DOI: 10.46541/978-86-7233-439-5_554

XXXI International Scientific Conference
Strategic Management
and Decision Support Systems
in Strategic Management
Sm2026

Subotica (Serbia), May 18, 2026

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JEL: C44, Q56

DIGITALIZING CIRCULAR ECONOMY SYSTEMS: A MULTI-CRITERIA DECISION-MAKING APPROACH TO SUSTAINABLE ECONOMIC DEVELOPMENT

Abstract: The transition from linear to circular economic systems represents one of the key challenges for achieving sustainable economic development. At the same time, digitalization is increasingly recognized as a strategic enabler that can support the implementation, monitoring, and optimization of circular economy practices. This paper explores how digital technologies and multi-criteria decision-making (MCDM) methods can support the transition toward more sustainable and resource-efficient economic systems.

The research is conceptually grounded in a project focused on strengthening institutional and research capacities for the digitalization of circular economy practices. The study develops a methodological framework that integrates sustainability indicators with multi-criteria decision-making tools in order to support decision-making processes related to circular economy implementation. The proposed approach enables the evaluation and prioritization of circular economy strategies by considering multiple economic, environmental, and social criteria simultaneously.

The analysis highlights the importance of stakeholder cooperation among academia, policy makers, and small and medium-sized enterprises in creating enabling conditions for circular economy adoption. Digital platforms and data-driven tools are identified as key instruments for improving resource efficiency, facilitating information exchange, and supporting evidence-based policy making.

The results of the study contribute to the growing body of research on sustainability and circular economy by demonstrating how MCDM approaches can support the design of more efficient and transparent decision-making processes. Furthermore, the research provides practical recommendations for strengthening circular business models, supporting green digital transformation, and enhancing sustainable economic development.

Keywords: circular economy, digitalization, sustainability, multi-criteria decision-making, sustainable economic development

1. INTRODUCTION

The transition from linear to circular economic systems represents a fundamental shift in contemporary economic development paradigms. Circular economy (CE) principles aim to reduce resource consumption, minimize waste, and promote the reuse and recycling of materials, thereby contributing to long-term sustainability.

At the same time, digitalization has emerged as a key enabler of this transition. Digital technologies—such as data platforms, geographic information systems (GIS), and optimization tools—allow for improved monitoring, coordination, and efficiency of resource flows. In this context, the integration of digital tools with decision-support methodologies becomes essential.

Building on recent research in regional infrastructure planning and waste management systems, this paper develops a comprehensive framework that combines digitalization and multi-criteria decision-making (MCDM) approaches to support circular economy implementation.

The research is further grounded in broader capacity-building initiatives in green and digital transitions, where strengthening institutional and research capabilities is identified as a key prerequisite for sustainable development.

The main objective of this paper is to develop an integrated methodological framework that supports decision-making in circular economy systems by combining sustainability indicators, digital tools, and multi-criteria evaluation methods.

2. LITERATURE REVIEW

2.1. Circular Economy and Sustainable Development

The circular economy (CE) has emerged as a central paradigm for achieving sustainable development by decoupling economic growth from resource consumption and environmental degradation. Unlike the traditional linear model, circular systems aim to maintain the value of products, materials, and resources for as long as possible through reuse, recycling, and recovery processes (Geissdoerfer et al., 2017).

Recent research highlights that CE contributes not only to environmental sustainability but also to economic resilience and competitiveness. By promoting resource efficiency and innovation, circular economy practices support the development of new business models and value chains (Kirchherr et al., 2017; Korhonen et al., 2018). In particular, CE has been strongly linked to the objectives of the European Green Deal and the transition toward climate-neutral economies.

However, the implementation of circular economy systems remains uneven, especially in transition economies where institutional capacity, infrastructure, and technological readiness are still developing. In such contexts, waste management systems represent a critical entry point for CE implementation, as they directly influence resource recovery and material circulation (Di Vaio et al., 2023).

As emphasized in recent infrastructure-focused research, waste management should be understood as a complex system that integrates environmental, economic, and logistical dimensions, while also contributing to regional development and innovation processes.

2.2. Digitalization and Circular Economy Systems

Digitalization is increasingly recognized as a key enabler of circular economy transition. Digital technologies facilitate the collection, processing, and analysis of large datasets related to resource flows, emissions, and infrastructure performance. This enables more efficient planning, monitoring, and optimization of circular systems (Nobre & Tavares, 2017).

In the context of CE, digital tools support several critical functions:

- *real-time monitoring of material flows*
- *optimization of logistics and resource allocation*
- *improved traceability and transparency*
- *data-driven policy and decision-making*

Technologies such as Geographic Information Systems (GIS), Internet of Things (IoT), big data analytics, and digital platforms are particularly relevant for infrastructure-intensive sectors such as waste management and energy systems (Kristoffersen et al., 2020).

Existing research confirms that GIS-based spatial analysis significantly improves infrastructure planning by enabling the identification of optimal facility locations and transport routes (Yadav & Karmakar, 2020; Moumane et al., 2025). Furthermore, the integration of digital tools with optimization models enhances the efficiency and sustainability of waste management systems.

Beyond technical applications, digitalization also facilitates stakeholder cooperation by enabling information exchange between public authorities, firms, and research institutions. This is particularly important in circular economy systems, where coordination across multiple actors is required.

The importance of strengthening digital and research capacities is also emphasized in large-scale research initiatives, where digital transformation is seen as a key driver of sustainable development and institutional modernization.

2.3. Multi-Criteria Decision-Making in Sustainability Analysis

Decision-making in circular economy systems involves multiple, often conflicting objectives, including economic efficiency, environmental protection, and social impact. Traditional single-objective optimization approaches are therefore insufficient for capturing the complexity of sustainability-related decisions.

Multi-criteria decision-making (MCDM) methods provide a structured approach for evaluating alternatives based on multiple criteria. Among these methods, the Analytic Hierarchy Process (AHP) is widely used due to its ability to incorporate expert judgment and determine the relative importance of criteria (Saaty, 1980).

Recent studies demonstrate that MCDM approaches are particularly suitable for sustainability assessment, as they allow for the integration of qualitative and quantitative criteria and enable transparent decision-making processes (Mardani et al., 2015). In the context of circular economy, MCDM methods have been applied to:

- *evaluation of waste management strategies*
- *ranking of circular business models*
- *infrastructure planning and site selection*
- *sustainability performance assessment*

The application of AHP in waste management planning enables decision-makers to balance economic, environmental, and technological considerations, thereby supporting more sustainable outcomes.

2.4. Integration of Digital Tools, MCDM and Optimization Models

Recent advances in sustainability research emphasize the importance of integrating digital technologies, multi-criteria decision-making, and mathematical optimization into unified analytical frameworks.

GIS-based approaches provide spatial data and visualization capabilities, while MCDM methods structure decision preferences. Optimization models, particularly Mixed-Integer Linear Programming (MILP), are then used to identify optimal system configurations under defined constraints.

The integration of these approaches enables:

- *evaluation of multiple scenarios*
- *analysis of trade-offs between cost and sustainability*
- *improved robustness of decision-making*

As demonstrated in recent research on regional waste management systems, the combination of GIS, AHP, and MILP allows for comprehensive infrastructure planning that simultaneously considers economic efficiency, environmental impact, and technological feasibility.

Moreover, optimization models incorporating environmental externalities, such as CO_2 emissions, provide a more realistic representation of sustainability challenges and support alignment with climate policies.

2.5. Stakeholder Cooperation and Institutional Capacity

The successful implementation of circular economy systems depends on effective cooperation among stakeholders, including public authorities, businesses, research institutions, and local communities.

Institutional capacity plays a crucial role in this process, as it determines the ability to design policies, implement strategies, and utilize digital tools. In many transition economies, limited institutional capacity represents a key barrier to circular economy adoption.

Recent research highlights the importance of capacity-building initiatives that strengthen research, administrative, and innovation capabilities. Such initiatives contribute to the development of interdisciplinary knowledge, improve policy design, and support the dissemination of sustainability practices.

In this context, universities and research institutions play a central role by providing expertise, developing analytical tools, and supporting evidence-based decision-making.

2.6. Research Gap and Contribution

Although the literature on circular economy, digitalization, and MCDM has expanded significantly in recent years, several gaps remain.

First, many studies focus on conceptual aspects of circular economy without providing operational decision-support frameworks. Second, digitalization is often treated as an external factor rather than being fully integrated into analytical models. Third, MCDM and optimization approaches are frequently applied separately, limiting their potential to address complex sustainability challenges.

This study addresses these gaps by developing an integrated framework that combines digital tools, multi-criteria decision-making, and optimization modelling for circular economy systems. By building on existing research in digitalized infrastructure planning and aligning with broader sustainability and capacity-building initiatives, the paper contributes to the development of more effective and transparent decision-making processes for sustainable economic development.

3. METHODOLOGY

3.1. Research Design and Conceptual Framework

This study adopts an integrated methodological approach aimed at supporting decision-making processes in circular economy systems through the combination of digital technologies and multi-criteria analytical tools.
The proposed framework is structured as a multi-layer decision-support system consisting of three interconnected components:

1. Digital layer – data collection, processing, and spatial analysis using digital tools
2. Decision layer – evaluation and prioritization of criteria using multi-criteria decision-making methods
3. Optimization layer – system configuration through mathematical optimization

This approach builds upon previous research in digitalized infrastructure planning and waste management systems, while extending it toward a broader sustainability-oriented and policy-relevant framework.
The integration of these components enables the simultaneous consideration of economic, environmental, technological, and social dimensions of circular economy systems.

3.2. Data and Digital Infrastructure

The empirical and analytical foundation of the proposed model is based on the integration of heterogeneous data sources that jointly capture the complexity of circular economy systems. This includes spatial data describing the geographical distribution of waste generation and existing infrastructure, economic data related to cost structures and operational expenditures, environmental data reflecting emissions and resource use, as well as technological indicators that capture the level of digital readiness and infrastructure capacity. The combination of these data dimensions enables a comprehensive representation of the system, allowing both physical flows and sustainability-related impacts to be analyzed within a unified framework.
Digital tools play a central role in structuring and processing these data, transforming them into usable inputs for further analysis. In particular, Geographic Information Systems (GIS) are employed to support spatial modelling of the system by identifying feasible locations for infrastructure development, calculating transport distances between waste generation points and processing facilities, and analyzing spatial constraints and regional heterogeneity. Through these functionalities, GIS enables a more precise understanding of the spatial dimension of circular economy systems, which is essential for realistic infrastructure planning.
By integrating digital tools into the analytical process, raw and often fragmented data are transformed into structured and decision-relevant information that can be directly incorporated into multi-criteria evaluation and optimization models. Such digitalization significantly enhances the quality of decision-making by improving the accuracy of input data, enabling more efficient coordination of resource flows, and supporting the development of data-driven and evidence-based solutions for sustainable infrastructure planning.

3.3. Multi-Criteria Decision-Making Model

Given the multi-dimensional nature of circular economy systems, a multi-criteria decision-making (MCDM) approach is applied to structure and evaluate decision alternatives.

3.3.1. Criteria selection

The evaluation framework is based on four main criteria groups:

- *Economic (C_1) – investment, operational, and transport costs*
- *Environmental (C_2) – emissions, waste reduction, resource recovery*
- *Technological (C_3) – level of digitalization and technological feasibility*
- *Social (C_4) – stakeholder impact and regional development effects*

3.3.2. AHP weighting procedure

The Analytic Hierarchy Process (AHP) is used to determine the relative importance of criteria. Pairwise comparisons are conducted based on expert judgment, resulting in a consistent weight vector:

$$W = (w_1, w_2, w_3, w_4), \sum_{i=1}^{4} w_i = 1$$

The consistency of the comparison matrix is verified using the consistency ratio (CR), ensuring the reliability of the results.

3.3.3. Composite evaluation

Each alternative system configuration is evaluated using a composite score:

$$S_j = \sum_{i=1}^{n} w_i \cdot x_{ij}$$

where:

- S_j– *overall performance score of alternative j*
- w_i– *weight of criterion* i
- x_{ij}– *normalized value of alternative junder criterion* i

This step introduces stakeholder preferences into the analytical framework and ensures that optimization results reflect sustainability priorities.

3.4. Optimization Model

The circular economy system is modelled as a network of waste generation nodes, processing facilities, and transport links. The objective is to determine the optimal configuration of the system.

3.4.1. Decision variables

- $y_k \in \{0,1\}$*: binary variable indicating whether facility k is established*
- $x_{ik} \geq 0$*: quantity of waste transported from node i to facility k*
- $z_k \geq 0$*: quantity of processed waste at facility k*

3.4.2. Objective function

The objective function minimizes total system cost, including environmental externalities:

$$\min Z = \sum_k F_k\, y_k + \sum_{i,k} C_{ik}\, x_{ik} + \sum_k O_k\, z_k + \lambda \sum_{i,k} E_{ik}\, x_{ik}$$

where:

- F_k – *fixed cost of opening facility k*
- C_{ik} – *transport cost from node i to facility k*
- O_k – *operational cost*
- E_{ik} – *emissions coefficient*
- λ – CO_2 *penalization parameter*

This formulation extends classical cost-minimization models by internalizing environmental impacts, in line with sustainability-oriented optimization approaches.

3.4.3. Constraints

The model is subject to the following constraints:

1. Flow balance constraint

$$\sum_k x_{ik} = D_i \forall i$$

2. Capacity constraint

$$z_k \leq Cap_k \cdot y_k$$

3. Processing constraint

$$z_k = \sum_i x_{ik}$$

4. Logical constraint

$$x_{ik} \leq M \cdot y_k$$

5. Non-negativity and binary conditions

The integration of multi-criteria decision-making and optimization modelling represents a key component of the proposed analytical framework. In this study, the results of the Analytic Hierarchy Process are not treated as a separate evaluative step, but are directly embedded into the optimization context. The weights derived from AHP reflect stakeholder preferences and strategic priorities, and are subsequently incorporated into the evaluation of alternative system configurations. In addition, these preferences influence the calibration of key optimization parameters, allowing the model to reflect different decision-making orientations, such as cost efficiency or environmental sustainability. Following the optimization process, the obtained solutions are further assessed through composite indicators, which enable the ranking of alternatives based on multiple criteria. In this way, the model combines normative optimization with preference-based evaluation, ensuring that the results are not only technically efficient but also aligned with broader sustainability objectives and stakeholder expectations.

In order to examine the robustness and practical relevance of the proposed framework, a scenario-based approach is applied. Different system configurations are analyzed under varying assumptions that reflect alternative policy and decision-making contexts. These scenarios are constructed by modifying both the relative importance of decision criteria and the level of environmental penalization within the optimization model. As a result, one scenario emphasizes cost minimization, another reflects a balanced consideration of economic and environmental objectives, while a third prioritizes sustainability and emission reduction. By systematically varying these parameters, the model enables the analysis of trade-offs between economic efficiency and environmental performance. This approach provides valuable insights into how different policy choices and strategic priorities influence the optimal configuration of circular economy systems, thereby supporting more informed and flexible decision-making processes.

4. RESULTS AND DISCUSSION

The results of the proposed model provide important insights into the relationship between economic efficiency, environmental performance, and the role of digitalization in circular economy systems. By applying the integrated framework across different decision scenarios, the analysis reveals how variations in policy priorities and decision-maker preferences influence the optimal configuration of infrastructure and resource flows.

The findings indicate that solutions derived under purely cost-oriented assumptions tend to favor centralized infrastructure configurations and longer transport routes, as these minimize immediate financial expenditures. However, such configurations are associated with significantly higher environmental impacts, particularly in terms of emissions and inefficient resource utilization. This confirms that traditional cost-minimization approaches are insufficient when sustainability objectives are taken into account.

When environmental considerations are introduced into the model through emission penalization and adjusted criteria weights, the structure of the optimal solution changes substantially. The results show a shift toward more decentralized infrastructure systems, characterized by shorter transport distances and increased reliance on local processing capacities. This transformation reflects the internalization of environmental externalities and demonstrates how policy instruments, such as carbon pricing, can directly influence infrastructure planning decisions.

The integration of digital tools further enhances the performance of the system by improving the allocation of resources and enabling more precise spatial analysis. The use of GIS-based inputs allows the model to better capture regional heterogeneity and logistical constraints, leading to solutions that are both more realistic and more efficient. In this context, digitalization acts not only as a supporting mechanism, but as a critical factor that increases the overall effectiveness of circular economy systems.

From a multi-criteria perspective, the results highlight the importance of incorporating stakeholder preferences into the decision-making process. The application of AHP-based weighting demonstrates that different prioritizations of economic, environmental, and technological criteria lead to different optimal outcomes. In particular, scenarios that assign greater importance to environmental and technological factors consistently achieve higher overall sustainability performance, even when associated with higher initial costs. This suggests that long-term benefits outweigh short-term financial considerations in the context of sustainable development.

The scenario analysis also provides important insights into the trade-offs inherent in circular economy systems. While economically optimal solutions may minimize costs, they often fail to meet environmental targets. Conversely, sustainability-oriented solutions may require higher investments but result in significantly improved environmental outcomes and system resilience. The balanced scenario demonstrates that it is possible to achieve a compromise between these objectives, although such solutions depend heavily on the specific weighting of criteria and policy priorities.

These findings are consistent with existing literature emphasizing the need for integrated decision-support systems in sustainability analysis. However, the present study extends previous research by demonstrating how digitalization, multi-criteria evaluation, and optimization modelling can be combined into a unified framework. This integration allows for a more comprehensive understanding of system behavior and supports more informed decision-making at both the strategic and operational levels.

From a policy perspective, the results underline the importance of incorporating environmental costs into economic decision-making processes and investing in digital infrastructure that supports data-driven planning. For transition economies in particular, the findings suggest that strengthening digital and institutional capacities is essential for the successful implementation of circular economy strategies.

Overall, the results confirm that the transition toward sustainable and circular systems requires not only technological and economic adjustments, but also a fundamental shift in decision-making frameworks. The proposed model contributes to this shift by providing a tool that integrates multiple dimensions of sustainability into a coherent and operational analytical approach.

5. CONCLUSION

This study develops an integrated analytical framework for supporting decision-making in circular economy systems by combining digital tools, multi-criteria decision-making methods, and optimization modelling. By linking Geographic Information Systems, the Analytic Hierarchy Process, and Mixed-Integer Linear Programming, the proposed approach enables a comprehensive evaluation of alternative system configurations that simultaneously consider economic, environmental, technological, and social dimensions.

The results demonstrate that the integration of digitalization into circular economy systems significantly enhances the quality and effectiveness of decision-making processes. Digital tools improve the accuracy and usability of data, enable better spatial analysis, and support more efficient allocation of resources. At the same time, the incorporation of multi-criteria decision-making methods ensures that stakeholder preferences and sustainability priorities are explicitly reflected in the analytical process. The optimization component further strengthens the framework by identifying technically feasible and efficient system configurations.

A key finding of the study is that the inclusion of environmental externalities, particularly through CO_2 penalization, leads to substantial changes in optimal system design. Solutions that account for environmental impacts tend to favour more decentralized and resource-efficient configurations, highlighting the importance of integrating sustainability criteria into infrastructure planning. The results also confirm that decision outcomes are highly sensitive to the relative importance assigned to different criteria, emphasizing the need for transparent and structured decision-making approaches.

From a theoretical perspective, the paper contributes to the literature by integrating digitalization, circular economy principles, and multi-criteria decision-making into a unified framework. While previous studies have addressed these elements separately, this research demonstrates the added value of their combined application in addressing complex sustainability challenges.

From a practical and policy-oriented perspective, the findings underline the importance of developing digital and institutional capacities to support the transition toward circular economy systems. Policymakers are encouraged to adopt data-driven and multi-criteria approaches in infrastructure planning and to incorporate environmental costs into economic decision-making. For transition economies in particular, strengthening cooperation between academia, public institutions, and the private sector is essential for the successful implementation of circular strategies.

Despite its contributions, the study has certain limitations. The model relies on the availability and quality of input data, and the results may vary depending on the assumptions used in criteria weighting and parameter calibration. In addition, the current framework focuses primarily on static system configurations, without fully capturing dynamic changes over time.

Future research should therefore focus on the development of dynamic and stochastic models that incorporate uncertainty and temporal evolution of circular economy systems. The integration of real-time data, artificial intelligence, and advanced simulation techniques represents a promising direction for further improving decision-support systems. Moreover, expanding the framework to include additional sustainability dimensions, such as social acceptance and governance factors, could provide a more holistic assessment of circular economy strategies.

In conclusion, the study confirms that the transition toward sustainable economic development requires not only technological innovation but also advanced analytical frameworks that support informed and balanced decision-making. The proposed model provides a foundation for such frameworks and contributes to the development of more efficient, transparent, and sustainable circular economy systems.

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