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SCIENTIFIC MANAGEMENT CULTURE IN THE AGE OF AI: BALANCING INNOVATION, ECOLOGY, AND STRATEGIC FORESIGHT

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ABSTRACT

In the era of rapid digital transformation and the widespread adoption of artificial intelligence, a paradox arises: despite the unprecedented growth of data volumes, the quality of strategic management decisions often declines. This article aims to present the results of a study examining the phenomenon of the "extrapolation trap"—a cognitive distortion of modern management culture in which linear financial growth trends in the form of GDP are mechanically projected into the future, ignoring the nonlinear dynamics of physical systems and the laws of thermodynamics. It also substantiates the need to transition to a new paradigm of "Scientific Management Culture," based on multicriteria data analysis and the verification of economic strategies using the fundamental laws of conservation of power. The methodological basis of this study is a method for analysing changes in the power of a socio-economic system, allowing development indicators to be translated into an invariant physical coordinate system (watts). A comparative analysis of long-term trends in the United States in 1960–2021 and the Baltic region in 1990–2019 reveals a profound divergence between declared economic growth and stagnation in actual physical energy consumption. It is shown that management decisions focused solely on financial metrics mask the loss of viability of complex systems, while digital transformation without considering the energy base risks becoming a tool for accelerating entropy. In conclusion, a "Triplex" model of multi-criteria decision-making is proposed, requiring the simultaneous assessment of energy security, technological efficiency, and the social utility of innovations. It is concluded that AI should not be used to generate virtual value, but rather to monitor and optimize useful power flows, ensuring a balance between technological progress and the physical sustainability of the biosphere.

KEYWORDS: Scientific Management Culture; Extrapolation Trap; Digital Transformation; Power Analysis; Sustainable Development; Multi-Criteria Analysis.

1. INTRODUCTION

The beginning of the 21st century is characterized by a "data paradox": never before has humanity possessed such a colossal volume of information and such sophisticated tools for processing it (Big Data, artificial intelligence), yet the quality of strategic management decisions at the macro level continues to decline. This decline is manifested in the deepening global environmental crisis, the growing fragility of supply chains, and the increasing frequency of socioeconomic shocks that traditional econometric models are unable to predict. We are witnessing a fundamental gap between "digital optimism," defined as the belief that digital transformation alone can solve the problem of resource constraints, and "physical realism," which points to the exhaustibility of the material base of modern civilization (Abramov et al., 2023). Modern management culture, both at the corporate and government levels, remains largely captive to the "extrapolation trap." This cognitive and methodological bias is based on the implicit assumption that historical financial growth trends (GDP, capitalization, revenue) can be mechanically projected into the future, ignoring the nonlinear dynamics of the physical systems that support these financial superstructures. As noted in Club of Rome reports (Meadows et al., 1972), overreliance on monetary indicators like GDP reflects costs rather than welfare and ignores benefits that exist outside the market (Weizsäcker & Wijkman, 2018). In the age of AI, this trap becomes especially dangerous: neural networks trained on historical financial data, free of physical constraints, tend to generate utopian scenarios of endless growth, creating dangerous illusions for decision makers.

The core of the problem lies in the ontological mismatch between the data used for decision making and the reality it purports to represent. Financial indicators are social conventions subject to inflation, speculation, and political manipulation. In contrast, the laws of nature—in particular, the laws of thermodynamics and conservation of energy—are invariant. A management culture that operates exclusively with financial metrics is like navigating a ship based on the prices on the first-class restaurant menu, not the engine room instruments. As has been shown, "society is forced to make strategic decisions within a coordinate system that depends on political decisions based on biased information" (Trusina & Jermolajeva, 2022).

This article argues that overcoming the extrapolation trap requires a paradigm shift toward a "Scientific Management Culture," which should not be confused with the Taylorism of the early 20th century. In this context, scientific culture implies the integration of fundamental laws of nature into the logic of management decision-making, and it requires a shift from single-criteria optimization (profit maximization) to multi-criteria data analysis, where the primary metric of success is not the generation of virtual value, but the optimization of the system's useful power—its physical ability to perform external work and maintain internal structure. The concept of "digital transformation" must be redefined: digital tools must serve as means of monitoring energy and material flows in real time, providing "physical verification" of economic strategies. Without this grounding, digital transformation risks becoming a tool for accelerating entropy—a mechanism for efficiently processing data about an increasingly inefficient physical reality.

The aim of this paper is to justify the need for such a cultural shift by analyzing empirical data from the US and EU countries demonstrating a discrepancy between economic indicators and physical sustainability parameters.

2. THEORETICAL BASIS: PHYSICAL LAWS AS THE LANGUAGE OF STRATEGIC MANAGEMENT

To build a scientifically based management culture, it is necessary to go beyond the limitations of neoclassical economics, which treats the economy as a closed, isolated system of circular flows between firms and households, ignoring the biophysical flow of matter and energy. The theoretical framework of this study is based on a synthesis of the theory of open nonequilibrium systems, biophysical economics, and the laws of thermodynamics. The fundamental premise of the proposed approach is the recognition that any socioeconomic system—be it a corporation, a city, or a state—is a living, open system. According to the principles of theoretical biology formulated by Erwin Bauer, living systems are characterized by the principle of "stable disequilibrium": they work against equilibrium (death/entropy), continuously consuming free energy from the environment (Bauer, 2002). Therefore, "sustainable development" is not a static state of conservation, but a dynamic process. Sustainable development is the ability of a system to perform external work (useful power) and maintain its internal complexity over time. As demonstrated in the works of Kuznetsov P. and Bolshakov B., "development is sustainable in a given cycle of a living system's existence if, during this period, there is a non-decreasing increase in the efficiency of using consumed power" (Kuznetsov, 2015; Bolshakov et al., 2019). This definition fundamentally shifts the focus of strategic foresight from the accumulation of financial capital to the management of power flows.

To overcome the relativism of monetary units, which complicates long-term historical comparisons and interregional analysis due to differences in purchasing power parity and inflation, an invariant coordinate system based on units of power (watts) is introduced.

The central governing equation for any production system is the law of conservation of power (Trusina et al, 2022):

$$N(t)=P(t)+G(t)$$

where:

N(t) is the total power (consumption) entering the system and represents the total flow of energy resources (fossil fuels, nuclear energy, renewable energy, human labor energy) consumed by society to support its activities. In management terms, this is the "cost" of the system's existence in physical terms;

P(t) is the useful power (work), which is the energy successfully converted into socially necessary work—the production of goods, the maintenance of infrastructure, the provision of human capital (education, healthcare), and the generation of innovation. P(t) determines the "standard of living" of the system in physical reality (.).

G(t) is the loss power (entropy), which represents the energy dissipated into the environment without creating a useful structure. In a broad socioeconomic context, G(t) includes not only heat loss but also the costs of pollution control, the energy cost of crime, bureaucratic friction, and the remediation of erroneous management decisions.

From this equation, the critical metric of technological efficiency (F) is derived:

$$F(t)=(P(t))/(N(t)) \times 100\%$$

In scientific management culture, the goal of digital transformation and AI implementation is to maximize F(t). However, the current "extrapolation trap" often leads managers to maximize N(t) (resource consumption) under the guise of GDP growth, without monitoring whether this leads to a proportional increase in P(t). The traditional management paradigm relies on single-criteria efficiency, usually expressed through financial ROI (return on investment) or GDP growth. A significant contribution to the development of the theory of economic growth was made by the American Nobel Prize laureate Solow (1994), who modified the Cobb-Douglas production function by introducing another factor - the level of technological development (Solow, 1994). In addition, supporters of this concept believe that economic growth leads to disruption of the biosphere of human life and is limited by the lack of raw materials and fuel resources of the planet. Lucas (1988) together with Romer (1990) created a concept of a new theory of economic growth, known as the Lucas-Romer model. According to this model, the main factor of economic growth is the increase in investment in research, development and human capital. One of the conclusions of the Romer and Lucas model is that an economy with human capital resources and advanced science has greater growth potential in the long run than an economy without these advantages. In complex systems, optimizing a single variable often leads to the degradation of the system as a whole—a phenomenon known as Goodhart's Law, which can be reinterpreted thermodynamically: "When a measure becomes a target, it ceases to be a good measure because the system adapts to imitate the target at the expense of increasing overall entropy" (Chrystal, 2003).

Data-driven decision making (DDM) in the context of scientific culture implies a multi-criteria approach in which decisions are evaluated simultaneously, in this case along three dimensions:

- Energy endowment: does the system have sufficient N(t) to support the proposed digital superstructure? As Daly (Daly, 2015) emphasizes, the economy is an open subsystem of a finite ecosphere; ignoring physical limits in strategic planning leads to "uneconomic growth," when the marginal costs of growth exceed the marginal benefits;
- Energetic efficiency: does the innovation increase the P/N ratio? For example, if the implementation of AI and blockchain significantly increases total energy consumption N(t) (due to data center cooling and computing), but creates value primarily in the virtual speculative sector (low P(t)), such an innovation is thermodynamically regressive, despite the potential financial return;
- Systemic stability: does the solution increase the system's resilience to external shocks? High G(t) (losses) indicates a fragile system, as sustainable innovation should aim to reduce G(t) through smart logistics, waste reduction, and circular economy principles.

A crucial component of this theoretical framework is the role of the human factor. Societal development is defined as "a creative process aimed at changing the direction and speed of free energy flows in space and time" (Georgescu-Roegen, 1986).

In this view, human capital is not simply labor force, but the primary anti-entropic factor. The function of AI and automation should be to free up human cognitive abilities for creative tasks—the generation of new ideas that improve the efficiency of the system F(t). However, if digital transformation leads to the degradation of human cognitive skills or mass displacement without the creation of high-energy alternatives for employment, the system's power to "capture" and manage future energy flows is reduced, creating a feedback loop: a degraded society cannot support complex technologies, leading to a further decline in useful power P(t). Thus, the theoretical foundation of scientific management culture rests on the assertion that economic value is a derivative of the transformation of physical power. Strategic foresight that ignores this hierarchy and attempts to extrapolate financial trends independently of their energy foundation inevitably falls into the trap of simulating a reality that physically cannot exist. In the context of the emergence of a multipolar world (Trusina et al., 2025), the theoretical basis of a scientific management culture is acquiring critical geopolitical significance, as the crisis of the monocentric model of globalization is accompanied by financial market volatility and the disruption of supply chains, making traditional monetary indicators (GDP, credit ratings) ineffective for strategic planning. In this new reality, a region's sovereignty is determined not by its monetary supply, but by its "energy sovereignty"—the ability to independently generate high-density useful power. Therefore, the transition to management based on QoLE indicators is a prerequisite for the survival and competitiveness of entities in a multipolar global economy.

3. METHODOLOGY

To verify the hypothesis of the "extrapolation trap" and assess the need for a transition to a scientific management culture, the study utilizes a comprehensive methodological approach combining methods of system dynamics, historical comparative analysis, and physical economics.

The study also recognizes that a successful transition to a scientific management culture requires the creation of a regional digital ecosystem—a comprehensive macroenvironment uniting citizens, businesses, and government. As demonstrated (Abramov et al., 2024), such an ecosystem, based on digital twin technologies and real-time data collection, enables the optimization of infrastructure operating costs, mitigation of emergency consequences, and the creation of new territorial development models—all of which are essential for the effective monitoring of energy flows N(t) and P(t).

Unlike traditional econometric approaches that rely on financial aggregates (GDP, market capitalization), this study is based on a power change analysis method. This methodology, described in detail in Trusina and Jermolajeva (Trusina, 2025), allows for the translation of socioeconomic system development indicators into an invariant coordinate system expressed in units of power (watts), eliminating inflation and exchange rate distortions in long-term analysis. The empirical basis of the study is formed by two data sets covering different time horizons and geopolitical contexts, ensuring the representativeness of the findings:

1. Macroanalysis of long-term trends (US case): data from the World Bank and the UN Statistics Division for the period 1960–2021 were used. The choice of the US was based on its status as a global leader in technological innovation and digital transformation, allowing the American model to be considered a benchmark for the implementation of a modern management paradigm (Jermolajeva & Trusina, 2024).
2. Comparative regional analysis (EU case): Eurostat data for the Baltic region countries for the period 1990–2019 were used. The sample is divided into two cluster groups: countries with a developed post-industrial model (Sweden, Finland) and countries with transition economies (Latvia, Lithuania, Estonia). This allows us to evaluate the effectiveness of sustainable development strategies under various starting conditions (Trusina, 2025).

The analytical procedure included three stages:

stage 1: Calculating the total power consumption N(t) as the sum of all incoming energy flows required to maintain the system's functioning;

stage 2: Calculating the useful power P(t) and technological efficiency F(t), using calibration coefficients that take into account the energy balance structure and the share of losses G(t);

stage 3: Comparing the dynamics of physical indicators (N, P) with the dynamics of financial indicators (GDP). At this stage, bifurcation points and trend divergences were recorded, which were interpreted as indicators of an "extrapolation trap."

The Quality of Life (QoL) assessment was not carried out through subjective surveys, but as a function of the useful power per capita, adjusted for life expectancy indicators and environmental quality, which is consistent with the principles of scientific management culture.

4. RESULTS

To compare the dynamics of physical indicators with the dynamics of financial indicators within the framework of SDMM (Trusina, 2025), in accordance with the above-described laws of sustainable development, a minimum set of sustainable development indicators was defined.

The sustainable development model includes indicators in energy units, as well as integrated indicators per inhabitant, including:

- power of final consumption N(t);
- useful power of final consumption P(t);
- standard of living as useful power of final consumption per capita U1(t);
- **quality of life in energy units per capita QoLE(t);**
- technological efficiency F(t).
- sectoral indicators of countries STINA

The set of socio-economic indicators included the population change indicator dM; the value of the gross domestic product at purchasing power parity GDP PPP(t). The calculations were carried out using data from the United States for the period from 1960 to 2021, as well as Sweden, Finland, Latvia, Lithuania and Estonia for the period from 1990 to 2021. For this study, a comprehensive data set was collected from reputable international and national sources. The primary data sources are:

- World Bank Data (World Bank): provides a wide range of socioeconomic indicators, including GDP, population, urbanization, education, and health indicators;

- International Energy Agency (IEA): is a key source of data on the production, consumption, and trade of various types of energy (coal, oil, gas, and renewable energy) by country;

- United Nations Statistics Division (UNDATA): Source of demographic data, as well as information on sustainable development and social indicators.

- Eurostat database (Eurostat data)

The analysis revealed fundamental contradictions between the declared economic growth and the physical state of the systems under study. The results clearly demonstrate the limitations of the current management culture, which relies on the linear extrapolation of financial data.

Analysis of data for the United States allows us to deconstruct the mechanism by which strategic illusions arise in modern management.

Financial projection (illusion of infinity): US gross domestic product based on purchasing power parity (GDP PPP) dynamics over the period under study (1960–2021) demonstrate consistent exponential growth, with the coefficient of determination for the GDP trend being $R^2 = 0.99$ (Figure 1), which is statistically interpreted as a near-perfect functional relationship.

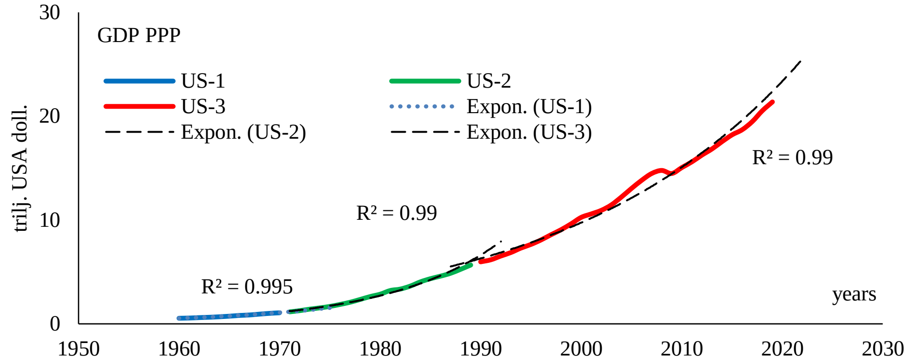

Figure 1: The GDP PPP Changes of the USA In 1960-2021.
Source: Calculated By the Author Using World Bank Data.

Managerial interpretation: A manager or AI algorithm trained on this dataset inevitably concludes that the existing model is highly efficient, and extrapolating this trend predicts continued prosperity, stimulating decisions to increase investment in virtual assets and expand digital infrastructure.

Physical reality (stagnation signal): Translating the data into a power coordinate system reveals a fundamentally different picture (Figure 2). The dynamics of total power consumption N(t) (energy resources) breaks down into three phases, which are not visible on the GDP figure (Figure 1):

period 1960–1973: a period of linear growth in power consumption ($R^2 = 0.98$), an era of real industrial expansion, when GDP growth was driven by physical growth in energy consumption.

period 1983–2008: a period of slowdown and transition to a nonlinear decline in power growth rates ($R^2=0.97$). It was during this period that active financialization of the economy began: GDP continued to grow thanks to the services and financial sectors, while the physical base began to lag.

period 2009–2021: a period of stagnation and instability. Full power consumption reached a plateau and effectively stopped growing, fluctuating around the achieved levels. The trend is taking a negative direction.

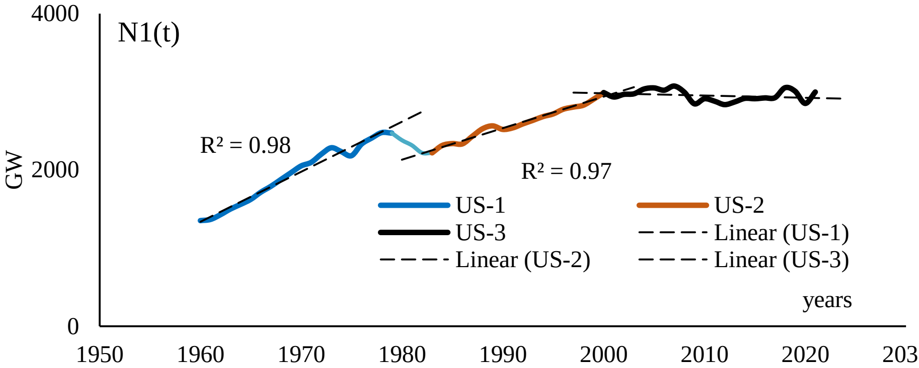

Figure 2: The Changes of the Final Consumption Power N1(T) For the United States (US) In 1960-2021.
Source: Calculated By The Author.

Diagnosis: the observed divergence between the GDP exponent and the energy consumption plateau is an "extrapolation trap." Modern management culture bases decisions on Figure 1 (GDP PPP), ignoring Figure 2 (Power N(t)), which creates risks of systemic fragility: digital transformation and AI development require colossal energy expenditures (increasing N), yet the US physical system demonstrates no power to support this growth. Virtual value is created faster than the system's physical power to perform useful work, which is thermodynamically equivalent to an increase in entropy.

A regional analysis of the European Union (1990–2019) demonstrates the consequences of making strategic decisions without regard for the law of conservation of power.

The Nordic model (high efficiency): leading countries (Sweden, Finland) are characterized by high indicators of technological efficiency F(t) and useful power per capita. Despite the general trend toward declining growth rates, these systems maintain a high level of structural complexity. For example, the technological sophistication index F in Sweden reaches 42%, while in Finland it is 41% in 2019 (Table 1), demonstrating the ability to transform consumed resources into useful social work. In terms of scientific management culture, this means that digital transformation in these countries is superimposed on a solid energy and industrial foundation. Calculation results (Table 1) present the minimum set of sustainable development parameters in the context of the SDMM methodology for three groups of leading countries: the United States, Sweden, and Finland in 2019. The data include the demographic indicator of population change (dM), technological efficiency (F1), the structural tension index of innovation (STINA), standard of living (U1), and quality of life in energy units (QoLE).

Table 1: Minimal Set of Sustainable Development Parameters in Context of SDMM For United States (US), Sweden (SE), Finland (FI) In 2019.

Countries		dM	F1	STINA	U1	QoLE
		%	%	x	kW	kW
Finland	FI	7	41	2.8	2.5	2.0
Sweden	SE	15	42	3.3	1.9	1.5
USA	US	32	37	4.3	2.3	2.0

Source: Calculated By The Author

Of particular note is the STINA (Structural Tension of Innovation and Adaptation) indicator—a proprietary composite index reflecting the degree of internal tension in a socioeconomic system that arises when attempting to reconcile high levels of consumption with the need to maintain technological efficiency. This index is calculated as the ratio of the shares of GDP PPP from the manufacturing and non-manufacturing sectors (Kaldor, 1996; Trusina, 2025). The higher the STINA value, the greater the imbalance between financial flows and the power (energy flows) of the system. The analysis shows that the United States exhibits the highest STINA value (4.3), signaling the highest structural stress among the countries examined. This confirms the "extrapolation trap" phenomenon identified in

Section 4: despite formal GDP growth, the physical system is experiencing excess stress due to stagnant energy consumption while consumption expectations remain high. Sweden (STINA = 3.3) and Finland (STINA = 2.8) exhibit significantly lower stress levels, which correlates with their high technological efficiency (F1 = 42% and 41%, respectively). This indicates that the Nordic model, based on energy-efficient technologies and balanced social policies, ensures a more sustainable balance between development ambitions and the power (physical capability) of the system. Critically important is the fact that among the leading countries, only Sweden and Finland demonstrate positive demographic dynamics (dM = +15% and +7%), while the United States displays nominally high population growth (+32%), which, however, is combined with extreme structural tensions. This demonstrates that population growth without an adequate increase in technological efficiency does not lead to greater systemic resilience, but, on the contrary, exacerbates internal imbalances.

Russian model (gap between planning and reality): Further empirical confirmation of the "extrapolation trap" comes from an analysis of the first year of digital transformation strategy implementation in Russian regions (2022–2024). The study (Abramov & Andreev, 2024) revealed a significant gap between planned and actual digital maturity indicators. While administrative plans extrapolate linear growth for 2023–2024, actual performance in 2022 in a number of key sectors (healthcare, public administration) demonstrates a significant lag. This gap, often exceeding acceptable margins of error, indicates that the management models embedded in the strategies ignore the real inertia of physical and social systems. Digital indicators (the "digital maturity index") are growing on paper faster than actual structural restructuring of processes is taking place, which creates the risk of failing to achieve strategic goals and illustrates the phenomenon of "digital optimism" disconnected from the resource base.

NIC model: applying this methodology to newly industrializing countries (NICs), such as China, India, and Brazil, reveals a fundamentally different development trajectory (Trusina et al., 2024). Unlike the G7 post-industrial economies, which exhibit high STINA values (indicating a hypertrophied service sector and Baumol's "price disease"), NIC countries maintain a balanced structure with a strong manufacturing sector, allowing them to sustainable growth in useful power P(t) and avoid the efficiency stagnation characteristic of Western economies (Baumol, 1967). Comparative analysis confirms that, in an invariant coordinate system, it is the ability to transform energy into real goods, rather than the size of the financial superstructure, that determines the potential for long-term sustainable development (IMF Report, 2022; Human Development Report, 2019).

Baltic model (Crisis of Viability): An analysis of indicators for Latvia, Lithuania, and Estonia reveals deep structural problems hidden behind the façade of institutional reforms.

Financial projection (illusion of infinity): the dynamics of GDP PPP of Latvia, Lithuania and Estonia (Figure 3) for the period under study (1990–2021) demonstrates stable exponential growth, while the coefficient of determination for the GDP trend is R^2=0.94–0.97, which is statistically interpreted as an almost perfect functional dependence.

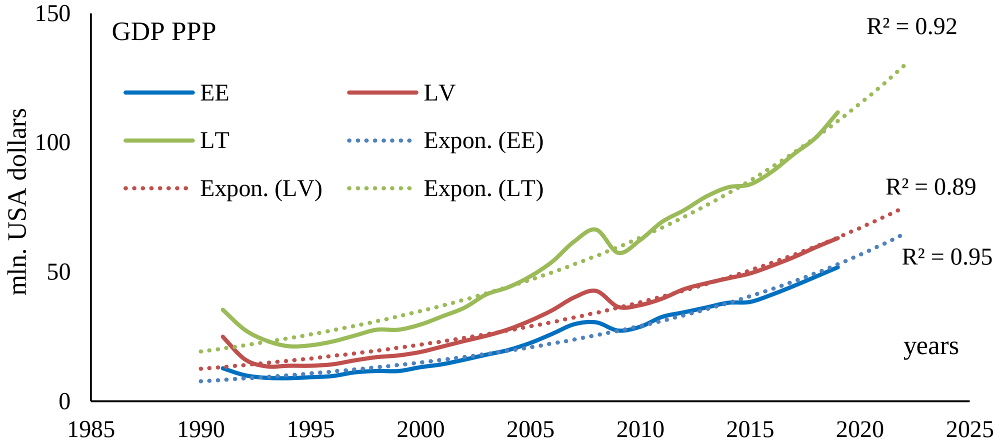

Figure 3: The GDP PPP Changes for Estonia (EE), Lithuania (LT), Latvia (LV) In 1990-2019.
Source: Calculated By the Author Using World Bank and Eirostat Data.

Decline in Standards of Living (Physical): In the 1990s, the useful power **P(t)** in these countries fell by a factor of 2–2.2 (Figure 4). By 2019, this indicator, although showing a recovery trend, remains significantly lower than that of its Nordic neighbours.

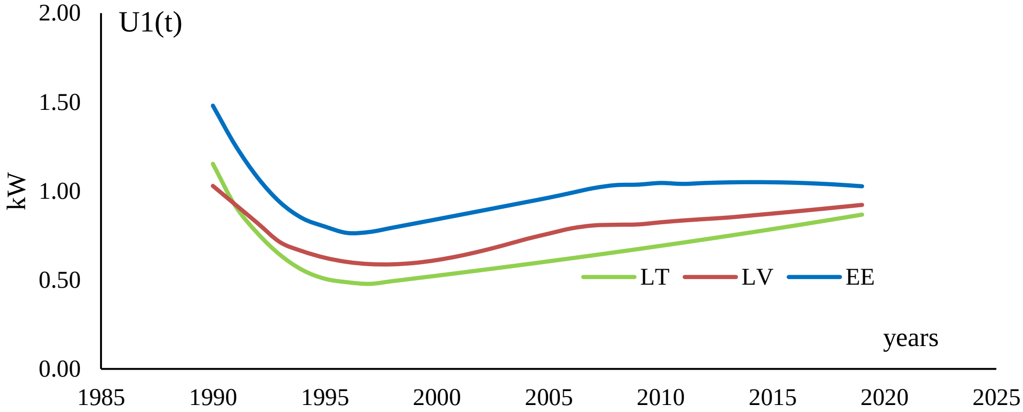

Figure 4: The Changes of the Useful Power Per Capita U1(T) For Latvia (LV), Lithuania (LT) And Estonia (EE) In 1990-2019.

Source: Calculated By the Author.

Demographic Response: The most alarming indicator is depopulation. Latvia and Lithuania lost approximately 20% of their population during the study period. From the perspective of open systems physics (Table 2), the loss of structural elements (population) is a clear signal of the system's inability to retain and transform energy flows. The system contracts to accommodate the reduced flow of available useful power.

Table 2: Minimal Set of Sustainable Development Parameters in Context of SDMM For Latvia (LV), Lithuania (LT), Estonia (EE) In 2019.

Countries		dM	F1	STINA	U1	QoLE
		%	%	X	kW	kW
Estonia	EE	-18	40	2.5	1.0	0.8
Latvia	LV	-28	33	3.3	0.9	0.7
Lithuania	LT	-28	32	2.9	0.9	0.7

Source: Calculated By the Author

Failure of the "Latvia 2030" strategy: An analysis of the implementation of Latvia's sustainable development strategy (Latvia 2030) shows that most target indicators are unattainable without a paradigm shift. The current strategy is based on aspirational political goals ("catch up with the EU level") but is not supported by a calculation of the power required to achieve this. As noted, "it is quite difficult to compile a unified picture of Latvia's progress toward sustainable development," as the indicators move in different directions. A management culture that ignores physical metrics (power) has led to a situation where the Baltic countries, while declaring a transition to an "innovative economy," are actually experiencing protracted stagnation in the real sector. Low F values (around 33% for Latvia and Lithuania) indicate that digital transformation is superficial and does not lead to a qualitative leap in resource efficiency.

The graph in Figure 5 clearly illustrates the divergence in the QoL development trajectories between the United States and countries in the European region. The United States (blue line) is characterized by high volatility with a general tendency toward stagnation after the peaks of the 1990s. The period over the last 5-7 years is particularly noteworthy, where the US curve exhibits a "sawtooth" lateral movement without any clear growth, confirming the "extrapolation trap" thesis: robust GDP growth during these years did not translate into a real improvement in physical quality of life, which hit an "energy ceiling." The Scandinavian countries (Finland - gray line, Sweden - orange) show the highest absolute QoLE values, which correlates with their high technological efficiency (F). However, in recent years (2014–2019), growth rates have slowed and even declined (especially in Finland), which may signal the reaching of efficiency limits within the current technological paradigm. The Baltic countries (Latvia – yellow, Lithuania – blue, Estonia – green) are starting from extremely low positions. Despite a positive recovery trend, the dynamics of recent years (2015–2019) show alarming signs of saturation: curves are flattening, and the rate of convergence with the leaders is slowing. The gap between the leading group (Scandinavia/USA) and the Baltic countries remains significant and is no longer narrowing, indicating the exhaustion of the "low base" effect and the inability of recent digital reforms to compensate for structural limitations in access to useful power (P).

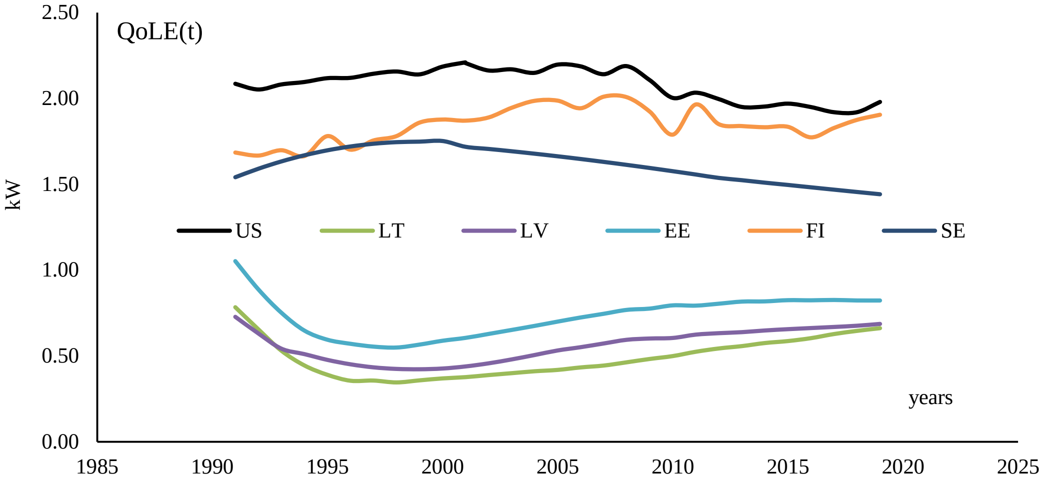

Figure 5: The Changes of the Quality-Of-Life Qole(T) For USA (US), Finland (FI), Sweden (SE), Latvia (LV), Lithuania (LT), Estonia (EE) In 1990-2019.
Source: Calculated By the Author.

The analysis confirms that management based solely on monetary data is blind to the real processes of degradation or stagnation in complex systems. In the case of the United States, "digital growth" masks the stagnation of physical development, creating a bubble of expectations that is not backed by energy. In the case of the Baltic countries, reliance on formal macroeconomic indicators of the European Union (GDP, inflation) has concealed the catastrophic loss of human capital and the decline in the energy density of the economy.

Overcoming the identified imbalances is impossible within the framework of the old management culture. A transition to multi-criteria analysis is necessary, where a solution is considered effective only if the conditions of economic feasibility and physical (energy) availability are simultaneously met.

5. DISCUSSION: A NEW MANAGEMENT CULTURE IN THE AGE OF DIGITAL TRANSFORMATION

The presented results reveal a profound disconnect between prevailing economic metrics and the physical realities of socioeconomic systems. The discrepancy between GDP growth and stagnant energy consumption in the United States, coupled with the structural degradation observed in the Baltic countries despite their digital aspirations, points to a systemic failure in current management paradigms. This section moves from diagnosis to prescription, outlining the contours of a "scientific management culture" necessary to align digital transformation with the immutable laws of nature.

5.1. Rethinking The Role of Technology

In contemporary discourse, digital transformation is often portrayed as a panacea for productivity stagnation and resource constraints. Governments and corporations are investing heavily in artificial intelligence (AI), big data analytics, and digital twins, operating under the assumption that the mere accumulation of data will translate into sustainable growth. However, when viewed through the lens of natural science approaches to economics, much of this activity boils down to erecting a "digital façade" over an increasingly fragile physical foundation. A critical flaw in contemporary digitalization strategies is the tendency to automate existing processes without fundamentally reengineering them based on physical efficiency. This leads to the "digitization of chaos," where advanced technologies are used to optimize local metrics within energy-inefficient systems. A striking example is the bureaucratization of public administration. The introduction of electronic document management systems in many jurisdictions, intended to reduce administrative friction, has paradoxically increased the volume of reporting and data generation. Although the transaction costs of document creation decrease, system entropy (bureaucratic noise) increases, consuming more human attention and energy without a corresponding increase in useful social return P(t) (Trusina & Jermolajeva, 2021).

From an energy perspective, such digitalization increases the system's total energy consumption N(t) (due to data centers and network infrastructure) without increasing its technological efficiency F = P/N. As a result, the system processes information faster, but performs useful work with decreasing efficiency. This is reminiscent of a ship that is equipped with complex sensors while its engines fail; the digital superstructure masks the degradation of the physical base.

To move toward a scientific management culture, the concept of the "digital twin" must be expanded beyond its current industrial application. A comparative analysis of existing practices (Singapore, New York) shows that modern digital twins of regions successfully address operational optimization challenges—reducing budget expenditures (by at least 20%), reducing emissions, and accelerating decision-making. However, most of them function as "administrative mirrors" reflecting existing processes (Abramov & Andreev, 2023). The transition to a scientific management culture requires transforming these tools from monitoring tools into predictive energy flow modelling systems. A true strategic digital twin must model not simply financial flows or geometric parameters, but fundamental flows of energy, matter, and entropy. It must serve as a dynamic model that answers the critical question: "If a specific strategic decision is implemented, how will the system's N=P+G power balance change over its lifecycle?" Consider the application of AI in supply chain management. The traditional approach optimizes for "minimum delivery cost," striving for the lowest possible combination of labor and fuel prices. This often leads to energetically absurd supply chains, where raw materials are transported across continents to exploit cheap labour, only to be returned as finished goods. While this is financially rational due to the externalization of environmental costs, it is physically irrational. A physically based AI, attuned to the criteria of a scientific culture, would optimize the "energy density of transportation" (joules per ton-kilometre). This criterion would automatically flag high-entropy logistics loops as inefficient, guiding decision makers toward regionalization and circularity, which are inherently more sustainable (Trusina et al., 2025).

Furthermore, artificial intelligence should assume the role of an independent "thermodynamic auditor." In the current accounting paradigm, significant entropy losses G(t)—such as pollution, waste generation, and the long-term social costs of low-wage labour—are treated as externalities invisible in financial statements. A scientifically based management culture requires AI algorithms capable of identifying and quantifying these hidden costs in real time. For example, an AI auditor could calculate a product's "end-of-life cost"—the energy and labour required to recycle or dispose of it—and integrate this value into a model of the product's initial cost. This shifts economic calculation from a "casino economy," where value is extracted by ignoring future consequences, to a "physical efficiency economy," where digital tools are used to maximize the long-term useful power of a system (Daly, 2015).

5.2. Overcoming Cognitive Biases: Scientific Thinking for Leaders

The main barrier to implementing a scientific management culture is not technological, but cognitive. The current generation of political and corporate leaders was educated primarily in neoclassical economics, which models the economy as a closed loop of cash flows between firms and households, ignoring the biophysical flow of energy and matter (Kuznetsov, 2015). This educational background fosters a specific set of mental models—linear thinking, short-termism, and a belief in the infinite interchangeability of resources—that fundamentally contradict the behavior of complex adaptive systems. The transition to a new culture requires a conscious shift from "Financial Thinking" to "Scientific Thinking" (Table 3).

Table 3: Comparative Analysis of Management Paradigms: Financial Vs. Scientific Thinking.

Parameter	Financial Thinking (Current Culture)	Natural Science Thinking (Scientific Culture)
Time Horizon	Short-Term (Quarterly Reports, Electoral Cycles)	Long-Term (System Life Cycles, 30-50 Years)
Growth Model	Linear Extrapolation (Infinite GDP Growth)	Logistic (S-Curve) with Saturation Limits
Source of Value	Money Generates Money (Financialization)	Energy Flow + Information = Useful Work
Nature	Externality (Off-Balance Sheet)	Boundary Condition (System Limit)

Leaders operating within a financial mindset view money as a finite resource and believe that with sufficient capital, any physical constraint can be overcome. In contrast, a physical mindset recognizes that money is merely a claim on energy, since without available energy flows N(t), financial capital is useless. As Podolinsky (Podolinsky, 2004) noted, the only true surplus in an economy is accumulated energy, achieved through the efficient application of labor and technology. This cognitive gap highlights a critical shortcoming of modern management education, particularly in MBA and MPA programs. These curricula excel at teaching financial engineering and marketing, but rarely address system dynamics, thermodynamics, or ecology. Consequently, managers are taught to optimize subsystems (for example, maximizing departmental profits), while remaining blind to the health of the system as a whole. This leads to decisions that are locally rational but globally catastrophic—for example, cost-cutting measures that undermine the resilience of critical infrastructure (Meadows, 2008). To address this, a scientific management culture requires the integration of "Physical Economics" and "System Dynamics" into the core curriculum for high-level decision makers. Building on the pioneering work of Jay Forrester and Dennis Meadows (Meadows et al., 1972; Forrester, 2003), such courses should use simulation modeling to demonstrate how exponential growth in a finite system inevitably leads to collapse or oscillation. Leaders must understand that a stable system is not one that grows indefinitely, but one that maintains a high level of useful power P(t) and internal complexity (Trusina et al., 2022).

The urgency of this cognitive shift is underscored by the phenomenon of "data blindness." In the era of big data, managers are drowning in terabytes of information but often fail to perceive the most critical signals about the system's health. This paradox is vividly illustrated by the US case discussed in Section 5.1. An analyst trained in financial thinking looks at a GDP chart (1960–2021) and sees a continuous exponential curve ($R^2 \approx 0.99$), interpreting it as a sign of robust health and creating strategies based on continued expansion. However, a physical-minded analyst looks at an energy consumption chart and sees a plateau beginning in the early 2000s. For the latter, the divergence between growing GDP and stagnating energy inflows is a flashing red light—a signal that the economy is detaching from physical reality and entering a speculative bubble (Trusina & Jermolajeva, 2022). Therefore, a scientific management culture is a cultivated ability to distinguish "noise" from "signal." In complex systems, noise consists of high-frequency fluctuations, such as stock prices or quarterly earnings reports. The signal is the long-term trend of physical parameters: energy return on investment (Hall et al., 2014), demographic structure, and the technological efficiency of infrastructure. Overcoming the trap of extrapolation requires leaders immune to the temptations of financial noise and attuned to the deeper frequencies of physical reality. The development of generative artificial intelligence (GAI) opens up new possibilities for implementing the principles of scientific culture at the micro level. GAI enables a transition from mass production to highly precise personalization of offerings (Stolyarov et al., 2025), which energetically means reducing entropy losses G(t) by producing only what a specific consumer actually needs at a given moment. However, without ethical and methodological filters (such as the Triplex model), the use of GAI risks only accelerating the generation of virtual noise without increasing the physical efficiency of the system.

5.3. Triplex Decision-Making Model

The theoretical foundations of scientific management culture, discussed in the previous sections, must be translated into practical frameworks for corporate and public governance. The transition from abstract principles to operational practice requires abandoning the binary logic of "profit/loss" in favor of a multi-criteria assessment system. This study proposes the "Triplex" model—a decision-making protocol designed to verify strategic initiatives across three fundamental dimensions of reality: thermodynamic feasibility, technological efficiency, and socio-ecological utility. Within the "Triplex" framework, a strategic decision—whether launching a new product line, constructing infrastructure, or implementing a national digitalization program—is considered valid only if it simultaneously satisfies the criteria of three filters.

Filter 1: Energy Return On Investment (EROI)

The first filter assesses the initiative's energy viability. It asks: does the project generate or conserve more useful energy than it consumes over its lifecycle?

In the context of the "extrapolation trap," many modern financial innovations are energetically parasitic. For example, cryptocurrency mining and high-frequency trading (HFT) generate significant financial returns but have low or negative social EROI. They consume enormous amounts of high-quality electricity (increasing N(t)) to perform computations that do not produce physical goods or services necessary for human survival (they contribute zero to real P(t)). From the perspective of scientific management culture, such activities represent "entropy pumps" – they accelerate the degradation of the system's energy base while creating virtual value. In contrast, "creative innovations" are those with high EROI. AI-powered precision agriculture, for example, minimizes fertilizer and diesel inputs per unit of crop yield, effectively increasing the clean energy available to society. Fourth-generation nuclear energy technologies offer EROI ratios exceeding 50:1, providing the high-density energy flow necessary to support complex urban civilizations. The Triplex model requires rebalancing investment portfolios to ensure the overall system EROI remains significantly above the critical threshold required to sustain civilization (Hall et al., 2014).

Filter 2: Technological Efficiency

The second filter assesses the efficiency of resource transformation. It addresses systemic failures observed in the development strategies of the Baltic countries. As detailed in Section 4, stagnation and depopulation in Latvia and Lithuania can be explained by investments that failed to improve the technological efficiency of the real economy. Investments in the service sector (e.g., e-commerce, call centers), while creating jobs, often act as "digital add-ons" that do not increase the physical power density of the underlying economy. Data show that the technological efficiency parameter f for Latvia hovers around 33%, significantly lower than 42% for Sweden (Trusina & Jermolajeva, 2023). This disparity means that for every watt of energy consumed, the Latvian economy generates significantly less useful social work than its Scandinavian counterpart. The Triplex model prioritizes projects that demonstrably increase f. This implies a preference for industrial modernization and knowledge-intensive production over purely transactional digital services. Without continuous growth, the system cannot maintain its internal complexity; as the example of the Baltic countries demonstrates, low efficiency leads to the "evaporation" of the most complex structural element—human capital—through migration to more efficient systems (Trusina et al., 2022).

Filter 3: Socio-Ecological Utility

The third filter aims to minimize entropy G(t), redefining the concept of "toxic assets." In traditional finance, a toxic asset is one that has lost market value. In scientific management culture, a toxic asset is any product or process that artificially inflates entropy for short-term financial gain. A paradigmatic example is "planned obsolescence." While financially rational for corporations because it encourages repeat purchases, it is energetically disastrous. It artificially increases the throughput of matter and energy, generating excess waste and requiring additional energy for disposal and replacement. The Triplex model requires calculating an "Entropy Tax," or shadow price, for such decisions. Strategic initiatives that reduce G—such as circular economy designs, modular repairability, and regenerative supply chains—receive a premium in valuation. This aligns corporate strategy with the second law of thermodynamics, viewing waste reduction not as a compliance cost but as an efficiency gain (Daly, 2015; Odum, 2007;).

Integrating Triplex into Corporate Governance

To institutionalize this model, corporate reporting must evolve beyond standard ESG (Environmental, Social, and Governance) disclosures, which often suffer from "greenwashing." We propose introducing a "Triplex Compliance Report" in annual reports.

This report should quantitatively disclose:

- The total EROI of the company's product portfolio.
- The year-over-year change in technological efficiency (F).
- The total entropy footprint (G), measured in physical units (joules of dissipated energy, tons of non-recyclable waste).

This shift transforms sustainability from a marketing narrative into a rigorous, physics-based accounting standard.

5.4. From Corporate Strategy to National Security: The Geopolitics of Power

The implications of scientific management culture extend beyond the boardroom into the realm of national security and grand strategy. In the emerging "Full World" economy, where physical limits, not capital accumulation, define the boundaries of growth, a nation's sovereignty is determined by its ability to manage power flows. Herman Daly's distinction between the "Empty World" (where human capital is the limiting factor) and the "Full World" (where natural capital is the limiting factor) is crucial for contemporary geopolitics. In a Full World, a nation that relies exclusively on financial services and digital platforms, while outsourcing its energy and material resources, loses strategic agency. The illusion of wealth created by high GDP becomes a vulnerability to the disruption of global supply chains (Costanza, 2004; Daly, 2015).

The case of the United States, discussed earlier, serves as a strategic warning. The divergence between GDP growth and stagnant energy consumption suggests a "hollowing out" of the physical economy. If a nation loses the ability to generate or supply high-density energy flows N(t), its ability to project power—military, technological, or soft—diminishes, regardless of its stock market capitalization. Financial wealth is a claim on resources; if physical resources are unavailable or cannot be efficiently utilized, the claim is nullified (Podolinsky, 2004).

The failure of the "Latvia 2030" (Latvia 2030) strategy to achieve demographic and economic goals illustrates the danger of ignoring physical parameters in national planning. Strategies, drafted primarily by economists, often function as "wish lists" of political goals—innovation leadership, population growth, green transition—without a verified energy foundation (Latvia 3020; Latvia SDR, 2022). As Trusina and Jermolajeva (Trusina et al., 2023) note, it is difficult to construct a unified picture of development when strategic indicators are divorced from the system's power potential. A scientific management culture dictates that national development plans should begin with a rigorous energy audit, not a political manifesto.

Strategic planning must answer three fundamental questions:

- What volume of gross power N(t) will be physically available to the nation over a 20-30-year horizon?
- What is a realistic trajectory of technological efficiency (F) given the country's industrial base?
- What is the minimum useful power P(t) required to support the target population and infrastructure complexity?

Only after mapping these physical constraints can economic and social goals be realistically formulated. A strategy aimed at population growth while the system's power density declines is physically impossible and inevitably leads to migration and structural simplification. Nations that are the first to implement a scientific management culture will gain a decisive competitive advantage. By optimizing EROI and f, rather than GDP, they will avoid the "middle-income trap," which in physical terms is a "low-efficiency trap." They will build a resilient infrastructure capable of withstanding the energy and climate shocks of the 21st century. This perspective redefines national security. It's no longer just about border security or cybersecurity, but about "energy sovereignty"—the autonomous ability of a state to capture, transform, and utilize energy flows to maintain its social order. In this light, the energy transition is not simply an environmental policy, but a prerequisite for survival. The ability to integrate AI and digital tools to maximize this sovereignty will become a defining characteristic of successful states in the coming decades (Weizsäcker & Wijkman, 2018).

5.5. Synthesis: Artificial Intelligence as a Bifurcation Point – Accelerator of Collapse or Agent of Resilience?

Artificial intelligence represents the most powerful cognitive lever ever created by humanity, amplifying the potential of management decisions by orders of magnitude. However, as cybernetics and systems theory dictate, a powerful amplifier applied to an erroneous signal does not correct the error; it merely magnifies the distortion (Meadows, 2008). In the context of global socioeconomic development, AI acts as a bifurcation point, offering two diverging paths depending on the ontological foundation of the management culture that guides it.

Scenario A: Entropy Accelerator

If AI continues to be implemented within the current "Financial Thinking" paradigm – characterized by the "extrapolation trap" and the pursuit of infinite monetary growth – it risks accelerating systemic collapse. In this scenario, algorithms optimize to maximize short-term financial metrics (quarterly profit, GDP, click-through rate) without regard for thermodynamic constraints. AI trained to maximize GDP in a "Full World" economy will inevitably identify the most efficient ways to extract and consume the remaining natural capital. It will optimize supply chains, making them leaner but more fragile, eliminating the redundancies that ensure resilience, and accelerating resource extraction to meet the exponential demand of virtual markets. As illustrated by the stagnation of physical energy consumption in the US, this optimization creates a dangerous divergence: financial wealth grows while the physical infrastructure supporting it degrades. Furthermore, the "digital façade" discussed earlier becomes a self-reinforcing delusion. AI-generated narratives and financial instruments can temporarily mask physical scarcity, creating speculative bubbles. When these bubbles burst—triggered by an energy crisis or supply chain disruption—the collapse will be more rapid and catastrophic, as AI-driven systems have eliminated systemic buffers. In thermodynamic terms, AI in this scenario maximizes the rate of entropy production G(t), accelerating the system's progress toward heat death.

Scenario B: Sustainability Agent (Scientific

Management Culture)

In contrast, if AI is integrated into Scientific Management Culture, it becomes the primary tool for navigating the transition to a sustainable steady-state economy. In this scenario, the objective function of AI algorithms is fundamentally rewritten. Instead of maximizing N(t) (consumption) or financial proxy variables, AI is tasked with maximizing Technological Efficiency f and Useful Power P(t), while minimizing Entropy G(t). Here, AI serves as the "nervous system" of the noosphere (Vernadsky, 2006; Ayres, 1998). It monitors planetary boundaries in real time, balancing energy flows in smart grids to align demand with the dynamics of renewable sources. It designs materials and products for circularity, calculating molecular recycling pathways even before the product is manufactured. It optimizes logistics not by price but by energy density, ensuring compliance with the "Triplex" criteria at the speed of automated decision-making. This approach also transforms the role of human capital. As routine cognitive tasks are transferred to AI, human creativity is freed to focus on the most challenging aspect of development: defining the system's purpose. While AI optimizes means (efficiency), humans define ends (social values, cultural preservation). This symbiosis is consistent with the biophysical imperative: using information (low energy cost) to more efficiently organize matter and energy (high energy cost), thereby extending the lifespan of civilization (Podolinsky, 2004).

5.6. Designing the Future

The future is not a predetermined destination, but a project. The quality of this project depends entirely on the ontology we embed in our digital tools. If we encode an "ontology of money"—treating it as a self-sufficient reality—we encode our own obsolescence, as money has no physical meaning in a devastated biosphere. If we encode an "ontology of life"—recognizing energy and information as the true currencies of the universe—we open the door to a new level of civilizational complexity. The window of opportunity for this shift is narrowing. Physical signals of stagnation in developed economies warn that the era of cheap energy and easy growth is over. The choice facing global leadership is stark: use AI to manage a retreat into the fortress of virtual wealth or use it to engineer a bridge to a physically viable future. Scientific management culture is not just an academic concept; it is a survival guide for this transition.

6. CONCLUSION

The study concludes that modern civilization is at a bifurcation point. We are moving from an "empty world" economy (in G. Daly's terminology), where resources seemed infinite and man-made capital was the limiting factor, to a "full world" economy, where the physical capabilities of the biosphere and the availability of free energy are the limiting factors. Under these conditions, old management methods based on the linear extrapolation of past financial trends are becoming not only ineffective but also mortally dangerous.

An analysis of data from the US and European countries has shown that without taking into account the law of conservation of power, digital transformation risks creating a "digital façade" on the crumbling edifice of the real economy. The illusion of endless GDP growth masks the stagnation of physical consumption and the declining viability of social systems, as is clearly evident in the demographic crisis in the Baltic countries. A scientific management culture is a response to the challenges of the new era. It is a return to the ontological foundations of management, an understanding that value is a derivative of energy and information, not a self-sufficient entity.

Implementing this culture requires:

- the shift in metrics: a transition from single-criteria financial indicators to multi-criteria physical indices (useful power, technological efficiency);
- the shift in toolkit: the use of AI and Big Data to monitor physical flows and thermodynamically optimize systems;
- the shift in mindset: the development of leaders with systems thinking and the ability to distinguish virtual growth from real development.

Artificial intelligence is the most powerful tool ever created by man, but like any tool, its effectiveness depends on the operator's goal setting. If we continue to task AI with maximizing GDP at any cost, it will only accelerate our thermodynamic impasse. If we reorient it toward maximizing useful power and minimizing entropy, it could become the key to humanity's transition to a new level of civilizational development. The future isn't predetermined—it's being designed, and the quality of this design directly depends on the scientific validity of our management culture.

Declaration of competing interest

The authors affirm that they have no known financial or interpersonal conflicts that would have appeared to have an impact on the research presented in this study.

Ethics Statement

Ethics approval was obtained from the Ethics Committee of Arid Regions Institute of Medenine. In addition, the participants provided their informed consent to participate in this study.

Authorship contribution statement

Viktor Abramov: conceptualization, investigation, data curation, formal analysis, methodology, and writing-review and editing.

Inese Trusina: conceptualization, investigation, data curation, formal analysis, methodology, and writing-original draft.

Vladimir Osipov: resources, supervision, writing–review and editing, and validation.

Sergey Vagin: data curation, visualization, writing – original draft

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