

# INTELLIGENT INFORMATION SYSTEMS FOR THE CIRCULAR ECONOMY: A NATIONAL SECURITY-ORIENTED APPROACH AND ADAPTIVE DECISION MAKING

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**ABSTRACT:** *The ability of states to implement sustainable and adaptive policies becomes essential for maintaining internal balance and protecting critical infrastructures. The circular economy, in this equation, is emerging not only as an alternative ecological model but as a genuine strategic instrument for strengthening economic and national security. This article aims to investigate how emerging digital technologies, such as artificial intelligence (AI), can support real-time decision-making within circular economic systems, thus contributing to optimizing resource allocation, anticipating imbalances, and attracting private investment in circular infrastructure. The method used for modeling is that of decision trees, chosen for its ability to highlight conditional relationships and critical thresholds in investment decision-making. The existence of significant correlations between the degree of circularity and the level of investment is highlighted, supporting the hypothesis that data-driven decision-making intelligence can become a catalyst for economic resilience. The paper formulates a series of recommendations for public policies aimed at integrating digitalization and the circular economy into national security strategies.*

**Keywords:** *information systems, adaptive decision, predictive modeling*

**JEL Classification:** C35; C38; E27; G28; H25

## 1. INTRODUCTION

In a context marked by the accelerated transition towards sustainability and increasing pressures on economic and social infrastructures, the circular economy is emerging as a development model capable of simultaneously responding to environmental, economic, and security challenges. Unlike the traditional linear economic paradigm – characterized by the extraction, use, and disposal of resources – the circular economy proposes a closed-loop system, based on reuse, remanufacturing, recycling, and the efficient use of materials [3]. This model not only conserves natural resources but also increases the strategic autonomy of states, reducing dependence on imports and the risks associated with global supply chains. In parallel, technological progress in the last two decades has allowed the development of intelligent systems capable of supporting adaptive decision-making in real time by integrating large volumes of data from diverse sources [8,9]. Technologies such as artificial intelligence (AI) and Big Data analysis provide the premises for a reactive and predictive circular governance, in which economic actors can anticipate fluctuations in material flows, assess emerging risks, and adjust operational policies with a high degree of finesse [5]. Thus, a convergence between

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digitalization, sustainability and national security is emerging, in which information systems become true mediators of macroeconomic stability and the protection of critical infrastructures [11,14,15].

This paper aims to investigate this interdependence through an empirical approach, focused on the analysis of a set of key indicators of the circular economy at the level of the European Union member states. The analyzed indicators – people employed in circular sectors (PE), resource productivity (RS), circular material use rate (CR), waste recycling rate (RW) and private investment in circular infrastructure (PVA) – are used to build a decision-making model based on decision trees, with the aim of identifying relevant relationships between these factors and substantiating the hypothesis that digitalization of decisions can stimulate investment and economic resilience [1,12,7]. The main objective of the research is to demonstrate that smart technologies, integrated into a real-time decision-making framework, can significantly contribute to optimizing the circular economy and, implicitly, to strengthening national security. The research questions guiding the approach are the following:

1. What are the significant relationships between circularity indicators and the level of private investment in circular infrastructure?

2. What decision-making rules can be extracted through decision tree modeling, and how can they be used in the context of strategic planning?

3. To what extent can intelligent digital systems be considered an essential factor in supporting adaptive decisions with an impact on economic security? By articulating these directions, the article contributes to expanding the conceptual and operational framework of the circular economy, bringing to the forefront the critical role of digitalization in the smart and secure management of resources.

## **2. INTELLIGENT INFORMATION SYSTEMS AND ADAPTIVE DECISIONS**

Accelerating transformations of global economic ecosystems, the ability to make adaptive decisions in real time is becoming an essential condition for the efficient functioning of sustainable economic models. Adaptive decisions refer to those decision-making processes that are able to respond quickly and flexibly to changes in the environment, based on a continuous interpretation of data, algorithmic rules or human intervention assisted by technology. Within the circular economy, this type of decision involves not only reacting to imbalances in supply chains or resource management, but also the ability to anticipate changes, optimize reuse processes and strategically capitalize on information flows [14]. The implementation of adaptive decisions is facilitated by an intelligent digital infrastructure, in which three fundamental technologies converge: artificial intelligence (AI), the Internet of Things (IoT) and Big Data. Artificial intelligence contributes to the development of sophisticated predictive models, capable of anticipating the demand for recycled materials, optimizing circular logistics routes or identifying areas at risk of imbalance between production and consumption. Big Data analysis, on the other hand, integrates and correlates large and heterogeneous data sets – originating from industrial infrastructures, economic platforms or recycling networks – to generate relevant insights that can inform strategic decisions at national or regional level.

Therefore, intelligent systems act as a binder between circular objectives and adaptive decision-making capacity, providing not only the speed and accuracy necessary for effective interventions, but also the informational robustness required in an environment characterized by uncertainty and volatility.

## 2.1. Circular Economy and National Security

The circular economy is no longer perceived exclusively as an environmental protection tool, but increasingly as a fundamental pillar of economic and national security. By reducing dependence on imported primary resources – often concentrated geopolitically in unstable regions – circularity directly contributes to strengthening the strategic autonomy of states. This autonomy is translated into the ability of economic systems to function and adapt in crisis conditions, ensuring the continuity of production, the protection of jobs and the stability of the internal market. In addition, the reuse and recycling of materials generate internal economic flows, which reduce vulnerability to external fluctuations and support the development of resilient industrial ecosystems. The link between circular infrastructure and critical infrastructure is increasingly evident in the security strategies developed at the level of the European Union and the Member States. While critical infrastructure includes those systems essential for the functioning of society – energy, water, transport, health, communications –, the circular economy directly influences their resilience by constantly providing secondary materials, reducing pressure on supply chains and extending the lifespan of equipment. In addition, the digitalization of these processes allows for real-time monitoring of risks, facilitating rapid decisions in the face of systemic threats, be they economic, ecological or cyber.

Thus, the integration of circular economy principles into critical infrastructure is not only an option for economic efficiency, but a necessity for national resilience, especially in a global context marked by geopolitical tensions, energy crises and climate instability. Sustainability becomes, in this sense, an integrated component of economic defense, and adaptive decisions supported by intelligent systems – a means of strategic protection.

## 3. METHODOLOGY

The methodology of this study aims to integrate decision-based analysis with an empirical framework based on key indicators of circular performance at the European Union level. Given the main objective of the research – to explore how intelligent systems can support adaptive decisions and investments in circular infrastructure – a quantitative approach was adopted, supported by predictive modeling using decision trees.

This methodological choice is motivated by the interpretable and robust nature of decision trees in complex contexts, where the relationships between variables can be nonlinear or conditional. Decision trees allow not only to estimate the values of a dependent variable (in this case, private investment in the circular economy – PVA), but also to extract logical rules and critical thresholds that can be directly used in strategic decision-making, including in automated decision support systems.

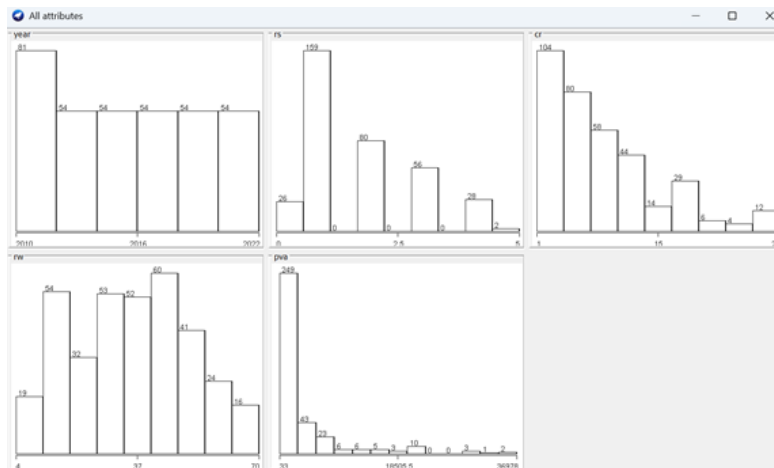
### 3.1. Data and its source

The data used in the analysis were taken from the official EUROSTAT platform, being selected for the period 2010–2022 and covering most of the Member States of the European Union. The dataset includes five indicators relevant for the analysis of circular performance, as follows:

- PE (Persons Employed) – Number of people employed in circular economy sectors, expressed in thousands of people.
- RS (Resource Productivity) – Resource productivity, measured in euro/kg, indicating the economic efficiency in the use of materials.

- CR (Circularity Rate) – Circular rate of material use, expressed as a percentage (%), reflecting the proportion of reused materials in total material consumption.
- RW (Recycling Waste Rate) – Municipal waste recycling rate, expressed as a percentage (%), representing the efficiency of collection and treatment systems.
- PVA (Private Investment in Circular Economy) – Value of private investments in circular infrastructure, expressed in million euros.

**Figure 1. Distribution of dataset values performed by the author using WEKA 3.8.6 software**



The figure shows the distribution of values for the variables used in the analysis, providing an overview of the structure of the data set used in the decision-making modeling. The analysis of the distribution of the year variable highlights a relatively uniform distribution of the data over the period 2010–2022, with a slight agglomeration recorded in 2010, when a frequency peak is noted (81 observations). This early concentration suggests that, although the data include the recent period in a balanced way, the representation before 2016 is slightly denser, which may influence the temporal consistency of the derived decision-making models.

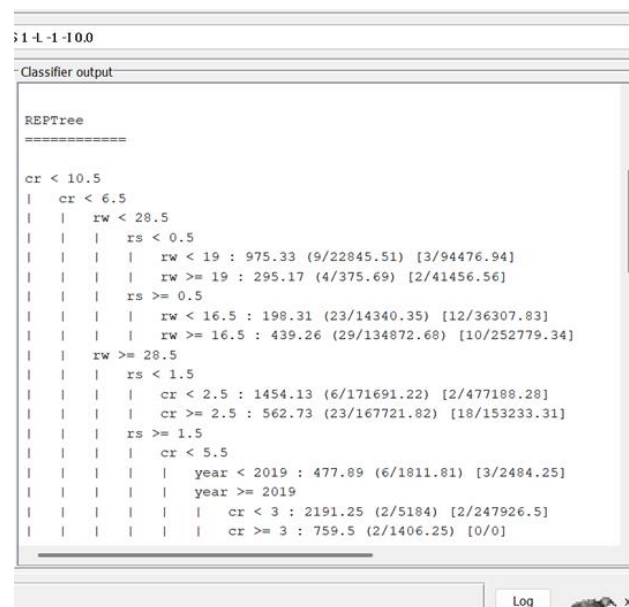
Regarding the distribution of the RS variable (resource productivity), it is characterized by a strongly positive asymmetric profile (skewed to the right), with an overwhelming majority of values placed below the threshold of 2 euro/kg. This strong trend towards low values reflects, in most of the countries analysed, a low economic efficiency in the use of resources, which can be attributed both to the low level of technological development of the productive sectors and to the absence of coherent national policies on the efficient recovery of materials. Only a limited number of observations exceed the value of 4 euro/kg, indicating that the high performance in this area is exceptional and concentrated in a few advanced economies. The variable CR (circular material use rate) also shows an asymmetric distribution, dominated by values between 1% and 2%, which indicates that the circular economy is still in its infancy in most European countries, and the actual proportion of reused materials remains modest in relation to the real recycling potential. Only a few observations exceed the upper thresholds of 15% or 20%, which highlights an advanced level of circularity only in certain countries with a consolidated tradition and infrastructure in the field of recycling. The distribution of the variable RW (waste recycling rate) is relatively balanced, but tends to be concentrated in an intermediate range, between 30% and 50%, which suggests that policies for selective collection and treatment of municipal waste are widely implemented in the EU, but with varying degrees of efficiency. Disparities become evident through the presence of extreme observations: a small number of states achieve excellent performance, with recycling rates above 65%, while others

fall below the 20% threshold, indicating systemic deficiencies. Regarding PVA (private investment in the circular economy), the distribution reveals a strong leftward skew, with an overwhelming majority of values below 10,000 million euros. Approximately 249 observations fall below this threshold, while only a few countries record significantly higher values, sometimes reaching almost 37,000 million euros. This distribution emphasizes a deep polarization of private capital in favor of a few strong economies, most likely Germany, France or the Netherlands, while the rest of the countries remain dependent on public policies or external investments for the development of circular infrastructure.

### 3.2. Results and discussion

The decision tree in the image (Fig.2) is generated with the REPTree (Reduced Error Pruning Tree) algorithm, a regression model that estimates the target variable pva (private investment in the circular economy) depending on the variables cr (circular rate), rw (waste recycling rate), rs (resource productivity) and year. The tree is trained on the full dataset (Use training set) and provides quantitative estimates of PVA based on combinations of logical conditions. The structure generated by the REPTree decision tree confirms the conceptual relevance of the circular material rate (CR) as the main decision factor in estimating private investment in the circular economy (PVA). This attribute functions as the root node of the model, segmenting the entire data set based on a critical threshold of 10.5%. This automatic choice of the CR variable as the starting point for branching suggests that the degree of material circularity of an economy constitutes, in predictive terms, the strongest explanatory variable of private investment behavior.

**Figure 2. Structure of the REPTree decision tree. Realized by author with WEKA software**



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Classifier output

REPTree
=====

cr < 10.5
| cr < 6.5
| | rw < 28.5
| | | rs < 0.5
| | | | rw < 19 : 975.33 (9/22845.51) [3/94476.94]
| | | | rw >= 19 : 295.17 (4/375.69) [2/41456.56]
| | | | rs >= 0.5
| | | | | rw < 16.5 : 198.31 (23/14340.35) [12/36307.83]
| | | | | rw >= 16.5 : 439.26 (29/134872.68) [10/252779.34]
| | | | | rs >= 1.5
| | | | | | cr < 2.5 : 1454.13 (6/171691.22) [2/477188.28]
| | | | | | cr >= 2.5 : 562.73 (23/167721.82) [18/153233.31]
| | | | | | rs >= 1.5
| | | | | | | cr < 5.5
| | | | | | | | year < 2019 : 477.89 (6/1811.81) [3/2484.25]
| | | | | | | | year >= 2019
| | | | | | | | cr < 3 : 2191.25 (2/5184) [2/247926.5]
| | | | | | | | cr >= 3 : 759.5 (2/1406.25) [0/0]

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For values below this threshold – i.e. in the case of low circularity economies – the tree introduces a series of additional conditions, based on the waste recycling rate (RW), resource productivity (RS) and the reference year (year). This hierarchical structure suggests an adaptive decision logic, in which the impact of each variable is dependent on the maturity level of the others. For example, in situations where both CR and RW are very low, and RS does not exceed 0.5 euro/kg, the estimated private investments are minimal, which reflects a systemic deficit of

economic attractiveness in the absence of minimum circular and technological performances. As the values of RW increase (e.g. above 19% or 28.5%) and RS reaches pragmatic levels ( $\geq 0.5$ ), the model indicates a moderate increase in investments, which can be interpreted as a progressive response of private capital to the functional improvement of recycling infrastructures and the achievement of a minimum of operational efficiency. However, the absolute levels of investment still remain relatively low in these scenarios, which confirms that recycling alone is not sufficient to generate a large-scale investment effect in the absence of appropriate technological support. An interesting direction of the decision analysis is given by the interaction between CR, RS and the reference year. Thus, under conditions where  $RS \geq 1.5$  and CR is still low (below 5.5%), the REPTree model distinguishes between observations made before and after 2019, identifying a temporal inflection point. After this year, if the level of circularity is extremely low ( $CR < 3$ ), private investment increases significantly, which can be correlated with recent European policy interventions, such as the European Green Deal, the Recovery and Resilience Plan (NRRP) or other financial instruments aimed at supporting the circular transition. This finding is essential for understanding the post-crisis investment dynamics, demonstrating that temporal interventions and public policies can transform marginal conditions into opportunities to attract private capital. The interpretation is supported by the decision rules of the generated tree, whose conditional nodes are presented below:

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IF cr < 10.5 THEN
  IF cr < 6.5 THEN
    IF rw < 28.5 THEN
      IF rw < 0.5 AND rs < 0.5 AND year < 19 THEN
        PVA ≈ 975.33
      ELSE IF rw >= 19 AND rs < 0.5 THEN
        PVA ≈ 295.17
      ELSE IF rs >= 0.5 AND rw < 16.5 THEN
        PVA ≈ 198.31
      ELSE IF rs >= 0.5 AND rw >= 16.5 THEN
        PVA ≈ 439.26
    ELSE IF rw >= 28.5 AND rs < 1.5 THEN
      IF cr < 2.5 THEN
        PVA ≈ 1454.13
      ELSE IF cr >= 2.5 THEN
        PVA ≈ 562.73
    ELSE IF rs >= 1.5 AND cr < 5.5 THEN
      IF year < 2019 THEN
        PVA ≈ 477.89
      ELSE IF year ≥ 2019 THEN
        IF cr < 3 THEN
          PVA ≈ 2191.25
        ELSE IF cr ≥ 3 THEN
          PVA ≈ 759.5
  
```

The decision-making model validated by these rules provides not only a quantitative estimate of investments based on circular performance, but also a logical map of the maturation of circular economies, highlighting critical thresholds, ceiling effects and inflection points that can guide both public strategies and the behaviors of private actors in the sustainable transition process.

#### 4. CONCLUSION

In conclusion, the REPTree not only provides a numerical estimate of PVA according to circularity indicators, but above all generates a logical map of the investment decision-making process, in which circular variables do not act in isolation, but in contextual interdependence. Each identified decision-making threshold – be it 10.5% in CR, 0.5 in RS or the year 2019 as a temporal benchmark – delimits strategic regions of policy intervention, thus providing a valuable tool for decision-makers who wish to align economic policies with those of sustainability and national security. The present study highlights, through an integrated decision-making and analytical approach, the major potential of smart technologies in supporting the transition to a circular economy, in close correlation with the objectives of economic security and strategic stability. By using a model based on decision trees, the research identified the concrete conditions under which circularity indicators – employment in circular sectors (PE), resource productivity (RS), circular material rate (CR) and waste recycling rate (RW) – can act as relevant predictors of private investment in circular infrastructure (PVA).

The results obtained demonstrate that, in contexts characterized by low resource productivity, investments can still be attracted by progressive improvements in recycling and reuse capacity. At the same time, in economies with high circular performance, investments are decisively influenced by the level of technology and the efficiency of industrial processes, signaling the existence of a maturity threshold beyond which only further technological progress can generate added value. Another key result aims to identify saturation effects: in certain contexts, the increase in the circularity rate no longer determines a significant contribution of private capital, suggesting the need for a recalibration of investment strategies and fiscal or financial stimulus instruments. This finding highlights the fact that, in order to support sustainable development, public policies must be dynamic and contextualized, adapting to the level of circular maturity of each state or region.

From the perspective of economic security, the paper confirms that the circular economy is not only a mechanism for making the use of resources more efficient, but also a tool for strengthening strategic autonomy, contributing to reducing external dependence, protecting supply chains and the continuity of critical infrastructures. In this sense, the integration of intelligent decision-making systems – capable of processing data in real time and generating adaptive reactions – becomes not only opportune, but necessary.

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