Managing Disruption of Enterprise System Order in Resilience of Supply of Aviation Fuels

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Abstract— **To provide aviation biofuels at a large international airport requires a structured approach to identify and mitigate risks across the supply chain. This study demonstrates an enterprise risk management tool to systematically track sources of enterprise risk associated with fuel production, distribution, and integration into existing aviation infrastructure. By analyzing key processes—feedstock sourcing, fuel conversion, blending, storage, and consumption— and tracking disruptions of system order, the approach highlights interdependencies and potential vulnerabilities across the supply chain. The analysis identifies critical factors, including feedstock availability, logistical constraints, regulatory compliance, economic feasibility, and infrastructure adaptation. This innovative approach to addressing risk as the disruption of system order promises to enhance resilience; align stakeholders, resources and regulations; and facilitate the large-scale adoption of advanced fuels in the aviation sector.**

Keywords— systems engineering; scenario-based preferences; uncertainty analysis; requirements analysis; airports; logistics systems

I. MOTIVATION

Any airport has unique opportunities to develop a localized alternative fuel supply chain, shaped by regional feedstock availability, infrastructure readiness, and stakeholder engagement. Washington Dulles International Airport (IAD), situated in Virginia, USA, represents a strategically valuable site to explore the integration of biofuel at scale. As a major international hub with growing passenger and cargo traffic, the facility demand for aviation fuel offers a real-world test for scalable biofuel industry [1]. Its surrounding region, in turn, provides favorable conditions for regional biofuel production, including access to diverse feedstocks such as municipal solid waste (MSW), end-of-life tires (ELTs), and woody biomass from its extensive forest lands [1],[2]. These pathways support multiple conversion technologies, including pyrolysis and gasification Fischer-Tropsch synthesis (GFT), that are increasingly viewed as viable alternatives to fossil-based jet fuel [1],[3]. This regional capability aligns with federal priorities around energy independence, rural economic development, and energy efficiency of hard-to-abate sectors like aviation [1],[4]. In this context, biofuel development in Virginia is not only technically and economically promising, but also emblematic of the broader reindustrialization and sustainability goals shaping U.S. transportation policy [4]. With this case study, this research highlights how site-specific strengths can be leveraged to overcome barriers to biofuel integration and offers a roadmap for similar efforts at other major airports.

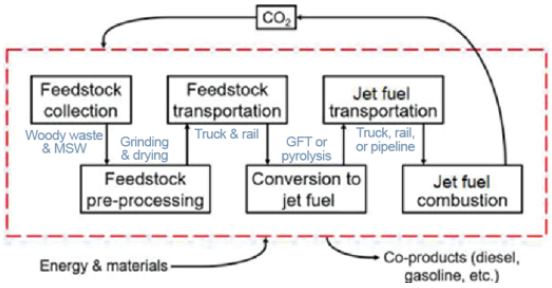

Fig 1. Biofuel supply chain for airports, adapted from Davis et al. 2024 [1].

II. PURPOSE AND SCOPE

The purpose of this paper is to track the disruption and evolution of system-component orders associated with the large-scale integration of biofuel at a major international airport. The paper thus uses an innovative approach to understand enterprise risk for a regional supply chain. This study applies an order-based enterprise risk management framework to systematically examine the fuel network, from feedstock acquisition and conversion to fuel blending, distribution, and consumption while accounting for regulatory, technical, economic, and logistical variables. The analysis incorporates region-specific inputs, such as available waste and biomass feedstocks, local infrastructure capacity,

TABLE I. RATING OF THE SYSTEM COMPONENTS ACROSS FIVE ORDER CRITERIA OF BIOFUEL SUPPLY CHAINS

How well does component x.## address criterion c.##?	x.01 - Tire Processing Facility 1	x.02 - Tire Processing Facility 2	x.03 - MSW Processing Facility 1	x.04 - MSW Processing Facility 2	x.05 - Hardwood Processing Facility	x.06 - Softwood Processing Facility	x.07 - Pyrolysis Refinery	x.08 - Fischer-Tropsch Refinery	x.09 - Blending Facility 1	x.10 - Blending Facility 2	x.11 - Transportation-Pipeline	x.12 - Transportation-Rail	x.13 - Transportation-Barge	x.14 - Transportation-Truck	x.15 - Storage Facility 1	x.16 - Storage Facility 2	x.17 - Airline 1	x.18 - Airline 2	x.19 - Airline 3	x.20 - Coproducts (Biodiesel, Biogas, Naphtha)	x.21 - Foreign and out of state SAF production
c.01 - Efficiencent Resource Management	●	●	●	●	◐	◐	◐	◐	–	–	◐	◐	◐	–	○	○	○	◐	○	◐	○
c.02 - Fuel Source Redundancy	◐	◐	◐	●	○	○	◐	◐	–	–	–	–	●	○	○	–	–	–	–	●	◐
c.03 - Domestic Fuel Production	–	–	–	–	–	–	●	●	–	–	–	–	–	–	–	–	–	–	–	◐	–
c.04 - Consumer Cost	◐	◐	○	○	○	●	◐	○	○	○	◐	◐	○	–	–	●	–	○	◐	○	○
c.05 - Community Economic Benefit	◐	◐	◐	–	○	◐	◐	○	○	◐	–	–	○	○	○	○	○	○	–	○	–

and policy environments, to identify key vulnerabilities and high-impact intervention points. With the particular region in view, the scope of this study includes assessing scenario-based disruptions. The findings are intended to inform investment decisions, infrastructure planning, and policy design necessary for enabling a scalable and secure biofuel network in the region including fuel blending, distribution, and consumption while accounting for regulatory, technical, economic, and logistical variables.

III. BACKGROUND

Fig. 1 describes the biofuel supply chain beginning with feedstock collection and preprocessing, guided by waste regulations and environmental management policies [5]. Mechanical shredding, chemical treatment, and contaminant removal ensure that feedstocks meet input requirements for downstream conversion processes. In refineries, thermal and chemical technologies convert processed feedstocks into fuel intermediates [6]. There is strict quality control, including temperature and pressure regulation, compliance with ASTM standards, and integration with carbon capture systems where applicable [7].

The pyrolysis production pathway focuses on converting end-of-life tires, municipal solid waste (MSW), and forest clearing residuals into biofuel. This involves heating organic material in the absence of oxygen, breaking it down into bio-oil that can serve as a crude biofuel precursor [8]. The region is particularly well-positioned for this pathway, as it generates large quantities of used tires and is a net importer of MSW, making these materials attractive and accessible feedstock sources for localized production [1],[2]. The second possible refinement route utilizes gasification by Fischer-Tropsch (GFT) synthesis to convert syngas into liquid hydrocarbons. Feedstocks in this pathway include MSW and woody biomass from the region, including forestry residues and sawmill waste [1],[3]. With extensive forest resources of the region, this method could be both regionally appropriate and scalable. However, the success of such a system depends on strategic siting and financing of refining infrastructure, which are critical for economic feasibility and supply continuity [1],[9],[10],[11].

After the refinery, the biofuel is blended with conventional Jet-A fuel, up to 50% to meet ASTM standards of aviation fuels [12]. Blending may occur either at pipeline hubs or dedicated fuel terminals. The result is a “drop-in” biofuel that meets all handling and performance criteria of traditional aviation fuels, can then be stored and distributed to aircraft via standard fuel infrastructure [13]. The final stage involves delivery to aircraft based on fuel contracts and airline commitments to alternative fuel sources.

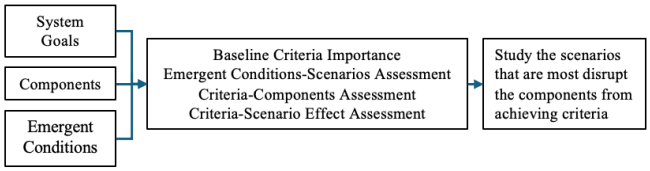

Fig 2. Conceptual diagram of systems methodology for alternative fuel supply chain integration adapted from Moghadasi et al. [14]

To evaluate risk and prioritize components within this regional supply chain, each stage must be modeled through a systems methodology that highlights interdependencies and potential vulnerabilities [11]. As shown in Fig. 2, the process begins by defining system goals and identifying the essential components and external conditions that influence system performance [14]. Disruptions arise when emergent conditions interact with critical components in ways that prevent the system from maintaining order or achieving its intended goals. Through a structured sequence of assessments—studying the influence of scenarios to disrupt system order—this methodology reveals how isolated disturbances can cascade and compromise system integrity [9],[10]. Each region must evaluate its unique configuration of resources, capabilities, and networks to design a resilient biofuel supply chain. With this airport and region as a testbed, stakeholders perform scenario-based risk analysis that uncovers how disruptions may undermine system stability and long-term viability. This approach supports informed decisions about infrastructure investments, policy development, and strategic planning for regional biofuel integration to guide long-term strategic decisions for integrating biofuel systems.

IV. METHODS

To track enterprise risk as disruptions of system order, this section adopts an enterprise risk register from Rebar (2022). The methods described below use indices to characterize priorities among assets, policies, locations, projects etc. that are involved with the development of biofuel production in a region [15]. This hypothetical supply chain includes three different feedstocks, MSW, woody waste, or ELTs, which

TABLE II. INFLUENCES OF THE SCENARIOS TO THE IMPORTANCE OF THE ORDER CRITERIA, USING THE METHOD OF SCENARIO-BASED PREFERENCES

Scenario impact on the relative importance of each criterion	s.01 Unsupportive Policy Change	s.02 Market Fluctuation	s.03 Technology Challenges	s.04 Natural Disaster	s.05 Sociotechnical Disruption
c.01 - Efficient Resource Management	Decreases	Decreases Slightly	Increases Slightly	Increases Slightly	Increases Slightly
c.02 - Fuel Source Redundancy	-	Increases Slightly	Increases Slightly	Increases Slightly	-
c.03 - Domestic Fuel Production	Increases Slightly	Increases Slightly	Decreases Slightly	-	Decreases Slightly
c.04 - Consumer Cost	Decreases Slightly	Increases	-	-	-
c.05 - Community Economic Benefit	Decreases Slightly	Increases Slightly	-	Increases Slightly	Increases Slightly

could supply either a GFT or pyrolysis refineries. These refineries would then deliver biofuel to two blending facilities

where it could be mixed with Jet-A before being sent to storage and ultimately consumed by airlines. In this scenario the refineries would produce byproducts such as biodiesel, naphtha, or biogas which can be used across the entire transportation network [6].

This assessment applies a resilience-informed, multi-criteria decision analysis framework to evaluate biofuel integration at the airport under varying conditions of risk and uncertainty. The method cross-references system goals (criteria), supply chain components, and emergent conditions to identify critical interactions that could negatively affect fuel production, blending, and distribution. The framework incorporates both internal operational factors (e.g., production capacity, blending infrastructure) and external relationship variables (e.g., feedstock supply, market demand, and regulatory stability) [16],[17],[18]. Components are evaluated based on their ability to meet stakeholder-defined system goals, and their rankings are compared across scenario-based disruptions. This comparative modeling approach is supported by a linear additive value function and a disruptiveness score, allowing for a structured evaluation of resilience across the fuel supply chain [1]. By integrating emergent system dynamics, this methodology provides actionable insights to inform infrastructure planning, policy interventions, and investment prioritization for an alternative fuel deployment in the region.

TABLE III. FIVE CRITERIA FOR ORDERING SYSTEM COMPONENTS, AND THEIR RELEVANCE TO THE SUPPLY OF BIOFUELS FOR THE AIRPORT

Index	System Criteria	Relevance
c.01	Efficient Resource Management	Medium
c.02	Fuel Source Redundancy	Low
c.03	Domestic Fuel Production	High
c.04	Consumer Cost	High
c.05	Community Economic Benefit	Medium

First the set of criteria in Table III, C = {c.01+c.02…c.0n}, was formed based on commercial and government stakeholder interests for the development of a new supply chain for the airport. Efficient resource management is the long-term goal for increasing the use of products that previously would have been discarded; this criterion was given a rank of medium [2]. Fuel source redundancy, which refers to increasing fuel availability for commercial and strategic national needs, was ranked low due to the limited feedstock supply available to meet the fuel demand of the region [14]. Domestic fuel production, aimed at reducing dependence on foreign fuel by establishing a local fuel supply, was ranked high due to national priorities [19],[20]. Consumer cost, which is essential to maintaining airline travel affordability and demand, was given a high ranking due to airline concerns [21]. Community economic benefit, which reflects the potential to increase job opportunities in disadvantaged communities, received a medium ranking based on state priorities [22].

Second the set of components $X = \{x_{.01}+x_{.02}\ldots x_{.0n}\}$ shown in Table I, was developed to form the possible supply chain for the airport. For this scenario, four different feedstock options are created as well multiple blending, storage and refinement options. Table I also shows the weighting of each component, where the filled circle indicates that the component fully meets the criteria, the half circle indicates partial fulfillment of the criteria, the empty circle indicates little fulfillment of the criteria, and the dash indicates that the component does not meet the criteria.

The analysis tool then modeled the inputted data and evaluated various components based on their effectiveness within the current operational state and under different scenarios. These components were then ranked using a linear additive value function**:** $V(x_i)^k = W_k X_i$. Components were prioritized based on their scores, with higher values indicating how strongly it address all of the criteria, this prioritization follows: If $V(x_i)_k > V(x_j)_k$, then $x_i > x_j$. Components were then ranked under alternate scenarios as $R(x_i)_k$ which defines the rank of a component xi is influenced by scenario S_k. Using these values, a disruptiveness score can be measured as $D(s_k)$. The correlation of these variables is described in (1).

$$D(s_k) = \sum_{i=1}^{n} (R(x_i)_b - R(x_i)_k k)^2 \quad (1)$$

From (1), $R(x_i)k$ is the ranking of a component x_i under a scenario s_k and $R(x_i)_b$ is the baseline initiative rank applied across all initiatives n. Once the scores are derived, they can be normalized and compared, thus demonstrating various scenario disruptiveness on the enterprise system.

TABLE IV. EMERGENT CONDITIONS THAT SINGLY AND IN COMBINATION DISRUPT A SUPPLY CHAIN FOR AVIATION BIOFUELS

Index	Emergent Condition
e.01	Inadequate Supply of Feedstock
e.02	Blockage by Social Movement
e.03	Incentive Instability
e.04	Lack of Public Investment
e.05	Lack of Private Investment
e.06	Competing Feed Stock Demands (Roads, Construction, …)
e.07	Economic Infeasibility
e.08	Equipment Failure
e.09	Contract Termination
e.10	Dependence on Imported Goods

e.11	Refinement Pathway Does Not Meet CORSIA Standard
e.12	Fuel Does Not Meet ASTM Standard
e.13	Lack of Renewable Power
e.14	Unexpected Energy Inefficiencies
e.15	Excessive Waste in Production
e.16	Labor and Talent Shortage
e.17	Fuel Instability
e.18	Fuel Contamination
e.19	Domestic Competition
e.20	Foreign Competition
e.21	Competing Fuel Demands (Biodiesel and Co-Products)
e.22	Transportation Incompatibility
e.23	Blending Percentage Limitation

To better understand the potential vulnerabilities in integrating an emerging fuel source into the supply chain at a major airport, a series of hypothetical scenarios, $S = \{s_{.01} + s_{.02} \ldots s_{.0k}\}$ was developed with a set unique emergent conditions $E = \{e_{.01} + e_{.02} \ldots e_{.0j}\}$ to model how the system may behave under conditions of disruption, uncertainty, and systemic interdependence (see Table IV). These scenarios are not predictions, but analytical constructs designed to explore the emergent properties of a complex socio-technical system. Each scenario is informed by a subset of emergent conditions (see Table V) that represent discrete yet interconnected factors affecting biofuel deployment. Table II then shows what effects that each of the scenarios has on the relevance of each criterion to show how disruptions will shift the systems priorities.

Scenario *s.01 Unsupportive Policy Change* describes a condition in which institutional support for biofuel weakens or becomes erratic. This includes *e.03 Incentive Instability*, where policy tools such as tax credits or subsidies fluctuate, and *e.04 Lack of Public Investment*, which reflects insufficient governmental commitment to infrastructure development. The scenario also incorporates *e.09 Contract Termination*, which may arise from shifting political priorities. From a technical compliance standpoint, *e.12 Fuel Does Not Meet ASTM Standard* presents a regulatory barrier to biofuel utilization. Infrastructural misalignment is represented by *e.22 – Transportation Incompatibility*, while *e.23 Blending Percentage Limitation* illustrates how blending restrictions may limit the contribution of the fuel to efficient resource management, despite availability.

Scenario *s.02 Market Fluctuation* describes how economic dynamics might destabilize the biofuel supply chain. *e.01 Inadequate Supply of Feedstock* explores the effect of constrained biomass availability, while *e.05 Lack of Private Investment* accounts for reduced investor confidence under volatile market conditions. *e.06 Competing Feedstock Demands* captures the competition between fuel producers and other industries (e.g., agriculture, construction) for shared resources. Variability in fuel performance, captured by *e.17 Fuel Instability*, introduces risk to operational reliability. *e.19 Domestic Competition* further complicates the market landscape by reflecting pressures from other renewable fuel sectors.

Scenario *s.03 Technology Challenges* describes potential points of failure in the technical systems required for biofuel production and delivery. *e.08 Equipment Failure* reflects operational interruptions at production or blending facilities. *e.11 Refinement Pathway Does Not Meet CORSIA Standard* addresses the risk that the fuel may fail to qualify under international sustainability frameworks. In addition, *e.13 Lack of Renewable Power* highlights how fossil energy inputs undermine the emissions profile, while *e.17 Fuel Instability* again points to performance risks that could limit adoption.

Scenario *s.04 Natural Disaster* describes the impact of environmental shocks on system continuity. Here, *e.01 Inadequate Supply of Feedstock* is considered again in the context of climate events (e.g., droughts or floods) disrupting biomass yields. Simultaneously, *e.16 Labor and Talent Shortage* reflects workforce disruptions caused by displacement, safety concerns, or migration patterns induced by natural disasters.

Finally, Scenario *s.05 Sociotechnical Disruption* describes the ways in which social and institutional dynamics interact with technological systems to create emergent challenges. *e.02 Blockage by Social Movement* reflects resistance to biofuel projects based on land use, justice concerns, or local environmental impacts. *e.03 Incentive Instability* and *e.05 Lack of Private Investment* appear again, emphasizing their cross-cutting influence on both institutional trust and capital flows. *e.10 Dependence on Imported Goods* introduces geopolitical and supply chain fragility, especially when critical materials or technologies originate from foreign sources.

TABLE V. SCENARIO DISRUPTIONS THAT ARE GENERATED AS COMBINATIONS OF EMERGENT CONDITIONS

Scenario	Emergent Conditions
s.01 Unsupportive Policy Change	*e.3, e.4, e.9, e.12, e.22, e.23*
s.02 Market Fluctuation	*e.1, e.5, e.6, e.17, e.19*
s.03 Technology Challenges	*e.8, e.11, e.13, e.17*
s.04 Natural Disaster	*e.1, e.16*
s.05 Sociotechnical Disruption	*e.2, e.3, e.5, e.10*

Collectively, these hypothetical scenarios function as a systems-oriented framework for modeling risk behavior and cascading effects within a proposed biofuels supply chain. They provide a structured approach for identifying leverage points and anticipating system responses under conditions of uncertainty, enabling a more resilient and adaptive fuel supply chains for the airport.

V. RESULTS

Fig. 3 presents a ranking of biofuel supply chain components for the airport, prioritized by their criticality to system goals under baseline and scenario conditions. The horizontal bars represent the performance range of each component across multiple scenarios, with red and blue segments reflecting the degree of variability or resilience across differing assumptions. Components toward the top of the graph, including the gasification Fischer-Tropsch (GFT) and pyrolysis refineries, exhibit the highest rankings. These facilities are central to domestic fuel production, providing both energy security and economic value by utilizing

regionally abundant waste resources. Their high and consistent scores suggest broad alignment with system criteria such as domestic fuel production, emissions reduction, and community economic benefit. Closely following in priority are the co-products (e.g., biogas, naphtha, biodiesel), which add system-wide value by diversifying output and providing revenue streams beyond jet fuel. The limited variability in these top-ranking components, especially for pyrolysis—indicates high reliability under current assumptions, policy structures, and market signals. In contrast, mid-tier components—including MSW and tire processing facilities, rail and barge transportation infrastructure, and pipeline blending—show wider error bars, reflecting higher sensitivity to emergent conditions. Their rankings vary based on assumptions about policy incentives, logistics constraints, and technological performance. For example, reliance on multimodal transport introduces uncertainties due to fuel compatibility and throughput capacity, particularly when feedstock volumes fluctuate, or intermodal connections are disrupted. Lower-ranking components such as truck-based transportation, localized blending, and airline-specific storage facilities demonstrate limited strategic impact under the current system criteria. Trucking, in particular, may be cost-inefficient and difficult to scale for fuel volumes required by major carriers. While these facilities may still play tactical roles, especially during the early deployment phase, their long-term contribution to system-wide goals is limited. Additionally, the inclusion of foreign and out-of-state biofuels production highlights possible external dependencies. These may serve as transitional solutions but pose challenges in terms of energy sovereignty, transport emissions, and regulatory misalignment. Overall, this study of system order illustrates how a structured evaluation framework can identify the most critical leverage points in the biofuels supply chain of a region. The ability to visualize component performance across variable conditions enables policymakers and stakeholders to prioritize investments and design adaptive systems that remain robust as technologies, regulations, and market forces evolve.

By incorporating different emergent conditions into the analysis, alternative supply chain scenarios can be developed to assess how various disruptions might reshape the biofuel integration strategy. Fig. 4 describes the disruptiveness score calculated using (1), highlighting *s.02 Market Fluctuation* and *s.05 – Sociotechnical Disruption* as the top two destabilizing scenarios. However, the remaining three scenarios could still create significant disruptions if different relevance are placed on the criteria. For instance, *e.11 refinement pathway fails to meet CORSIA sustainability standards*, would become a much larger disruption if high relevance is placed on *c.01 Efficient Resource Management*. Similarly, *e.11 Lack Of Renewable Power* for production facilities would hinder the scalability of biofuel, if the aviation industry moves toward more stringent sustainability commitments. Additionally, *e.03 Incentive Instability*, such as unpredictable tax credits or changing subsidy structures, could arise as an emergent condition due to *s.02 Market Fluctuations* rather than *s.01 Unsupportive Policy Changes*, especially if national priorities shift in response to an economic downturn.

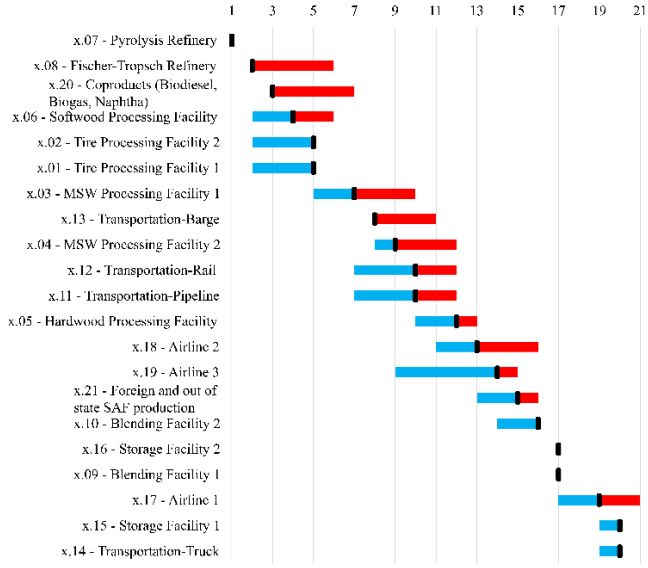

Fig. 3 Component ranking assessment of biofuel supply chain

By modeling these variations, stakeholders can better anticipate vulnerabilities and develop adaptive strategies to mitigate risks. Strengthening policy support, ensuring stable incentives, and advancing renewable energy infrastructure will be essential to creating a resilient and scalable biofuel supply chain for the airport.

VI. Discussion and Conclusions

TABLE VI. Key results of addressing enterprise risk as the disruption of system order for the supply chain of aviation biofuels

Result	Description
Most disruptive scenarios	*s.02 Market Fluctuation.* was the most disruptive scenario followed by *s.05 Sociotechnical Disruption*
Highest ranked components in baseline	The *x.07 Fisher-Tropsch* and x.08 *Pyrolysis Refineries*, have the highest ranking with low variability.
Lowest ranked initiatives in the baseline	*x.14 Truck-based transportation*, *x.09,x.10 Localized Blending*, and *x.15,x.16 Airline-specific storage facilities* had the lowest baseline rankings.

Follow-on steps of this effort will provide a techno-economic analysis (TEA) for the supply chain using the U.S. Department of Energy Fuel Transportation and Optimization Tool (FTOT) to generate financial transportations data and optimized supply chain models for policymakers and investors in the aviation sector [1],[23]. This analysis will provide precise go/no-go decision points, helping to identify potential failure risks while also assessing the quantitative financial and environmental returns of aviation biofuel investments in the region. By leveraging these models, stakeholders can make informed decisions regarding the feasibility and scalability of biofuel production, ensuring that investments align with both economic and sustainability goals [9]. Additionally, this data-driven approach will support the development of policies and incentives that

promote the adoption of biofuel, fostering long-term growth in the industry.

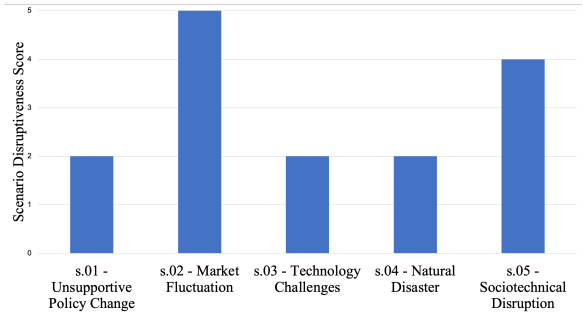

Fig 4. Disruptiveness scores for five scenarios that disrupt the priority order of twenty-one system components needed for a biofuel supply chain

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