

Life Cycle Modeling for Utility Infrastructure in Municipal Entities

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Abstract. The current development stage of utility infrastructure is characterized by structural changes resulting from the existing property rights, as well as institutional, organizational, economic, concessional, innovative, and resource-saving mechanisms, the accelerated introduction of new technologies and materials, and the implementation of actions aimed at the reduction of physical and functional depreciation of facilities. The key objectives of managing the reconstruction, upgrade, and repairs of the public utility sector (PUS) facilities include the sustainable development, update, and operation of the housing stock and utility infrastructure (UI), preservation, and technical operability of structures and utility systems. Therefore, the public utility services currently require new strategic planning methods for the social and economic development of the PUS as a key element of municipal entities based on the use of reproduction policy tools throughout the utility infrastructure life cycles and the improvement of project and program approaches necessary to ensure the investment in the sector and facilitate the interactions between the municipal entities, business community, and residents. . This article deals with the methodological approach to the life cycle modeling for utility infrastructure in municipal entities based on balancing the phases and innovation activities concerning the features of utility service production and consumption and the necessity to use digital and smart-city technologies to maintain proper operational modes and parameters throughout the life cycles of utility infrastructure units. This requires accelerating reproduction processes, maintaining the best proportion of capital and current costs, expected profitability, and management risks for utility property portfolio.

1. Introduction

Utility infrastructure is a crucial element of the spatial development framework for regions and municipal units because it facilitates the living environment, comfortability, and safety. The current development processes in cities increase the mutual influence of innovative, technological, economic, and social factors. As a result, the changes related to the quickly changing consumer requirements to property parameters, their innovation rate, city development policies, infrastructure development, etc tend to accelerate in the long term.

Nowadays, state policies aim at regulating and controlling the acceleration of development processes in engineering and utility structures. Targeted program and project mechanisms for utility infrastructure design, funding, construction arrangement, reconstruction, upgrade, and major repairs in municipalities supported by federal and regional funds and private investments allowed for a significant increase in the number of reproducible activities that take into account the implementation features of investment projects for small, medium, and large cities, as well as the preference for the



application of innovative technologies and energy saving methods under various funding schemes and the planned outcome levels.

Although several federal, regional, and municipal upgrade programs for utility infrastructure have been implemented over the recent years and despite the scope of these programs and the new structural quality improvement and energy-saving goals for business processes, the level of physical and functional obsolescence of utility units and networks remains high, as well as their fault rates. The existing funding sources cannot ensure the implementation of required activities, while the resource providers' activities do not create the investment capacities required either for the development or the reconstruction, upgrade, major repairs, and current operational costs of resource production, transportation, and distribution to consumers.

To maintain the standard fault-free operation modes and parameters throughout the life cycle of utility infrastructure units and improve the quality and comfort of living conditions according to the public health regulations, it is necessary to have balanced reproduction processes, keep the best proportion between the capital and current costs, the expected profitability and property portfolio risk management while taking into consideration the goals and preferences of owners, investors, and municipal authorities.

2. Relevance

The adoption of an innovative development model for utility services within the life cycle of utility infrastructure components is subject to extensive research and debates in the Russian economic literature. While the research works acknowledge significant improvements in the utility infrastructure sector, they focus on the problems that remain unsolved. They are connected to the lack of funds and the search for new sources of capital investments, the gap between the actual and the required upgrade rates, the significant differentiation across territories in terms of the quality of the utility services provided, the occurring faults, and the non-productive losses of utility resources, the closedness of natural monopolies, the lack of economic mechanisms to promote the balance between the investment and current costs, as well as the resource-saving technologies in the life cycle of utility infrastructure components. [4. 5. 7,10].

3. Statement of problem

This article presents a methodological approach to modeling the development life cycle of utility infrastructure in municipal entities. In this research, we analyzed the operation and development of utility infrastructure and concluded that it is necessary to model the development life cycle of utility infrastructure in municipal entities based on the coordinated phase conjugation and the application of innovative digital and smart-city technologies. The application of the modeling method was based on the formalized description of the life cycle structure for the outstripping development of the utility infrastructure components. [3.8].

We aimed at identifying some features of the utility infrastructure sector in terms of property rights, cross-sector interactions, the prospects of the current property development projects, monopolies of utility service producers and providers, natural monopolies, the strategic dependency of the development process on the population count and other local factors, the lack of a funded amortization system for the realignment of the existing engineering system.

Currently, the key aspects of the utility infrastructure system cover the demand for utility services, the efficiency assessment for resource production and transfer, the reliability of transfer and the quality of the resources supplied, the environmental impacts of resource production. We believe that this list must be complemented with such areas as the innovation rates of the production and the resource transfer and consumption management.

Depending on the goals, the following groups of investment projects for construction and realignment can be found in the utility infrastructure sector:

1. Building utility infrastructure facilities to connect new structures and consumers, replacing faulty obsolete facilities to improve reliability and the efficiency of resource use and reduce emissions;

2. Upgrading and renovating utility structure facilities that increase prospective capacities, updating the existing systems;

3. Major repairs of utility infrastructure components;

4. Decommissioning physically worn and faulty facilities, laying-up and dismantling of excessive heat sources; turning boilers into the combined electricity and heat generation units.

Project implementation practices stipulate the following organization forms: attracting investors, public-private partnerships, organizations involving local government authorities, and the existing resource providers.

The projects can be classified by their duration and payback periods as follows: highly efficient projects (payback period up to 7 years through the effects achieved), long-payback projects (7-15 years through the effects achieved at the average investment costs), and projects with payback periods of over 15 years [6,1.13].

4. Applicability

The generic development life cycle for utility infrastructure in municipal entities can be presented as a structure-and-process chart including 5 phases and 6 blocks of multicomponent modular indicators. Figure 1.

The development of a comprehensive life cycle model for utility infrastructure might involve a number of multicomponent modular blocks to facilitate the initiation and maintain the generation of accelerated effects. These may include the following:

1. The legal regulation for investment, construction, and realignment activities, environmental security, energy efficiency, technical procedures and social relevance, reconstruction, upgrade, and repair management processes for utility infrastructure components creates conditions for the sustainable operation of the system and the stable quality of the provided services, financing mechanisms, balancing the investment and current costs, required recovery investments, “extra investments”.

2. The long-term tariff policy as a driver in demand and availability assurance for utility services, and as a source of investment component in the tariff that facilitates to fund realignment activities in utility infrastructure.

3. The economic, project and engineering synchronization of development and operations includes methods, techniques, and conditions determining their impact on utility structure reproduction. The identification of methodological features of the interaction, coordination, and conjunction of the following structural blocks: governmental regulation, funding source structure, implementation rates for housing construction programs, etc, including utility connections, reconstruction, upgrade and major repairs, price environment, social support, renovation strategies and programs for urban utility infrastructure facilities requiring upgrades.

4. The factors influencing the investment capacity of the region (municipal entity) determined by the macroeconomic and social parameters of the internal and external environment.

5. The investment attractiveness of a territory characterized by the indicators of social and economic development, resource needs, and the possibility of obtaining investment capital in full or in part, as well as the income associated with its use.

6. The technical and economic capacity of utility infrastructure characterized by qualitative and quantitative indicators of its components, as well as their technical conditions and physical wear, reliability of operation and longevity, fault rate, asset value, property forms, and contractual system, the efficiency of existing facilities, the quality of operation, problems and solution methods, the financial and economic state of organizations, and the availability of funds required for development and repairs.

In life cycle structure modeling, we suggest using 5 main phases:

Fcs — the phase of outstripping development strategy concept for utility infrastructure in a municipal entity;

Fas — the phase of draft listing of regional investment programs aimed at the development and

renovation of utility infrastructure;

Fit — the phase of synchronized application of innovations and digital technologies in construction and realignment projects of utility infrastructure;

Frs — the phase of construction development and the implementation of investment projects for utility infrastructure targeting new structural characteristics and innovations;

Fre — the phase of realignment and further upgrade, reconstruction, and major repairs in the utility infrastructure involving innovations.

The dynamic development of construction and innovation technologies results in the rapid amendment of project decisions during the construction of property units. [2,9.11].

Changes in utility infrastructure must be intensified, which is crucial for the sustainable realignment capacity of the facilities in operation.

The life cycle model for utility infrastructure as a strategic, organizational, economic, and innovative mechanism of sustainable development can be expressed as an objective function of LCM:

$$\text{LCM} = F(\mathbf{Fcs}, \mathbf{Fas}, \mathbf{Fit}, \mathbf{Frs}, \mathbf{Fre}) * \mathbf{Cui}, \mathbf{Cur}, \mathbf{Cmz}, \mathbf{Cmn}, \mathbf{Cs}, \mathbf{Ceo} \rightarrow \text{opt}, \quad (1)$$

$$\mathbf{Cmz} \rightarrow \text{max}, \mathbf{Cmn} \rightarrow \text{min}, \quad (2)$$

where: LCM is the objective function of the life cycle model for utility infrastructure;

Cui is the life cycle acceleration coefficient for utility infrastructure investment and construction projects;

Cur is the realignment acceleration coefficient for the utility infrastructure in operation;

Cmz is the coefficient determining the actions impacting the renovation acceleration rates for the existing utility infrastructure implemented by the participants of municipal development;

Cmn is the coefficient determining the actions impacting the acceleration rates of utility infrastructure renovation that do not depend on the municipal development entities;

Cs is the synchronization coefficient for the construction and realignment using innovative approaches and smart-city technologies.

Ceo is the useful effect coefficient of the outstripping utility infrastructure development.

The **Cui** acceleration coefficient is determined by the life cycle price of investment and construction project implementation ($\mathbf{Fcs} + \mathbf{Fas} + \mathbf{Fit} + \mathbf{Frs} + \mathbf{Fre}$) **t** and the funding level **Ufo** over the period of **t**, characterized by the following:

Ufotr stands for the gap between the required, economically justified amounts of funding and the actual funding

$$\mathbf{Uff} (\mathbf{Ufotr} < \mathbf{Uff}), \quad (3)$$

Usp is the compliant or exceeding level of ($\mathbf{Usp} \geq \mathbf{Uff}$) throughout Δt . (4)

The **Cur** acceleration coefficient is determined by **T** rates characterized by the amounts of funding, the implementation rates and intensity of realignment project for utility infrastructure, where:

Tvf is the rate of financial in-flow used in the project throughout Δt .

Tve is the rate of commissioning utility infrastructure components throughout Δt .

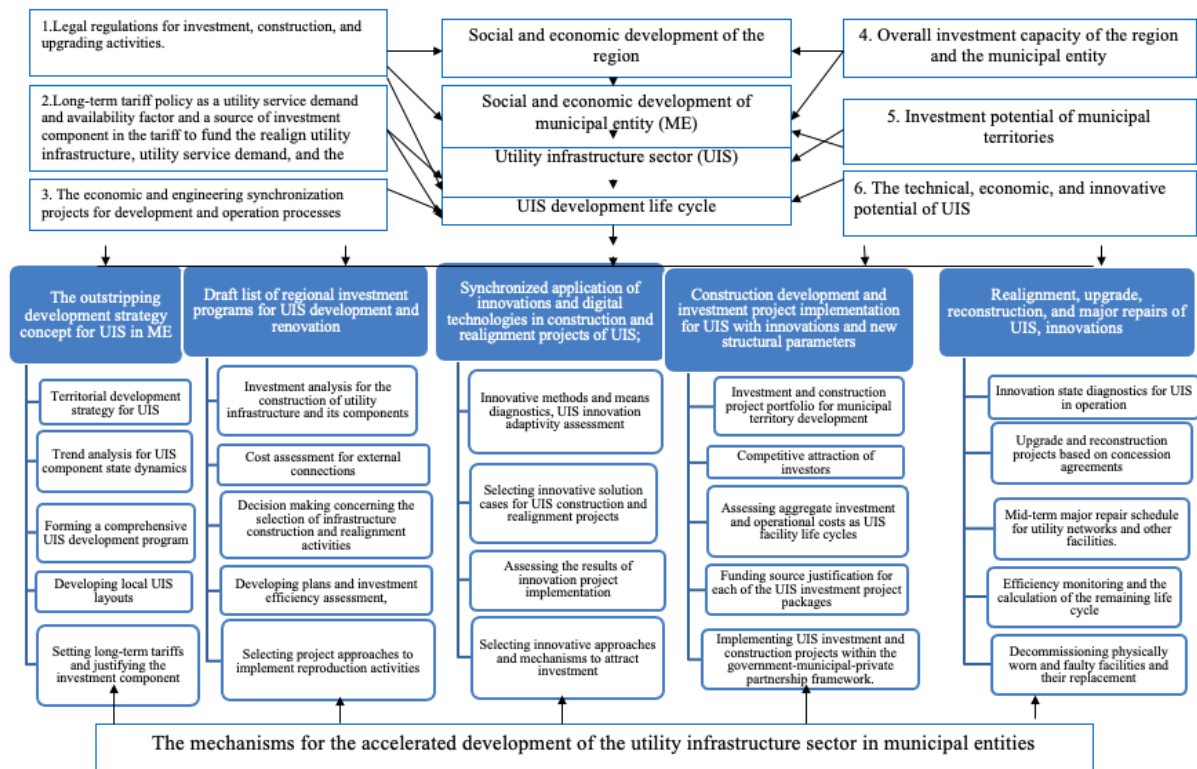


Figure 1. The structure-and-process model of development life cycle of utility infrastructure.

The accelerated utility infrastructure development and renovation is the optimization criterion for the life cycle model, provided that

$$U_{fo} \rightarrow \max, T \rightarrow \max \tag{5}$$

Thus, the outstripping development strategy concept is based on the evaluation of the forecast acceleration of UIS parameter dynamics and life cycle implementation through the sustainable increase of F_{re} realignment rates balanced with the construction rates of property units and the new utility system of F_{rs} as the basis of local spatial infrastructure of the municipal entity. The outstripping development of utility infrastructure components may be achieved if C_{ui} and C_{ur} are funded by U_{ff} and the additional resources of ΔU_{fo} to the proportion of at least 35% of the level achieved on average.

5. Conclusions

The current municipal development processes increase the impact of organizational, managerial, financial, economic, operational, technological, innovative, and informational factors in the utility infrastructure sector and lead to the formation of long-term acceleration mechanisms for intensive changes during the life cycles of various utility units represented as the investment-and-process structure of interrelated phases, stages, periods, functions, objectives, and works constituting the reproduction development, operation, and decommissioning.

The methodological basis of the life cycle model is the structural-and methodological system of accelerated development mechanisms in the utility infrastructure of a municipal entity, including mobile basic principles and evaluation approaches to the acceleration of the UIS development, the goals and rates of UIS development, the development and efficiency increase for concession agreements, the search for new funding sources, investment proportions and balance planning digitalization at various phases of UIS life cycle, the increase in the investment component in tariffs, the implementation of life cycles based on information technologies, accelerated cross-cutting

development of information and communications technologies in construction and operation, organizational, managerial, and technological synchronization of development actions and UIS realignment involving innovative technologies, smart system application and digitalization programs in the form of benchmark cases. BIM-technologies and information models of UIS components that accelerate design processes, utility internet controlling resource supply, etc.

Methodological approaches to life cycle modeling facilitate the proportionate and balanced development of its phases over time through the acceleration and intensive resource supply on one hand, and the conjunction of reliability, longevity, quality, and innovation technology synchronization with the implementation of reproduction activities on the other hand. They allow for the optimization of life cycle duration and the justification of outstripping development type and utility infrastructure renovation. That being said, projects and programs must be integrated into the uniform regional (municipal) set of program goals for the development of utility infrastructure during the pre-investment stage.

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