

From linear to circular defense industry using disruptive technology and AI

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Abstract. Due to sustainability requirements in Europe, the defense industry is under pressure to adopt a circular economy model instead of a linear one. This paper describes the conceptual plan for Circular Defense Economy (CDE) platform, a modular, data-driven ecosystem designed to support circular practices across the entire Soldier Protection Equipment (SPE) life cycle. By using emerging technologies such as AI-driven decision support systems, blockchain for life-cycle monitoring and bio-based materials and recycling technologies, the CDE supports the eco-design, reuse, repair, remanufacturing and recycling of high-value defense composites. The platform aligns with the objectives of the European Commission under the Circular Economy Action Plan (CEAP) and the Incubation Forum for Circular Economy (IF CEED) initiative, providing replicable models for sustainability, innovation and cross-border cooperation.

Keywords: circular economy, defense innovation, soldier protection equipment, disruptive technology, sustainability, lifecycle tracking

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Introduction

The defense industry, long aligned with linear industrial practices, now stands at a crossroads. Volatile geopolitical dynamics, resource depletion, and mounting environmental challenges demand an accelerated shift toward sustainability. This transformation aligns with the principles of the Circular Economy (refuse, reduce, reuse, repurpose, and recycle) providing a paradigm that minimizes waste and environmental impact while preserving competitiveness and economic resilience.

Within this context, the Circular Defense Economy (CDE) framework emerges as a strategic approach to embed sustainability into defense operations. It emphasizes the integration of advanced digital infrastructures capable of orchestrating material flows, managing equipment lifecycles, and fostering collaborative stakeholder engagement. The paper focuses on the life cycle of SPE, analyzing how the CDE platform can support circular management of materials and components.

The following principles are fundamental to the concept: phasing out non-recoverable waste and reducing pollution, keeping products and materials at their highest use value for as long as possible and restoring natural systems. The circular economy is an approach that aims to separate economic activity from the use of natural resources by recycling materials and reducing waste and pollution. In response to limited resources and a rising global population, this approach encourages reviewing production, consumption, and growth models to account for social, environmental, and economic factors.

Literature review

Global demand for raw materials is growing rapidly, especially in developing nations, which has amplified Europe's dependence on critical raw materials. China serves as the primary supplier for 15 of the European Union's 25 critical raw materials, which is equivalent to approximately 60% of the key materials needed for its strategic industries, indicating a significant EU reliance on Chinese exports.

At the national level, Romania relies on imports for 92% of its metal ore requirements and 54% of its fossil energy resources, underscoring a significant dependence on external suppliers. According to a report by the Joint Research Center, the trade balance of raw materials in Romania in 2018 was negative, including minerals, metals, stone, and glass [1].

The circular economy represents an economic model that differs from the traditional linear system by changing material and energy flows from a linear process to a cyclical one. It involves practices such as reuse, remanufacturing, reconditioning, repair, modernization, and the use of renewable energy across the product's value chain and throughout its life cycle. [2] The value chain is a process that analyzes all the stages through which goods and services pass, from supply to the end user, to identify and maximize the value created in each phase of this process.[3]

Adopting circularity principles promises significant economic, environmental, and strategic benefits. According to the Circularity Gap Report 2021, circular economy strategies could reduce global greenhouse gas emissions by up to 39% and reduce pressure on virgin resources by 28%. [4] The European Commission estimates a net positive impact: the implementation of circular economy measures could increase EU GDP by 0.5% by 2030 and create around 700,000 new jobs. These figures highlight the potential of circularity to stimulate sustainable growth and generate opportunities on the labor market, while protecting the environment. In fact, the transition to a circular economy directly or indirectly aligns with no less than 49 of the 169 targets of the UN Sustainable Development Goals.[5]

In the defense industry, sustainability concerns are starting to take shape through European initiatives dedicated to circular economies. A major example is the Incubation Forum for Circular Economy in European Defense (IF CEED), launched under the aegis of the European Defense Agency in 2021. IF CEED operates as a collaborative platform bringing together 26 EU Member States and around 300 experts. [6]. The initiatives of this forum aim to incubate concrete projects and exchange best practices in areas such as: circular materials science (identifying sustainable alternatives for critical raw materials and developing advanced reusable materials), end-of-life reuse strategies (addressing ways to reuse end-of-life military equipment, such as remanufacturing or upgrading key components) or sustainable logistics and waste management (optimizing military logistics chains to reduce waste, including hazardous waste management according to environmental directives).

A notable case of circular application in defense is the reuse and recycling of advanced composite materials. Equipment such as ballistic armor, military helmets, armored vehicle components, and aircraft structural elements contain carbon fiber reinforced composites (CFRC) or glass fiber reinforced composites (GFRG), which are expensive to produce and have a significant carbon footprint. Pilot initiatives in European defense are exploring the recovery of these materials: for example, re-inserting carbon fibers recovered from end-of-life aircraft panels or

recycling armor plates to extract ceramics and aramid fibers from ballistic inserts, which can be reused in new applications. Such approaches not only reduce hazardous waste, but can also reduce dependence on imported materials, closing the loop between the end of life of military equipment and the production of new ones. [7]

Para-aramid fibers, such as Kevlar and Twaron, with a density of 1.44 g/cm³, have been widely utilized in helmet elements. [8][9]. The production is increasingly utilizing crystallized fibrils olefin ethylene UHMWPE fibers (such as Dyneema, Spectra, and Endumax) with a density of 0.97 g/cm³, which have replaced para-aramid fibers in terms of V50 performance and weight. UHMWPE features a high strength-to-weight ratio, low friction, strong cut resistance, and minimal creep, but has a relatively low melting point of approximately 145–153 °C [10]. Soldier Protection Equipment (SPE) can vary depending on the elements in the composition, for example, ballistic helmets can be categorized into three categories based on their materials: UHMWPE-based helmets, aramid-based helmets, and hybrid helmets that combine these two materials or include others (Figure 1). [11]

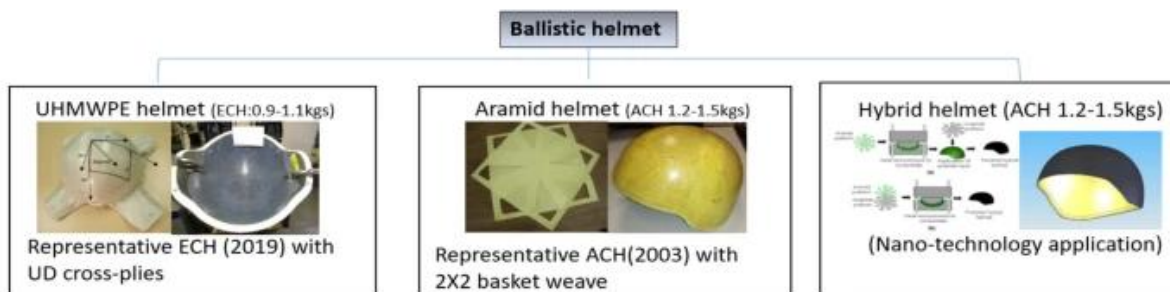


Figure 1: Categories of ballistic helmet on material base

Source: Liang, Y., Chen, X., & Soutis, C

Circular economy principles align with the United Nations (UN) Sustainable Development Goals (SDG). The strongest relationships and synergies between CE practices and the SDGs are found in SDG 6 (Clean water and sanitation), SDG 7 (Clean and affordable energy), SDG 8 (Decent work and economic growth), SDG 12 (Consumption and sustainable production) and SDG 15 (Land Life), scoring high for both direct and indirect contributions. SDG 1 (No poverty), SDG 2 (Zero hunger) and SDG 14 (Underwater life) are affected by Circular Economy (CE) practices indirectly.

In 2015, the European Commission (EC) adopted the first EU Circular Economy Action Plan. This plan included measures related to various EU priorities such as employment, economic growth, investment, climate change, energy, social policies, industrial innovation, and global sustainable development efforts [12]. Building on CE actions implemented since 2015, the CE adopted the new EU Circular Economy Action Plan (CEAP) in 2020 to achieve a cleaner and more competitive Europe, in cooperation with economic actors, consumers, citizens and civil society organizations [13]. CEAP has announced initiatives throughout the product life cycle, aimed at both consumers and producers, which focus on product design, production processes, consumption, as well as waste and pollution prevention, ensuring that resources used remain in the EU economy as long as possible. The main product value chains considered under CEAP include electronics and telecommunications, batteries and vehicles, plastics, packaging, textiles, construction and buildings, as well as food, water, and nutrients. EC targets are also included in the EU's "Zero Pollution" action plan, whereby waste generation should be significantly reduced, and in particular municipal waste should be reduced by 50% by 2030. They do part of a list of other goals that contribute to the "2050 vision of zero pollution" [14].

CEAP also announced and referred to an initiative on circular electronics, a comprehensive EU Textiles Strategy and the EU Plastics Strategy (2020) [15]. In the latest circular economy package from 2022, the EC adopted the Sustainable Products Policy Initiative, including the proposal for a Regulation on the Eco-design of Sustainable Products, as well as the EU Strategy for Sustainable and Circular Textiles [16].

The Sustainable Products Policy Initiative seeks to ensure that products available on the EU market become progressively more sustainable. This initiative aims to enhance circularity, thereby promoting greener production and consumption practices, while minimizing waste and pollution. Covering many economically important sectors in the EU, the new CEAP is central to the European Green Deal, which is the new European agenda for sustainable growth, as expanding the circular economy will contribute to achieving climate neutrality by 2050, meeting the SDGs and decoupling economic growth from resource use. To date, 17 EU Member States have already developed EC

strategies (in general terms). These include Poland, Slovakia, and the Czech Republic as Eastern European countries. The CE roadmap for Hungary is under preparation. To align with European trends and utilize circular economy (CE) principles, Romania participates in initiatives that seek to identify opportunities for economic competitiveness, employment, and environmental quality improvement [17].

Methodology

The proposed Circular Defense Economy (CDE) platform adopts a modular architecture designed to support the practical implementation of the circular economy in the defense sector, ensuring the digital integration of all actors and phases of the military equipment life cycle.

The phases of the military equipment life cycle start from the identification of needs and the feasibility study, continues with research, design, construction, testing, production, and use of the product, and finally includes its disposal, recovery or modernization for a new use. Figure 2 presents the stages analyzed by Nicolae MORO (2018). There are also additional stages, parallel to the main flow, that additionally apply for modernization, reconstruction, testing, and re-entry into production or use. [18]

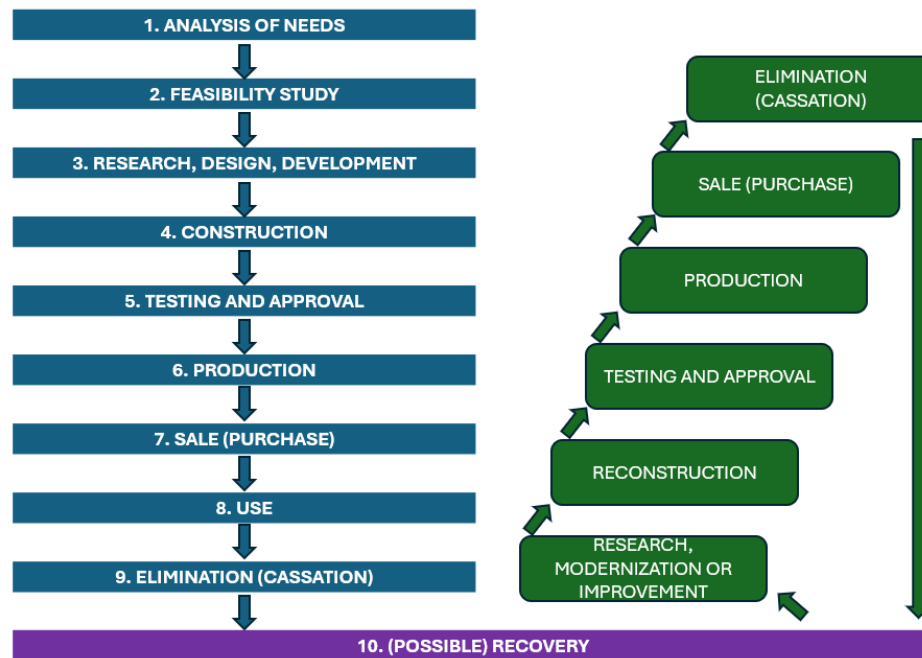


Figure 2: Stages of the military equipment life cycle (adapted from Moro, 2018)

Source: Authors' own contribution

The architecture of CDE platform comprises three major interconnected components presented in *Table 1*.

Table 1: CDE Components

Component	Description
Information Management System (IMS)	A central data hub that aggregates information generated across all the equipment life cycle, integrating data provided by actors involved in the value and logistic chains such as suppliers, manufacturers, maintenance units, recyclers, and military stakeholders
Decision Support System (DSS)	A set of analytical tools and algorithms that use IMS insights to guide decision-makers towards the most sustainable and efficient options. It guides technology adoption, material choices, and service models.
Single Entry Point (SEP)	SEP represents a unified interface through which all participants can access the services of the CDE platform. SEP facilitates cross-sector collaboration, allowing for the

	controlled exchange of information.
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Source: Authors' own research.

The following should serve as the foundation for the CDE platform (Figure 3).

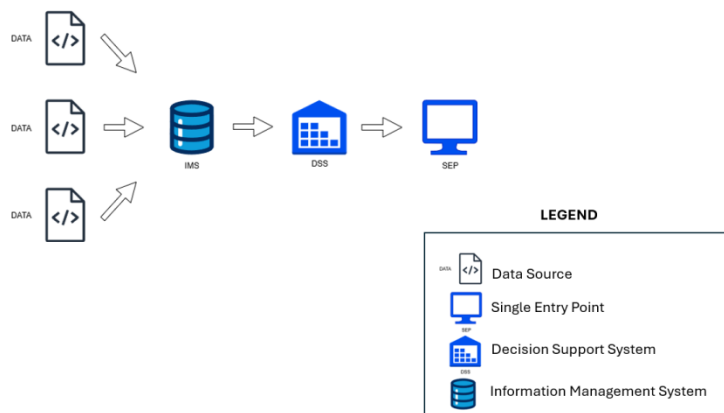


Figure 3: CDE platform architecture
Source: Authors' own contribution

Within the CDE platform, the use of disruptive technologies is a central element of the digital transformation and the transition to a sustainable framework. Disruptive technologies are defined as those technologies that radically change the way markets, industries, or society operate, replacing existing products and services with more efficient, accessible, or convenient ones. [19] The integration of disruptive technologies such as blockchain, Machine Learning, and Artificial Intelligence into the CDE platform allows for the creation of a secure and intelligent digital ecosystem for the circular economy.

An intelligent data-driven decision support system (DSS) is needed to achieve the CDE's goal of integrating and monitoring circularity adoption in SPE (Figure 4). DSS should be able to rank different materials and strategies based not only on their environmental/circularity potential, but also on the specific structural requirements of the instrument being analyzed. DSS coordinates data exchange and integration between different branches of CDE. The Circular DSS connects all actors in the value chain, gives them the opportunity to share data, information and experiences, and connects them with data from other sources and platforms, thereby transforming the underlying paradigm of the circular economy. As pillars of the circular economy, the process combines these services to build a set of services that support efficient and sustainable practices of refuse, reduce, reuse, repurpose, and recycle.

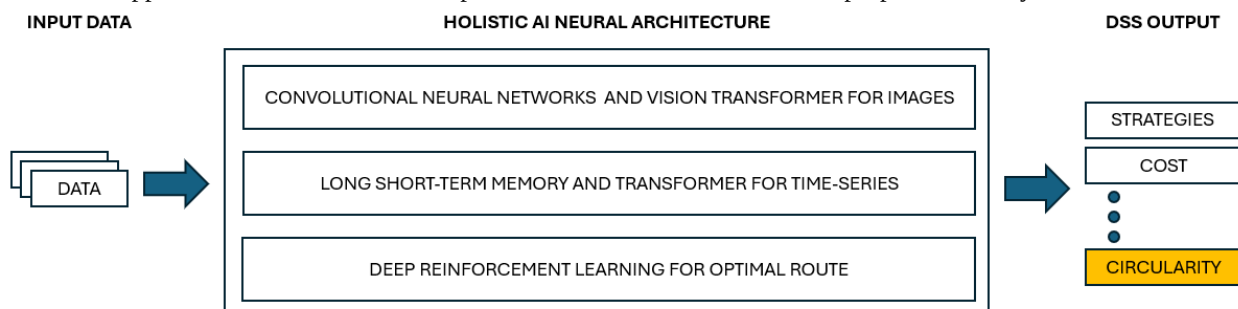


Figure 4: Holistic CDE platform
Source: Authors' own contribution

Within the CDE platform, special attention should be paid to key SPE circular processes presented in *Table 2*.

Table 2: Key SPE circular processes

Process	Description
Eco-design and material substitution	The CDE platform stores and analyzes data on the behavior of

	different materials over time, providing beneficiaries with recommendations on optimal solutions such as choosing materials with a longer life cycle and a reduced ecological footprint.
End-of-life dismantling and fiber recovery	The CDE platform promotes standardized procedures for dismantling SEP so that reusable elements can be extracted without being unnecessarily damaged.
Customization and remanufacturing for reuse	The CDE platform also supports the customization of remanufactured equipment so that the resulting products meet current operational requirements, extending the total useful life of the original resources.
Lifecycle tracking and blockchain-based microtransactions	To encourage collaboration and exchange of materials between different actors, the platform should integrate a blockchain solution so that no party can manipulate the data and the complete history of each component is available to all participants.

Source: Authors' own research.

Technological innovation

The implementation of the circular economy in the defense industry is based on a set of cutting-edge technological innovations, aimed at solving the challenges specific to military materials and products.

Composite Material Recovery

Modern military equipment widely uses reinforced polymer composite materials (with carbon, glass, or aramid fibers) due to their exceptional strength-to-weight ratio. An important innovation is the new chemical depolymerization processes that allow the recovery of whole fibers.

Blockchain Integration

Blockchain plays a significant role in ensuring traceability and trust along the circular logistics chain. The innovation lies in the use of smart contracts and distributed ledgers to automate and secure information exchange and transactions.

A smart contract can be programmed to track a component from manufacturing to retirement (with every transfer or modification, the details are recorded on the blockchain). When the component reaches the end of its life, the smart contract can be triggered, informing all relevant actors that the part is available for recycling.

Bio-Based Materials

Innovations are aimed not only at the end of the life cycle, but also at its beginning, by introducing environmentally friendly materials into the manufacture of military equipment. An important direction is the development of biomaterials from biodegradable polymers for non-critical components, to resins obtained from renewable resources for application in composites. At the same time, the use of eco-friendly solvents and biodegradable polymers for non-critical components or packaging contributes to reducing pollution and risks to workers' health.

Expected results

The implementation of the circular economy model in defense through the CDE platform anticipates a series of concrete benefits on multiple levels.

Cost savings for member state defense forces

It is estimated that costs will be reduced by reusing materials, remanufacturing components and extending the life cycle of equipment. This optimization allows the release of financial resources that can be redirected towards modernization, research and development.

Strategic autonomy and reduced supply chain volatility

Limiting dependence on critical imports and developing domestic recycling and substitution capabilities supports security of supply. In this way, armed forces can maintain operational continuity even in unstable geopolitical contexts.

Cross-border cooperation among SMEs, MoDs, and RTOs

The CDE platform can support the creation of a collaborative European ecosystem that stimulates innovation, knowledge exchange and the development of a more competitive and united defense industry.

Scalable models for green public procurement

Through the CDE platform, an expected result is the creation of scalable models that allow the integration of sustainability criteria into public procurement procedures. By applying them at European level, they can generate

economies of scale, strengthening demand for products and services with a low environmental impact. At the same time, these mechanisms facilitate transparency and traceability of the procurement process.

Environmental impact

Beyond the immediate quantifiable benefits, implementing CDE has broader implications for the environment and society. For example, by recycling carbon from fibers and resins, an 85% reduction in the environmental footprint of recycled carbon fiber compared to virgin production is estimated, due to energy and raw material savings.

Also, widespread reuse of components can lead to cost savings of 50–70% in certain equipment programs, allowing a greater number of units to be equipped with the same budget. In addition, by reducing the volume of military hazardous waste, the risks of soil and water pollution are reduced, improving the relationship between the military and local communities in the vicinity of the bases.

Further research

A general direction for future research on the CDE platform is the development of integrated monitoring and evaluation methodologies, which correlate the technological performance of digital components with environmental impact and economic efficiency, so that the platform can be optimized and replicated on a European scale as a reference model for the transition to a circular economy in defense.

Managerial implications

Implementing the CDE platform involves major managerial adaptations to combine sustainability with security and operational performance requirements.

Thus, within organizations, managers must rethink the life cycle of equipment, making the transition from a linear logic to a circular one, which involves adopting concepts such as reuse, repair and recycling.

The management must facilitate partnerships between public and private actors to ensure a circular logistics chain. The coordination of these entities requires transparency, shared responsibility and clear sustainability and efficiency objectives.

The integration of digital technologies such as IoT, AI and blockchain requires making decisions regarding cybersecurity, interoperability and staff training. The platform must allow for component traceability and support predictive maintenance, while respecting confidentiality standards.

Also, to create a monitoring framework that supports decision-making in conditions of sustainability and security, it is necessary to implement clear performance indicators, adapted to the context. These can contribute to both economic efficiency and environmental responsibility.

Conclusions

The CDE outlines a transformative framework for the sustainability and resilience of the defense sector. By integrating digital infrastructures, eco-design principles and disruptive technologies such as artificial intelligence, blockchain and green materials, the CDE proposes a paradigm shift in the way military assets are designed, used and reused. This approach directly supports the strategic independence of Member States, contributes to reducing dependence on critical imports and ensures compliance with the ambitious objectives of the European Green Deal.

The CDE platform distinguishes itself from existing approaches through its integrated, digital and modular character, which brings together eco-design, traceability, decision-making analysis and inter-institutional collaboration processes in a unique framework. Through its modular and replicable mechanisms, the platform facilitates technological innovation, stimulates the emergence of new "green" jobs and increases cost efficiency throughout the life cycle of military equipment.

The implementation of the CDE platform brings long-term economic, social and environmental benefits. Its adoption favors the reduction of environmental impact by decreasing emissions and the volume of waste, reinforcing Europe's role as a leader in integrating sustainability into the defense sector.

Abbreviations

The abbreviations used in this paper are described in Table 3.

Table 3: Abbreviations

Abbreviation	Definition
CDE	Circular Defense Economy
SPE	Soldier Protection Equipment
AI	Artificial Intelligence

CEAP	Circular Economy Action Plan
IF CEED	Incubation Forum for Circular Economy
CFRC	Carbon fiber reinforced composites
GFRC	Glass fiber reinforced composites
GDP	Gross Domestic Product
UN	United Nations
SDG	Sustainable Development Goals
CE	Circular Economy
CEAP	Circular Economy Action Plan
EC	European Commission
IMS	Information Management System
DSS	Decision Support System
SEP	Single Entry Point

Source: Authors' own research

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