INDUSTRY 5.0 ACROSS THE ATLANTIC: A COMPARATIVE ANALYSIS OF EUROPEAN VALUE-BASED AND AMERICAN MARKET-BASED INDUSTRIAL PARADIGMS

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Rezumat. *Industria 5.0 reprezintă o schimbare de paradigmă către sisteme industriale centrate pe om, sustenabilitate și reziliență. Lucrarea prezintă o analiză comparativă a Uniunii Europene și a Statelor Unite în raport cu principiile Industriei 5.0. Abordarea europeană este caracterizată de un cadru bazat pe valori, care pune accent pe etică, sustenabilitate și aliniere la reglementări. Perspectiva SUA prioritizează inovația tehnologică, eficiența pieței și implementarea industrială rapidă. Studiul dezvoltă un model multicriterial care integrează indicatorii Sustainability Index (SI), Ethical Risk Index (ERI) și Resilience Score (RS) prin metodele AHP, TOPSIS și ELECTRE. Cercetarea evidențiază diferențele cheie în politica industrială și strategiile de implementare, demonstrând că cele două abordări sunt complementare și oferă oportunități pentru un model hibrid care combină responsabilitatea etică cu competitivitatea tehnologică.*

Abstract. *Industry 5.0 represents a paradigm shift towards human-centered, sustainable and resilient industrial systems. This paper presents a comparative analysis of the European Union and the United States regarding Industry 5.0 principles. The European approach is characterized by a values-based framework emphasizing ethics, sustainability and regulatory alignment. In contrast, the US perspective prioritizes technological innovation, market efficiency and rapid industrial deployment. The study develops a multi-criteria model integrating Sustainability Index (SI), Ethical Risk Index (ERI) and Resilience Score (RS) through AHP, TOPSIS and ELECTRE methods. The research highlights key differences in industrial policy and implementation strategies, demonstrating that the two approaches are complementary and offer opportunities for a hybrid model combining ethical responsibility with technological competitiveness.*

Keywords: Industry 5.0, multi-criteria decision making, sustainability, resilience, engineering ethics

1. Introduction

The evolution of industrial systems has been marked by successive transitions between technological paradigms, culminating with Industry 4.0, characterized by advanced digitalization, cyber-physical systems, IoT/IIoT integration, and

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recently artificial intelligence [1-5]. Industry 4.0 primarily aims at process optimization through efficiency gains, cost reduction, and quality improvement. However, this exclusively economic performance orientation has generated significant challenges: environmental impact, excessive resource consumption, increased automation dependency, and reduced human involvement [6-8].

As a response to these limitations, the ***European Commission*** promoted ***Industry 5.0*** as a new strategic direction [9-11]. Unlike its predecessor, Industry 5.0 integrates social, ethical, and sustainability dimensions into industrial system design and operation, introducing three fundamental pillars: human-centricity, sustainability, and resilience [12]. Human-centricity reintegrates specialists into decision-making processes using technology as support rather than replacement. Sustainability targets environmental impact reduction and responsible resource use, while resilience refers to system adaptive capacity [13,14].

In contrast, the United States has not formally adopted the Industry 5.0 concept but continues developing advanced industrial systems based on technological innovation and competitiveness [15,16]. The American model is market-driven, where decisions are primarily influenced by economic efficiency and competitive advantage. US companies adopt Industry 5.0 pillars such as collaborative robots or energy efficiency under labels like "Advanced Manufacturing" or "Smart Manufacturing" without explicitly adopting the Industry 5.0 terminology [15].

These divergent approaches raise important scientific questions regarding compatibility and efficiency. Is the European approach too restrictive for rapid innovation? Is the American model sufficiently robust for long-term sustainability? Existing literature treats these aspects separately, lacking systematic comparative analyses [9,17,18]. This paper addresses this gap by developing a multi-criteria decision-making model that integrates Sustainability Index (SI), Ethical Risk Index (ERI), and Resilience Score (RS) through AHP [19], TOPSIS [20], and ELECTRE [21] methods, proposing an operational framework for Industry 5.0 implementation.

2. Conceptual Framework of Industry 5.0: Connecting European and American Paradigms

2.1 Core Principles and Evolution from Industry 4.0

Industry 5.0 represents an evolution of the Industry 4.0 model, extending the focus from technological optimization to integrating human, social, and environmental values into industrial systems. While Industry 4.0 was defined primarily through digitalization, automation, and operational efficiency, Industry 5.0 introduces a socio-technical approach where technology serves broader objectives related to sustainability and human well-being. This paradigm shift moves from exclusively economic performance to multi-dimensional value encompassing social and ecological impact [10,13].

From an engineering perspective, this transition requires extending classical decision models based on cost, time, and quality criteria towards multi-criteria models integrating additional dimensions. This creates the need for analytical tools capable of quantifying and balancing heterogeneous criteria, preparing the framework for operational models in the Industry 5.0 context [14,22].

2.2 European vs. American Industrial Models

The European and American approaches reflect fundamental differences in conceptualizing industrial transformation. The European model is predominantly value-driven, built around a normative framework explicitly integrating ethics, sustainability, and social responsibility [15,23]. Industry 5.0 is promoted as a strategic direction where technological development is subordinated to broader societal objectives, supporting circular economy principles, environmental impact reduction, and human factor protection.

In contrast, the American model is market-driven, where technological innovation and economic competitiveness are the primary determinants [16,24]. Transformation is guided by market dynamics, private investment, and innovation ecosystems. While concepts like sustainability, ethics, and human-centered design are present, they are integrated pragmatically as performance-enhancing factors rather than normative objectives formalized into a unified conceptual framework [25,26].

This difference produces two complementary models: a normative value-oriented model and an operational efficiency-oriented model. While Europe excels in defining and conceptualizing Industry 5.0, the United States demonstrates superior capacity for implementing emerging technologies and transforming them into competitive advantages [27].

2.3 Fundamental Dimensions for Industrial System Evaluation

To operationalize Industry 5.0 principles in real industrial contexts, a set of fundamental dimensions is proposed: Technology (T), Human-centricity (H), Sustainability (S), and Resilience (R). The technological dimension includes digitalization level, cyber-physical systems integration, and advanced technologies like AI and IoT [28]. Human-centricity targets the operator's active role in decision-making and system impact on workforce well-being, safety, and competencies [29]. Sustainability reflects environmental impact and responsible resource use, integrating energy efficiency, carbon footprint, and process circularity indicators [30]. Resilience is associated with system capacity to withstand disruptions and adapt to dynamic conditions, including operational flexibility, robustness, and recovery time [31].

The integration of these four dimensions defines a conceptual model of industrial performance in the Industry 5.0 context:

$$I5.0 = f(T, H, S, R) \tag{1}$$

This formulation highlights the multi-criteria nature of evaluation, where each dimension contributes to overall system performance, extending evaluation beyond economic indicators to a complex process integrating technological, social, and environmental aspects.

2.4 Current Limitations and Research Gap

Despite growing interest in Industry 5.0, existing approaches present significant limitations [12, 32]. Most studies are predominantly conceptual or descriptive, focusing on principle definition without providing operational models for real-world implementation [33]. A primary limitation is the absence of integrated engineering frameworks translating Industry 5.0 dimensions into measurable, quantifiable variables [34]. Additionally, existing literature lacks robust multi-criteria decision mechanisms balancing economic, social, and environmental criteria simultaneously [35]. The absence of synthetic indicators incorporating ethical dimensions and the lack of correlation between European and American approaches further limit the development of global, adaptable industrial solutions [17].

2.5 Proposed Integrated Framework

The identified limitations highlight the necessity of an integrated approach enabling the translation of Industry 5.0 principles into operational engineering models. Multi-Criteria Decision-Making (MCDM) methods represent a promising direction for integrating heterogeneous dimensions. Methods such as AHP, TOPSIS, and ELECTRE allow alternative evaluation under multiple conflicting criteria, providing a formal framework for balancing economic performance with social and environmental impact. The proposed framework uses three synthetic indicators: Sustainability Index (SI), Ethical Risk Index (ERI), and Resilience Score (RS), bridging European value orientation with American implementation pragmatism.

3. Methodology: Multi-Criteria Decision-Making Model for Industry 5.0 Integration (MCDM)

3.1 Methodological Approach and Research Plan

This research adopts a conceptual-engineering approach, aiming to develop an operational model integrating Industry 5.0 principles into industrial evaluation and decision processes. The methodology is built on multi-criteria modeling, considered appropriate for the Industry 5.0 context where system performance can no longer be evaluated exclusively through economic indicators. The process is structured in four stages: (a) defining Industry 5.0 fundamental dimensions, (b) identifying and formalizing performance indicators, (c) integrating them into a mathematical model, and (d) applying a multi-criteria decision mechanism for industrial system evaluation.

3.2 Model Architecture

The model architecture is structured on three principal levels: input, processing (decision core), and output, complemented by a performance indicator-based feedback mechanism. The input level includes the technological dimension (T) providing digital infrastructure, and the *human-centric dimension* (H) *introducing decisional and contextual factors*. Sustainability (S) and resilience (R) dimensions *are integrated both as objectives and system constraints*. The processing level aggregates information from all dimensions through multi-criteria mechanisms, where technology enables sustainable solutions, human factors influence selection and adaptation, and sustainability/resilience requirements impose decision constraints.

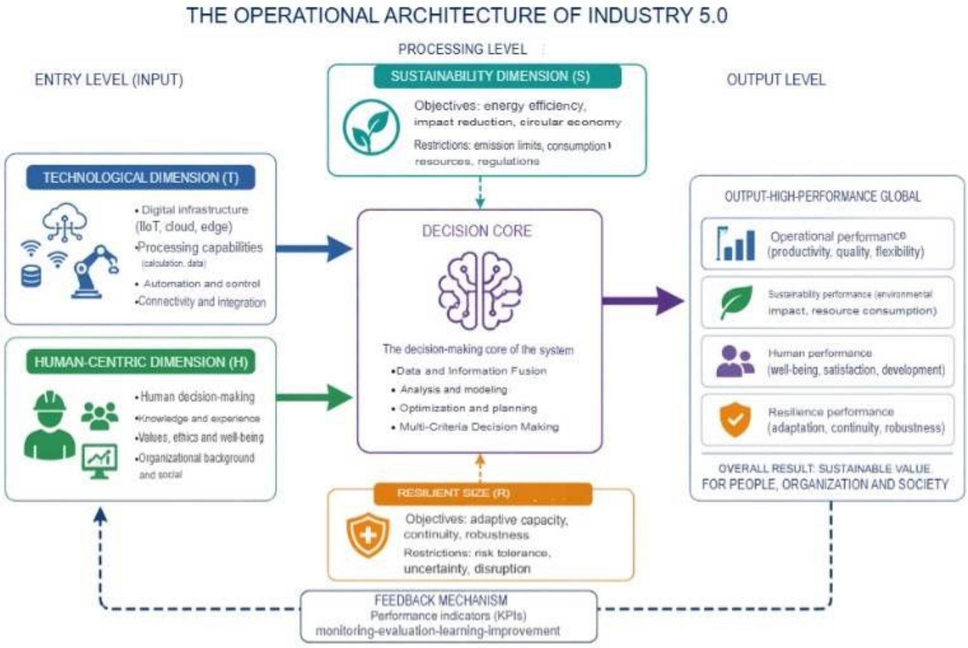

Fig. 1. Operational architecture of the Industry 5.0 model integrating technological (T), human-centric (H), sustainability (S), and resilience (R).

The output level represents operational system results evaluated through performance indicators generating a feedback mechanism for continuous adjustment [22].

Fig. 1 illustrates the operational architecture of the proposed Industry 5.0 model, showing the integration flow between technological, human, sustainability, and resilience dimensions within the decision-making core.

3.3 Performance Indicators (KPIs)

To operationalize the model architecture, three synthetic indicators are defined*:* **Sustainability Index** (**SI**), **Ethical Risk Index** (**ERI**), and **Resilience Score** (**RS**). The Sustainability Index measures system environmental impact and resource use efficiency, integrating energy consumption, carbon emissions, and process circularity as a weighted combination of normalized factors:

$$SI = \Sigma\, w_i \cdot x_i \qquad (2)$$

where x_i represents specific sustainability indicators and w_i are associated weights. The Ethical Risk Index reflects ethical risks associated with technology use and impact on human factors, including operator safety, decision transparency, and automation negative effects, defined through probability-impact assessment:

$$ERI = \Sigma\, v_i \cdot (P_i \cdot I_i) \qquad (3)$$

where P_i represents risk probability, I_i its impact, and v_i are risk type weights. The Resilience Score measures system capacity to respond to disruptions, integrating operational flexibility, robustness, and recovery time:

$$RS = \Sigma\, u_i \cdot r_i \tag{4}$$

where r_i are specific resilience indicators and u_i corresponding weights. These indicators enable holistic evaluation where system performance is analyzed from multiple perspectives beyond traditional economic criteria [30,31].

3.4 MCDM Integration

The decision process is organized in three complementary stages. First, the **Analytic Hierarchy Process** (**AHP**) determines **criteria weights through hierarchical problem structuring and pairwise** comparisons between SI, ERI, and RS indicators using a standardized 1-9 scale [19]. Second, the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) evaluates and ranks alternatives by identifying the optimal solution through relative distance to ideal positive and negative solutions. Third, the **ELECTRE** (**Elimination et Choix Traduisant la Realité**) method validates results and eliminates alternatives not meeting minimum performance requirements through outranking relationships [21].

This integration combines each method's advantages: AHP provides transparent weight determination, TOPSIS ensures rigorous numerical evaluation, and ELECTRE introduces additional validation filtering, making the decision process coherent, reproducible, and adaptable to different industrial contexts.

3.5 Mathematical Formulation

Based on the model architecture and indicator framework, industrial system performance in the Industry 5.0 context is formulated as a multi-criteria optimization problem. The objective is maximizing overall system performance considering sustainability, ethical risks, and resilience simultaneously:

$$F = \alpha \cdot SI - \beta \cdot ERI + \gamma \cdot RS \tag{5}$$

where α, β, γ are weighting coefficients reflecting relative criterion importance, satisfying the condition:

$$\alpha + \beta + \gamma = 1, \quad \alpha, \beta, \gamma \geq 0 \tag{6}$$

The negative sign associated with ERI reflects its cost criterion nature (to be minimized), while SI and RS are benefit criteria to be maximized. The indicators are defined as aggregate functions of normalized variables for comparability within a unified framework, with constraints reflecting minimum performance requirements:

$$IS = \sum_{i=1}^{n} w_i \cdot x_i, \quad x_i \in [0,1]$$

$$IRE = \sum_{j=1}^{m} v_j \cdot (P_j \cdot I_j)$$

$$SR = \sum_{k=1}^{p} u_k \cdot r_k, \quad r_k \in [0,1]$$

$$\max F(T,H,S,R)$$

$$SI \geq SI_{min}, \quad ERI \leq ERI_{max}, \quad RS \geq RS_{min} \qquad (7)$$

This formulation enables direct indicator integration into the multi-criteria decision process, providing a coherent mathematical framework for alternative evaluation and comparison with flexibility for weight and constraint adaptation depending on application specifics.

3.6 Implementation Procedure

The model is implemented through a structured, reproducible evaluation procedure integrating data preparation, criteria weighting, alternative evaluation, and result validation. The procedure begins with defining industrial alternatives and preparing evaluation data, followed by AHP-based weight determination with consistency ratio verification. Alternative evaluation uses TOPSIS through decision matrix construction, normalization, ideal solution identification, and relative closeness coefficient calculation. Results are validated through ELECTRE's concordance and discordance matrices, outranking relationships, and suboptimal alternative elimination (Fig. 2). Final performance evaluation applies the global performance function, comparative analysis, and sensitivity assessment.

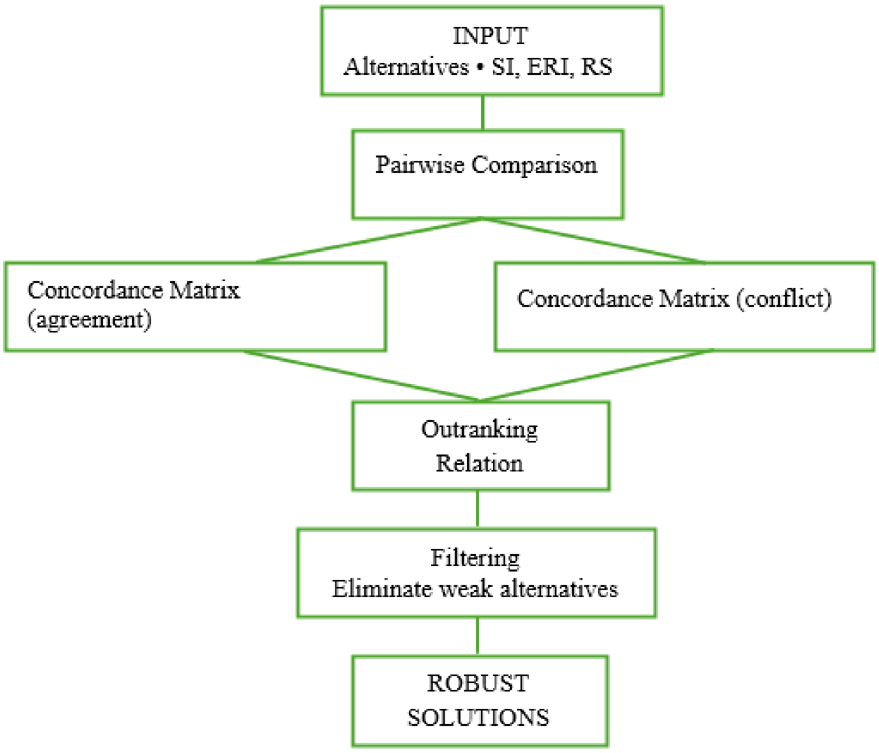

Fig. 2. Structure of the ELECTRE-based validation and filtering process applied to Industry 5.0 performance indicators (IS, IRE, SR).

4. Conceptual Validation and Application Guidelines

4.1 Case Definition

To demonstrate model applicability, a representative conceptual scenario is considered for a modern industrial production system in transition towards Industry 5.0 principles. Three conceptual alternatives are defined: Alternative A1 is technology-performance oriented, emphasizing automation and efficiency (American paradigm). Alternative A2 prioritizes sustainability and social values (European model). Alternative A3 proposes a balanced approach integrating technological performance with sustainability and resilience objectives, representing a hybrid model.

4.2 KPI Structure

For each alternative, three indicator categories (SI, ERI, RS) are considered. Using relative levels (low, medium, high), A1 is characterized by high performance but higher ethical risk and moderate sustainability. A2 shows high sustainability and low ethical risk but moderate technological performance. A3 offers balance across all dimensions. This structuring enables model behavior evaluation without dataset-specific dependency.

4.3 Model Application

Model application follows the defined stages: AHP weight determination, TOPSIS evaluation, and ELECTRE validation. Fig. 3 illustrates the complete decision model workflow, integrating KPI definition, AHP weighting, TOPSIS evaluation, and ELECTRE-based validation.

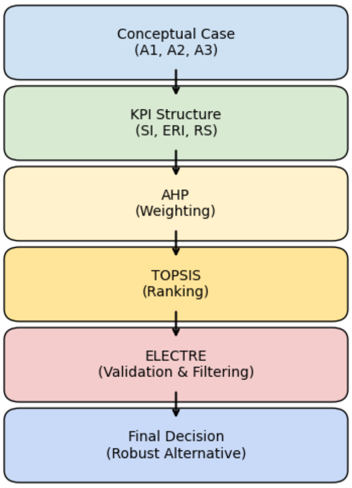

Fig. 3. Workflow of the proposed multi-criteria decision model for Industry 5.0, integrating KPI definition, AHP weighting, TOPSIS evaluation, and ELECTRE-based validation and filtering.

4.4 Expected Results and Comparative Analysis

Conceptual model application suggests Alternative A3, characterized by dimensional balance, is the most probable optimal solution. A1, despite technological performance, may be penalized by ethical risks, while A2 may be limited by operational performance. This analysis highlights that the model does not favor extremes but balanced solutions, consistent with Industry 5.0 principles. Table 1 provides a comparative summary of industrial paradigm characteristics across evaluation criteria.

Table 1. Comparative summary of industrial paradigm characteristics

Criteria	Industry 4.0	Industry 5.0	EU (I5.0 Level)	US (I5.0 Level)
Paradigm	Technology	Socio-technical	High (conceptual)	Medium (implicit)
Primary Goal	Efficiency	Societal value	High	Medium
Technology Role	Purpose	Enabler	Medium	High

Criteria	Industry 4.0	Industry 5.0	EU (I5.0 Level)	US (I5.0 Level)
Human Role	Operator	Central	High	Medium
Optimization	Cost-time-quality	Multi-criteria	Medium	Medium
System Type	Automated	Resilient, collaborative	Medium	High
Digitalization	Efficiency	Purpose-driven	Medium	High
Social Impact	Limited	Integrated	High	Medium
Sustainability	Optional	Fundamental	High	Medium
Resilience	Low	Essential	Medium	High
Economic Model	Profit	On-Planet-Prosperity	Medium	High (profit-driven)
Ethics	Marginal	Integrated	High	Medium
Value Chain	Optimized	Responsible, circular	Medium	Medium
Decision Type	Deterministic	Complex	Medium	Medium

4.5 Sensitivity Analysis

Sensitivity analysis is performed conceptually by evaluating criteria weight variation impact on final results. If sustainability is prioritized, Alternative A2 becomes more competitive. If technological performance dominates, A1 may become preferable. This flexibility demonstrates model adaptability to different industrial contexts and organizational strategies, ensuring robust decision-making under varying priority configurations.

4.6 Implications for EU vs. US Paradigms

The conceptual results highlight differences between European and American paradigms and the proposed model's role in reconciling them. Fig. 4 illustrates the conceptual positioning of paradigms and industrial alternatives within Industry 5.0, showing the transition from performance-based (US) to value-based (EU) approaches and the emergence of a hybrid solution. The value-performance matrix demonstrates that the hybrid model (A3) occupies an optimal position, combining the normative rigor of the European approach with the operational pragmatism of the American model.

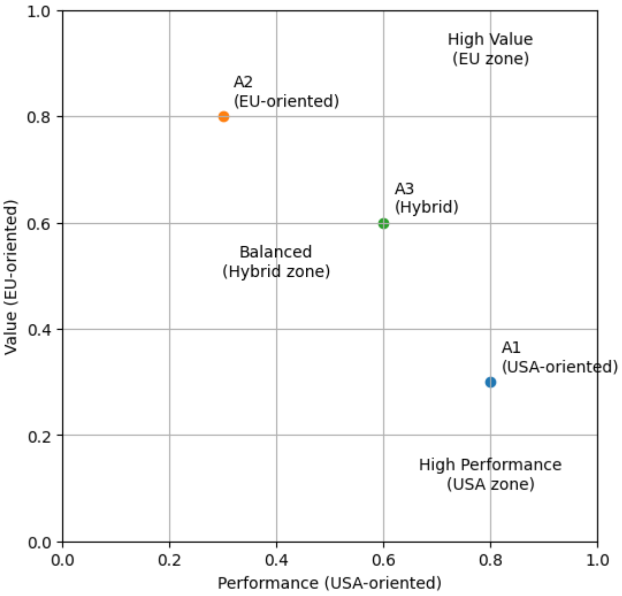

Fig. 4. Conceptual positioning of paradigms and industrial alternatives within Industry 5.0, showing the transition from performance-based (US) to value-based (EU) approaches and the emergence of a hybrid solution.

5. Conclusions

This paper analyzed European and American industrial paradigms in the Industry 5.0 context, highlighting fundamental differences between value-oriented and performance-oriented approaches. The analysis demonstrated that although built on different principles, these paradigms are not contradictory but complementary, offering premises for developing an integrated industrial model.

The main contribution is the development of a multi-criteria engineering framework integrating Industry 5.0 essential dimensions into decision-making processes. Through **Sustainability Index** (**SI**), **Ethical Risk Index** (**ERI**), and **Resilience Score** (**RS**) definition, and **AHP**, **TOPSIS**, and **ELECTRE** method utilization, the proposed model provides a coherent mechanism for evaluating and optimizing industrial systems under multiple conflicting criteria. The conceptual validation demonstrated the model's capacity to favor balanced solutions integrating technological performance with sustainability and ethical responsibility.

Compared with predominantly conceptual or fragmented existing literature, this work proposes an integrated operational model capable of translating Industry 5.0 principles into applicable engineering tools. Future research directions include model application in real case studies, development of industry-specific indicator sets, and integration into digital decision support systems. Exploring political and economic implications of the proposed hybrid model may contribute to developing more coherent global industrial strategies.

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