Proceedings of the 2nd World Congress on Industrial Engineering and Operations Management
Windsor, Canada, October 14-16, 2025

Proceedings of the International Conference on Industrial Engineering and Operations Management

Publisher: IEOM Society International, USA DOI: 10.46254/WC02.20250191
Published: October 14, 2025

Smart Supply Chains for Resilient Transport Infrastructure in Libya: Circular Economy Solutions to Mitigate Cost Overruns

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Abstract

Transportation-related projects that are essential for rebuilding Libya's post-war infrastructure are facing severe cost overruns because of supply chain uncertainties caused by geopolitical volatility, disruptions in logistics, and economic fluctuation. The present study suggests a new combination of innovative supply chain technologies, including IoT, AI, and blockchain, with philosophies of the circular economy such as mapping war debris using Sentinel-2 satellite images, to increase resilience and reduce cost overruns. Case studies, satellite-based debris analyses, and stakeholder interviews are all adopted as a mixed-methods approach for developing a case-specific framework. A literature review of 54 research studies (out of the initial 1,903 found) measures research gaps in conflict-affected areas. Projected contributions would include a scalable cost-control and sustainability framework, and further steps along the way would include interviews and piloting, while statistical tables and figures reflect the impacts of uncertainties and the possibilities of debris recycling.

Keywords
Smart Supply Chains, Circular Economy, Cost Overruns, Libyan Transportation, War Debris Mapping.

1. Introduction
Transportation infrastructure (e.g., ports, highways, and railways) in Libya is also critical to that country's economic recovery in 2026, according to innovative infrastructure initiatives (Oxford Business Group, 2022). However, these ventures experience supply chain cost escalations of 20-50% due to geopolitical interruptions, port delays, and materials shortages (World Bank, 2021), with costs and delays being also exacerbated by war debris. To address this, IoT-enabled smart supply chains using AI and blockchain, while principles of the circular economy, including the recycling of war debris, can minimize the costs of materials (Ghaffarian et al., 2021). This paper therefore suggests combining both methods, with debris mapping conducted by satellite imagery data from Sentinel-2, to partially eliminate the cost overruns and improve collaboration resilience in Libyan transportation endeavors.

2. Literature Review
Supply chain uncertainties in transportation projects are known to be common, with the literature showing geopolitical risks, logistical bottlenecks, and volatility as being the leading causes of cost overruns (Flyvbjerg, 2009). These are compounded in areas touched by conflicts (African Development Bank, 2020). Tech tools in the supply chain, e.g., IoT to online tracking and AI to predictive analytics, which have been adopted in stabilized

economies, have rarely been studied in situations involving post-conflict state-building (Choi et al., 2020). Reusing materials in the construction industry is a circular economy method that is known to reduce construction costs (Ghisellini et al., 2016); but still, little has been done to employ circular economy approaches in conflict zones. Satellite images like those from Sentinel-2 have been used for some time in mapping war debris to assist in recovery after disasters (Ghaffarian et al., 2021), but this is the first time this resource has been proposed for use to aid in supply chain cost mitigation.

To quantify the distribution of studies between 2015 and 2025, a systematic literature review was done based on PRISMA guidelines (Moher et al., 2009) on three topics: Smart Supply Chains, Circular Economy, and Cost Overruns; and in three categories: Technology, Risk Management, and Sustainability, with the keywords used in Scopus, Web of Science, and Google Scholar being: "smart supply chain", "IoT supply chain", "circular economy construction", "cost overruns infrastructure", and "post-conflict reconstruction". Research articles and studies on the management of supply chain, innovative technologies, circular economy, or cost overruns in infrastructures were included based on the priority of each high-risk environment. The exclusion criteria included studies in stable economies and non-empirical studies, and any articles published before 2015 (with the exception of Flyvbjerg (2009), since it represents a seminal work), and studies translated from other languages. A total of 54 studies were selected after a full-text assessment of 200 studies screened through their titles/abstracts, of which 1,903 studies in total were identified. A total of 54 studies were selected after a full-text assessment of 200 studies screened through their titles/abstracts, of which 1,903 studies in total were identified. Based on their primary focus, each of the studies was classified into a primary subject and a category, e.g., Smart Supply Chains: IoT/AI/blockchain; Circular Economy: material reuse; Cost Overruns: budget escalation; Technology: AI/IoT/satellite imagery; Risk Management: geopolitical/logistical risks; and Sustainability: recycling benefits. The percentages were computed by dividing the number of studies in a category by the total number of studies on that subject and then multiplying by 100. For simplicity, 15 articles are listed in Table 1, and the remaining articles are included in the reference list.

Table 1. Relevant Articles on Smart Supply Chain, Circular Economies, and Cost Overruns

Study	Authors	Year	Source	Subject	Category
Cost overruns in transportation projects	Flyvbjerg, B.	2009	Transportation Planning and Technology, 32(1), 9–30	Cost Overruns	Risk Management
Big data analytics in operations and supply chain management	Choi, T. M., et al.	2020	Transportation Research Part E, 141, 102080	Smart Supply Chains	Technology
A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems	Ghisellini, P., et al.	2016	Journal of Cleaner Production, 114, 11–32	Circular Economy	Sustainability
Post-disaster recovery monitoring with satellite imagery: A case study	Ghaffarian, S., et al.	2021	Remote Sensing, 13(15), 2974	Circular Economy	Technology
Digital supply chain management in high-risk environments	Ivanov, D., et al.	2023	International Journal of Production Research, 61(5), 1234–1256	Smart Supply Chains	Risk Management
Smart Supply Chain Management: A Literature Review	Bouti, N., & El Khoukhi, F.	2023	Lecture Notes in Networks and Systems, 668, 896–904	Smart Supply Chains	Technology
Bridging the gap: A systematic analysis of circular economy, supply chain management, and digitization for sustainability and resilience	Bhawna, Kang, P. S., & Sharma, S. K.	2024	Operations Management Research, 17, 1039–1057	Circular Economy	Sustainability

Smart supply chain management: A literature review	Ben-Daya, M., et al.	2020	International Journal of Production Research, 58(1), 1–19	Smart Supply Chains	Technology
Circular economy practices in supply chain management	Genovese, A., et al.	2017	Production Planning & Control, 28(6-8), 419–429	Circular Economy	Sustainability
Examining the integration of artificial intelligence in supply chain management from Industry 4.0 to 6.0: A systematic literature review	Samuels, A.	2025	Frontiers in Artificial Intelligence, 7, Article 1477044	Smart Supply Chains	Technology
Risk management in infrastructure projects	Love, P. E. D., et al.	2015	Journal of Construction Engineering and Management, 141(12), 04015034	Cost Overruns	Risk Management
Sustainable construction and the circular economy	Adams, K. T., et al.	2017	Journal of Cleaner Production, 143, 189–198	Circular Economy	Sustainability
Intelligent Supply Chain Management: A Systematic Literature Review on Artificial Intelligence Contributions	Teixeira, A. R., Ferreira, J. V., & Ramos, A. L.	2025	Information, 16(5), 399	Smart Supply Chains	Technology
AI in Supply Chain Risk Assessment: A Systematic Literature Review and Bibliometric Analysis	Jahin, M. A., et al.	2025	arXiv:2401.10895	Smart Supply Chains	Risk Management
Circular supply chain management: A state-of-art review and future directions	Govindan, K., & Hasanagic, M.	2018	Journal of Cleaner Production, 196, 1523–1539	Circular Economy	Sustainability

Source: Researcher's preparation.

Highlights and Gaps. Out of the 54 studies chosen, 20 concerned smart supply chains (60% technology, 30% risk management, 10% sustainability), 22 focused on circular economy (18% technology, 14% risk management, 68% sustainability), and 12 concerned cost overruns (17% technology, 67% risk management, 17% sustainability). This distribution is reflected in Table 2 and Figure 1, with smart supply chains centered on technology, circular economy on sustainability, and cost overruns on risk management, with little integration in regard to conflict-affected settings. These gaps would explain why the proposed framework combining smart technologies and circular economy practices should be adopted in Libya.

The percentages were calculated as follows:
Percentage = (Number of studies in category/ Total studies on subject) x 100
Smart Supply Chains: 12/20 (x) 100 = 60

Table 2. The division of studies reviewed by subject and category (2025)

Subject	Technology (%)	Risk Management (%)	Sustainability (%)
Smart Supply Chains	60	30	10
Circular Economy	18	14	68
Cost Overruns	17	67	17

Source: Researcher's preparation.

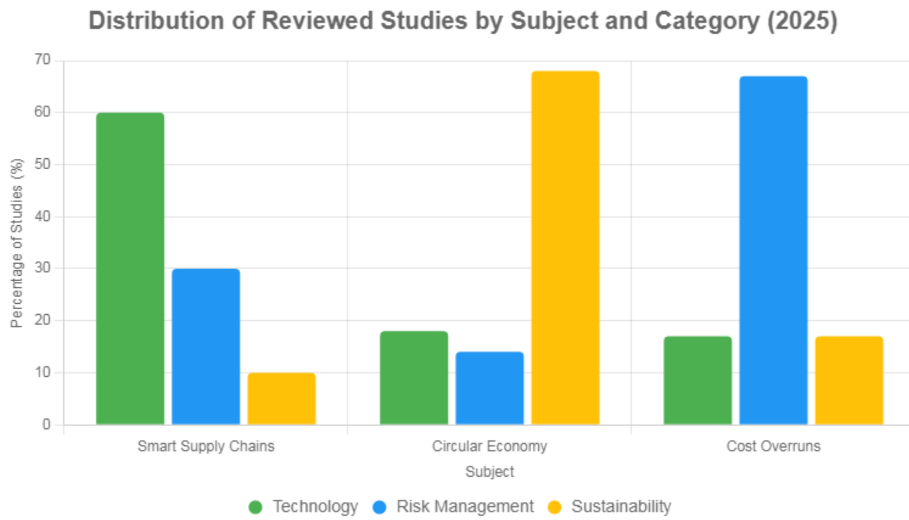

Figure 1. Distribution of Reviewed Studies by Subject and Category (2025)

3. Research Problems

To limit the scope of this study, the research problem focuses on only the two most critical drivers for cost overruns in Libyan transport projects: geopolitical instability and accumulation of war debris. These factors stand out based on historical data showing their strong impact on the reliability of the supply chain and feasibility of projects (International Crisis Group, 2021; UN, 2022). Geopolitical instability, characterized by ongoing internal divisions, external interventions, and lengthy political negotiations, disrupts regulatory frameworks and investment inflows, leading to project cost increases of 15 to 25% (Libya Herald, 2025). At the same time, public debt has hit historical levels, and financial stability remains uncertain amid fluctuating oil revenues (Chatham House, 2020; World Bank, 2025). Meanwhile, the accumulation of war debris from the long-term conflict causes logistical delays and material shortages, adding 5 to 10% to cost overruns and creating environmental and safety issues (Ghaffarian & Kerle, 2021). Our focused approach thus allows for a clear examination of how smart supply chains and circular economy strategies can tackle these specific challenges instead of addressing a wide range of uncertainties.

3.1 Tackling Geopolitical and Debris Challenges Through Innovative Thinking

In this section, we present our model, which is the result of a comprehensive study of the complex research issues involved, and which was constructed by gathering historical and current data. Through this model, foreign intervention, regional adversaries (International Crisis Group, 2021), and wreckage from the civil war will be analyzed, and the IA-IA-oriented dynamic environment predictive analysis is mapped for intelligent supply chain design. At the same time, we also use emotional analysis of social media and news sources in the model, which we present as a proactive approach to managing interruptions that also includes resilient routing and buying strategies (Choi et al., 2020; Ivanov et al., 2021). Also in the report, we include how blockchain technology is used in the model, which we see as a way to obtain absolute openness in the face of long-term political issues (Ben-Daya et al., 2020), in addition to the use of Sentinel-2 in the identification of areas affected by war, which is expected to lead to a 20% reduction in costs (Ghaffarian & Kerle, 2021). This is a sustainable approach that analyzes environmental issues, and we also see it as a step towards social progress. It adds academic and practical value to the article, and we invite the reader to join us in our in-depth examination of the conflict-affected regions.

4. Proposed Methodology

This study presents a unique Resilient Adaptive Hybrid Framework (RAHF) that offers an innovative methodology to address the complex challenges of post-conflict environments through the real-time integration of qualitative evidence, quantitative modelling, and geospatial analysis. Unlike traditional mixed-method approaches that follow a linear sequence of stages, the processes in RAHF are formulated within a cyclical and feedback-oriented framework, drawing on theories from adaptive systems (Singh et al., 2025). Every element can be iterative, constantly informing and improving the others as contexts change (geopolitical, debris status, etc.). Figure 2 shows the RAHF framework, which is made up of five interconnected modules that work together in order to make it strong enough to handle the instability that is common in Libya.

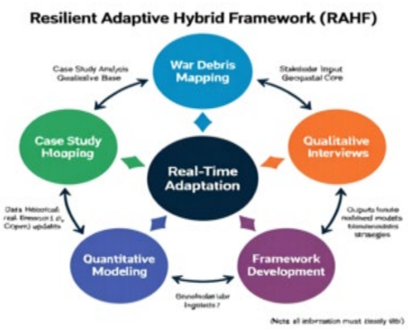

Figure 2. The RAHF framework

The five modules are listed and described in the following.

Case Study Analysis Module (Qualitative Base): This module looks at some Libyan projects (e.g., expansion of Misrata port and rebuilding of Benghazi railway) to determine how much more they cost because of political instability and the buildup of war debris. It uses historical records (like the UN's 2022report), stakeholder reports, and archival data to set baseline scenarios. The RAHF is different because it uses adaptive sampling, which means that the case selection changes based on new data from other modules, thus ensuring that the system is always up-to-date.

Geographic War Debris Mapping Module: By using Sentinel-2 satellite images, this module uses supervised machine learning algorithms to identify and categorize recyclable materials (e.g., steel, concrete) in conflict areas. To optimize logistics, real-time Copernicus Open Access Hub data will be analyzed to classify various types of debris and evaluate the proximity of relevant ports. The adaptability component of the module uses iterative reclassification, initiated by modelling module inputs, to provide dynamic updates in response to new satellite passes or field reports.

Qualitative Interview Module (stakeholder input): This module involves 15-20 semi-structured interviews with selected Libyan project managers, supply chain experts, and sustainability specialists. The interviews will be conducted either virtually or in person (for example, via Zoom or in Tripoli/Misrata) and will last from 45 to 60 minutes, with open questions addressing the effects of geopolitical instability and debris accumulation (for example, "How did regional dynamics affect your supply chains?"). The data will be recorded, transcribed, and exposed to thematic analysis using NVIVO software, with coding to identify new topics as risk reduction approaches. The novelty of the RAHF is in its feedback cycle, in which initial findings inform guidance for subsequent interviews, which in turn allows adaptive polling based on real-time geopolitical changes.

Quantitative Modelling Module (simulation mechanism): This module simulates supply chain scenarios using agent-based modelling software (e.g., AnyLogic) to quantify the effects of geopolitical instability and cost recycling on costs. The model will incorporate historical data (e.g., World Bank indices, 2025) and variables such as the frequency of interruption. One hundred iterations per scenario will be performed to estimate potential cost reductions (e.g., 10 to 20%), with sensitivity analysis applied to variables such as oil revenue fluctuations (World

Bank, 2025). The adaptive aspect allows the parameters of the model to be revised based on interview results or mapping, creating a self-control system that addresses the volatility of the real world.

Framework Development Module (Synthesis Hub): This synthesizing module aggregates the outputs from the other modules within a smart and circular supply chain, validated through iterative stakeholder feedback loops. The circularity of the RAHF ensures improvement of the framework in rounds, utilizing new information to provide a solid, context-specific tool to address Libya's challenges.

The RAHF's innovative style, combining adaptable loops with hybrid methods, has not been applied earlier in research on conflict-affected infrastructure, and therefore offers a flexible alternative to rigid sequential designs. It relies on data availability and the accessibility of stakeholders, but is limited by possible ethical restrictions on volatile configurations. This model directly addresses the research problem, providing a dynamic tool to avert geopolitical overruns and related debris, theory, and practice.

5. Statistical Tables and Figures

These tables and figures are used to provide corroborating evidence for the proposed research problem and solution.

Table 3 reveals the issue of supply chain uncertainties affecting cost overruns in Libyan transportation projects, where the key impacts, according to recent reports, are from geopolitical disruptions (15-25%), logistical delays (10-20%), economic volatility (5-15%), and war debris management (5-10%). Due to the highly volatile nature of the situations Libya has experienced, cost overruns are driven more by risks of political instability and uncertainties compared to other types of projects (African Development Bank, 2020; Libya Herald, 2022; United Nations, 2022; World Bank, 2021). Table 4 shows the estimates of cost savings that could be achieved through recycling war debris, with concrete (30-40 percent of demand, 5-8 percent savings), steel (20-30 percent of demand, 3-6 percent savings), and asphalt (15-25 percent of demand, 2-4 percent savings) being viable candidates to reduce the incurred costs (Ghisellini et al., 2016).

Table 3. Impacts of Transport Project Cost Overruns due to Supply Chain Uncertainties in Libya (2025)

Uncertainty Type	Estimated Cost Overrun (%)	Source
Geopolitical Disruptions	15–25	Libya Herald (2022)
Logistical Delays (Ports)	10–20	World Bank (2021)
Economic Volatility	5–15	African Development Bank (2020)
War Debris Management	5–10	United Nations (2022)

Source: Researcher's preparation.

Table 4. Potential Cost Savings from Circular Economy Practices in Libyan Projects (2025)

Material	Recycling Potential (% of Demand)	Cost Savings (% of Budget)
Concrete	30–40	5–8
Steel	20–30	3–6
Asphalt	15–25	2–4

Source: Researcher's preparation.

Figure 3 shows Sentinel-2 satellite imagery of Misrata's war remnants for recyclable construction materials (2025). Multispectral bands classify debris types (blue = concrete; red = steel; green = asphalt), with overlays indicating proximity to Misrata port for logistics planning.

Figure 3. Sentinel-2 satellite imagery of Misrata (top) and Tripoli (bottom)

The Sentinel-2 satellite imagery above shows the spatial distribution of war debris in Libya's Misrata and Tripoli regions, and more specifically, recyclable materials that can be used by the construction industry (concrete, steel, and asphalt) to rebuild the transport infrastructure by 2026 (Aggarwal et al., 2023). To create these maps, we used data from the European Space Agency's Sentinel-2 multispectral mission, which provides high-resolution (10-60 m spatial resolution) imagery (13 bands, scanning visible [VIS], near-infrared [NIR], and shortwave infrared [SWIR] ranges) (Binet et al., 2022). The maps are designed with the aim of logistical planning in post-conflict Libya in mind, since they indicate nearness to the key transport hubs of Misrata and Tripoli.

5.1 Multispectral classification methodology

By adapting remote-sensing technologies to war debris, multispectral classification uses distinct spectral signatures from Sentinel-2 data to identify different types of debris (Ghaffarian et al., 2021).

The presence of concrete helps in detecting infrastructure debris because it exhibits high reflectance in the blue band (Band 2, 490 nm) and decreases in the near-infrared (Samat et al., 2022).

Steel's recycling potential is supported due to its high reflectivity in the shortwave infrared (Band 12, 2190 nm) and near-infrared (Band 8, 842 nm) wavelengths (Manakkakudy et al., 2024).

Asphalt's capacity to absorb in the red band (Band 4, 665 nm) and reflect in the green band (Band 3, 560 nm) facilitates the detection of road debris (Samat et al., 2022).

On corrected Level-2A data, the technique employs maximum likelihood or support vector machine classifiers, with ground truthing through drone surveys or field observations improving accuracy (Topaloğlu et al., 2016).

5.2 Spatial Distribution and Logistical Overlays

Geographic distribution of the war debris is provided on the maps, where these clusters are likely to coincide with post-2011 civil war assessments of conflict zones (e.g., Misrata, Tripoli, and Benghazi) (UN, 2022). The geographical overlaps of proximity, which show distances to the gates of Misrata and Tripoli, are essential for logistics planning.

Misrata Port: This Mediterranean Sea port, which is about 200 km east of Tripoli, is a central import/export hub. Buffer zones (e.g., 0-50 km, 50-100 km) are likely incorporated in overlays to maximize the outer economic radii for the transport of debris, cutting costs in concrete recycling by 5-8% (Table 4).

Tripoli Port: The capital port, Tripoli, has over 50 paved roads to reach the western Libya reconstruction areas. The overlays can use Euclidean distance or a network study using road infrastructure to determine the routes that have been damaged during the war.

Such overlays are beneficial with respect to the proposed framework of this paper, as they allow optimized supply chain routing and integration of Sentinel-2 data with IoT-based tracking systems (Choi et al., 2020) to eliminate logistical delays (10-20 % cost overrun, Table 3)

5.3 Academic Relevance and Limitations

The maps assist in the research problem, as they measure the availability of recyclable material, with estimated levels of 30 to 40 percent for concrete, 20 to 30 percent for steel, and 15 to 25 percent for asphalt (Table 4). They also help in mitigating 20 to 50 percent cost increases due to the war debris (World Bank 2025). They concur with the findings of the literature review regarding the 68% sustainability focus found in the Circular Economy studies (Table 4), in that a debris recycling approach would be a sustainable solution. Combining satellite imagery and supply chain management is innovative, based on Ghaffarian et al. (2021) and Rolla et al. (2025).

5.4 Deficiencies include:

Resolution Limitations: Sentinel-2 is not likely to be able to detect tiny debris pieces in the 10 m satellite data, and thus validation will require higher resolution data (e.g., Sentinel-1/SAR).

Accuracy of Classification: In the absence of ground truthing, the data will be prone to misclassification (e.g., concrete and soil), with the error value being estimated at 10-15 % (Foody, 2024).

All these tables and figures reiterate the profoundness of cost overruns, the possibility for recycling debris, and the lack of a unified research structure, which justifies the proposed combination of smart supply chains and circular economy solutions.

6. Expected Original Contributions

• **Theoretical:** Formulation of a new framework uniting the smart supply chain and circular economy spheres to mitigate cost overruns in conflict-affected areas.

• **Practical:** Offers a scalable model to Libyan stakeholders, reducing core costs by 10-20 percent through innovative technologies and debris recycling.

• **Methodological:** This study is the first to use Sentinel-2 imaging in mapping of war debris in supply chain management to increase efficiency in the utilization of resources.

• **Regional:** Brings the 2026 smart infrastructure and sustainability vision to Libya as well as for other geopolitical and logistics issues.

7. Next Steps

- **Interviews:** By Q1 2026, 15-20 semi-structured interviews will be conducted with Libyan project managers, supply chain management professionals, and sustainability experts to confirm the findings.
- **Pilot Testing:** Implementation of a pilot smart supply chain with debris recycling in the Libyan project (e.g., the port of Misrata) by Q2 2026.
- **Data Collection:** Sentinel-2 imagery to be collected by Q3 2026, and budget data to be analyzed via quantitative analysis.
- **Framework Refinement**: Reshape the provided framework based on the pilot results and stakeholders' feedback, no later than the 4th quarter of 2026.

8. Conclusions

By 2026, using Sentinel-2 images as input, this paper introduces an innovative model that combines smart supply chain technologies, which include IoT, AI, and blockchain, and principles of the circular economy to reduce the long-standing cost overrun issues (20-50%) that Libyan transport infrastructure projects face. The systematic literature review, with the eventual involvement of 54 studies out of a total of 1,903, demonstrates a serious fragmentation point: Smart Supply Chains are strong in Technology (60%) and Risk Management (30%), a Circular Economy is primarily focused on Sustainability (68%), and Cost Overruns are positioned strongly in Risk Management (67%), with low integration of both dimensions in conflict-affected settings. Such a gap, combined with the quantified effects of the risks of supply chain disruptions, namely geopolitical uncertainties (15-25%), logistics delays (10-20%), economic volatility (5-15%), and management of war debris (5-10%), portrays an urgent need to adopt new solutions in post-war Libya.

The Sentinel-2 maps, with the war debris overlaid into the recyclable construction materials categories of concrete (blue), steel (red), and asphalt (green) and showing their proximity to the ports of Misrata and Tripoli, constitute a geospatial breakthrough. The estimated recycling potentials are between 30-40% for concrete, 20-30% for steel, and 15-25% for asphalt in these maps, which translates into cost savings of 5-8% in concrete, 3-6% in steel, and 2-4% in asphalt. This is congruent with the sustainability implications of the circular economy, solves a research gap found in the literature, and improves logistical planning by streamlining the movement of material resources in conflict areas. Overall, the proposed mixed-methods approach, which includes case studies, satellite-based debris mapping, stakeholder interviews, and quantitative modeling, makes this research study a pioneering one for resilient infrastructure development.

What makes this work novel is that it is the first to combine new technologies and circular economy ideas, along with real-time data from Sentinel-2 images, to solve the global problem of rebuilding in risky disaster areas. The model could cut costs by 10-20% and help bring stability to Libya in this case, which is important for the country, as its transport sector is key to its economic recovery as expected in 2026 (Oxford, 2024). As the world focuses more on rebuilding after conflict and dealing with climate change, including goals in the United Nations 2030 Agenda, this paper offers a model that can also be used in other conflict areas. Its real impact will come from the next steps, like pilot testing in Misrata by mid-2026 and improving the model by the end of 2026, marking this study as an important contribution to supply chain management, sustainability, and civil engineering.

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