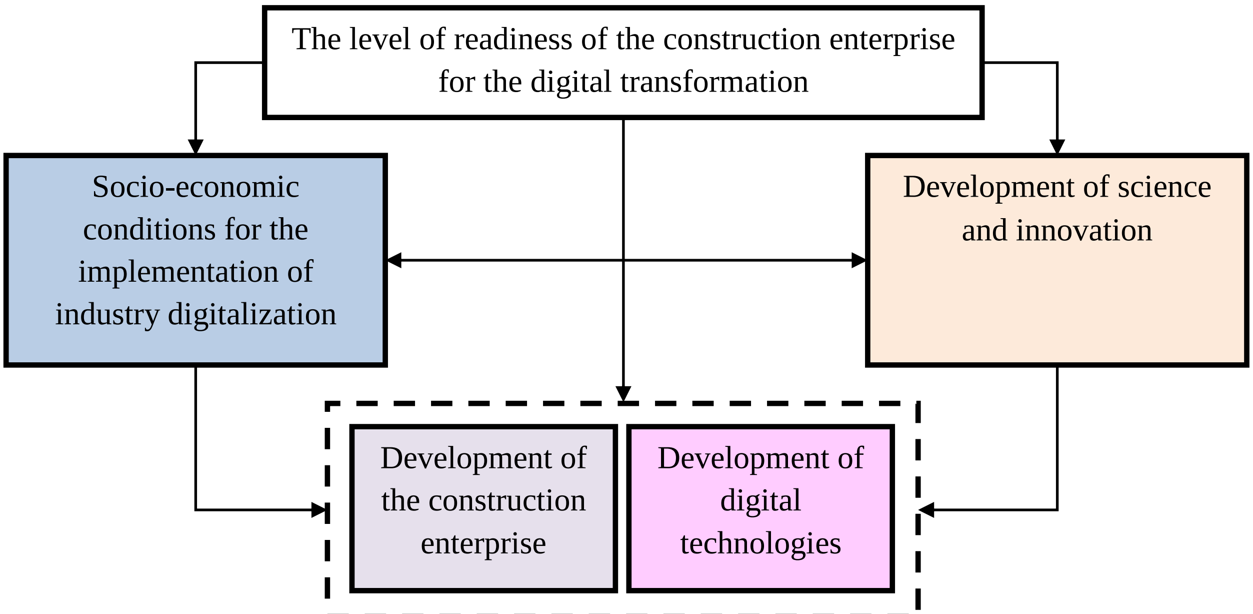


Figure 2.4 – Interrelation of groups of indicators «The level of readiness of the construction enterprise for the digital transformation »

It will check the indicators and apply regression analysis to determine the level of significance.

To conduct the regression analysis, we will take the basic selected indicators for 2019-2021 (Appendix B, Table B.1), as well as their reduced values using the natural logarithm, which will allow us to compare the obtained result, since due to the strong scatter of indicators during the first construction of the regression model, R^2 may be low, and the standard error may be large, the confidence intervals may be erroneous. Therefore, using the «regress» query in Stata software, we will calculate the linear regression, the result of which is presented in Figure 2.5. Note that when calculating multiple regression, the value of the ratio of GRP by the type of activity Construction to the population will be taken as Y. In this regard, it is necessary to remove the indicator X14 from the basic sample of parameters when conducting the analysis.

```
regress y1 x1 x2 x3 x4 x5 x6 x7 x8 x9 x10 x11 x12 x13  x15 x16 x17 x18 x19 x20
```

Source	SS	df	MS			
				Number of obs	=	254
				F(19, 234)	=	9.83
Model	757375.861	19	39861.8874	Prob > F	=	0.0000
Residual	949072.516	234	4055.86545	R-squared	=	0.4438
				Adj R-squared	=	0.3987
Total	1706448.38	253	6744.85525	Root MSE	=	63.686

y1	Coef.	Std. Err.	t	P>|t|	[95% Conf.	Interval]
x1	1471.029	219.5115	6.70	0.000	1038.558	1903.501
x2	-14.62861	4.221629	-3.47	0.001	-22.94587	-6.311355
x3	.0014492	.0007579	1.91	0.057	-.000044	.0029423
x4	-2.093633	1.108958	-1.89	0.060	-4.278451	.0911846
x5	.0104045	.0192395	0.54	0.589	-.0275003	.0483092
x6	-.0230411	.0438508	-0.53	0.600	-.109434	.0633517
x7	-.0074223	.2097691	-0.04	0.972	-.4206996	.405855
x8	.0012046	.0009713	1.24	0.216	-.000709	.0031183
x9	.0187537	.2490735	0.08	0.940	-.4719594	.5094668
x10	-.068894	1.182808	-0.06	0.954	-2.399208	2.26142
x11	-.0065676	.0034852	-1.88	0.061	-.013434	.0002989
x12	11.6185	1.906363	6.09	0.000	7.862676	15.37433
x13	-.002243	.0029431	-0.76	0.447	-.0080413	.0035553
x15	-14.59465	12.53886	-1.16	0.246	-39.29813	10.10884
x16	6.672367	2.028239	3.29	0.001	2.676425	10.66831
x17	-.2693094	8.527171	-0.03	0.975	-17.06915	16.53053
x18	-.6741441	.4533711	-1.49	0.138	-1.567355	.2190666
x19	1.900961	.8237996	2.31	0.022	.2779493	3.523973
x20	-3.118136	1.011824	-3.08	0.002	-5.111585	-1.124687
_cons	-1174.147	208.7857	-5.62	0.000	-1585.487	-762.8072

Figure 2.5 – Multiple regression of selected indicators

As can be seen from Figure 2.5, due to the fact that the distribution of the base values is not correct for the analysis, the value of R^2=0.4438 and adjusted R^2=0.3987 reflect the overall significance of the statistical relationship, which is low. The root mean square error = 63.686, which also indicates a poor sample of the model. Analyzing the result by indicators, let's consider the graphical interpretation in Figure 2.6, which we will build using the query «cprplots, lowess».

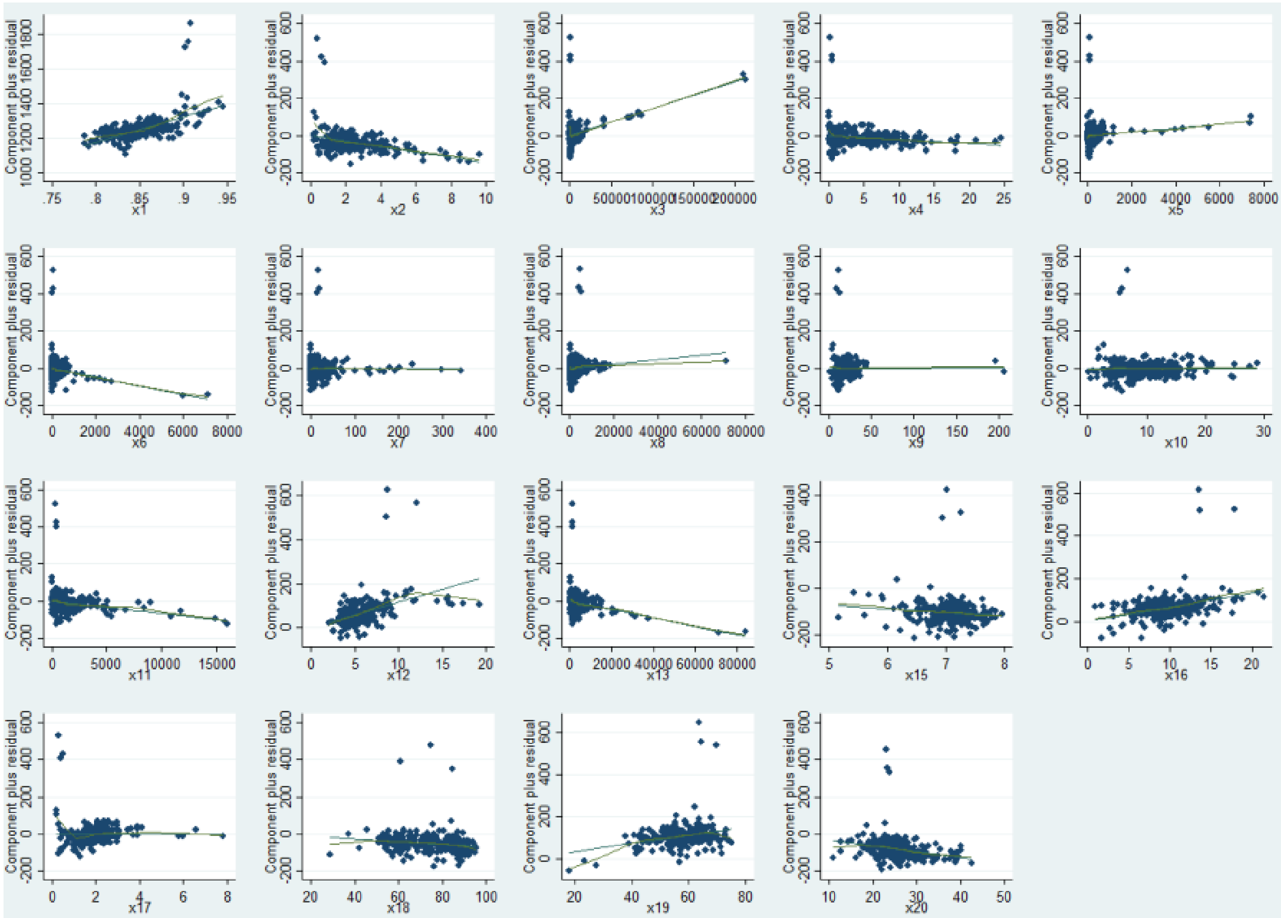


Figure 2.6 – Graphical interpretation of the results of regression analysis of selected indicators

According to Figure 2.6, we note that the incorrect distribution of indicators was confirmed, since there are leading regions in terms of indicators that significantly fall outside the sample, therefore, the correctness of the interpreted result is violated. In this connection, we will perform a new calculation of multiple regression on the given values of the base sample using the natural logarithm. The calculation result is presented in Figure 2.7.

```
regress y x1 x2 x3 x4 x5 x6 x7 x8 x9 x10 x11 x12 x13 x15 x16 x17 x18 x19 x20
```

Source	SS	df	MS		
				Number of obs =	243
				F(19, 223) =	67.80
Model	91.5859466	19	4.82031298	Prob > F =	0.0000
Residual	15.8533073	223	.071091064	R-squared =	0.8524
				Adj R-squared =	0.8399
Total	107.439254	242	.443963859	Root MSE =	.26663

y	Coef.	Std. Err.	t	P>|t|	[95% Conf.	Interval]
x1	12.16716	.8432896	14.43	0.000	10.50532	13.82899
x2	-.106886	.0526289	-2.03	0.043	-.2105997	-.0031724
x3	.0258109	.0269185	0.96	0.339	-.0272361	.078858
x4	-.077581	.0183745	-4.22	0.000	-.1137908	-.0413712
x5	.0222291	.0579077	0.38	0.701	-.0918872	.1363455
x6	-.0920136	.0500174	-1.84	0.067	-.1905808	.0065535
x7	.0132895	.0155577	0.85	0.394	-.0173694	.0439484
x8	.1665676	.0323888	5.14	0.000	.1027403	.2303949
x9	.0132327	.0621281	0.21	0.832	-.1092006	.1356659
x10	.0207581	.0562102	0.37	0.712	-.0900131	.1315293
x11	-.1932703	.035412	-5.46	0.000	-.2630552	-.1234854
x12	1.013712	.0616904	16.43	0.000	.8921412	1.135283
x13	.142662	.0493671	2.89	0.004	.0453762	.2399477
x15	-.0180006	.3914495	-0.05	0.963	-.7894139	.7534128
x16	.042766	.0693989	0.62	0.538	-.0939956	.1795277
x17	-.3474621	.058197	-5.97	0.000	-.4621485	-.2327757
x18	-.0100558	.1378869	-0.07	0.942	-.2817838	.2616722
x19	.7126992	.1983609	3.59	0.000	.3217974	1.103601
x20	-.2448381	.1273356	-1.92	0.056	-.4957732	.0060969
_cons	.5472569	1.04278	0.52	0.600	-1.507707	2.602221

Figure 2.7 – Multiple regression of selected indicators with given values using natural logarithm (Source: Compiled by the author in *Stata* software)

According to the calculated indicators (Figure 2.7), it can be said that the given sample of basic indicators is more correct, relative to the original one. R^2=0.8524 and adjusted R^2=0.8399 reflect the overall significance of the statistical relationship, which is high. The root mean square error = 0.2666, which indicates a good sample of the initial data in the model. Analyzing the indicators tested by multiple regression, the following conclusions can be made:

– Indicators X1, X8, X12, X19 fall within the positive confidence interval, therefore, with an increase in these indicators, the Y under consideration will increase.

– Indicators X2, X4, X11, X17 fall into the negative confidence interval, therefore, with an increase in these indicators, the Y under consideration will decrease.

– Indicators X3, X5, X6, X7, X9, X10, X13, X15, X16, X18, X20 fall within the confidence interval, which includes the zero value, therefore, there is a connection, but it is not very significant.

Let us consider a graphical interpretation of the results of the given sample of initial data (Figure 2.8). When rebuilding the regression graphs, it is clear that the result is now more correct, a linear relationship is observed. Note that the greater the slope, the more significant this or that indicator X is relative to the base Y, i.e. when X changes, small changes in Y occur.

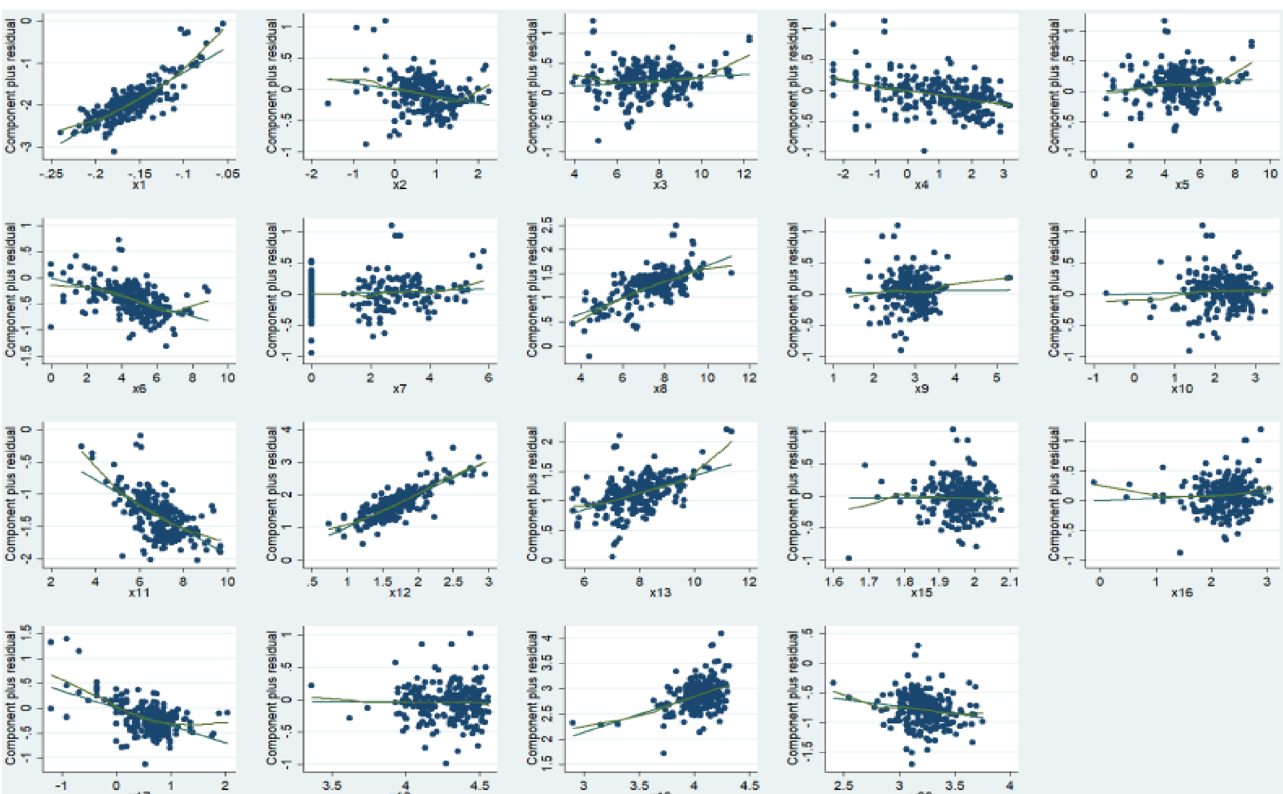


Figure 2.8 – Graphical interpretation of the result of regression analysis of selected indicators with given values using the natural logarithm

Source: Compiled by the author in Stata software

Next, it is necessary to form a rating in accordance with the methodology described in paragraph 1.2.2, using the fuzzy set method. The basis for constructing the rating will be the selected groups of indicators, including those that have little significance.

The formation of a rating of the level of readiness of regions for the digital transformation of the construction complex using the fuzzy set method is presented in the study [].

Based on the selected indicators in Table 2.12 for four Y groups, we will construct a basic rating of the level of readiness of regions for the digital transformation of the construction complex for 2021 using the fuzzy set method. We will assign a weight coefficient r_1=0.25 to each group (Y_1, Y_2, Y_3, Y_4), since the groups have the same impact on the developed indicator Y as the sample of factors included in these groups. It should be noted that the X2-X20 data are available for the period under review, the X1 data were published for 2019, therefore, when taking this parameter into account when calculating the rating, the indicator was taken for 2019, taking into account the % of its change over the previous 5 years, which is presented in the document published by the Analytical Center [69].

To classify the developed aggregate indicator Y, we will use a 5-level scale, where level 1 corresponds to very low [0.000; 0.333] and level 5 to very high [0.667; 1.000] (Table 2.7).

As an example, we will calculate the aggregated Y indicator for LLC "Alfa service" with a detailed algorithm for the group «Development of digital technologies of regions (Y4)». We will conduct an analysis that will allow us to form the Y4 indicator in accordance with the stages established by the methodology.

Step 1. We introduce the linguistic variable Y4 «Development of digital technologies in LLC "Alfa service" (Y4) ». The resulting scale of fuzzy values of the introduced linguistic variable (Y4) was similar to the scale presented in Table 2.6.

Step 2. During the calculation, quantitative (statistical data [21]) indicators X16-X20 and qualitative (Digital literacy level of the population) indicator X15 for 2021 were collected, which are characterized by the following values: X15=6.79; X16=13.4%; X17=3.7%; X18=75.4%; X19=53.8%; X20=30.9%.

Step 3. The selection of the interval from the minimum value to the maximum serves as the range for determining the factors, sets of values and triangular numbers of the linguistic variable (Y4) (Table 2.13).

Table 2.13 – Range of determination of factors, sets of values and triangular numbers of Y4 indicators for LLC "Alfa service”

Scale	T-numbers	X15	X15	X15	X15	X15	X15
Very Low	-1.000	5.17	3.10	0.20	57.50	27.30	16.10
	-0.667	5.58	5.27	1.58	62.52	33.98	20.10
	-0.333	5.99	7.43	2.97	67.53	40.67	24.10
Low	-0.667	5.58	5.27	1.58	62.52	33.98	20.10
	-0.333	5.99	7.43	2.97	67.53	40.67	24.10
	0.000	6.40	9.60	4.35	72.55	47.35	28.10
Average	-0.333	5.99	7.43	2.97	67.53	40.67	24.10
	0.000	6.40	9.60	4.35	72.55	47.35	28.10
	0.333	6.80	11.77	5.73	77.57	54.03	32.10
High	0.000	6.40	9.60	4.35	72.55	47.35	28.10
	0.333	6.80	11.77	5.73	77.57	54.03	32.10
	0.667	7.21	13.93	7.12	82.58	60.72	36.10
Very High	0.333	6.80	11.77	5.73	77.57	54.03	32.10
	0.667	7.21	13.93	7.12	82.58	60.72	36.10
	1.000	7.62	16.10	8.50	87.60	67.40	40.10

Stage 4. When normalizing the coefficients using formula (2.1), the following values were obtained: X15=0.062; X16=0.396; X17=-0.149; X18=0.039; X19=0.136; X20=0.100. Table 2.14 shows the matrix of values of factors X15-X20 and their significance level r_{iY1}=0.167 (stage 5); the range of values is from -1.000 to 1.000 (see Table 2.10, T-numbers).

Table 2.14 – Matrix of factor values of the linguistic variable Y4 for LLC "Alfa service"

Name of the factor	Subset scale					Significance level *ri*
	λ1(xi)	λ2(xi)	λ3(xi)	λ4(xi)	λ5(xi)	
X15	0,000	0,000	0,407	0,593	0,000	0,167
X16	0,000	0,000	0,000	0,407	0,593	0,167
X17	0,000	0,224	0,776	0,000	0,000	0,167
X18	0,000	0,000	0,440	0,560	0,000	0,167
X19	0,000	0,000	0,295	0,705	0,000	0,167
X20	0,000	0,000	0,350	0,650	0,000	0,167

According to the aggregate indicator calculated using formulas (2.2) and (2.3), Y4 (stage 6) of LLC "Alfa servicet" had a value of 0.607 in the group «Development of digital technologies of regions (Y4)». Comparing the obtained value with the scale presented in Table 2.5, as well as the classification of the risk level in Table 2.6, we can say that the development of digital technologies in LLC "Alfa servicet" is at level 4 (83%) and level 5 (17%). In this regard, the obtained value of the indicator can be classified as approaching a confidently high level. In this study, the aggregate indicators for groups Y1, Y2 and Y3 were formed similarly to the Y4 indicator and amounted to 0.598, 0.558 and 0.352, respectively. The final aggregate indicator Y, which determines the level of readiness of the region for the digital transformation of the construction complex, amounted to 0.529, taking into account the weighting coefficient ri=0.25. Thus, according to the obtained indicator, LLC "Alfa service" was 83% ready for the digital transformation of the construction complex at an average level and 17% at a high level.

Digital transformation has a different impact on the areas of activity (design and construction) of construction companies (operating in the market for the construction of non-industrial facilities - residential buildings that combine the functions of a technical customer and a general contractor); BIM modeling can be called a cross-cutting innovation [190]. A BIM model or digital twin of a capital construction project is the basis for the construction of objects, as well as for passing an examination [55, 30]. «The process of transition to BIM begins directly with the reorganization of the work of the design department, where, in accordance with requests and technical equipment, the interconnected activities of working groups in the areas (sections) of design in the BIM context are organized. The main areas of design include: architectural solutions (AS); design solutions (DS); water supply and sewerage (WS); heating, ventilation and air conditioning (HVAC); electrical networks (EN); low-current networks (LCN); master plan (MP); design (D); calendar-network schedule (CNS) including the construction organization project (COP), as well as the work execution project (WEP)» [155].

The traditional approach to building design involves the following broad stages [156]: formation of technical specifications – development of a draft design (concept) – development of design documentation for the project (PD) – passing an examination and obtaining a building permit – development of working documentation for the project (WD) – construction site and logistics – construction of a capital construction project – commissioning of the project. The design part includes everything up to the work on the construction site. The development of project documentation is divided into two blocks – PD and WD, therefore, when improving business processes, in accordance with the stages of the life cycle of capital construction projects, this division can be abolished with a complete transition to BIM modeling. Single-stage design will allow digital twins to be created immediately with the required level of detail.

The purpose of the analysis and improvement of business processes of construction companies should be the following five groups of indicators [78]:

1) business process efficiency;

2) business process cost;

3) business process time;

4) business process quality;

5) business process fragmentation.

When improving and further automating business processes of the design department, focusing on the listed groups of indicators is of no small importance when setting the task of transitioning to BIM, which subsequently guarantees the scalability of the work [90].

During the initial examination of a construction company, business processes must be described by forming an «as is» model, which will reflect the current state within the organization. Next, based on the «as is» model, it is necessary to form a «as should be» business process model, taking into account the adjustment for improvement and the transition to single-stage design. The constructed business process models should reflect the company's high-level processes with the required input data, as well as their interrelationships [155].

Figure 2.9 shows a step-by-step diagram of the survey of the design department of a construction company. The diagram is built in relation to the stages of the survey of a construction company with a focus on the design department:

1) Form an «as is» model;

2) Form a «as should be» model;

3) Conduct an analysis of directions; build high-level algorithms in directions;

4) Conduct a detailed analysis of directions; build decomposed algorithms into 1-n levels;

5) Provide a text description at the lowest level of process decomposition in directions.

Business process analysis consists a step-by-step decomposition of each design direction to the lowest level.

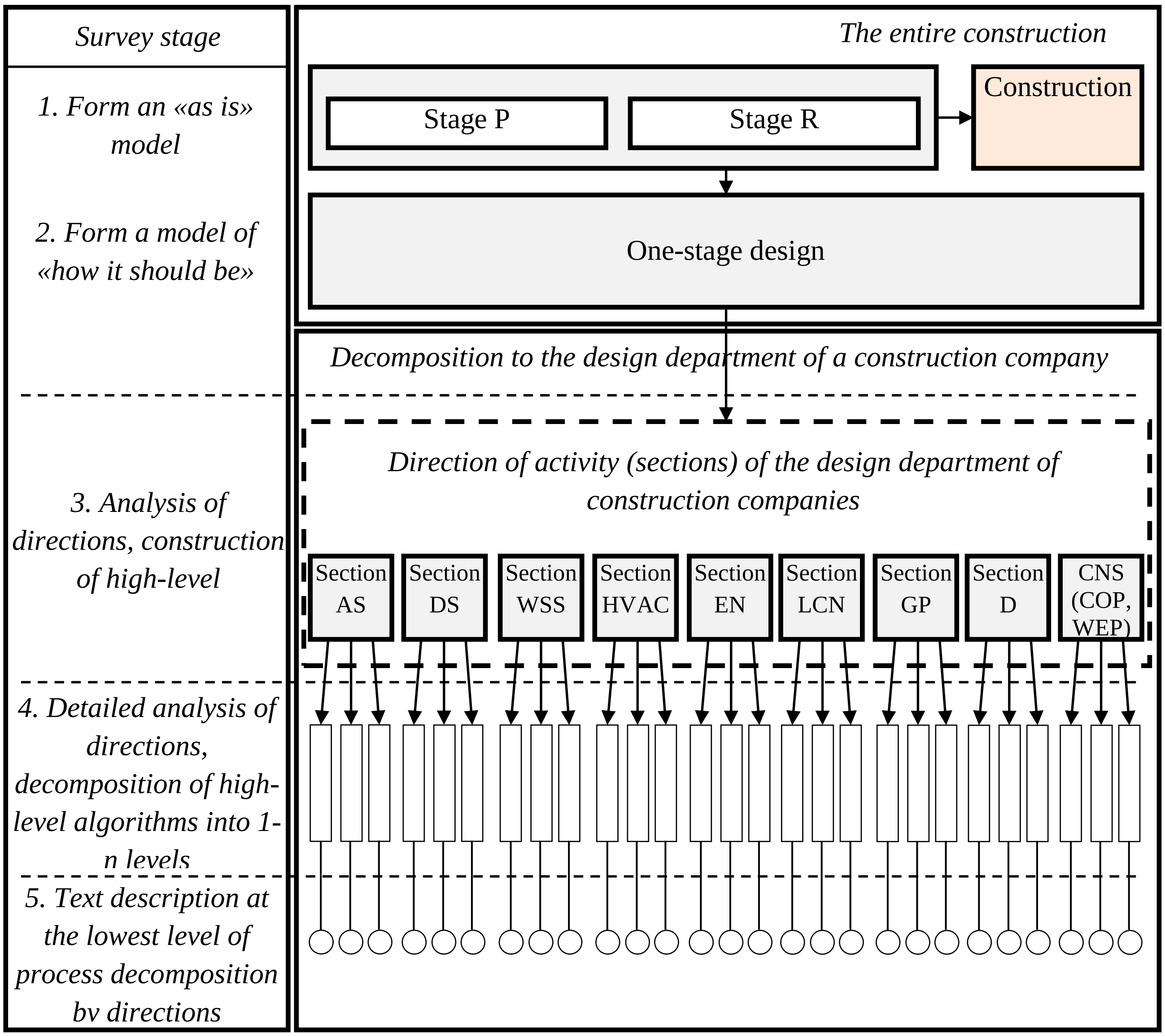


Figure 2.9 – Step-by-step diagram of the survey of the design division (department) of a construction company

For further automation of business processes of design departments of a construction company, it is possible to propose:

1) Restructure the work of the company's design department. Implement BIM in the design areas (AS, DS, WSS, HVAC, EN, LCN, GP, D, CNS (COP, WEP)) taking into account the specifics of the software.

2) Transfer the survey results to development for the purpose of debugging work on design sections within the design department.

3) Writing plugins, add-ons, programs or unified software for design automation in a construction company. Implementation of artificial intelligence.

4) Transition to the international standard for designing construction projects – IFC, which will help to level out existing software on the market and quickly adapt the work of the design department in accordance with the market situation.

«The considered option for improving business processes within the design department of a construction company is quite relevant, since labor costs are reduced, the cost of business processes is reduced, and quality is increased due to a comprehensive transition to BIM modeling from two-stage to one-stage. The solutions considered are applicable in construction companies of the designated type. Proposals for the automation of business processes in construction companies will have a positive effect when focusing on them in aggregate.

Next, it will consider the level from the perspective of the formation of a management system for the construction complex in municipalities and regions of Russia in the context of the digitalization of the economy.

Interaction with construction organizations at the municipal and regional level in the digital environment plays an important role in ensuring the development of urban space. It is in the digital environment that it is possible to exercise control over the implementation of large-scale infrastructure projects, optimizing and balancing the urban environment [170, 173]. «For this interaction, it is necessary to form and implement an information system for managing urban development and municipal space, which should be synchronized with the projects of objects under construction, creating a digital analogue of the municipality/region. The information system will be able to systematize data on construction projects, including energy consumption and resources, as well as within the framework of forming project budgets. The process of operation of this system should be organized from the stage of holding tenders for the development of a capital construction project with the sending of requests to construction organizations and enterprises. Next, it is necessary to validate projects at the municipal level with further support for the optimal ones within the framework of urban environment development. This system will be able to generate requests for the development of projects in accordance with the developed urban development plan, as well as conduct tenders remotely with the granting of the right to construction to a particular construction organization based on the projects received in digital format. The key condition for construction organizations should be the provision of information on the planned facility in digital form, including with the application of a digital federal model of the building (see Figure 2.10).

To move towards digitalization of investment and construction projects at the municipal level, it is necessary:

1) Develop and implement a unified urban information system aimed at monitoring and developing capital construction projects that shape the urban space.

2) Develop federal standards that will ensure encryption of elements of BIM models of capital construction projects.

3) To form a unified pricing system that will correlate with the new BIM design technology with an annually updated database. It is possible to introduce adjustments to prices according to the «fair price» rule, depending on territorial characteristics and the current economic situation.

«It is worth noting that at present the main drawback in the implementation of this algorithm is the lack of state and municipal standards for BIM. It is also recommended to form a new price base, updated annually, with correction factors in accordance with the level of socio-economic development of the region.

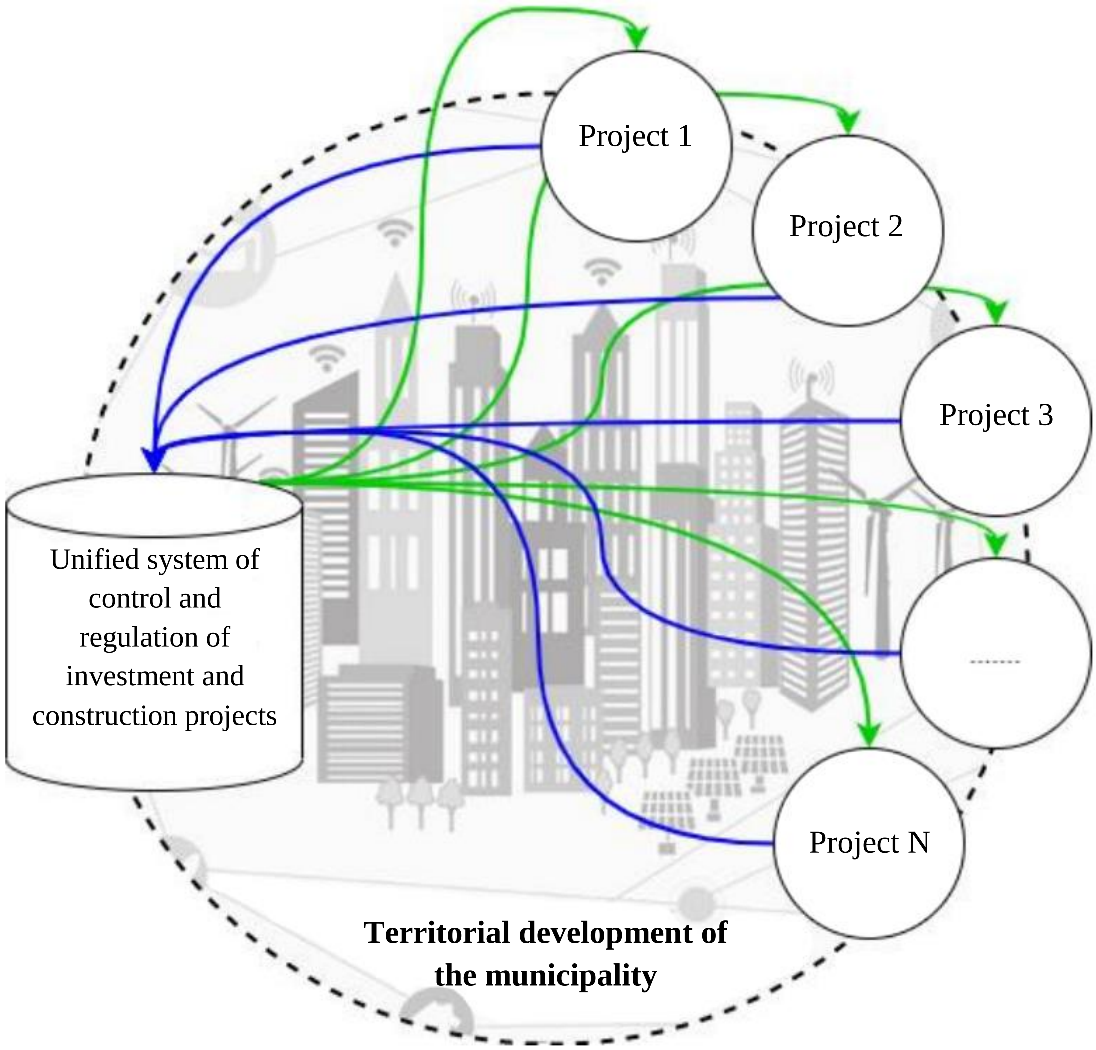


Figure 2.10 – General structure of regulation of investment and construction projects

A more detailed model of integration of digital transformation of an investment and construction project with the municipal and federal levels is presented in figure 2.11. When forming a model for integrating the digital transformation of an investment and construction project with the municipal and federal levels, an interpretative approach was used [96], which allowed, based on approaches to the implementation of construction complex management [83, 101, 109], as well as the possibilities for the development of BIM technologies [103, 133, 134, 148], the formation of a logically consistent model.

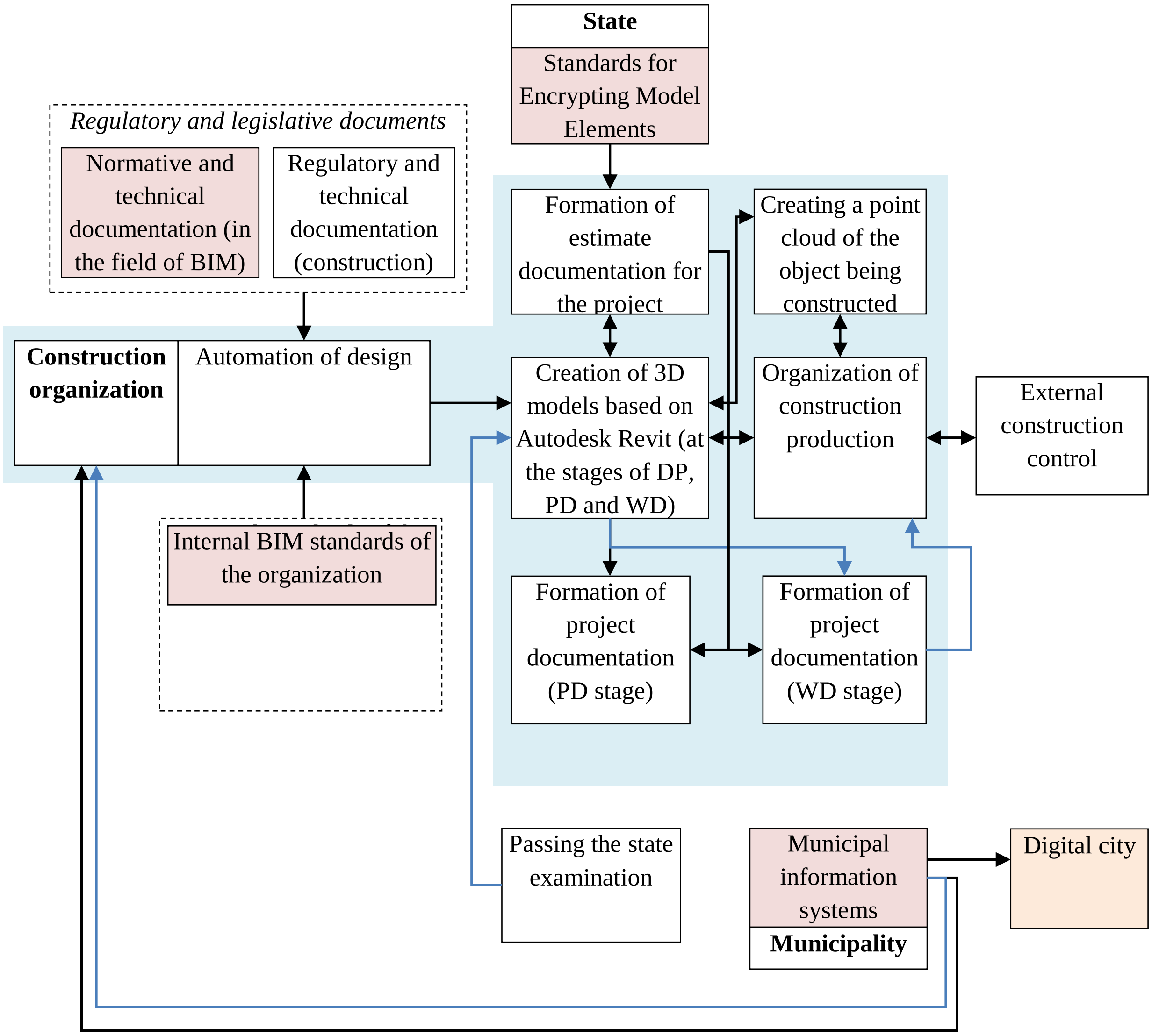


Figure 2.11 – Model for integrating digital transformation of an investment and construction project with the municipal and federal levels

«This model reflects the step-by-step process of implementing the project development, the formation of project documentation at the PD and WD stage, and passing the examination. The characteristic links reflect the steps, i.e. the sequence that is necessary when implementing this algorithm. It should be noted that the red blocks require development and implementation, the main blocks characterizing the activities of the construction organization are placed on a blue background, the black arrows indicate the first circle, the blue ones indicate the second, after the approval of the design documentation, passing the examination, issuing a construction permit and receiving the appropriate financing from the municipality» [156].

According to Figure 2.11, the «Municipality Information System” issues a construction request to construction organizations, which, after processing the request, begin the automated design process. As part of the automated design process, a 3D model or “digital twin” of the future object is created, which is proposed to be done based on Revit software, since this software allows for maximum coverage of design processes by creating a single model of the future object (BIM 360) using cloud services» [156]. Based on the created digital twin of the construction object, it is possible to ensure the formation of estimate documentation for the project, which will only be possible with the correct coding of the model elements. «It is also possible to automatically upload the required documentation of the PD and WD stages. Consequently, the state examination process is significantly accelerated and the model together with the documentation is returned to the «Municipality Information System», the received projects are assessed and some projects are supported by investments. The generated model can be used later on at the construction site when organizing construction production, and by reading the erected building elements using a point cloud, it will be possible to control the quality of construction. By organizing such an approach, a visual and transparent system of external control over construction is formed, and the modeled objects, with financial support, can become the basis for the formation of a digital city» [156].

When implementing an information system for managing urban development, including the construction complex, the following key problems can be identified:

1) lack of developed standards for regulating digital modeling of buildings;

2) low level of employees’ proficiency in software packages that form BIM at the micro level;

3) need for continuous professional development of employees;

4) poor integration of some software products with each other, etc.

The problems are mainly related to BIM standards and the organization of activities within construction companies and organizations; therefore, in order to organize an information system for managing urban development, it is necessary to ensure a comprehensive approach focused primarily on the micro level of this chain.

At this stage, the proposed system approach can be used as a basic structure for managing the information space of construction complexes at the municipal and regional levels. Moreover, using the proposed approach, it is possible to organize the activities of a large number of stakeholders in accordance with the strategy of scientific and technological development» [157].

In terms of technological development, it is possible to organize such a regional information system in territories with a high and medium level of readiness at the present time. Based on the results of this study, it will be possible to form the structure of an information system for managing urban development and municipal space, which will be linked to the strategy for developing the economic activity of the subjects of the region’s digital potential.

Conclusions to chapter 2

1. Tools and methodological solutions have been developed for the practical formation of an economic and digital model of the development of a construction enterprise.

2. An author's methodology for assessing the level of digital readiness and economic adaptability has been developed, which is based on a combination of quantitative and qualitative indicators and allows for a comprehensive assessment of the enterprise's ability to implement digital technologies in a transformational environment. The methodology includes a differentiated system of indicators that covers the level of digital infrastructure, flexibility of management processes, human resources potential and investment openness to digital solutions.

3. An approach to assessing the effectiveness of the transformation of functional processes has been developed, based on a system of economic and digital indicators.

4. The key processes of a construction enterprise that are most affected by digitalization have been structured, in particular, procurement logistics, production planning, monitoring of work performance, cost management). The indicators of the transformation effectiveness assessment are determined, in particular productivity, energy efficiency, digital integration, which allows to track the dynamics of changes in the functional blocks of the enterprise.

5. A structural-functional model of economic and digital development is proposed, which takes into account the features of the organizational structure of the construction enterprise, the specifics of digital processes and the requirements for adaptive management. The model is presented as an integrated system of interconnected components: digital analysis, strategic planning, resource management, risk management and feedback monitoring. Its architecture provides for flexibility of

adaptation to changes in the market environment, as well as open connection to industry information platforms, which made it possible to set clear parameters of the model for its further testing and analytical support at subsequent stages of the study.

6. A methodology for creating a single digital space that ensures information exchange and interaction both within the enterprise and with external stakeholders has been developed and proposed. The architecture of a digital enterprise based on the Smart Factory concept is described, including the enterprise's production facilities with integrated automation and production process management systems, a digital twin of the enterprise, and an integrated digital production platform. A structural-functional model of economic and digital development has been developed based on an integrated digital platform of Smart components: Product Lifecycle Management (PLM), enterprise resource planning (ERP), business intelligence (BI), customer relationship management (CRM), and Quality Management System (QMS). The mechanisms of the impact of the implementation of these stages on the efficiency of enterprise operations have been determined.

CHAPTER 3. PRACTICAL GUIDELINES FOR EMBEDDING AN ECONOMIC AND DIGITAL MODEL INTO THE DEVELOPMENT ARCHITECTURE OF CONSTRUCTION ENTERPRISES

3.1. Systemic integration of the economic and digital model into the decision-making architecture for the development of construction enterprises

Using the example of LLC " Alfa service" to manage operational activities based on the proposed methodological approach using the procedure developed within the framework of Section 2 of this work, the following process roles of business process management groups should be created, which are presented in Fig. 3.1.

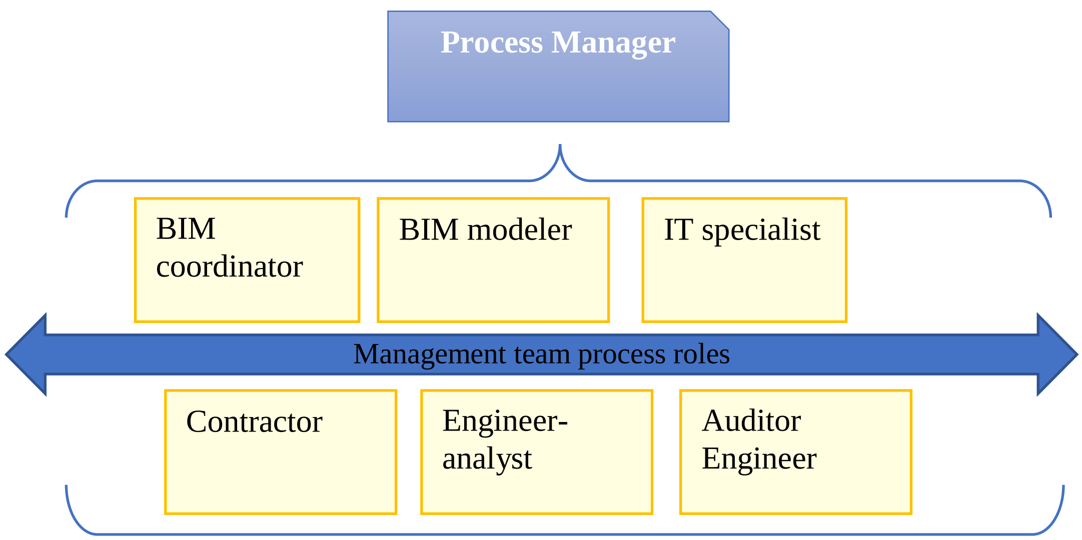


Figure 3.1 – Role structure of the management group of LLC " Alfa service"

Table 3.1 systematizes the description of the above-mentioned roles and their functional responsibilities in relation to the stages of the production subsystem management procedure using building information modeling technology (BIM technology).

Table 3.1 – Distribution of powers and responsibilities in managing the activities of LLC "Institute of Local Development"

Stages of the management procedure	Process role	Responsibility and functional authority within the framework of business process management
Step 1	Process Manager	▪ Monitors the execution of the step. ▪ Resolves any problems that arise.
	BIM coordinator	▪ Conducts an audit of the information model provided by the designer ▪ Controls the implementation of software settings for further enrichment of the model.
Step 2	Process Manager	▪ Controls the execution of the step. ▪ Approves technical solutions. ▪ Resolves emerging problems.
	Analyst Engineer	▪ Works with the organization's databases. ▪ Works with the original information model of the construction object. ▪ Provides collection of unstructured data and its processing. ▪ Prepares proposals (and corresponding justifications) for construction production technologies.
Step 3	Process Manager (Chief Engineer)	▪ Controls the execution of the step. ▪ Approves technical solutions. ▪ Resolves emerging problems.
	Analyst Engineer	▪ Provides preparation of engineering information from the construction site in a structured form for further development of the PPR in the information environment and transfers it to BIM specialists.
	BIM Coordinator	▪ Audits the results of data enrichment of the information model. ▪ Performs the most complex parts of the work in the area of interactive PPR modeling.
	BIM Modeler	▪ Enriches the information model with data from interactive PPR according to the data provided by the analyst engineer.
Step 4	Process Manager	▪ Monitors the execution of the step. ▪ Approves the basic work schedule. ▪ Resolves any problems that arise.
	Analyst Engineer	▪ Under the guidance of the chief engineer, conducts research on the operation of the "network" of the construction of an enriched information model under various conditions. ▪ Prepares a basic version of the work schedule, including justification for the choice of the proposed option.
Step 5	Contractor (by qualifications)	▪ Provides production of construction and installation works at the DB facility. ▪ Performs continuous local optimization of entrusted

		processes (works) when implementing environmental uncertainty factors.
Step 6, 7	Process Manager	▪ Monitors the execution of the step. ▪ Reports to the project manager about changes in work plans at the facility. ▪ Resolves problems that arise.
	Analyst Engineer	▪ Provides a plan - a fact of analysis of the performance of work and formulates proposals for making changes to previously adopted technologies for performing work. ▪ Evaluates the effectiveness of the work performed and proposes measures to optimize the entire construction "network". ▪ Performs analytical studies on the stability of previously established forecasts, makes adjustments if necessary. ▪ Updates construction plans.
	Auditor Engineer	▪ Provides visual control and registration of data on the physical state of the progress of work on the construction site. ▪ Provides recording of the fact in the information model of the site.
	IT Specialist	▪ Participates in all business processes within steps 1-4, 6, providing technical support for the application of information modeling software tools

In the professional space of the construction industry, an urgent demand has been formed and there is an urgent need for a unified systematic approach to industry-specific digital modeling technologies and the development of relevant state standards. The development of technical and regulatory documentation in the field of information modeling of capital construction objects is still carried out unsystematically and in a fragmented manner. A single concept of data standardization has not yet been formed. There are still no single directions and stages for solving practical tasks of informatization of the construction industry. There are no specialized integrated solutions. Further digital transformation of a construction company requires solving problematic tasks (Fig. 3.2).

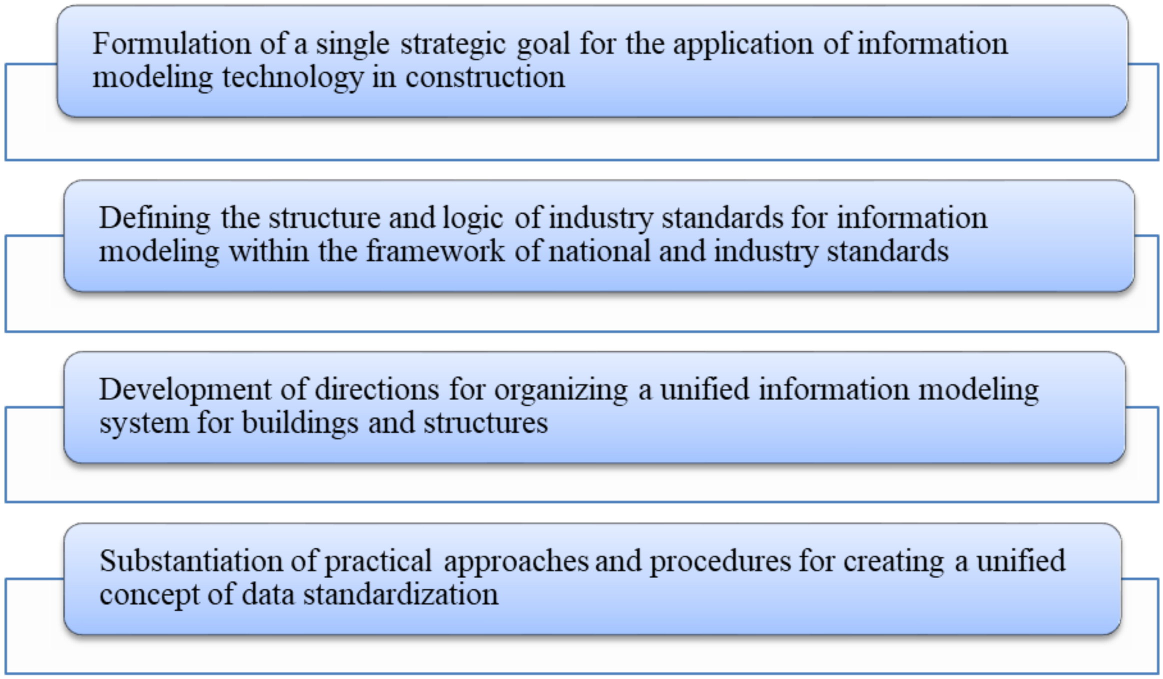


Fig. 3.2 – Unresolved tasks of digital transformation of the construction company management system

Consolidation of accumulated practical experience and professional competencies allows the author to propose a system-technical scheme for the digital transformation of a construction enterprise in terms of entity aggregation (figure 3.3), which will make it possible to determine the feasibility (or infeasibility) of applying BIM technology in the operational activities of a construction organization. The presented logical-semantic scheme in the paradigm of cybernetics of problem-oriented modeling abstractly highlights the main subject-object and object-subject horizontal connections of the constituent elements, each pair of which is determined by the correspondence of its own level of digital transformation.

In the system-technical scheme of digital modeling, seven levels are distinguished, which correspond to six levels of aggregation of entities in terms of subject-object (object-subject) relationships: "plan-goal", "object-project", "process-time", "technology-economy", "system-resource", "complex-convergence".

At the first (I) level of digital transformation, subject-object relationships are formalized in a simple format that establishes a direct correspondence between a set of plans and a set of goals. The inverse object-subject relationship assumes the influence of goals on plans for their implementation, and the conditionally symmetric subject-object relationship changes the priority scheme to the opposite one - a set of goals is associated with a set of plans. For the conceptual general logic of the scheme, the presented system technology of digital modeling establishes a conditionally direct correspondence of the levels of digital modeling to the levels of BIM detail. Therefore, the first level of digital modeling corresponds to the first level of BIM 1D.

At the second (II) and third (III) levels, the design process formalizes two-dimensional and three-dimensional models of the design object, respectively. The inverse object-subject relationship assumes the influence of a set of design conditions and constraints on the object itself, and the traditionally symmetric subject-object relationship changes the correspondence priority scheme to the opposite when the object is created based on a design priority established for any reason (for example, using a typical project).

It should be noted that the essence of the "object-project" relationship of the second (II) and third (III) levels of digital modeling is not limited to two- and three-dimensional visualization of the object, but is the basis for automating the development of project options for planning solutions and project parameterization. The second (II) and third (III) levels of digital modeling are determined by the second (2D) and third (3D) levels of BIM detailing, respectively.

At the fourth (IV) level, the process that defines a certain work is formalized with the necessary deadline for its execution. Reverse object-subject communication assumes the influence of time constraints on the processes under consideration, and conditionally symmetric subject-object communication changes the priority scheme of compliance to the opposite, when the set of processes is formed based on conditions and time constraints (for example, fixed deadlines for commissioning critical for the infrastructure object). The essence of the "process" in the scheme is reduced to their exhaustive formulation of a specific set of tasks (production, organizational, management processes, etc.). The fourth (IV) level of digital modeling corresponds to the fourth (4D) level of BIM dimension.

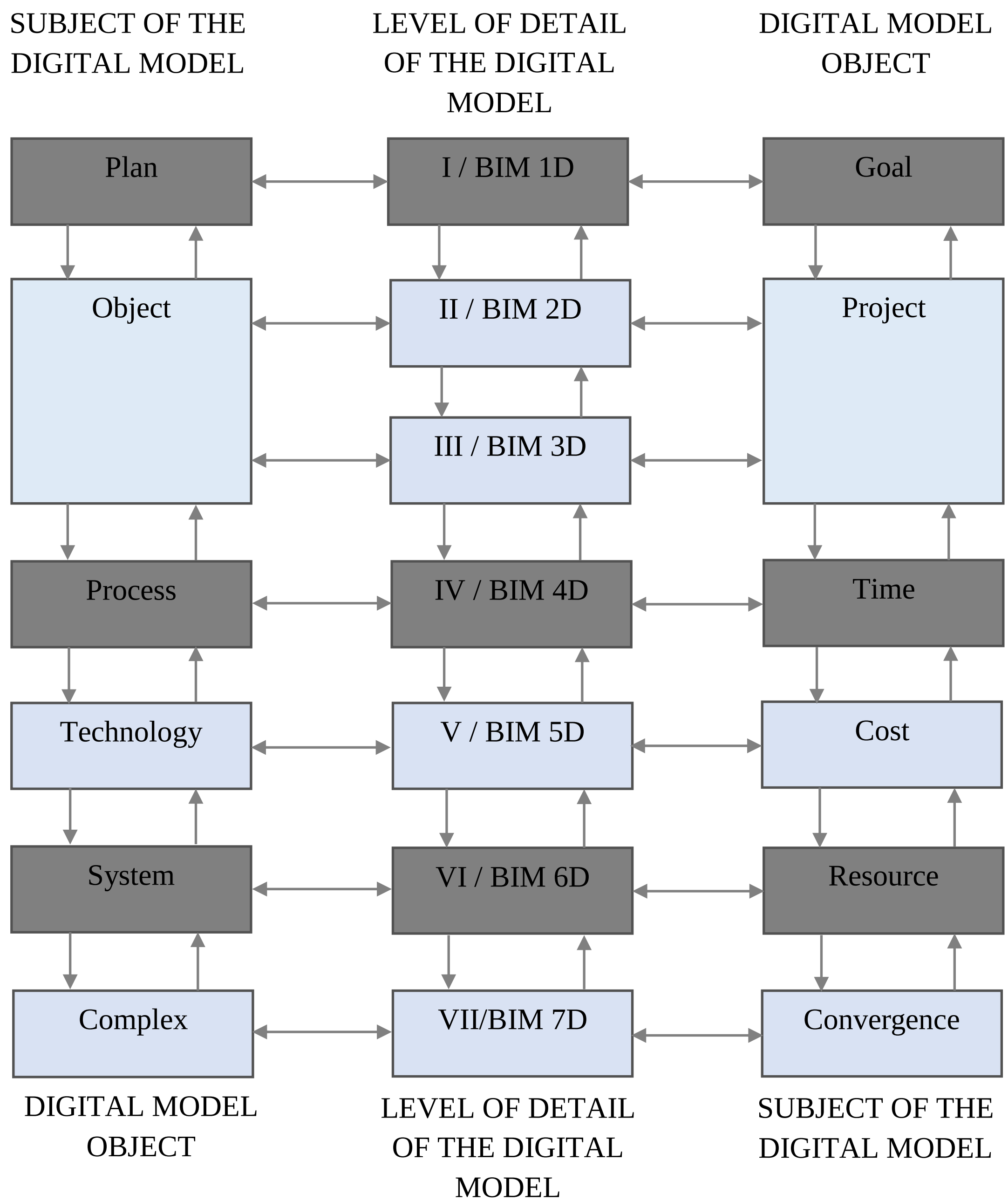


Figure 3.3 – System-technical diagram of the digital transformation of a construction company in terms of entity aggregation

At the fifth (V) level, technologies are formalized by assessing the cost of their application. Reverse object-subject communication assumes a direct influence of economic conditions and constraints on the technologies used, and conditionally symmetric subject-object communication changes the priority scheme of compliance to the opposite, when technological schemes are formed based on financial conditions and constraints (for example, the availability of technological equipment or financial resources). The fifth (V) level of digital modeling is defined as the fifth (5D) level of BIM dimension.

At the sixth (VI) level, objects, processes, and technologies are considered as constituent components of the construction system, which are formalized by aggregating all types of resource provision presented at the previous levels of digital modeling of the economy and time. The inverse object-subject relationship assumes the influence of resource conditions and constraints on the systems under consideration, and the conditionally symmetric subject-object relationship changes the correspondence priority scheme to the opposite, when the construction system itself is formed based on conditions and resource constraints (for example, construction in conditions of undersupply of building materials or lack of qualified personnel). The essence of the "system" in the diagram corresponds to the definition of a "building system" as a finite set of functional components (elements, objects, processes) and the relationships between them, distributed according to a specific purpose during a certain time interval. The essence of "resources" is reduced to their exhaustive formulation for a specific set of tasks (material, technical, labor, organizational, etc.). The sixth (VI) level of digital modeling corresponds to the sixth (6D) level of the BIM dimension.

At the seventh (VII) level, building systems are combined into complexes that additionally include qualitatively different systems (for example, urban and biosphere) and represent a new class of digital modeling object from the point of view of convergence. The reverse object-subject relationship assumes the influence of qualitatively different systems in relation to the building on the complexes in which they are considered, and the conditionally symmetric subject-object relationship changes the scheme of priority of correspondence to the opposite, when qualitatively different systems in relation to the building significantly affect the complexes of building systems, regardless of their location in relation to the complex under consideration (for example, the influence of the geopolitical situation on the course of construction projects dependent on it). The seventh (VII) level of digital modeling is defined by the extended seventh (7D) level of BIM detail, which provides for further abstraction of any subsequent level of digital modeling of the qualitative convergence of system components of different properties.

The described approach to building subject-object and object-subject direct and feedback relationships at the model level makes it possible to correctly understand the essence and reconsider the emphasis in many quite practical areas of innovative development and regulation of the construction industry. In fact, it is necessary to rethink the usual stages of implementing a construction project. In particular, the "design" stage, which usually ends with the receipt of project documentation, will culminate in the creation of a digital twin of the future real estate object, which has been checked for collisions and other inconsistencies, supported by an appropriate library of digital elements necessary for the implementation of the project, containing complete information about all types of building materials, structures and engineering equipment. This prototype of the construction project is a digital information model BIM. At the same time, a digital model of a construction object can include all the comprehensive information necessary not only for construction, but also for operation, modernization and reconstruction (liquidation) of the object.

The emergence of new and transformation of old responsibilities are inevitable when a construction company transitions to BIM management. Figure 3.4 presents a model of organizational transformations in the project management system when BIM technologies are implemented in construction projects. Recommendations for project managers on monitoring project implementation are developed using BIM logic in connection with the active development of the use of information technologies and information about the object throughout its life cycle through the use of BIM models.

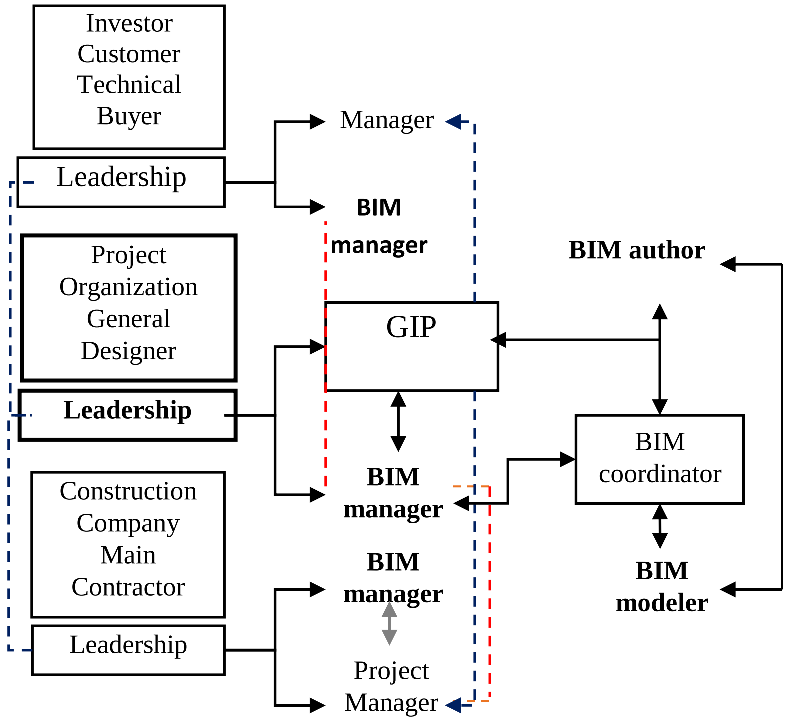


Fig. 3.4 – Model of organizational transformations in the management system when implementing BIM technologies in a construction company

Figure 3.5 shows the BIM model of the project management team. Before the project begins, the project team defines an overall model development strategy, after which the BIM manager prepares a project file for collaboration based on the created template. It is the BIM manager who "launches" the project for execution. Then other participants connect to it, creating their local copies, linked by synchronization in the Unified Information System.

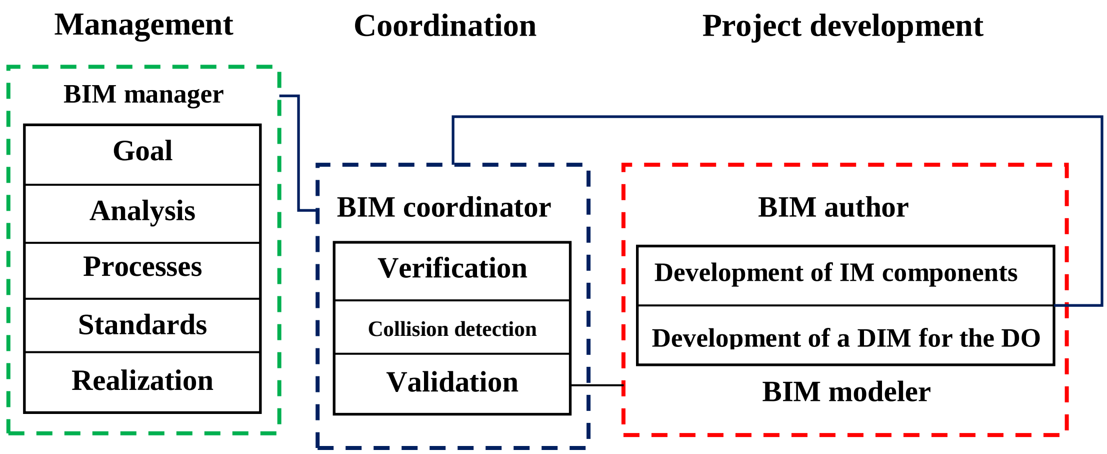


Figure 3.5 – BIM model of the construction company management team

BIM modeler. This specialist creates component libraries and, as needed, reproduces data from 2D drawings into a 3D model. This specialist does not solve engineering problems, but is responsible for creating components that fill the information model. It should be noted that these functions can be performed by both the BIM author and the BIM coordinator in parallel with the main responsibilities.

BIM author. This specialist develops the project, maintains the model, provides technical coordination, performs engineering functions of the designer using BIM software, and supports the BIM concept. The BIM author's qualifications in working with software must correspond to his engineering competence and the complexity of the design work assigned to him. The minimum qualification threshold for a BIM author is basic knowledge of the software in which he will work, understanding of the principles of collaboration in the EUS, and knowledge of the BIM standard.

BIM coordinator. This specialist develops a BIM verification and validation plan for the project, conducts regular audits of the information model and checks it for conflicts. This is the person responsible for the information modeling process in a BIM project. The BIM coordinator does not make or approve design decisions.

BIM manager. This specialist is involved in developing a BIM process management strategy, internal regulations, training methods, BIM implementation plan, and information model audit. If the roles of BIM author and BIM coordinator are inherent only to project organizations, then the BIM manager must interact with the services of the technical customer and the general construction contractor. The responsibilities of a BIM manager in a project organization differ from the responsibilities of a BIM manager in a customer support service and a BIM manager in a construction company.

3.2. Alignment of strategic and tactical development parameters of the enterprise in the new digital environment

The transition of a construction company to management in a single digital space is not limited to changing organizational relationships between direct participants in the interaction, but requires a radical change in the entire management structure of the company.

The transformation of the management structure can occur in several directions:

1) First, the organization can focus on standardizing and formalizing production tasks, introducing standards for their implementation. However, standardization does not guarantee that tasks are performed correctly and on time, so the organization “strengthens” horizontal connections between performers, introduces the roles of the owner or coordinator of the process. This form is called a functional management structure with a horizontal superstructure, as shown in Figure 3.6. Note that the process owner cannot directly contact the performer, he must do so through the appropriate functional manager, which significantly complicates management and increases overhead costs.

2) Secondly, the owner does not manage resources, he can independently make a decision regarding the performer, but together with the functional manager. The role of the owner turns out to be degenerate, reduced to coordination, has no real levers of influence on the performer. Since appeals through the functional hierarchy are not

effective enough, the organization moves to a matrix organizational structure, as shown in Figure 3.7.

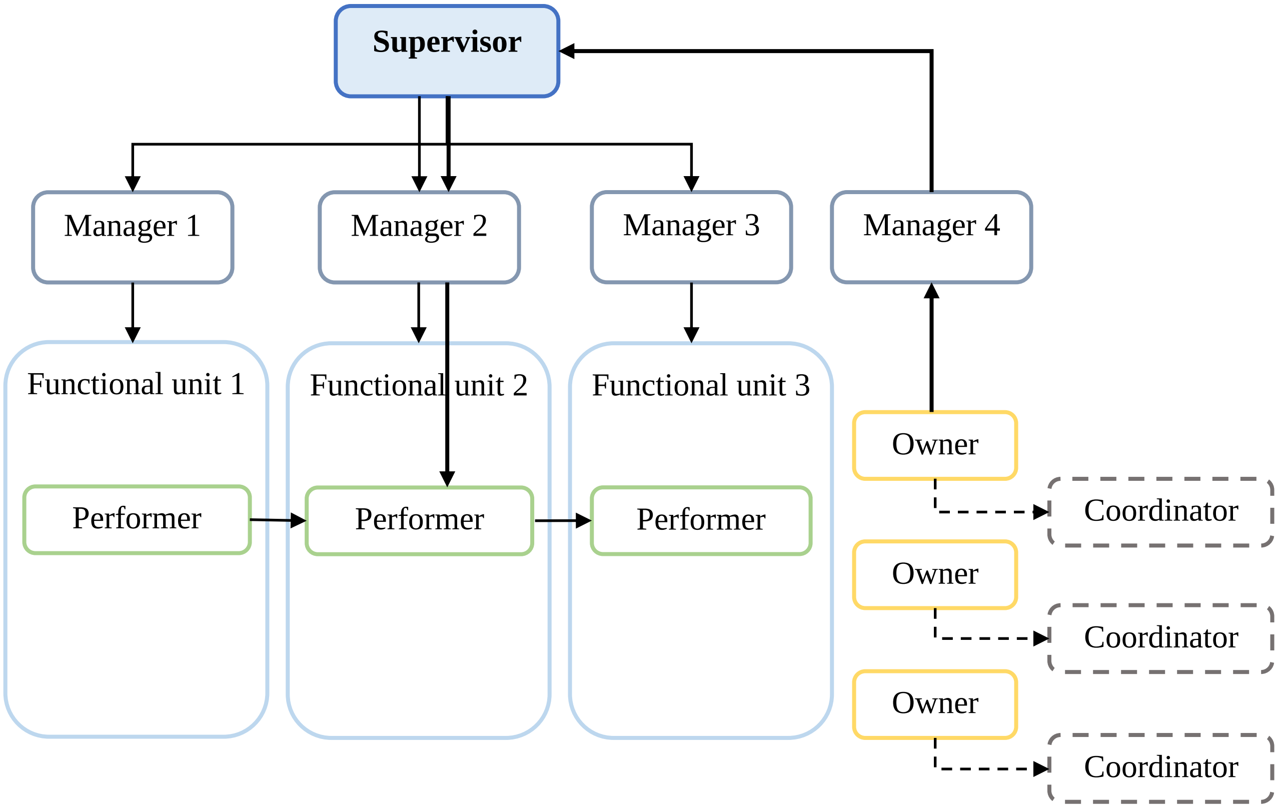


Figure 3.6 – Functional structure with horizontal superstructure.

In a matrix organizational structure, the performer finds himself in a double subordination, firstly, on all current issues of performing operational activities within the process, he reports directly to the process owner, and secondly, on other issues, he reports to his immediate supervisor. The process owner is empowered to encourage and punish the performer, therefore he has the levers of process management. It is important to maintain a balance between the two branches of power. It is customary to separate the relations of subordination and coordination, the former are depicted on the organizational chart by solid lines, and the latter by dotted lines. In a matrix structure, an employee is subordinate to a functional manager and coordinates work with the process owner, which causes the shortcomings of the matrix management system.

Processes are most often differentiated by the product being produced, so horizontal working groups are built on the product principle. At the same time, the organization can use the territorial principle of dividing its activities, in this case the matrix structure turns out to be three-dimensional, its creation and management are complicated. The disadvantage of such a structure is the complexity of the division of powers between the two branches of government and, as a result, possible conflicts.

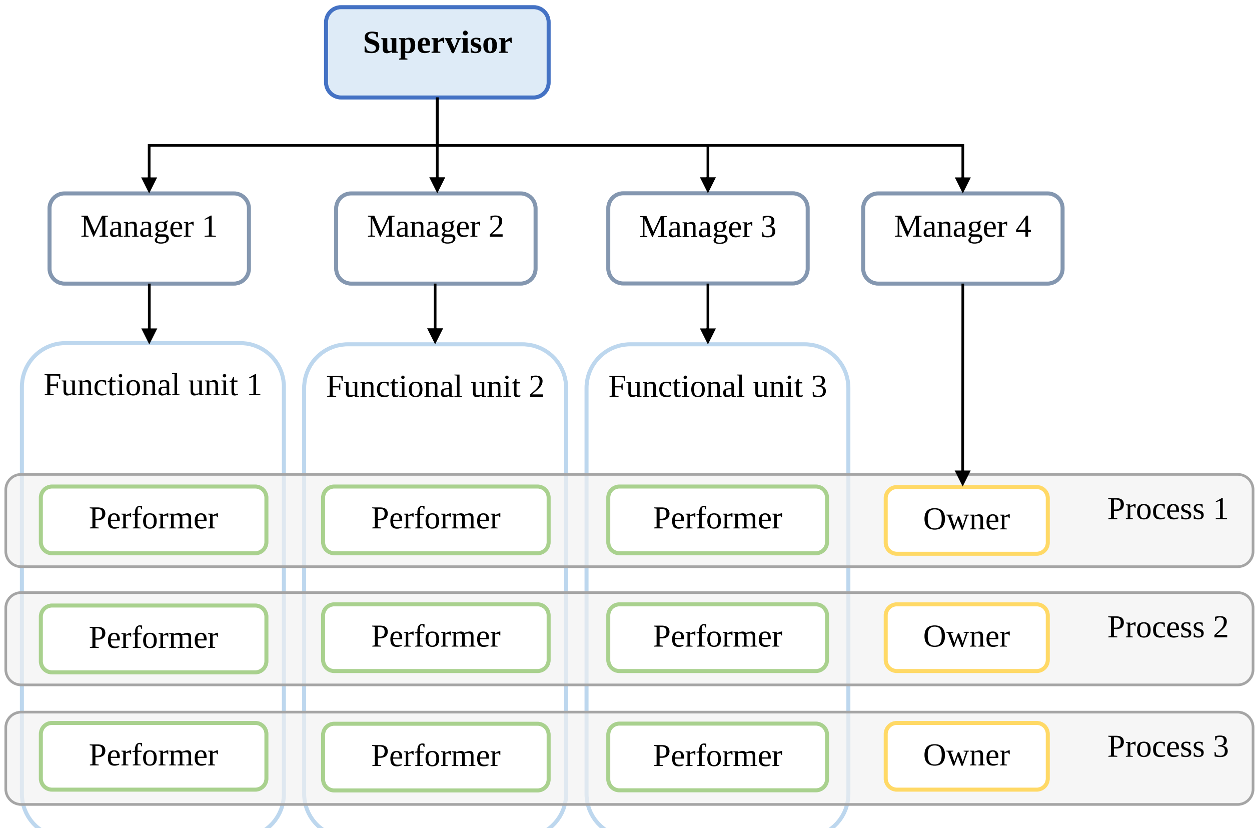


Figure 3.7 – Matrix organizational structure

To get rid of dual subordination, enterprises are moving to a process-based organizational structure, which is shown in Figure 3.8.

In a process organization, all activities are built around the company's business processes. First, the company's main processes are identified, each with a dedicated owner assigned to it, who has sufficient resources to manage all the performers. All performers are directly subordinate to him, which eliminates any ambiguity in the relationship. To unite individual processes into a single system, the company creates a process committee, which includes the owners of individual processes, they are responsible for coordinating the implementation of individual processes. Each process is associated with a competence center, its tasks are: continuous improvement of processes and formalization of methods of performing work.

For example, if an enterprise is faced with the need to solve a new task for the first time, it may be necessary to develop a new business process. The company may retain functional support units, but only to solve corporate-wide tasks, for example, for personnel management, payroll, and IT services, the latter being considered as services provided to operational units.

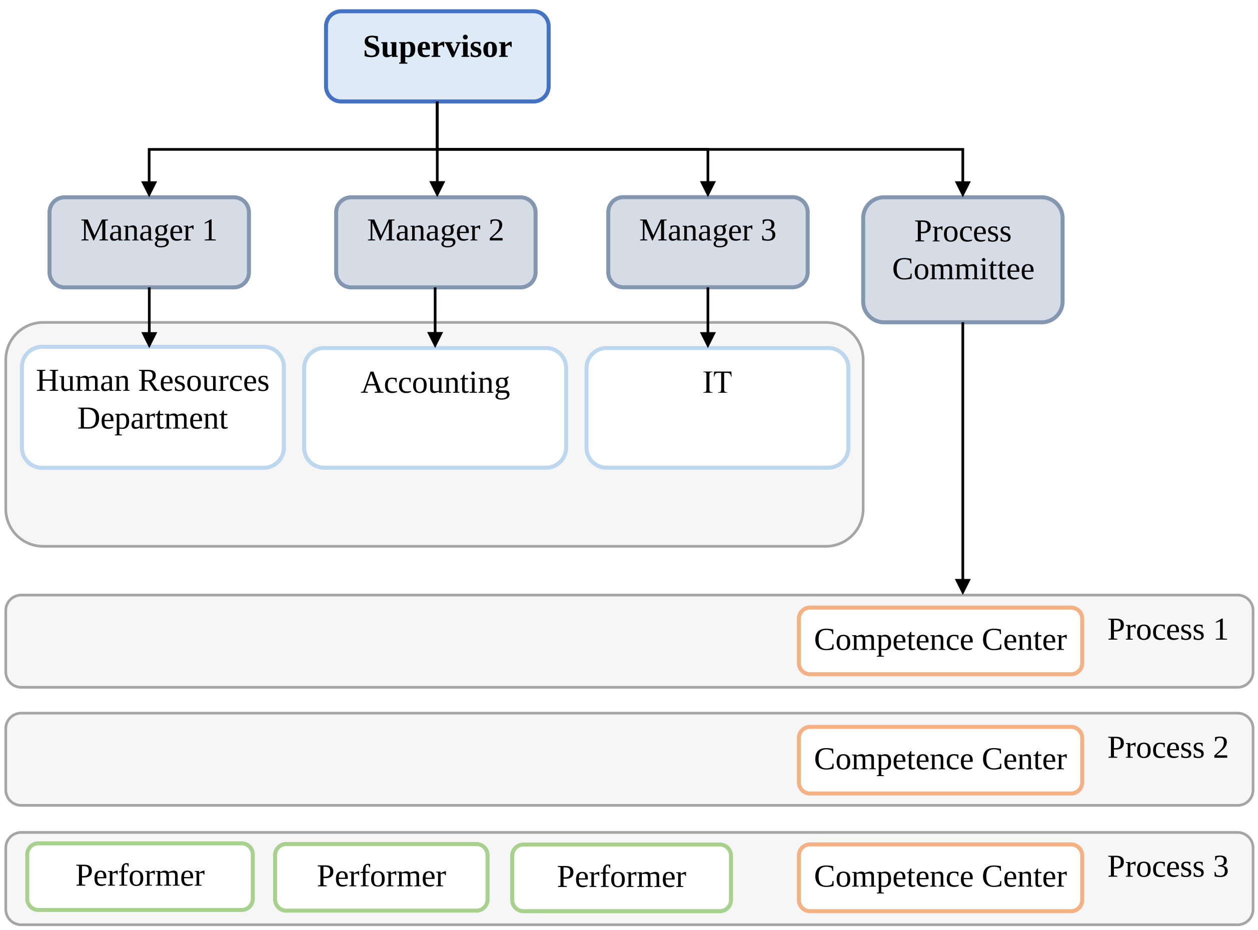


Figure 3.8 – Process organizational structure

Let us consider in more detail the process organization shown in Figure 3.9, all its activities are divided into areas, each of which has its own main production processes. To coordinate the main processes of the company, a process committee is needed, which unites the owners of all processes. Changes to processes and their interactions are carried out with the participation of the company's process architect. For each area of activity, a process competence center has been created, which, in addition to the owner, includes: a technologist responsible for the correct execution of the production process, an analyst responsible for process modeling, and process executors.

The disadvantage of a purely process-based organizational structure is the loss of connections between employees who perform a similar function in different structural divisions of the enterprise. Therefore, it is possible to envisage the roles of functional managers who coordinate the work of specialists with similar functions, but in different processes of the enterprise, in Figure 3.9 the connection is depicted by a dotted line. Such a structure is usually called a process organization with a functional superstructure.

Directions of transformation of the organizational structure of an enterprise during the transition to process management.

We conclude that the task of increasing labor productivity of non-industrial enterprises requires a holistic approach to the reorganization of the entire complex of organizational and economic relations of enterprises, including: transition to current methods of organizing production; structuring the enterprise's activities around business processes; restructuring the enterprise's management structure in accordance with the selected forms of labor organization; introduction of new "horizontal" information systems aimed at supporting new organizational and economic relations.

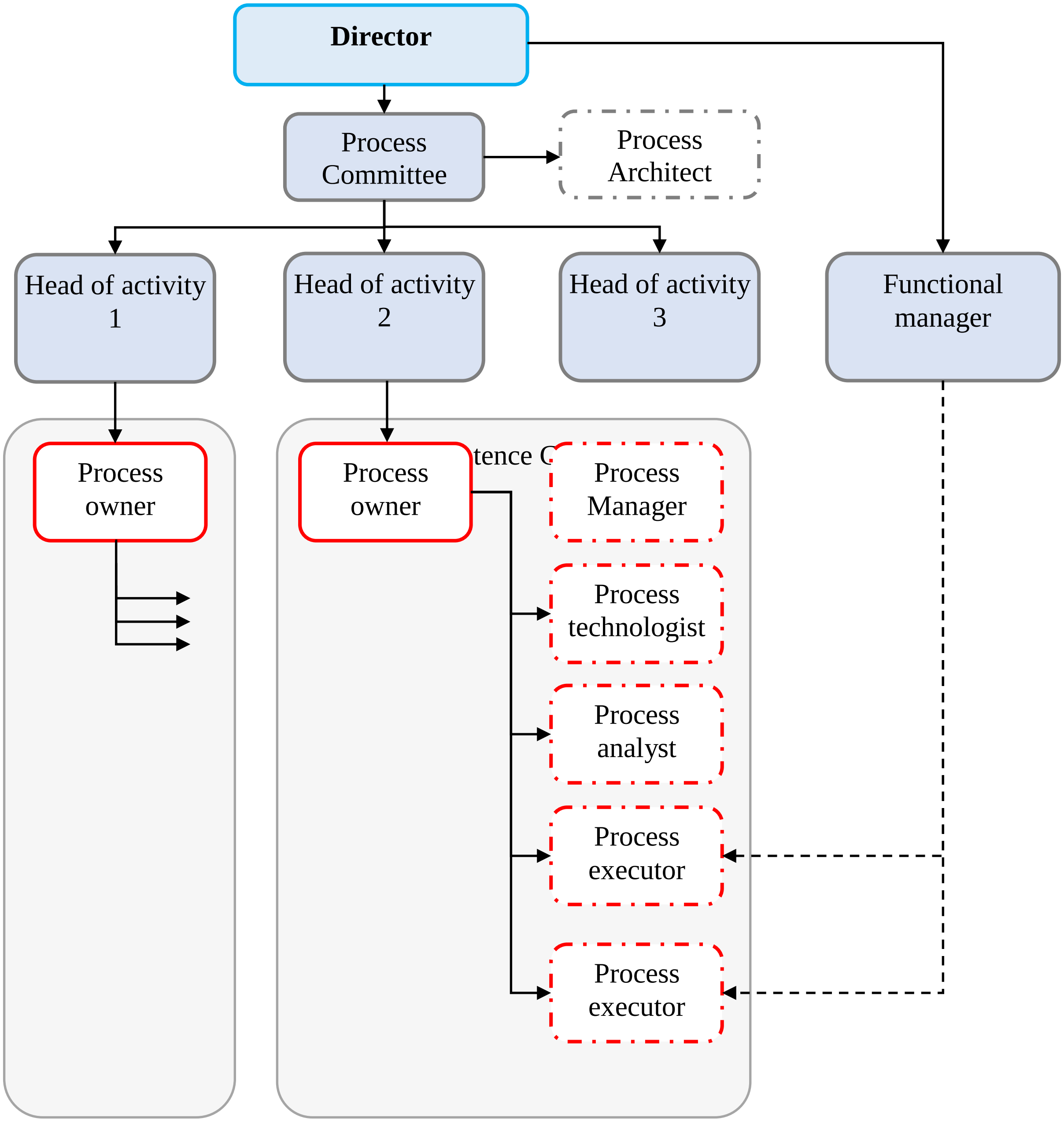


Figure 3.9 – Process organization

The analysis showed the need for a comprehensive change in organizational and economic relations at the enterprise, as a necessary condition for increasing productivity and labor efficiency. Reengineering, structuring and improvement of the business process system are necessary, but insufficient conditions for the transition to process management. In order to realize all the advantages of process management, a transition to flow production methods and a change in the structure of enterprise management are necessary. Within the functional structure, process management is difficult due to the conflict of interests of various structural units and the inability of the process owner to directly dispose of the necessary resources, which is perhaps the reason for the failure of business process reengineering projects. The organizational structure must be transformed in such a way that it objectively reflects the management relations that develop within the framework of a given production system.

We conclude that there is a need for new modern IT tools that connect employees at the same level of the hierarchy, which provide management with control over the progress of production tasks. To support process management at the enterprise, a new class of "horizontal" information systems has been proposed, the task of which is to automate the workflows of production tasks. Such systems perform transport and coordination functions: they transfer tasks between participants strictly in accordance with the developed regulations, notifying management of all violations, deviations and exceptional situations. Such systems should not automate existing inefficient information flows, but should be aimed at supporting new forms of production relations within the enterprise.

3.3. Analytical instruments for measuring the economic impact of digital technologies in construction business activities

Based on the results of the conducted research, a conclusion can be drawn about the need to form a single digital space for the construction industry, the groundwork for which is the development of leading domestic vendors in the development of TIM, the formation of a common data environment, and standardization in the presentation of this data regardless of the software. A single digital space will help coordinate actions and technical solutions, form consolidated models created in different tools, carry out any checks, maintain various documentation on digital models created on their basis, and supplement it with other data.

When creating a unified digital environment for the construction industry, it is necessary, firstly, to clarify the terminology of regulatory and technical documentation. In the development of regulatory frameworks for the digitalization of construction, as well as in its practical implementation, there is no consensus regarding the concepts and correlation of terms and definitions of the digital environment, digital platform, digital ecosystem.

Information space (information or digital environment), according to [27], is «a set of information resources created by subjects of the information sphere, means of interaction between such subjects, their information systems and the necessary information infrastructure». Information infrastructure is understood as a set of information systems, information technology objects, as well as communication networks and Internet sites [26].

In a narrow sense, a digital platform can be understood as a group of digital technologies used to create a digital interaction system [18]. The effects of the digital platform should be considered as savings in transaction costs, increased labor productivity, creation of favorable conditions for analytics, forecasting and multifunctional services.

The digital economy ecosystem is, first of all, a partnership of organizations that ensure continuous interaction of technological platforms, applied Internet services, and information systems [27].

With such an interpretation of the terms platform and ecosystem, we have implemented a fundamental scheme for digitalization of construction based on a single digital platform, providing the possibility of interaction in electronic form based on the CDE at all stages of the life cycle of the ICP (Figure 3.10)

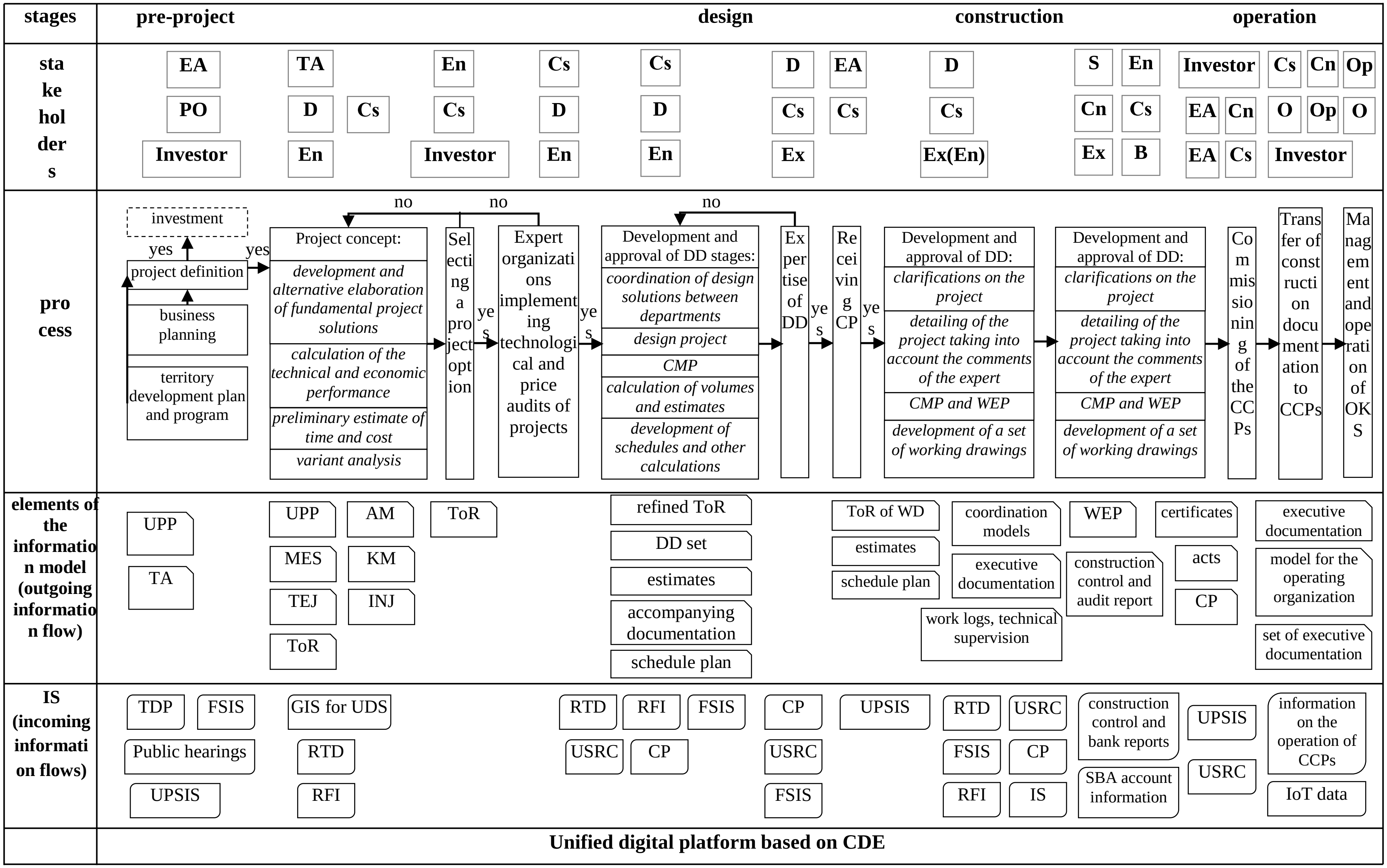


Figure 3.10 – Schematic diagram of digitalization of construction based on a common digital platform

where: Cs – customer, EA – executive authorities (regional, municipal), TPA – expert organizations implementing technological and price audit of projects, D – designer, Cn – contractor, Ex– state or non-state bodies of expertise of design and estimate documentation (DED), En– engineering, expert organizations, S – suppliers of building materials, structures, equipment, SB – state construction supervision bodies, construction control and audit organizations, B– bank, Op – operating organizations, O – owner (user) of the facility, PO – public organizations, public, PH – public hearings, INJ – investment justification, TA – technical assignment, DD – design documentation, WD – working documentation, EXOP– expert opinion, ES – expert support, CP – construction permit, CMA– commodity and material assets, ED – executive documentation, COC – conclusion on the compliance of the CCPs with the requirements of the DD, SBA – separate bank account, PC – permit for commissioning of the CCPs, CCPs – capital construction projects, UPP – urban planning passport, TA – technical assignment, TDP – territory development program, AM – architectural model, KM model of structures, MES – model of engineering systems, ToR – terms of reference, TEJ – techno-economic justification, WEP – work execution plan, CMP – construction management plan, FSIS – Federal State Information System, UPSIS – Urban Planning Support Information System, GIS for UDS – Geoinformation System for Urban Development Support, RTD – Regulatory and Technical Documentation, USRC – Unified State Register of Conclusions, CP – Construction Pricing.

The most important characteristic of the digital transformation of construction should be its omnichannel nature, that is, maximizing the integration and quality of interaction across all available channels.

Considering that the services provided by the digital platform may be of a paid nature, on the one hand, it is necessary to assume the possible multiplicity of digital platforms for different categories of manufacturers and consumers in construction. On the other hand, given the specifics of regulation and standardization in construction, it is advisable to create a single common digital construction platform (Fig. 3.11)

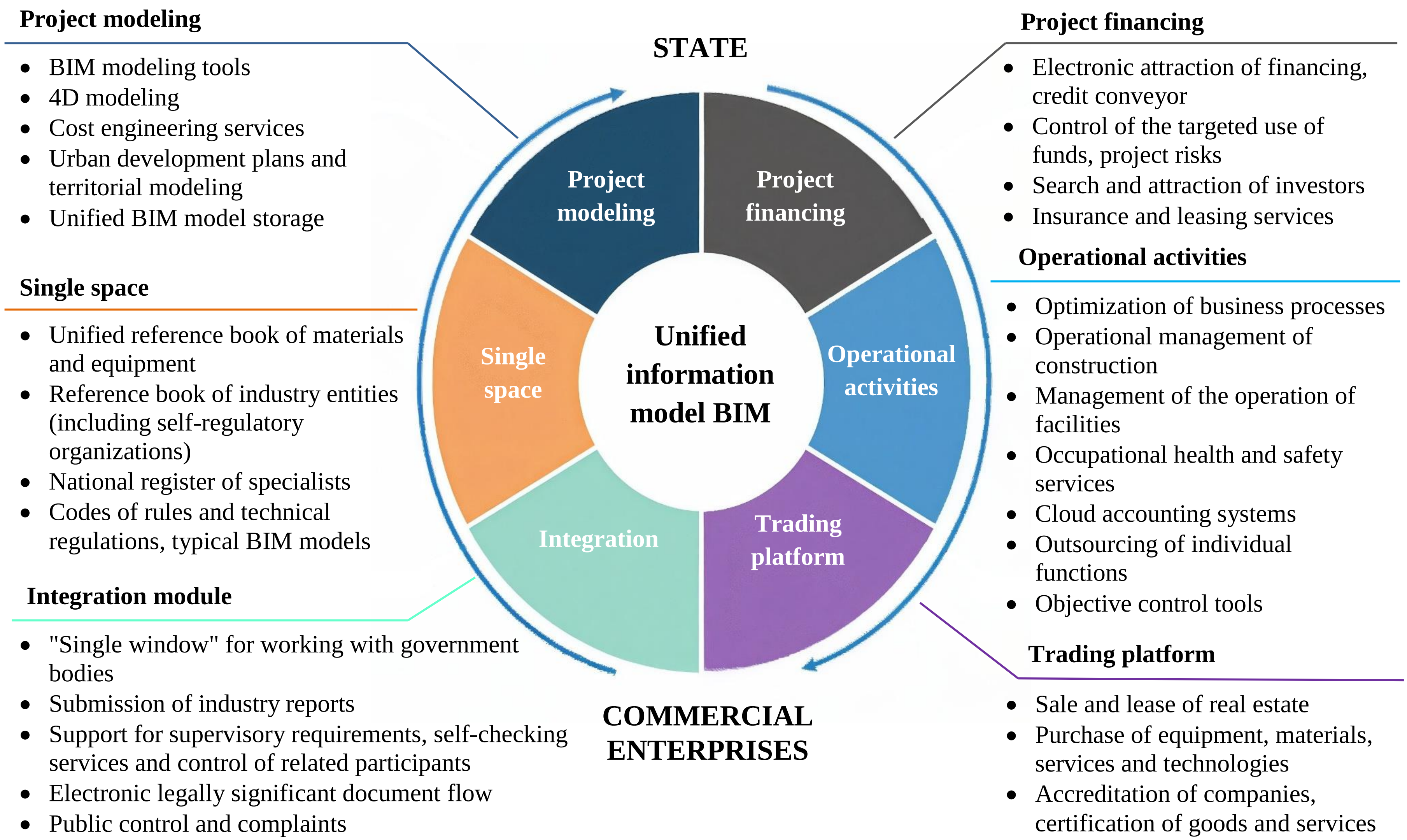


Figure 3.11 – Functional architecture of the digital construction platform

A number of models provide for the creation of ecosystems around a digital platform [1] to ensure active interaction between industry entities and the development of high-tech production (Figure 3.12).

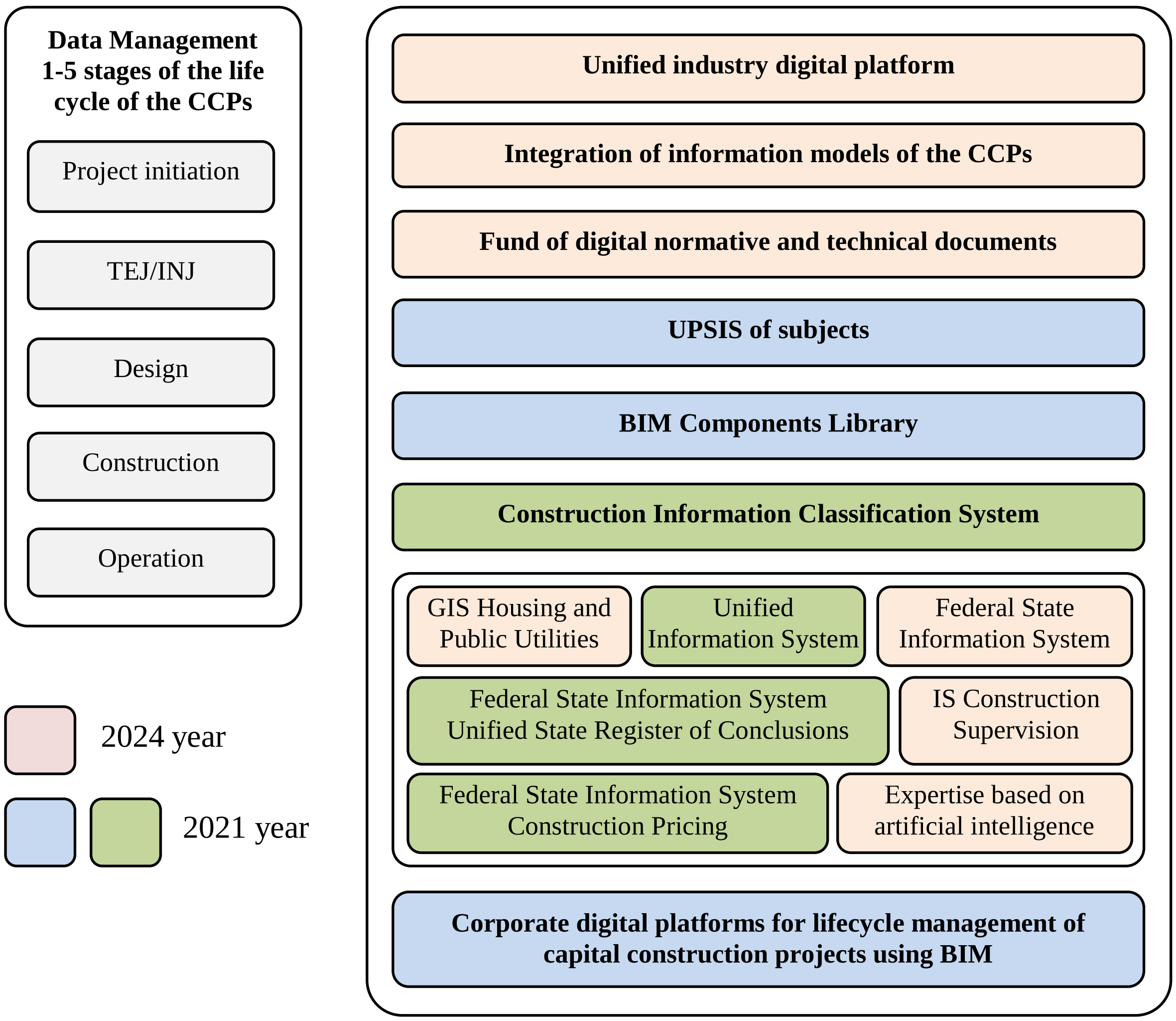


Figure 3.12 – Model of the digital ecosystem for lifecycle management of construction facilities

In a number of cases [7,10] the ecosystem is identified with the information environment integrating a number of information systems in construction (Figure 3.13), which, in our opinion, is incorrect.

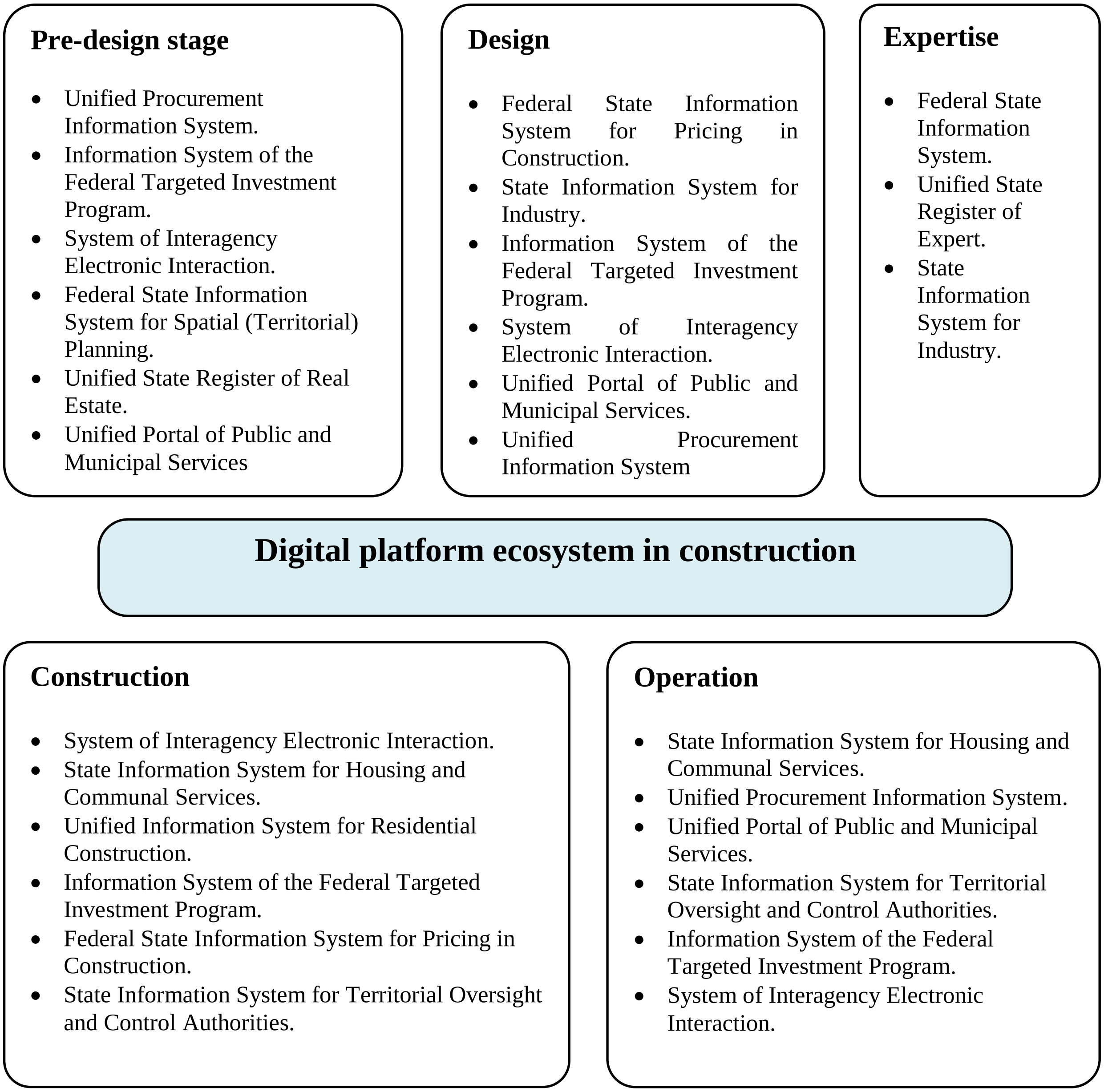


Figure 3.13 – Digital platform ecosystem in construction

We believe that information systems are the basis of a digital platform. Information systems accumulate a set of information circulating between construction management entities and are the basis of management in the digital economy. However, as can be seen from the data in the figure, today in construction this information is not a complete system, but represents an element of the information space.

The basis for communications in construction should be an information model of the construction project, which is a shared information resource about the project, the main function of which is to ensure the possibility of collective work on the project by all participants in the investment and construction project at all stages of the life cycle of the project [36]. The implementation of the main function of the information model is possible only if the model is part of a single digital environment capable of ensuring the continuous receipt, processing, recording and analysis of information from various sources throughout the entire life cycle of the object.

The creation of a single digital environment is also of strategic importance due to the need to reduce interaction procedures during the implementation of construction investment projects. Thus, according to [22], from 129 to 139 procedures have been established for housing construction.

The creation of a unified digital environment can be accomplished in several ways:

1. Internal solution. Different schemes are used using network folders or some software that ensures operation within the company itself. This method does not provide basic functions of the CDE and cannot be considered as a way to organize the UIS.

2. Client-server solution. Specialized software is used. The scheme generally looks like this: the company's server has software, and each user's PC has a client part. Only the company that owns the system can take full advantage of the system.

3. Cloud solution. The most promising way to organize the CDE. The main feature is that it provides full-featured operation of the CDE without being tied to specific PCs. The project can have any number of participants. Teamwork is provided.

The advantages of cloud solutions are:

– systematization of interaction between ISP participants;
– improvement of work quality;
– possibility of instant access to current design documentation remotely;
– reduction of work deadlines and signing of executive documentation;

– accumulation of large volumes of data about the facility during the construction period.

The final effects of the introduction of cloud technologies into the implementation process are a reduction in the cost of work, the cost of the project and compliance with the deadlines for the implementation of the ICP, or their reduction.

The advantages of creating a unified information system based on the CDE, according to the results of the conducted marketing analysis, include:

– the possibility of joint work both within each organization participating in the investment and construction project, and between organizations, government bodies and local government bodies;

– legally significant technical document flow in electronic form between organizations;

– project development control, analytics and reporting;

– prompt verification of the relevance of documents;

– creation of organizational structures of the organization and delimitation of access rights;

– checking documents and models with the ability to compare versions and make comments;

– coordination of sets of documentation for the custom procedure;

– signing of the full package of initial permitting documentation and as-built documentation using digital signature;

– the ability to connect modules for the formation and maintenance of information models with the assembly and verification of consolidated interdisciplinary models from several files.

The main results and effects of creating a digital platform for organizing a single digital space in the construction industry based on the CDE are the reduction of construction times due to the optimization of administrative procedures and digital construction management, attraction and turnover of investments, transparent management and analytics on projected construction volumes, including unfinished construction, analysis of resource needs, and assessment of regional urban development potential.

The existing mechanisms for attracting investors and positioning the region include the certification of regions and municipal districts, the presentation of regions, sites, priority development areas and industries in need of priority investment, including on the basis of public-private partnerships. The established practice of attracting investment to the region also includes support by the executive bodies of state power of the region of the procedures for reviewing, coordinating and monitoring the implementation of investment projects in accordance with the one-stop-shop principle; providing investors with curators (traditionally, specialized agencies), whose functions include support of the investment project, aimed at its successful implementation, rapid completion of administrative procedures and effective control.

At the planning stage of an investment project, investors focus their attention on preparing and submitting documents to executive state authorities to consider the issue of including the project in the list of particularly significant ones in order to receive the corresponding benefits. For their part, executive government bodies must make informed and balanced decisions regarding the criteria for including investment projects in the list of particularly significant projects. We believe that in the current conditions of economic instability, the issues of compiling a list of particularly significant projects and assessing the need to include a specific investment project in this list are of primary importance for executive government bodies in order to optimize the distribution of budget funds and create appropriate benefits for investors.

In order to speed up the process of project evaluation and decision-making, it is important not only to be able to submit documents electronically, but also to have the UIS functioning, which will allow the accumulation of necessary information about investment projects throughout the entire life cycle of their implementation, including creating a single template for maintaining the project information model (BIM model).

As one of the most important areas of digitalization of the investment project management system in the region, we have identified the creation of an interactive map of the region, which is one of the elements of the digital platform, a digital service that allows the investor not only to reduce the time spent on searching for information, but also serves as a kind of digital assistant when choosing a site for the implementation of the project, the type of project, assessing the possibility of its implementation on the basis of public-private partnership, justifying the financing scheme, and a preliminary assessment of the significance of this project for the region. Thus, the main result of using the interactive map should be the creation of an investor roadmap, which will outline all the necessary steps and relevant documentation for the implementation of the selected project in the selected region.

We believe that the basis of digital online services should be regulatory documentation, including the maximum amount of information about the region, including strategic development documents, regional and municipal passports, ratings, and so on. Also, the basis for creating an interactive map should be information systems or databases reflecting the typology of investment projects in the region, priority investment areas, including those based on PPP, platforms for implementing investment projects in the region, containing an information system of regional legislation, including existing measures of state support for investment projects and the possibility of interactive interaction through a “single window” system.

All of the above leads to the conclusion about the need to integrate all disparate elements of digitalization at the planning stage of an investment project by creating a digital platform. Based on the conducted marketing analysis, we will present a digital platform for planning, implementing and monitoring the implementation of investment projects in the region as follows (Fig.3.14)

It is possible to broadly identify two groups of effects from the digitalization of the process of implementing investment projects in the region.

For the investor, the main effects of digitalization will be a reduction in project risk due to a more complete consideration of regional conditions, due to the elimination of project collisions; a reduction in project costs due to the elimination of collisions at the design stage, due to a more accurate calculation and planning of project resources, due to a reduction in the time for preparatory, permitting and approval procedures during the implementation of an investment project.

For executive government bodies, the main effects will be an increase in the share of investment projects completed on time, a reduction in the time and costs of consulting and project support, and an increase in the objectivity of including projects in the list of particularly significant ones, which in total will lead to an increase in the efficiency of spending budget funds. As a result, a synergistic effect of digitalization will also be achieved, consisting in increasing the investment attractiveness of projects and regions, and, accordingly, in increasing the efficiency of investment activities.

Based on the conducted analysis of the functions of existing mechanisms for monitoring investment projects and the institutions implementing them, it is possible to draw conclusions about the need for systemic integration of existing institutions into a single effective mechanism that eliminates duplication of information flows and distortion of information. As a result of digital transformation, the systemic integration of institutions should be carried out on the basis of a single digital environment, an information model of the project and digital platforms.

We believe that the solution to the problem of effective integration of mechanisms for monitoring the implementation of investment projects in construction based on digitalization will significantly improve the effectiveness of investment programs and projects at all levels of the construction industry management hierarchy.

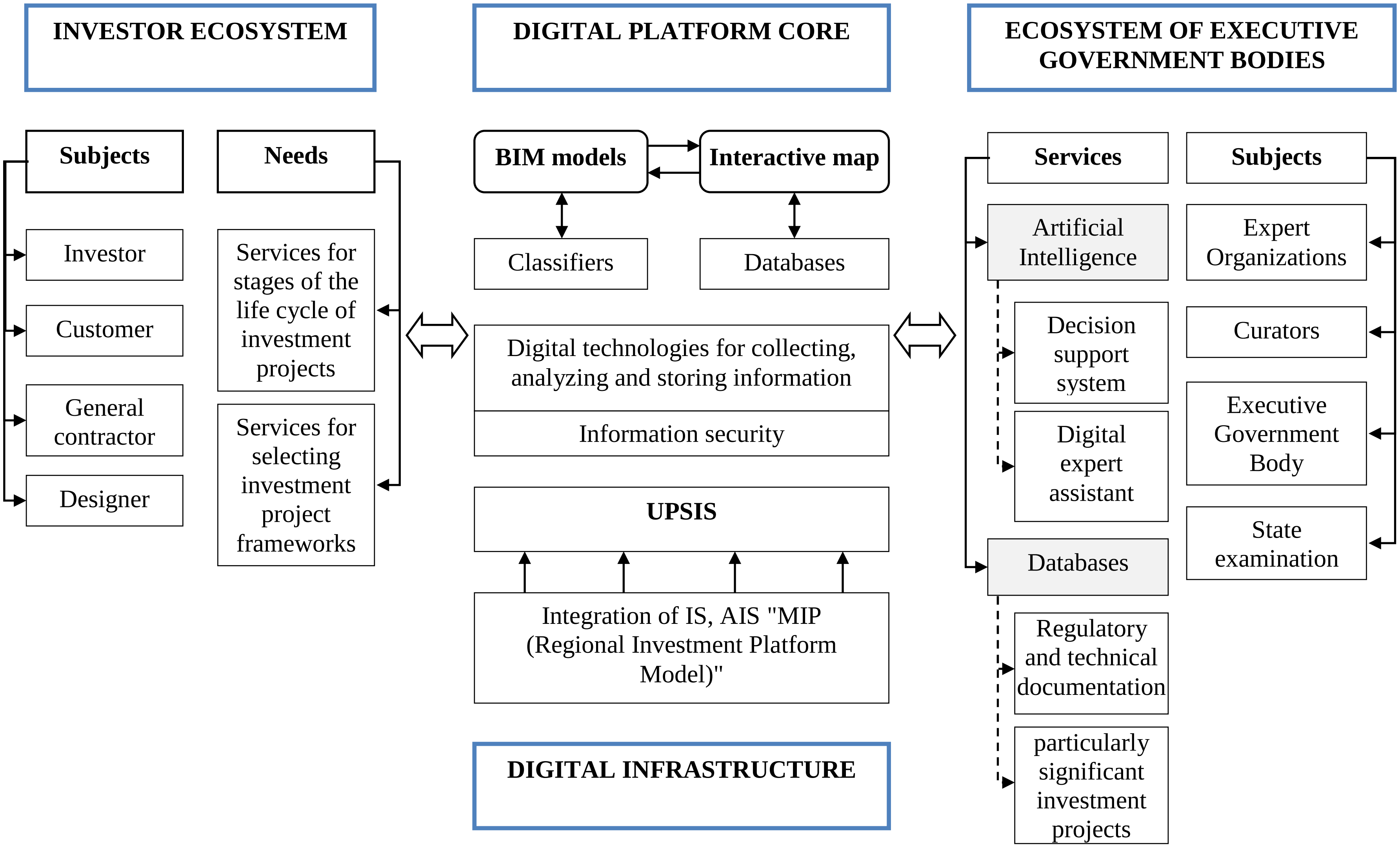


Figure 3.14 – Model of a digital platform for planning, implementation and control over the implementation of investment projects

Conclusions to chapter 3

1. A system-technical scheme for digital modeling of an everyday project has been developed, which consists of seven levels, which represent six levels of aggregation of entities in terms of the subject-object relationship (object-subject): “plan-meta”, “object-project”, “process-hour”, “technology-economy”, “system-resource”, “complex-convergence”. Descriptions of the subjective-objective and objective-subjective direct and reversal ligaments on the same model allow one to correctly understand the essence, the completeness and the level advanced information modeling technologies for developing digital BIM models of varying degrees of detail.

2. The need for transformation of the approach to the formation of teams for managing live projects in the context of digitalization of live work based on modern BIM technologies has been brought to light. As a result, two models of organizational re-creation of the BIM-project management system and BIM-project management teams, which are both the “brain” and the main resource, which represent the power of management, were created. mutualism, encouragement and success of team work on the project.

3. An approach to the systematic integration of the model into the architecture of management decisions is proposed, which involves its gradual inclusion in the existing management contours of the enterprise. Based on the modeling of development scenarios, it is demonstrated how the economic and digital model can be adapted to the organizational specifics of the enterprise, taking into account the level of digital maturity, availability of resources, type of construction activity and strategic goals.

4. A methodology for forming coordinated management decisions in a digital environment is developed, which is based on the principles of dynamic balancing of short- and long-term development priorities, the use of KPI indicators, as well as adaptive planning tools. An algorithm for synchronizing strategic guidelines with

operational performance indicators is proposed, which allows for the controllability of transformation processes and flexibility in making management decisions.

5. An economic and analytical toolkit for assessing the effectiveness of the implementation of digital solutions is created, which allows quantitatively measuring the results of digital transformation. The toolkit includes a system of comparative indicators "before" and "after" the implementation of digital solutions, takes into account economic feasibility, the level of process automation, increased productivity, reduced costs, reduced work deadlines and other operational effects.

6. The proposed model was tested on the example of a construction enterprise Alfa-Service LLC, which confirmed its effectiveness and practical value in modern conditions of the construction industry and allows us to recommend the developed economic and digital model for implementation in the development management system of a construction enterprise.

CONCLUSIONS

The dissertation solves the urgent task of forming an economic and digital model of development of construction enterprises, which combines modern approaches to economic diagnostics with digital management technologies to ensure adaptability, innovative activity and sustainable functioning of business entities in the transformational environment of modern construction development.

The significance of the dissertation results for science lies in the deepening, systematization and further development of scientific provisions on the formation of digitally oriented economic models of enterprise development in the construction sector. The work first proposes a comprehensive interpretation of the "economic-digital model" as a dynamic management circuit that combines economic development mechanisms with digital tools, technologies and analytical platforms. Significant scientific improvement has been achieved in conceptual approaches to structuring the digital architecture of construction enterprises, taking into account the institutional and economic environment; theoretical principles for assessing the digital maturity and adaptability of enterprises; methodology for transforming functional processes in construction through the integration of economic and digital indicators; and understanding the balance between strategic vision and tactical actions in the digital environment. The proposed theoretical provisions form the scientific basis for further research in the field of enterprise development management in the context of digital transformation, and can also be used to clarify the terminology, develop classifications and typical structures of digital management models.

The significance of the dissertation results for practice is due to the fact that the results of the study can be used in the management activities of construction enterprises, in particular in the form of experimental use of the economic-digital model in the processes of digitalization of production and management processes. The research results have significant practical value for managers, consultants, digital strategists, and developers of innovative solutions working in the field of construction development and related industries, namely:

1. A critical analysis of the evolution of scientific approaches to building digitally-oriented economic models in the construction sector has been carried out, taking into account the modern challenges of the transformational environment. The conceptual foundations of the formation of an economic and digital model of the development of construction enterprises have been improved - through a critical analysis of the evolution of scientific approaches to building digitally-oriented economic models, taking into account the challenges of the transformational environment, which made it possible to identify chronological and functional trends in the development of digital solutions in construction, in particular, their transition from the instrumental to the strategic level of managerial application.

2. The institutional and economic prerequisites and key technological factors influencing the formation of the digital architecture of construction enterprises have been determined, in particular in the context of foreign experience (on the example of the PRC). The institutional and economic platform for the formation of the digital architecture of enterprises in the construction sector has been improved, which takes into account the adaptability of management practices to foreign experience (on the example of the PRC), which allowed us to detail the key external and internal factors of digital transformation in the context of the national (Ukrainian) specifics of the market.

3. The financial and resource limitations of digitalization have been identified and the cost parameters of implementing BIM technologies into the structure of the economic and digital model of the enterprise have been analyze. The theoretical justification of the financial and resource limitations of digitalization in the construction sector has been further developed, with an emphasis on the cost aspects of implementing BIM technologies, which made it possible to objectify the decision-making process

regarding digital investments, taking into account the profitability, payback period and scalability of the implemented solutions.

4. A methodology for assessing the digital readiness and economic adaptability of a construction enterprise to operate in the conditions of digital transformation has been developed. Methodological provisions have been developed for assessing the digital readiness and economic adaptability of a construction enterprise, based on a combination of quantitative (digital maturity index, adaptability coefficients) and qualitative (expert evaluation) indicators, which allows for a comprehensive determination of the enterprise's potential for digital transformation in the face of risks and resource constraints.

5. Substantiated approaches to assessing the effectiveness of the transformation of the functional processes of the enterprise based on economic and digital indicators. An approach to assessing the effectiveness of the transformation of functional processes of a construction enterprise has been improved, based on the use of a system of economic and digital indicators (digital asset productivity, digital flexibility coefficient, etc.), which makes it possible to identify bottlenecks in digital integration in the enterprise's internal processes.

6. A structural and functional model of the development of a construction enterprise has been formulated, adapted to the conditions of the digital economy and transformational challenges. The structural and functional model of the economic and digital development of a construction enterprise has been further developed, which combines modules of strategic planning, digital monitoring and operational management, which allows the model to be adapted to different types of enterprises depending on their digital maturity and market conditions.

7. The directions and tools for adapting the economic and digital model into the strategic and operational contours of the development management of a construction enterprise are substantiated. The directions and tools for integrating the economic and digital model into the strategic and operational contours of enterprise management have

been further developed, revealing the features of implementing dynamic management tools (BSC, OKR, digital KPIs) in the digital development environment.

8. The analytical principles for ensuring consistency between the strategic vision and tactical management actions in a digitally oriented environment are formulated. The analytical principles for ensuring the coherence of strategic vision and tactical management actions in a digitally-oriented environment, based on the principles of digital balance, information symmetry and adaptive synchronization, have been further developed, which allows for effective management of changes in the digital context.

9. The economic and analytical tools for assessing the effectiveness of implementing digital solutions in the activities of construction enterprises are developed and their applied effectiveness is confirmed through testing at enterprises operating in a transformational development environment. The economic and analytical toolkit for assessing the effectiveness of the implementation of digital solutions has been further developed, containing a set of indicators and methods (in particular, ROI of digital projects, flexible efficiency index, digital payback ratio), confirmed by testing at construction enterprises operating in a transformational environment.

The aim of the study is to confirm the quality and economic indicators when using digital platforms at all stages of the CCPs life cycle, by conducting a marketing analysis of construction industry enterprises for the implementation (use) of specialized software and digital platforms. The study was conducted using a survey method (questionnaire) and structured interviews with representatives of the construction industry who use BIM technologies in their activities. Calculations were also made of the efficiency of using BIM technologies (including the Electronic Document Management System, CDE and digital platforms) using pilot projects in construction as an example.

The study revealed that construction requires the creation of a single digital platform based on a common data environment and the digitalization of document flow between all stakeholders of an investment and construction project, ensuring:

– prompt receipt of data on risks and the status of implementation of investment projects in online mode, based on objective, verified and machine-readable data obtained through electronic document management;

– reducing the time required for communication between construction participants during the implementation of investment projects by exchanging information in digital form on a single platform;

– creation of a BIM model of an object at the construction stage in order to transition completely to a digital format;

– elimination of excessive administrative burden on all participants in the investment and construction process by converting most procedures, documents and data into electronic form;

– formation of objective analytical reports based on information contained in a single repository of analytical information for their subsequent analysis;

– ensuring the completeness and reliability of information necessary for the implementation of operational urban planning activities.

The study revealed that the use of BIM and digital platforms at all stages of the CCPs life cycle contributes to increased economic efficiency of investment and construction activities, including the following:

The use of BIM (including on the basis of the electronic document management system of digital platforms) has the following systemic effects:

– increasing the accuracy of ICP cost estimates by 10-30%;

– 30% increase in construction rates;

– Reduction of collisions, requests for information and changes in the project by 25-40%;

– reduction of transaction costs of interactions between ICP stakeholders by 20-30%.

The use of EDMS and digital platforms at the construction stage creates the following effects:

– reducing the costs of construction support and control by 2 times;

– reduction of the time required to correct comments by 2-5 times;

– reduction of the time required to prepare executive documentation by 5 times;

– reduction of construction time by 20%.

In addition to the noted economic effects, the study revealed a number of non-economic effects, including a reduction in ICP risks and an increase in the quality of both the project and the construction site. The development and application of a single digital platform for interaction between ICP stakeholders will improve the efficiency of state investment policy and increase the transparency of investment and construction activities.

The main problem of interaction in the process of implementing investment and construction projects was identified as the duration of approval procedures, project changes and document signing.

Accordingly, the effectiveness of introducing digital document flow between all participants in the construction market at all stages of the CCPs life cycle is estimated at 7 points out of 10 possible.

The main obstacles to the implementation of a single digital construction platform are the lack of preparedness of participants for digital interaction, insufficient software, and the high cost of equipment and software.

The implementation of investment and construction activities is advisable on the basis of digital interactions by implementing electronic document management within the CDE on a single digital platform that has the ability to seamlessly exchange data (including when using BIM and other digital technologies) at all stages of the CCPs life cycle; using cloud solutions and optimal pricing policy; ensuring intercompany and interdepartmental interaction and corresponding to information security criteria.

As a result of the study, the qualitative and economic efficiency of using digital platforms at all stages of the life cycle of the CCPs was confirmed.

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169. **Qian Jing.** Features of managing construction developer projects under the digital transformation of the environment and functional interaction of stakeholder enterprises. Materials of the VI International Scientific-Practical Internet Conference: abstracts of reports *'Marketing strategies, entrepreneurship: current state, development directions'*. Kyiv: 2025, pp. 334–336.

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172. **Qian Jing.** Innovative analytical and applied tools for modeling the organization of construction and developer project support. V International Scientific-Practical Conference '*Energy-saving machines and technologies', dedicated to the 60th anniversary of the Faculty of Automation and Information Technologies* (May 22–24, 2024). Kyiv: KNUCA, 2024, p. 43.

173. **Qian Jing.** Modern analytical and applied toolkit for creating models of construction organization and developer project support. Roundtable *'Managerial, economic, accounting, organizational-technological, digital and communication aspects of improving educational and scientific processes as imperatives of construction industry transformation'* (July 1, 2024). Kyiv: KNUCA, 2024, p. 22.

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175. **Qian Jing**. Economic assessment of the digital ecosystem for managing a construction enterprise under innovative transformations. Program and abstracts of the roundtable 'Adjusting educational trajectories in the training of construction managers in the context of Ukraine’s reconstruction'. Kyiv: 2023, p. 25.

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

1. Mudra M.S., **Qian Jing** (2023). Modern technologies for the formation of marketing management strategies of enterprises as an imperative of their innovative development. *Spatial Development*, Issue 4, pp. 176–185. *Author's contribution*: development of approaches to adapting marketing strategies in the transformational environment of development. DOI: 10.32347/2786-7269.2023.4.176-185.

2. Mudra M.S., **Qian Jing** (2023). The state and prospects of economic development of developer companies: new technologies and models of administration. Development *Management of Complex Systems*, Issue 55, pp. 158–165. *Author's contribution:* development of approaches to assessing risks and uncertainties in the administration of developer companies, as well as modeling dynamic scenarios of their economic development considering the implementation of digital management technologies in a transformational environment. DOI: 10.32347/2412-9933.2023.55.158-165. Access: http://nbuv.gov.ua/UJRN/Urss_2023_55_22

3. Mudra M.S., **Qian Jing** (2023). Information-analytical support and formalized administration of business processes in operational systems of construction developer enterprises. *Development Management of Complex Systems*, Issue 56, pp. 147–154. *Author's contribution:* development of structural-logical approaches to formalized administration of operational systems using digital technologies (particularly BIM, VDC, IPD), which enhances management decision-making efficiency in the context of digital transformation. DOI: 10.32347/2412-9933.2023.56.147-154.

4. Khomenko O.M., **Qian Jing**, Nikolaiev H.V., Prykhodko O.O. (2023). Modern technology for modeling the organizational preparation and developer support of construction projects. *Spatial Development*, Issue 3, pp. 162–172. *Author's*

contribution: development of a digitally-oriented structure of interaction between project participants, ensuring management efficiency at all stages of the developer cycle. DOI: 10.32347/2786-7269.2023.3.162-172.

5. Fedorov V.V., Bartko V.F., ***Qian Jing*** (2024). Economic assessment of the trajectory of innovative development of construction stakeholder enterprises in the format of a digital ecosystem. *Construction Production*, Issue 78, pp. 80–87. *Author's contribution:* determination of effectiveness criteria for the integration of digital technologies into strategic management of innovation processes. DOI: https://doi.org/10.36750/2524-2555.78.80-87.

6. Bartko V.F., ***Qian Jing,*** Khomenko O.M. (2024). Conceptual and theoretical aspects of the transformation of the construction developer project environment into a digital ecosystem format. *Spatial Development*, Issue 9, pp. 361–372. *Author's contribution:* disclosure of the mechanisms of interaction between digital, organizational and economic components, and definition of structural conditions for effective digital integration at all stages of the project life cycle. DOI: 10.32347/2786-7269.2024.9.361-372

7. Omelianenko M.M., **Qian Jing** (2024). Business models of personnel management in the coordinates of the digital economy: new parameters and strategic vectors of transformation of construction development. *Spatial Development*, Issue 10, pp. 641–655. *Author's contribution:* development of a business model that integrates digital tools with innovative approaches to forming the human resource potential of enterprises. DOI: 10.32347/2786-7269.2024.10.641-655

8. Fesun A.S., Fedorov V.V., **Qian Jing** (2024). Paradigmatic concept of modern construction development in the context of strategic goal-setting of construction stakeholder enterprises. *Development Management of Complex Systems*, Issue 60, pp. 200–208. *Author's contribution:* substantiation of conceptual principles of goal-setting under digital transformation and increased dynamics of the external environment. DOI: 10.32347/2412-9933.2024.60.200-208.

9. **Qian Jing** (2025). Intellectualization of construction stakeholder management: digital technologies and ecosystem development. Spatial Development, Issue 12, pp. 133–145. DOI: 10.32347/2786-7269.2025.12.133-145

Articles in scientific periodicals of other countries

10. Krychevs'ka Y., **Qian Jing** (2025). Economic-analytical and functional-managerial components of operational system diagnostics in construction development enterprises. Colloquium-journal / Economic sciences, No. 45 (238), pp. 40–45. (Poland). *Author's contribution:* substantiation of tools for evaluating performance, adaptability, and efficiency of systems functioning under digital transformation and strategic development goals. DOI: https://doi.org/10.5281/zenodo.15119398

11. **Qian Jing** (2025). Managerial-administrative and process-oriented imperatives of investment and construction project development. Colloquium-journal / Economic sciences, No. 46 (239), pp. 122–129. DOI: https://doi.org/10.5281/zenodo.15119327

Conference materials where the research was tested

12. . **Qian Jing.** Features of managing construction developer projects under the digital transformation of the environment and functional interaction of stakeholder enterprises. Materials of the VI International Scientific-Practical Internet Conference: abstracts of reports *'Marketing strategies, entrepreneurship: current state, development directions'*. Kyiv: 2025, pp. 334–336.

13. **Qian Jing.** Managerial challenges and development strategies of construction development under digital transformation. Program of the international scientific-practical conference *'Problems of the genesis of the economy of intellectual-innovative capital'* (November 5–6, 2024). Kyiv: KNUCA, 2024, p. 28.

14. **Qian Jing.** Ensuring digital concordance of enterprise innovations under transformation of the operational environment in construction. Business Forum *'Vectors*

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18. Qian Jing. Economic assessment of the digital ecosystem for managing a construction enterprise under innovative transformations. Program and abstracts of the roundtable 'Adjusting educational trajectories in the training of construction managers in the context of Ukraine’s reconstruction'. Kyiv: 2023, p. 25.

APPENDIX B

22.11.2024 № 889-в

ДОВІДКА

про впровадження результатів дисертаційного дослідження

ТОВ БФ «Альфа-Сервіс» (код ЄДРПОУ 22965175), що здійснює діяльність у сфері проєктного супроводу, технічного контролю та організації будівельного виробництва, підтверджує впровадження у формі експериментального використання результатів дисертаційної роботи Цзін Цянь на тему: **«**Формування економіко-цифрової моделі розвитку будівельних підприємств в умовах трансформаційного середовища**»**.

У період 2023-2024 рр. результати наукового дослідження були використані в рамках пілотного проєкту цифровізації внутрішніх виробничих і управлінських процесів підприємства. Зокрема, впроваджено наступні підходи та інструменти:

- структурно-функціональну модель економіко-цифрового розвитку підприємства, адаптовану до реальних умов господарської діяльності;
- методику оцінювання цифрової готовності та адаптивності операційних підрозділів;
- індикатори ефективності впровадження цифрових рішень у контурі стратегічного і тактичного управління;
- систему внутрішньої аналітики на основі показників цифрової продуктивності та гнучкості функціональних процесів.

Експериментальне застосування зазначених розробок дало змогу підвищити керованість проєктними циклами, зменшити витрати часу на обробку технічної документації та покращити інтеграцію між підрозділами за допомогою цифрових платформ (зокрема, адаптація під BIM-рішення). У результаті впровадження зазначених рішень підприємству вдалося досягти відчутного економічного ефекту, зокрема:

- зменшення непродуктивних витрат на організаційно-технічні помилки та повторне виконання проєктних етапів на 12,8%**;**
- скорочення середнього часу погодження управлінських рішень завдяки цифровій інтеграції на 18%**;**
- підвищення загальної продуктивності праці персоналу в межах проєктних команд на 15–17%**;**
- оптимізація витрат на інформаційно-аналітичну обробку документації — економія орієнтовно 140 тис. грн на рік**.**

Експериментальне застосування розробок Цзін Цянь підтвердило їх практичну доцільність та стало основою для підготовки плану впровадження цифрової моделі управління у проєкти компанії. Результати впровадження були позитивно оцінені управлінським персоналом підприємства та рекомендовані до поетапного розширення на інші проєкти.

Дана довідка видана для подання до Київського національного університету будівництва і архітектури з метою підтвердження практичного значення дисертаційного дослідження.

Заступник директора
канд. економ. наук

БУДІВЕЛЬНА ФІРМА "АЛЬФА-СЕРВІС" Ідентифікаційний код 22965175

А.М. Кравченко

POLIMIN
експерт будівельних сумішей

ТОВ «Фомальгаут-Полімін»

Київський національний університет
будівництва і архітектури

№24 від 19.02.2025 р.

Про результати застосування результатів науково-прикладних досліджень Цзін Цянь в практиці діяльності компанії «Фомальгаут-полімін»

Компанія ТОВ «Фомальгаут-полімін» спеціалізується на виробництві будівельних матеріалів та впровадженні інноваційних технологій в системи логістики, управління виробництвом і маркетингу, підтверджує впровадження у формі експериментального використання результатів дисертаційної роботи Цзін Цянь на тему: «Формування економіко-цифрової моделі розвитку будівельних підприємств в умовах трансформаційного середовища».. На підприємстві здійснено впровадження окремих методичних рішень дисертаційного дослідження в управлінські процеси, пов'язані з цифровізацією операційної діяльності, оптимізацією комунікаційних потоків та впровадженням індикативних цифрових моделей у стратегічне планування. Зокрема, використано:
- систему оцінювання цифрової зрілості бізнес-процесів підприємства;
- методику адаптації економіко-цифрової моделі до внутрішніх функціональних контурів виробництва та маркетингу;
- аналітичні індикатори результативності управлінських дій на основі KPI і цифрових метричних показників;
- інструменти прогнозування ефективності цифрових рішень у логістиці та дистрибуції.

Результатом впровадження стало:

- скорочення витрат часу на внутрішнє погодження логістичних і виробничих операцій на 17%;

- зменшення витрат, пов'язаних із дублюванням рішень, на 11,4%;

- підвищення ефективності стратегічного планування завдяки впровадженню цифрових моделей контролю за ресурсними потоками;

- річна економія коштів підприємства склала орієнтовно 98 000 грн. Результати апробації підтверджують практичну значущість дисертаційної роботи Цзін Цянь та рекомендовані до подальшого масштабування в корпоративну цифрову платформу підприємства.

Директор
к.т.н. **С. А. Єршов**

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Architectural Construction Innovations

ТОВАРИСТВО З ОБМЕЖЕНОЮ ВІДПОВІДАЛЬНІСТЮ "АРХІТЕКТУРНО-БУДІВЕЛЬНІ НОВАЦІЇ"

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№341 від 18 грудня 2024 р

Проректору
з наукової роботи КНУБА
к.т.н., с.н.с. Ковальчуку О.Ю.

ДОВІДКА
про впровадження результатів дисертаційного дослідження

ТОВ «АБН» що здійснює діяльність у сфері генпідряду та комплексної реалізації проєктів у будівництві, підтверджує впровадження у формі експериментального використання результатів дисертаційної роботи Цзін Цянь на тему: «Формування економіко-цифрової моделі розвитку будівельних підприємств в умовах трансформаційного середовища».

На базі підприємства було проведено апробацію наукових результатів у межах внутрішнього пілотного проєкту з цифровізації процесів координації, планування та моніторингу в інвестиційно-будівельній діяльності.

У процесі експериментального застосування були впроваджені та протестовані такі підходи та інструменти:
- економіко-цифрова модель розвитку підприємства, адаптована до реальних виробничих і управлінських умов будівельних проєктів;
- методика оцінювання цифрової зрілості проєктних команд із використанням ключових показників ефективності (KPI) та коефіцієнтів гнучкості процесів;
- аналітичний модуль моніторингу ефективності впроваджених цифрових рішень (зокрема елементів BIM-планування та відстеження ресурсів);
- методичні положення щодо синхронізації оперативних управлінських рішень зі стратегічними цілями проєкту в умовах нестабільного зовнішнього середовища.

У результаті впровадження було досягнуто низку позитивних ефектів, зокрема:

- оптимізовано оперативну комунікацію між підрядниками та субпідрядниками (обсяг документообігу знижено на 30%);

- скорочено час формування технічної та фінансової звітності по проєктах на 22%;

- підвищено узгодженість між плановими та фактичними показниками використання ресурсів;

- річна економія від автоматизації та цифровізації склала орієнтовно 165 000 грн.

Практична цінність результатів дисертаційного дослідження Цзін Цянь підтверджена технічним керівництвом підприємства та рекомендована до використання в інших інфраструктурних проєктах ТОВ «АБН».

Дана довідка видана для подання до Київського національного університету будівництва і архітектури з метою підтвердження практичного впровадження результатів дисертаційного дослідження.

Директор
ТОВ «Архітектурно-будівельні новації» С.М. Архіпенко

МІНІСТЕРСТВО ОСВІТИ І НАУКИ УКРАЇНИ

КИЇВСЬКИЙ НАЦІОНАЛЬНИЙ УНІВЕРСИТЕТ БУДІВНИЦТВА І АРХІТЕКТУРИ

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05.09.2024 №1-54/91

ДОВІДКА ПРО ВПРОВАДЖЕННЯ НАУКОВИХ РЕЗУЛЬТАТІВ
дисертаційної роботи Цзін Цянь
в науково-дослідний та навчально-методичний процеси КНУБА

Окремі результати дисертаційної роботи Цзін Цянь на тему «Формування економіко-цифрової моделі розвитку будівельних підприємств в умовах трансформаційного середовища» використовуються в освітньому процесі Київського національного університету будівництва і архітектури. Зокрема, теоретичні положення, методичні підходи та аналітичні інструменти, розроблені здобувачкою, були адаптовані для використання при викладанні навчальних дисциплін: Діджитал-менеджмент, Економіка інноваційного розвитку підприємства, Управлінський консалтинг для здобувачів вищої освіти за спеціальностями 051 «Економіка» та 073 «Менеджмент».

Результати дослідження отримано в рамках реалізації науково-дослідної роботи КНУБА «Розбудова сучасного аналітичного інструментарію девелоперського управління підрядним будівництвом» *(*державний реєстраційний номер *0115U000860).* в межах якої дисертанткою було здійснено адаптацію сучасних цифрових інструментів стратегічного планування до потреб підприємств будівельного сектору. Авторка обґрунтувала доцільність інтеграції економічного аналізу з цифровими системами управління (зокрема ERP, BIM, CRM-платформами) з метою створення цілісної економіко-цифрової моделі розвитку, що здатна оперативно реагувати на зміни трансформаційного середовища.

Окремі положення дисертації сформовані у процесі реалізації теми НДР КНУБА «Розвиток управлінської взаємодії інституційних учасників девелоперських проєктів» (державний реєстраційний номер 0121U111793). в якій Цзін Цянь брала участь при формуванні системного підходу до управління цифровими змінами в девелоперських структурах. У цьому контексті авторкою запропоновано інноваційні рішення щодо структурування цифрової екосистеми будівельного підприємства, а також алгоритм оцінювання ефективності цифрових інвестицій з урахуванням показників економічної результативності та технологічної зрілості підприємства.

Перший проректор **Денис ЧЕРНИШЕВ**

МІНІСТЕРСТВО ОСВІТИ І НАУКИ УКРАЇНИ КИЇВСЬКИЙ НАЦІОНАЛЬНИЙ УНІВЕРСИТЕТ БУДІВНИЦТВА І АРХІТЕКТУРИ Ідентифікаційний код 02070909