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The Complex Approach to Environmental and Technological Project Management to Enhance the Sustainability of Industrial Systems

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Abstract: To achieve sustainability, industrial systems need to be modernized to improve resource efficiency while optimizing environmental and social performance. The implementation of environmental and technological projects is a complex management process and requires sufficient innovative potential and serious investments, which not every company can provide. Network integration of companies, providing synergy of resources and potentials, is an effective tool for the development and implementation of innovative technologies that allow achieving optimal resource efficiency indicators. An integrated complex approach to the formation of a cross-industrial system on the principles of network integration and partnerships ensures technological interaction between companies, optimizes the methods and forms of their economic activities, allows integration participants to achieve strategic goals and ensure environmental and social effects for the territory of presence. The sustainability of such a system is expressed in its ability to withstand internal threats and external challenges. Approaches to balancing environmental and technological effects while simultaneously analysing social efficiency have not received sufficient development in scientific research. This article discusses an approach to the selection of environmental-technological projects based on criteria for assessing the sustainability and resilience of industrial systems. The authors’ approach has been tested using two industrial symbioses of advanced socio-economic development territories in the city of Novotroitsk (Orenburg region, Russian Federation). The authors presented calculated indicators of resource efficiency before and after the formation of a cross-sectoral industrial system in order to identify social and environmental effects in Novotroitsk. This approach to the assessment of environmental and technological projects allows to concentrate government support measures on the general priorities of the implementation of regional economic and industrial policies.

Keywords: sustainability; industrial systems; cross-sectoral interaction; social performance; environmental and technological projects



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1. Introduction

To achieve priority goals for strategic industrial sector development, it is vital to renovate domestic production to enhance its resource efficiency as well as environmental and social performance. In many cases, large, medium, or small sized companies acting alone are unable to achieve ambitious economic goals along with reduction of natural resource consumption and minimization of negative environmental impacts [1]. By contrast,

network integrations of companies as clusters, industrial symbioses, technology parks, and ecosystems are an effective tool for the development and implementation of promising environmental and technological projects [2]. Within such frameworks, various systems both interact with each other and create value from various data flows to increase productivity within each company, optimize logistics processes, and contribute to the technological development of the participants [3].

Implementation of strategic projects to achieve technology leadership through environmental and technological modernization is unrealistic without cooperation between different market participants: federal authorities, financial institutions, educational establishments, public organizations, citizens, and other stakeholders [1–3]. Such interactions empower joint implementation of environmental and technological projects to increase both competitiveness of enterprises and industries, and resource efficiency of each player [1].

Effectiveness of environmental and technological projects is assessed in terms of commercial efficiency and social performance, wherein commercial efficiency generally receives more attention since the financial component is paramount when deciding on project implementation [3]. Assessment of social performance is complicated as it indicates whether implemented projects were useful both for the project participants and stakeholders, and for the territory of presence, state, and society. In this article, social performance refers to project benefits which can be evaluated through social, environmental, and technological indicators at micro-, meso- and macro levels. Thus, we consider effects that are not shown in financial and economic activity indicators of project participants, but which are evidenced in (i) cost indicators for enterprises and organizations, transport, communications, wholesale and retail trade, and non-productive sectors (public and private services, education, health care, culture, PE and sports, tourism, etc.), and (ii) in revenues and expenditures of federal and regional budgets [4]. Such effects stimulate economic activity in related industries and focus on areas where these economic entities are located, providing a multiplicative economic result from the project implementation. Besides, it is critical to note such effects as environmental safety; resource efficiency; an increase in employment and housing; an increase in availability and quality of services (education, culture, healthcare, transport, housing, and communal services, etc.). This generally leads to quality of life enhancement.

It should be noted that despite the challenging problem of increasing social performance of implemented investment projects, there are few developed, recognized and applied approaches to its assessment at the stage of project initiation. We consider an assessment system to be an effective tool for increasing various effects from the investment project implementation [2]. Assessment permits identification of available reserves for setting development priorities that provide benefits for all participants, including state and society, and subsequently development of strategic management decisions. However, it should be considered that technological, environmental, and social effects from projects implemented through inter-sectoral integration could only be achieved along with formation of a system of conditions, including institutional mechanisms promoting green economy, environmental awareness and responsibility of the society, collaborative interaction between enterprises, and a high-level promising domestic technology [1].

This problem is getting more complicated in the view of such ongoing processes as inter-sectoral integration of enterprises in the form of clusters, technology parks, symbioses, and ecosystems, which make it necessary to use original methodological approaches and tools. This paper discusses development and approbation of a methodological approach to assess predominantly social and environmental effects arising from implementation of various circular economy-related inter-sectoral projects. The goal of the study is to propose an approach to the selection and evaluation of innovative environmental and technological projects that increase the sustainability of industrial systems and are implemented on the basis of cross-industrial interaction. The authors' approach has been tested using evidence of two industrial symbioses of advanced socio-economic development territories in the town of Novotroitsk (Orenburg region, Russian Federation). Such a perspective on

assessing investment projects would allow focusing of state support measures on common priorities for the implementation of regional environmental and industrial policies.

We believe that a balanced approach to assessing socio-ecological-technological systems will contribute towards more transparent decision-making and help to determine the potential role of industrial enterprises and their integrations in the sustainable development of regions where they operate. The novelty of the proposed approach lies in the authors' assumption that technological innovation shall be seen in conjunction with social and environmental management, thereby catalysing a shift towards sustainable development.

The article is organized as follows. A literature review of the research problem and developed research hypothesis is presented in Section 2. Section 3 describes the research methodology based on the opportunity cost concept. This methodological approach was originally described by the authors in their earlier works [5]. In the present study, the developed approach was supplemented and expanded with another type of industrial symbiosis (circular-economy-related) being the research object. Section 4 describes two cases regarding development of circular economy-related symbioses in the city of Novotroitsk. The first symbiosis (the "Chemical symbiosis") is based on the technology of obtaining lime from production waste of chromium compounds (part of the lime is then used in soda ash production). The second (the "Green Cement symbiosis") is an integration of enterprises with slag processing technology to use steel industry waste in cement production. The authors present calculated resource efficiency indicators before and after implementation of the circular development-related projects to reveal social and environmental effects thereof in Novotroitsk. In Sections 5 and 6, the authors draw conclusions and discuss recommendations resulting from the conducted analysis. This section also highlights key findings of the study and presents its theoretical contribution and practical significance. Some limitations of the research and future research perspectives are also discussed here.

2. Literature Review and Hypothesis Development

Industrial integration as a core of industrial systems is an effective tool for socio-economic development at all management levels (enterprises, territories, industries) [6]. At the same time, regional endowment with factor potentials (labour, capital, infrastructure, transport, institutional, innovation and technological, etc.) is crucial for territorial and sectoral division of labour and production localization. It is these factors that are decisive for industrial integration processes in a certain territory. Since different regions are situated in different geographic locations, they are endowed with varying opportunities for the implementation of circular economy-related development projects [7]. Based on the factor endowment theory, for each country or region that is endowed with different factors of production, each region would produce goods requiring inputs that are relatively abundant in the region, thus leading to a comparative advantage in that good [8]. Especially for regional industrial integration, regional production factors and industries would be distributed spatially, based on the principles of mechanisms with the participation and coordination of government and nongovernment bodies [9,10]. Accordingly, sustainable development and green growth within regions can be achieved given the cumulative impact of market, government, and organisations. The impact of institutional status on integration is reflected in the functions of various organisations, ranging from the determination of property rights for economic entities, transference of information, planning of the development model for regional economies, and formulation of laws and policies to balance interests between parties.

Classical theories that explain benefits of integration for various stakeholders form a theoretical basis for industrial processes. In this context, it is worth mentioning the concept of the industrial district described by Alfred Marshall [11], demonstrating that firms tend to congregate to achieve economies of scale in the process of joint activities. According to Marshall, industrial integrations (clusters) are formed under the influence of historical, natural, and geographical factors with optimal labour division and high productivity [8]. According to another theory, economic agents select locations that optimize their welfare,

and individuals aim at maximizing their utility [12]. Reasons for spatial aggregation of industries in certain regions were studied by Alfred Weber in his theory of location of industries. According to Weber, the main reasons for industrial clustering are the development of technical equipment, emergence of production organizations, market forces and cost reductions because of infrastructure construction [13].

Major contributions to the location theory were made by Walter Christaller and August Lösch [14,15]. Christaller proposed the formation of the hexagonal lattice as a spatial structure of production, where a higher-order good, i.e., the centre, is localised at the central area and located at the same distance from each edge of the hexagons associated with the production of a lower-order good, i.e., sub-centres. Later, Walter Isard integrated the models of Johann Heinrich von Thünen, Weber, Christaller, Lösch and others into a unified model and established General Equilibrium Theory, which deals with an economy where all factors and producers, commodities and consumers are, in effect, congregated at one point [16]. The importance of the theory is to optimize placement in production chains of varying degrees and efficiency. The core-periphery model by John Friedman aimed at building industrial communications between regions; distribution of resources, production factors and formation of a regional industrial division of labour [17] could be also considered. Though the above theories explain formation of industrial value-added chains, they do not consider inter-sectoral connections and interactions. The new economic geography contributes to filling these gaps by emphasizing the study of social aspects, including path dependence and institutional factors, as a theoretical framework for the industrial integration and spatial location of production [18,19].

As already noted, industrial integration has a direct impact at all levels of socio-economic systems [3]. This paper considers the influence of circular-economy-related projects for formation of industrial integrations (clusters, symbioses, ecosystems) on the factor potentials of the territories of the presence thereof.

When studying impact of integration, authors often either focus merely on economic effects (reduction of transaction and cost implications, reduction of production cycle duration, reduction/sharing of risks, etc.), or only on description and assessment of economic and environmental efficiency within industrial integration [20–22].

For example, the resource efficiency enhancement is considered by the Solow–Swan model of economic growth, the theory of international economic (technological) structures developed by Ekins, Hughes, et al., the resource-based view theory, and concept of sustainable development which determined directions of modern research in economics, ecology (environmental science in particular), sociology, and other sciences [23–25].

Stefan Schaltegger and Andreas Sturm first proposed use of the Environmental Performance Index, a ratio of economic burden to benefits for the environment [26]. The studies included temporal and spatial characteristics of industrial environmental performance: industrial labour, capital, and natural resources, expected results (predominantly economic output) and other system indicators for assessing the production environmental performance [27]. Gradually, other factors were added to the environmental performance assessment indices: environmental pollution that accompanies economic growth [28,29]; industrial waste and industrial wastewater [30]. Methods for measuring these factors include product life cycle analysis, ecological footprint, fuzzy-set theories, and data envelopment analysis (DEA) modelling [31–34].

Speaking of pollution prevention, one should mention the concept of Best Available Techniques (BAT) used in many countries to control most material- and energy-intensive industrial installations. According to the European Industrial Emissions Directive (Directive 2010/75/EU), “Best Available Techniques” means the most effective and advanced stage in the development of activities and their methods of operation which indicates the practical suitability of particular techniques for providing the basis for emission limit values and other permit conditions designed to prevent and, where that is not practicable, to reduce emissions and the impact on the environment as a whole [35]. Directive 2010/75/EU focuses on setting environmental permit conditions, but we believe that opportunities

opened by implementing BAT are much wider. First, the criteria for determination of BAT include such important provisions as: “the use of low-waste technology”, “the furthering of recovery and recycling of substances generated and used in the process and of waste, where appropriate”, and “the consumption and nature of raw materials (including water) used in the process and energy efficiency” [36]. This means that BAT can be implemented to minimize waste formed within one installation and to provide for integrating various industries to form materials and energy cycles. The latter aspect could also have a social value, especially in regions where significant amounts of waste accumulate due to ‘linear’ economy prevalence [37,38].

We believe that issues related to the social performance of industrial integrations have received much less attention in the literature [39]. In our opinion, it is necessary to consider and study industrial systems, which affect the interests of all stakeholders in the territory of industrial enterprises presence, in terms of the unity of economic (technological) efficiency, and environmental and social performance (Figure 1). It will provide a systematic and comprehensive approach to the problem being studied.

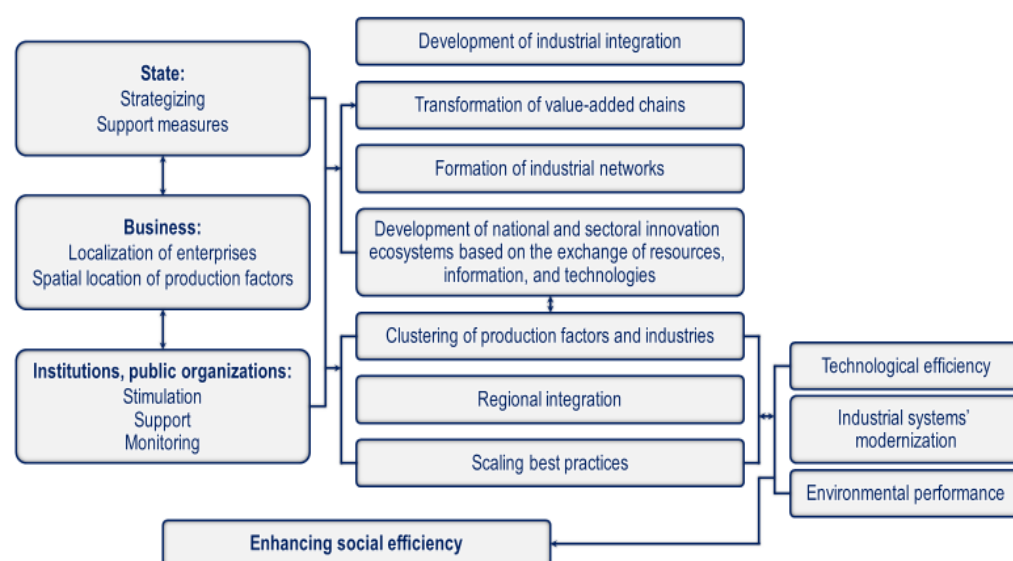


Figure 1. A mechanism for territorial development projects based on industrial systems. Source: Prepared by the authors.

Most authors focus on studying the environmental effects of implementation of technological innovation projects. For example, Tian J. et al. analyse the relationship between technological innovation and greenhouse gases (GHG) emissions [40]. The study, with the Chinese electric power industry as the subject of empirical research, examined the impact of energy generation-related projects on GHG emissions and proposed policy recommendations for the further development of the Technology & Innovation Sector in China.

In another article, the need to analyse projects as part of dynamic socio-ecological-technological systems is emphasized [41]. The authors concluded that Swedish mining policy and impact assessment guidelines ignore key aspects of social, ecological and technological systems, and superficially address many social aspects of sustainable development. Indeed, manufacturing companies today are forced to balance between the need for rapid technological development in the context of Industry 5.0 and formation of a human-oriented industry. In the quest for transformation, innovation is critical. However, the issue of limited resources requires careful assessment and selection of innovative projects, which causes difficulties.

The key challenge is development of practical approaches to implementation of innovative industrial projects that can ensure their competitiveness, minimize negative environmental impacts, and provide for the social development of the territory. As noted by Cherepovitsyn et al., a project assessment system taking into account social effects of

their implementation is needed, but this represents a special research problem [42]. In this context, of interest is the work of the authors, which substantiates, based on an analysis of data from the Global Competitiveness Report and the Global Entrepreneurship Monitor, that achievement of the Sustainable Development Goals leads to positive impacts on the development of entrepreneurship and the competitiveness of individual regions [43]. Social effects can be extremely diverse and, in some cases, it is easy to quantify them. A rather controversial issue is how exactly an enterprise should “share” the effects it creates with society. For example, see [44]. In some cases, local people and non-governmental organizations (NGOs) can consider (mistakenly or not) circular economy-related development projects as leading to deterioration of the state of the environment in the surroundings of waste or wastewater treatment plants [45–48].

In modern research, when talking about the social performance of innovative projects and the social aspects of sustainable development, scientists focus exclusively on the corporate social responsibility of business [49,50]. However, corporate social responsibility presumes, first of all, a mechanism for sharing generated effects between all stakeholders through self-regulation. By social performance, we mean assessment of the results of such a division of effects, which includes not so much specific aspects, but rather determines the general vector of the enterprise’s movement in this area. At the same time, it is also important to take into account the interests of the enterprises themselves, since implementation of circular economy-related projects is often extremely capital-intensive and sometimes long-paying, which, first of all, requires ensuring the economic efficiency of the production itself, based on which heterogeneous social effects can follow [1–3]. The study shows that Chinese investors believe that such projects often conflict with shareholders’ interests, indicating that firms need to sacrifice profits for a greater social responsibility [51]. Although both corporate social responsibility and environmental and technological innovation are beneficial to the development of companies, little is known about whether they can be optimally coupled in the enterprise. The authors’ work sheds light on this issue through an analysis of Chinese industrial companies between 2010 and 2021 [52]. Results show that in certain cases, corporate social responsibility has a negative impact on technological innovation.

Thus, there is a need for a balance between the interests of all stakeholders (state, society, business), including the company itself, rather than pursuing a socially oriented policy for the right to implement projects with high technological and economic risks. Such a balance necessitates the direct participation of the state, on the one hand, as a regulator of the interaction of project stakeholders, and on the other, as one of the direct participants in the project which can create the necessary conditions for enhancing social effects [42].

The authors of [53] show that technological capabilities influence economic performance of SMEs indirectly through open innovation and eco-innovation practices. Of interest is their conclusion on the need for joint evolution of technological and social innovation in companies in order to maximise all effects [54].

From the above review, we can conclude that research on this issue is inconsistent and ambiguous. This actualises the search for new approaches to assessing innovative circular economy-related projects from the point of view of optimality and balance of planned results, taking into account the interests of all stakeholders. The research hypothesis is as follows: projects implemented through inter-sectoral integration on the principles of Best Available Techniques result in enhanced social performance, as well as improved resource efficiency and environmental performance of the key actors implementing circular economy-related development projects.

3. Research Methodology

The methodological basis of the study is the systematic approach developed by the authors, which is a constructive toolkit for studying complex cross-industry systems [50–57].

Further, we will consider requirements for innovative environmental and technological projects (IETP) aimed at developing industrial systems on the principles of sustainable

development. The very term comes from the practice accumulated by the New Independent States (and, in particular, Russia) where the BAT concept is seen as a driver for industrial modernization. Due to inherent functional specificity, IETP possess some characteristics that distinguish them from other technological projects and determine principles for selection and development thereof.

First, it is inter-territorial and cross-sectoral in nature, and that implies a need to consider the following:

- cross-sectoral technological and environmental project requirements;
- goals of numerous project actors and stakeholders with possible conflicts of interest;
- infrastructure development of those territories that are part of the project implementation.

Second, formation of industrial systems in the form of industrial symbioses should be built based on trust, partnership, and collaboration at all levels of IETP implementation and management, provided preliminary long-term experience of interaction [1–3].

Finally, expected IETP outcomes should include economic and technological indicators, ensure improvement in resource efficiency and environmental performance, and lead to positive social effects. This requirement is met by:

1. environmental impact assessment (of the potential partner industries) and strategic social and environmental assessment (of the planned symbiosis as a system);
2. democracy in making mutually acceptable decisions for all project participants, i.e., recognition of the right to participate in the decision-making process of all interested parties.

Implementation of these principles for IETP development and selection involves the following guidelines for the assessment thereof (Figure 2).

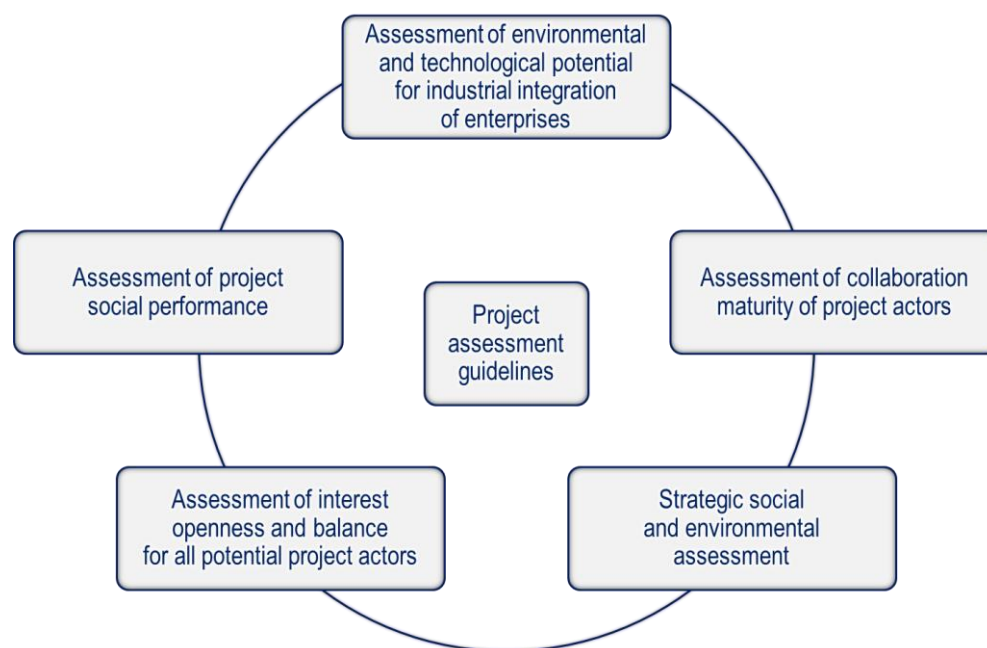


Figure 2. Guidelines for the IETP assessment. Source: Prepared by the authors.

1. Assessment of environmental and technological potential for industrial systems of enterprises involves technological capital; human capital; natural capital; secondary resources (waste to be recycled) as a special type of capital; processes; finance; and consumers for economic, environmental, and social subsystems in terms of the technological development both for an individual actor and for an industrial ecosystem. The internal company policy and potential of project actors should resemble the strategic direction of the implemented project.

2. Assessment of collaboration maturity of the project actors presupposes goal openness of all project participants; an impeccable reputation; positive experience of long-term cooperation; and similarity of corporate cultures. We believe that cooperation and trust are the key factors for IETP implementation.
3. Strategic social and environmental assessment entails implementing environmental industrial policy at the regional level. The project should contribute towards sustainable development of territories; enhancement of the resource efficiency and environmental performance of enterprises; and formation of a circular economy. Therefore, the project implementation should provide for crucial scientific, technological, and socio-economic effects for enterprises and industries.
4. Assessment of interest openness and balance for all potential project actors involves considering various interests of enterprises and territories. Since these interests significantly differ in several aspects, goal alignment is vital for the IETP development and implementation.
5. Assessment of project social performance.

The key and priority factor for the IETP assessment is implementation of the BAT as a core of modern policy for sustainable environmental and technological development of enterprises. Skobelev defines the Best Available Techniques “as a set of economically feasible technological, technical, and managerial solutions, which allow enterprises to achieve high resource efficiency and good environmental performance of the production processes while also reducing carbon intensity of products” [58]. BAT is a concept that has significant potential for socio-economic systems development. It contributes to formation and strengthening of social responsibility and involvement of project actors in the processes of modernization of production technologies in order to improve their resource efficiency and environmental performance.

The development of innovative environmental and technological projects can be divided into several stages (see Figure 3).

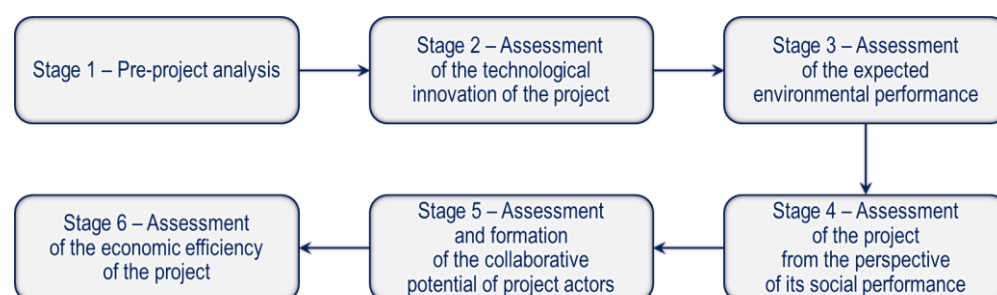


Figure 3. Key stages for the IETP development. Source: Prepared by the authors.

The IETP assessment includes both analytical indicators that represent technological and regulatory environmental factors, and expert indicators that consider social factors which are difficult to measure, as well as key environmental issues.

Selection of appropriate innovative environmental and technological projects consists of several stages.

Stage 1—Pre-project Analysis:

- Analysis of problems of enterprises, the industry, and the territory (expert analysis, analytics, forecast).
- Inventory of enterprises, industries, and territory resources based on assessment of their potential (expert assessment).
- Analysis of the existing business processes, logistical connections and information flows between enterprises and territories.
- Analysis of the infrastructure of the technological development of the territory.

Stage 2—Assessment of the Project Technological Innovation:

- Formation of a project evaluation criteria system for meeting the objectives of all project actors.
- Determination of key characteristics of technological solutions and assessment of the project's strategic technological perspective for all actors.
- Assessing the project by comparing threshold values of the project's innovativeness with the trend indicators in development of maximum indicators of such characteristics of the market.
- Analysis of the projected outputs due to expected improvements in productivity, technological efficiency, and management systems.

Stage 3—Assessment of the Resource Efficiency and Environmental Performance of the Project Actors:

- Assessment of resource consumption by the project actors (consumption of raw materials, energy, water, etc.).
- Assessment of the project compliance with BAT requirements; these requirements cover sectoral environmental performance and resource efficiency levels and, for some sectors, carbon intensity of products (see a more detailed description below).
- Assessment of the project's environmental risks.
- Assessment of additional income for the project actors, which in the forecast will arise with waste recycling, water closed loops, etc.

Stage 4—Assessment of the Project from the perspective of its social impacts:

- Assessment of the anticipated changes in the state of the environment ("environmental friendliness of the project").
- Analysis of the expected changes in the territory's infrastructure, job growth, business opportunities, etc.
- Forecast of the project's impact on future generations' development (scientific, educational, technological, and socio-economic effects for the territory).

Stage 5—Assessment and Formation of Collaborative Potential of Project Actors:

- Assessment of the environmental and technological potential of industrial systems.
- Assessment of the collaboration maturity of the project actors.
- Assessment of the openness and balance of interests of all potential project actors.
- Formation of a system of goals and motivation for project implementation for the project actors.

Stage 6—Assessment of the Project Economic Efficiency:

- Cost-benefit analysis for each project actor.
- Analysis of the project's economic feasibility for the actors and all project stakeholders (potential benefits from the project for some participants do not cause direct or indirect damage to other participants).

The main decision-making approaches when developing the IETP are the following:

1. Cost-benefit analysis. This tool allows analysis of economic, technological, social and image consequences of the project in cost terms from the perspective of assessing the project's overall benefit for both project stakeholders and society. Such analysis should identify risks to project benefits which may be received by certain participants to the detriment of others.

2. Compliance check with environmental and resource efficiency requirements. To ensure projects comply with the BAT requirements, national Reference Documents on Best Available Techniques (BREFs) are used. BREFs establish sectoral BAT-Associated Environmental Performance Levels, BAT-Associated Resource Efficiency Levels, as well as so-called indicative Carbon Intensity Levels (for the most resource-intensive sectors). This system of BAT-associated criteria is essential for industrial enterprises to set goals and objectives for the development thereof. BREF criteria help public and regulatory authorities to assess achieved IETP outcomes for technological transformation and green production. Federal authorities use BREFs and BAT-associated criteria as a tool for making

decisions on supporting leaders and stimulating lagging enterprises for environmental and technological modernization. Banks apply this criteria system to develop new products in the field of green financing.

Currently, BREFs are extensively applied to prepare applications for the Integrated Environmental Permits and to justify projects aimed at increasing production resource efficiency [59,60]. It is particularly important that so-called green projects (for example defined by “International Organization for Standardization 1400-3:2020” standard) implemented in industry should also lead to the implementation of the BAT (as a minimum requirement) and to resource efficiency enhancement [61,62]. In many countries and regions, green projects gain special support from governments and certain preferences from the leading banks. Among green projects, circular economy-related ones play a special role allowing achievement of several Sustainable Development Goals (SDGs), such as SDG 9: Industry, Innovation and Infrastructure; SDG 12: Responsible Consumption and Production; and SDG 13: Climate Action.

3. Expert assessment methods. These are the most common methods, since assessment of environmental, technological, and social benefits of IETP, and formation of a platform for network interaction of enterprises in the industrial sector, are weakly structured. Such methods perform most effectively when there are explicit decision criteria, stakeholders are consulted, experts and advisors are appropriately qualified and experienced, and decisions are supported by formal justifications. In the Russian Federation, the expert community plays a key role in preparing new and reviewing existing BREFs. This community includes over 150 highly qualified experts with practical experience in the areas of BAT implementation [63].

4. Environmental assessment methods. When assessing projects in terms of corporate social performance, it is necessary to consider challenges of balance between environmental and socio-economic impact. Socio-economic consequences should be subject to systematic analysis using environmental assessment methods. This paper suggests evaluation of the innovative environmental and technological projects of the formation of circular economy-related projects (industrial symbioses) based on their technological, environmental, and social performance.

The key principles underlying the management of technology interactions are self-organization, partnership, and collaboration [1–3]. The implementation of these principles implies the exclusion of external management, where each company develops its own policy considering the goals of its partners (Figure 4).



Figure 4. An organizational and management model based on technological cooperation to ensure the sustainability of industrial integration. Source: Prepared by the authors.

Ensuring this interaction requires a joint structure, the functions of which will be to coordinate strategic goals and operational decisions. To support the implementation of technological interaction between enterprises in the field of cross-sectoral environmental and technological projects, we propose creation of a project office to optimize management decisions. The project office has no management functions. Its objective is to provide top management with managerial decisions that would balance the interests of all stakeholders of the technological interaction.

In the next section, the proposed methodological approach is tested in two industrial symbioses of advanced socio-economic development territories in the town of Novotroitsk (Orenburg region, Russian Federation).

4. A Case Study of Industrial Symbioses in Novotroitsk Advanced Socio-Economic Development Territory

4.1. Data Sources and Experts Involved in Case Study Implementation

Data characterising Industrial Symbioses in Novotroitsk originate from two sources. Firstly, we used open-source data (such as regional reports on the state of the environment and local online and offline publications). Secondly, we used data collected in the Russian BAT Bureau's information system. The Bureau develops and reviews national Reference Documents on Best Available Techniques, and manages the Expert Society set up by the Ministry for Industry and Trade of the Russian Federation in 2014 [59]. The Expert Society consists of engineers, environmentalists, sector BAT specialists, economists, and sociologists, who evaluate national and international projects aimed at the enhancement of resource and environmental efficiency of individual industries and industrial symbioses. Being members of the Expert Society, authors of this article were involved both in the review of sectoral BREFs (on the production of cement, lime, and on waste management) and in the assessment of technological and environmental projects designed by Novotroitsk practitioners. Experts prepared a number of recommendations considered by the project developers; initial projects were improved by the adoption of these recommendations. There are no conflicts of interests, and some data characterising the projects is available on the websites of the industries and regions concerned (in Russian).

4.2. Case Study Results

The Russian Federation considers the triple planetary crisis of climate change, nature and biodiversity loss, and pollution and waste to be incredibly challenging for the development of industrial activities and modern technologies [64]. The country implements the Environmental Industrial Policy (EIP) aimed at resource efficiency enhancement and environmental impact minimization of Russian industry.

At the sectoral level, the EIP is based on development and implementation of the Best Available Techniques (this concept is described in Section 2. Literature Review and Hypothesis Development, above). Most BREFs establish recommendations on recycling, replacement of natural resources by waste, etc. These issues are addressed in the sectoral BAT-Associated Environmental Performance and Resource Efficiency Levels.

For several sectors, recommendations on the Best Environmental Practices for remediation of damage caused by industrial systems are also developed. National BREFs for the mining industry (in particular, coal and iron ore mining) contain such recommendations. Regional case studies show that biodiversity issues are considered while restoring older mines and damaged landscapes. Thus, increasing resource efficiency is one of the priority tasks for the development of Russian industry (first of all, metallurgy, building materials, and chemical industry). Setting interaction between these key economic sectors, classified as areas of BAT implementation, can greatly contribute to sustainable development.

The authors consider systemically the possibility of managing the aggregate components of enterprises that are part of an industrial system. The complex approach in industrial systems is a way of managing enterprises, in which they are considered as a system of elements, where interaction is aimed at achieving a common goal. System analysis

serves as a methodological framework that integrates methods, research tools, activities and resources to evaluate industrial systems. Implementation of the systems approach in industry allows optimization of all business processes.

The municipality of the town of Novotroitsk located in the Orenburg region is a large industrial centre of Russia with substantial natural resource potential. Mineral resources are represented by various types of raw materials that are used in metallurgy, chemical, and construction industries. The key strategic priorities of the town are transition to green economy through a set of measures implemented in order to modernize enterprises, development of inter-sectoral integration, and improvement of social performance and quality of life. In 2017, Novotroitsk became a territory of advanced socio-economic development. It includes JSC Novotroitsk Chromium Plant, Novotroitsk Soda Plant LLC, and Novotroitsk Plant of Bisulphite and Metabisulphite Ltd. Attracting investments and IETP implementation in special status territories is one of the priorities for regional development [65].

Novotroitsk Chromium Plant (JSC NPCC) has been implementing the full cycle of chromium production (from ore processing to obtaining pure metal and a wide range of chromium compounds) for more than 50 years. For many years, when processing chromium ores, sodium salt sludge was formed as a waste. At JSC NPCC, the specific amount of waste is assessed as 2.5 tonnes of sludge per 1 tonne of sodium monochromate. The major part of the sludge was disposed of in special tailing ponds [66]. In 2014, JSC NPCC implemented a large-scale modernization project, switching to dolomite-free sodium monochromate production technology. This project is vital for the region as a valuable natural resource—dolomite—has been replaced by recycled waste.

The next stage in the territory's development was the launch of LLC Novotroitsk Soda Plant (LLC NSP) to facilitate production of chromium compounds by JSC NPCC with soda ash as the main charge component in producing sodium monochromate. In 2022, the only plant to produce bisulfite and pyrosulfite—Novotroitsk Plant of Bisulphite and Metabisulphite Ltd. (NPBM Ltd. Novotroitsk, Russia)—was opened in Russia. The enterprise produces 3500 tonnes of sodium pyrosulfite and 2500 tonnes of sodium bisulfite every year [67]. As a result of cross-sectoral integration of three enterprises (JSC NPCC, LLC NSP, NPBM Ltd.), a chemical-industrial system contributing towards sustainable development has emerged (Figure 5).

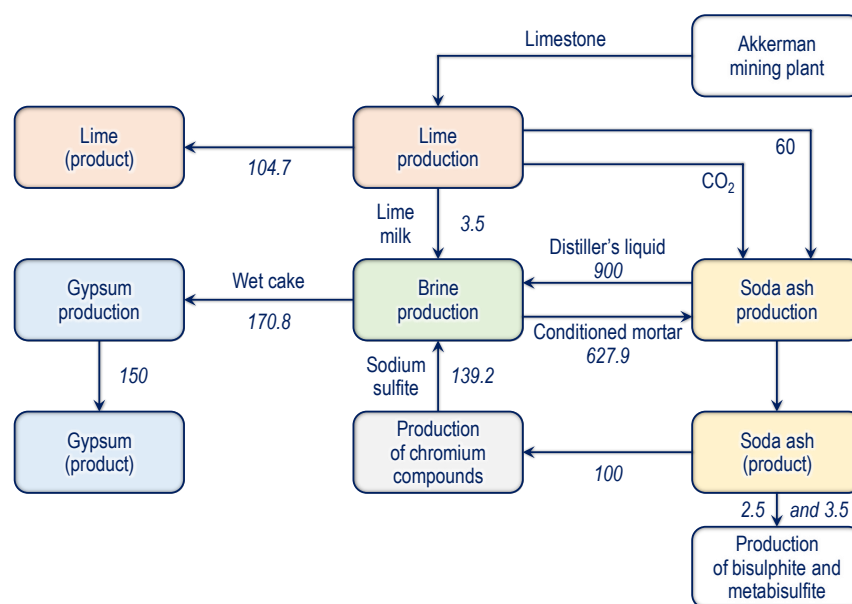


Figure 5. Principal scheme of Novotroitsk Industrial system. Source: Prepared by the authors. All indicators are given in thousand tonnes per year.

A part of the finished product (lime), formed in lime kilns, is used in the production of soda ash after slaking. Then, soda and brine are supplied as raw materials to JSC NPCC and NPBM Ltd. Thus, JSC NPCC acts as a supplier of raw materials (sodium sulfate) and the main consumer of the finished product (soda ash) produced at LLC NSP.

Development of the above-described industrial system leads to:

- reduction in specific heat energy consumption to 4.25 GJ per tonne of soda (the range of values established in BREF 19-2020 is 4.6–5.9 GJ per tonne of soda);
- reduction in dolomite and limestone consumption by 160 thousand tonnes per year;
- reduction in the specific amount of waste from 2.5 to 1.1 tonnes of sludge per 1 tonne of sodium monochromate generated in the main production;
- extra absorption of over 60 thousand tonnes of CO₂ [68].

Rational use of raw materials in the industrial system provides for reduced consumption of natural resources, an expanded range of end products, and manufacture of additional products from recycled waste. Hence, environmental and technological characteristics of the Novotroitsk industrial system meet the principles of the Environmental Industrial Policy of the Russian Federation. From the social point of view, it is important that the area covered by the older tailing ponds gradually decreases and diffused emissions of pollutants reduce. The local population considers such effects as positive changes. For instance, during the Environmental Impact Procedure, Novotroitsk NGOs at first were concerned about development of another chemical installation in the highly industrialised urban area, but later, once the new production and its role in the development of an innovative industrial system was explained, they decided to support the initiative of Novotroitsk. In 2021, all members of this industrial system pioneered in obtaining BAT-based Integrated Environmental Permits (new licenses granted by the environmental authorities to larger industries).

Another sustainable development project in Novotroitsk is Green Cement, an industrial system including JSC Ural Steel and companies of the construction materials sector. The industrial system operates on the principle of symbiosis—when waste from some enterprises is a resource for others. The basis for the industrial system's formation is innovative technology for slag processing—Biscuit (Figure 6) with a capacity of 300 tonnes per hour.

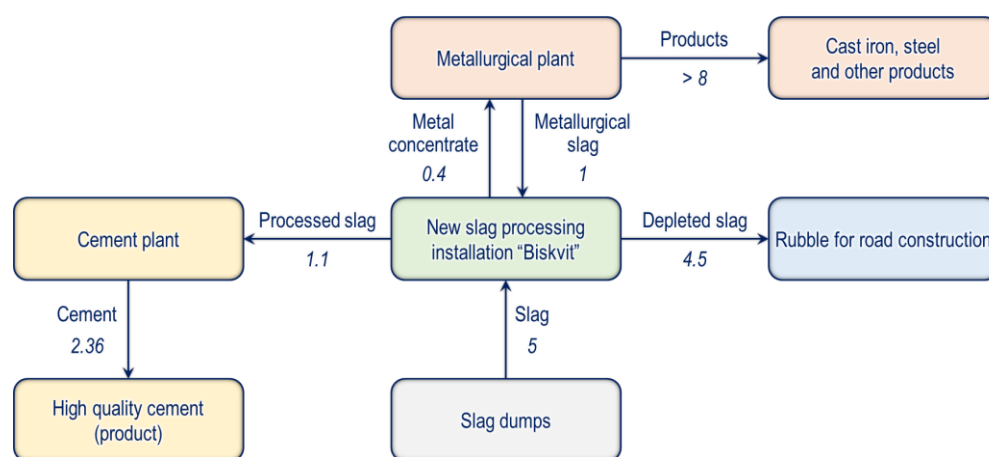


Figure 6. Principal scheme of the Green Cement industrial system. Source: Prepared by the authors.

According to the Russian Encyclopaedia of Technologies, waste rock (1.5–2.5 tonnes), slag (0.5–1.0 tonnes), sludge (0.08–0.12 tonnes), dry dust (0.08–0.12 tonnes), and scale (0.03–0.04 tonnes) are formed because of extraction and beneficiation of iron ore during the production of 1 tonne of rolled metal. As a result, 450 thousand tons of metal can be obtained from 1 million tons of iron-containing waste (Encyclopaedia of Technologies). Production of Portland cement is one of the promising areas of metallurgical slag recycling [69].

The dry process of cement manufacture is that raw materials are dried before or during grinding and the raw charge comes out in the form of a finely ground dry powder. The main advantage of this technology is lower energy consumption for clinker production (2.65–4.65 GJ/t clinker) compared to other technologies, e.g., wet-processing technology [70]. Some wastes (belite-containing and blast-furnace slag, ash) by their properties are similar to natural components used in the cement industry but are free from carbonates. Therefore, a rationale for saving fuel and reducing GHG emissions during clinker burning is an extensive use of metallurgical waste [71].

Nowadays, Akkermann Cement uses limestone, clay, and processed metallurgical slag (both from JSC Ural Steel and accumulated in older dumps) as raw materials to manufacture cement. The slag content in the raw meal used to produce cement clinker reaches 30%. An innovative ‘Biscuit’ installation processes a total of 6 million tons of JSC Ural Steel slag, including 5 million tons of slag accumulated in 1960–2000. Up to 1 million tons of processed slag is consumed to manufacture cement; 0.4 million tons of iron ore concentrate returns to JSC Ural Steel; 4.6 million tons of rubble (crushed stone) are used for road construction, which is important from the point of view of urban infrastructure development [72]. Replacing natural components with waste decreases heat consumption (from 4.5 to 3.0 MJ per 1 ton of clinker), and electrical energy (from 129.6 to 86.4 kWh per 1 tonne of clinker) along with a decrease in CO₂ emissions by 2.1–2.2 times. The latter effect is achieved because of both reduction of the co-called energy-originated emissions (formed by burning fuel) and technology-originated emissions (formed as a result of limestone decomposition).

As mentioned above, the Green Cement industrial system provides for using metal concentrates in metallurgical production. Moreover, metallurgical enterprises, being elements of the industrial symbiosis, supply all enterprises in Novotroitsk with electricity, water, and steam from their thermal power plants. Based on the methodological approach described in the previous sections of this article, a balance of material flows of the Green Cement industrial system has been prepared. Thus, Green Cement is a typical project providing for the sustainable development of the town of Novotroitsk. Total savings from reducing resource consumption and minimizing waste during industrial systems formation were calculated (Table 1).

Table 1. Resource efficiency indicators of cement production prior to and as a result of a circular economy-related development implementation (Green Cement).

Indicators	Industrial Enterprises	Industrial Symbiosis	Savings, Million RUB
Thermal energy consumption, million GJ	8.97	3.19	1702.15
Slag usage, million tonnes	–	1.00	–
Consumption of primary resources (limestone, clay, gypsum), million tonnes	3.78	1.88	820.8
Cement production, million tonnes	2.36	2.36	–
CO ₂ -equivalent, million tonnes	1.6	0.75	850.0
Total:			3372.95

In 2024–2025, it is planned to implement several environmental and technological projects: to decrease emissions of nitrogen oxides down to 300 mg/m³; to set a continuous emission self-monitoring system; and to reduce diffuse dust emissions.

From the social perspective, it is very important that older slag heaps, which look like dark-grey hills surrounding the JSC Ural Steel plant, are being gradually removed. The “visual pollution” is minimized and people living in Novotroitsk appreciate this positive socio-environmental effect. In addition, the Green Cement project plans to green the area (planting at least five hectares of trees) and to flood an older limestone quarry.

Local authorities have already initiated a strategic environmental assessment procedure. It is anticipated that together with the slag heaps removal, the new water reservoir will contribute to forming a more attractive urban landscape and to improvement of the air quality in the long term.

The formation of two industrial systems in the town of Novotroitsk leads to significant social and environmental effects (Table 2).

Table 2. Social and environmental impacts of circular economy-related projects in Novotroitsk.

Social and Environmental Impacts	Scale of Impact	Types of Impact	Qualitative/ Quantitative	Source
State				
Implementing strategic initiatives and national programmes, including transition to green economy	macrolevel	environmental	+ / −	official databases
Scaling successful experience of circular economy-related projects (industrial symbioses) through network integration	meso and micro levels	environmental and social	+ / −	field surveys
Improving technological independence	macrolevel	technological	+ / −	official databases
Increasing tax payments to budgets at all levels	macro and meso levels	economic	− / +	official databases
Public				
Increasing service availability and quality	macro and meso levels	environmental	+ / −	official databases
Improving state of the environment and decreasing “visual pollution”	macro and meso levels	environmental	+ / −	official databases
Implementing national projects—“Environmental Protection” and “Circular Economy”.	macro and meso levels	environmental and social	+ / +	official databases
Territory (region)				
Increasing production of construction materials needed to develop the town of Novotroitsk and its surroundings	meso and micro levels	economic	− / +	regional official databases
Developing infrastructure	meso and micro levels	economic and social	− / +	regional official databases
Increasing employment levels in the region	meso and micro levels	economic and social	− / +	regional official databases
Industrial enterprises				
Enhancing resource efficiency	micro level	environmental and economic	− / +	Sustainable enterprise development report (SDR)
Cutting costs of raw materials	micro level	economic	− / +	operational report
Reducing GHG emissions	micro level	environmental and economic	− / +	SDR
Developing high-tech jobs	micro level	economic and social	− / +	SDR
Developing human capital	micro level	economic and social	− / +	SDR

Public interests are one of the most important principles when assessing the social and environmental performance of sustainable development projects. The formation of industrial systems in Novotroitsk led to:

- increased employment levels (430 jobs with a more comfortable work environment created);
- additional tax revenues of RUB 900 million for the regional budget;
- increased accessibility and quality of services through the development of social infrastructure, including construction and repair of housing stock, transport development, further development and maintenance of urban municipal infrastructure (in 2022 the total area of refurbished premises was about 7.0 thousand m²; 24 residential buildings with 780 apartments were redeveloped);
- solving socially significant issues and developing the town (historical part of the town was reconstructed; the Ice Palace built; over RUB 750 million was allocated for renovation of children's educational institutions, healthcare, cultural, and sports facilities).

Cumulative social and environmental effects increase along with industrial systems development.

5. Discussion

Network integration of companies, providing synergy of resources and potentials, is an effective tool for the development and implementation of innovative technologies that allow achievement of optimal resource efficiency indicators. A systematic complex approach to the formation of a cross-industrial system on the principles of network integration and partnerships ensures technological interaction between companies, optimizes the methods and forms of their economic activities, and allows integration participants to achieve strategic goals and ensure environmental and social effects for the territory of presence.

According to research [73], industrial ecosystem synergy must exist for technology-driven innovation to be successful. A mechanism that balances satisfaction of socio-ecological-economic interests is based on the indicators of socio-ecological-economic system balance [39]. The ecosystem approach allows us to take a new look at the structure of socio-economic systems at different levels, to rethink their structure and connections, and to optimize ways and forms of economic activity to enhance the benefits of synergy from the symbiotic interaction of various economic agents in the form of enhanced social performance due to coordination of their interests, achievement of common goals, and development of common values.

Balance is characterized by a state of dynamic equilibrium, continuity of system processes, energy and information exchange, rational use of natural resources, and adaptation to a changing environment in accordance with innovative development goals. The balancing of social, environmental, and economic interests of actors allows levelling of imbalances and disproportions within the system, thus ensuring its sustainability and the ability to withstand external and internal threats [74].

Various methods and approaches have been developed to assess industrial symbioses. Some of these relate to assessing stability of a network of industrial actors in a symbiosis; level of productivity; relationships between industrial actors, etc. [75–78]. It is shown that the process of industrial symbioses development should adhere to the principle of considering public interests to obtain positive social effects, including increased levels of employment, replenishment of regional budgets, increased availability and quality of services through the development of social infrastructure, and an improved urban environment.

In this article, we confirmed the research hypothesis that projects implemented through inter-sectoral integration on the principles of Best Available Techniques result in enhanced social performance, as well as improved resource efficiency and environmental performance of the key actors implementing circular economy-related development projects.

6. Conclusions

This paper discusses development and approbation of a methodological approach to assess predominantly social and environmental effects arising from implementation of various circular economy-related inter-sectoral projects. The authors' approach has been tested using evidence of two industrial symbioses of advanced socio-economic development territories in the town of Novotroitsk (Orenburg region, Russian Federation). Such a perspective of assessing investment projects would allow focusing of state support measures on common priorities for the implementation of regional environmental and industrial policies.

However, it is important to note that the study has several limitations.

1. The article deals with a type of industrial symbiosis in which surplus resources or waste or by-products are exchanged between enterprises located close to each other (territorial proximity).
2. Indicators selected for evaluation must be applicable to all potential participants in the symbiosis. Indicators can be calculated by quantitative characteristics or by qualitative characteristics through expert assessment.
3. Indicator evaluations can be quantified, where the dynamics of the indicator are assessed, and scores are assigned. For qualitative indicators, a scale with a description of grades is proposed.
4. Experts jointly assign weights to the indicators. Distribution of weighting coefficients can be done by the initiators of the study.

The experience of successful implementation of industrial symbiosis in the town of Novotroitsk evidences that industrial systems provide for fundamental changes in resource efficiency and environmental performance of the installations involved in the projects. The symbioses achieved reduction in: (i) energy consumption in cement and soda production by approximately 1.5 times; (ii) GHG emissions by more than 2 times; (iii) waste of sodium monochromate production by approximately 2.3 times. Such industrial symbioses meet criteria established for sustainable development projects in the Russian Federation. In terms of metallurgy and construction materials industry symbiosis, accumulated experience can be replicated in regions where in the past metallurgical enterprises generated significant amount of slag, and where deposits of raw materials necessary for cement production are available. Such projects can be implemented with the support of the state or the banking sector by developing green financial instruments.

Future research directions may also be highlighted. For example, developing tools for assessment of territorial co-operation and collaboration, and the influence of enterprises and organizations on the formation of various models of industrial systems and the effectiveness of their implementation. It seems promising to use a methodology for assessing the combination of regional factors (infrastructural maturity, logistical connections, level of support of territorial authorities, etc.) in terms of creating various models of industrial systems. According to Streimikiene et al. ([79], p. 1), culture plays an important role in implementing sustainability principles, and approaching sustainable development goals across different countries can be considered as an impulse for further research. The fundamental difference between the presented research and previously conducted studies is our consideration of environmental and social factors in project evaluation.

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