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Resilient or fragile? Modelling economic disruptions in India's electronics sector due to the Red Sea crisis

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ABSTRACT

The Red Sea crisis and the recent attacks on commercial ships have drawn significant attention worldwide, underscoring the need to understand how such geopolitical conflicts can disrupt global supply chains and economic stability. This paper thoroughly examines the complex impacts of the crisis on India's electronics and photonics sector, recognizing the sector's crucial importance as a fundamental pillar in the country's economic structure. The study creates a mathematical model to assess how disruptions in the Electronics and Photonics Sector affect India's economy in light of the Red Sea Crisis. The model uses two specific methods: interval programming and input-output modelling. How disruption in one area of the economy ripples to another is studied using Wassily Leontief's Inoperability Input-output Model (IIM). IIM now includes interval programming to handle data uncertainties. The findings disclose that, because of the Red Sea crisis, Indian Sector has experienced a huge economic loss of 605.52 million USD. The study also determines which sectors are anticipated to suffer significant losses due to the crisis, allowing decision-makers to prioritize their investment plans. Further, the research uses the inoperability value to analyse the interconnections between the sectors. Additionally, a decision-support conclusion is included in the research to analyse the sectors under various situations.

1. Introduction

The Red Sea has shaped cultures from ancient times as a commercial route (Diem et al., 2023). It is an important economic corridor and waterway for freedom of passage and international commerce. This non-state entity deploying ballistic missiles and Unmanned Aerial Vehicles (UAVs) against commerce boats from numerous states legitimately passing international seas must be addressed by those who value freedom of navigation. (Austin, 2023). The Red Sea issue, characterised by continuous attacks on commercial ships staged by Houthi militants, has sparked international concern because of its severe global economic repercussions (Clark and Patt, 2024; Milhiet and Vellayoudom, 2024; Jagtap et al., 2024). The crisis's gravity stems from disrupting the world's busiest shipping route, vital for transferring commodities required by the electronics and photonics sector. The electronics and photonics sector, known for its just-in-time production methods with minimal inventory levels, is at risk during this turbulent moment. The sector's reliance on the prompt arrival of components and final goods is critical to maintaining continuous operations. The Red Sea crisis threatens the industry's production deadlines (Peng et al., 2024) and complex supply chain networks (Lee, 2024; Menon and Ravi, 2022; Rajesh and Ravi, 2015; Siddiqui and Raza, 2015). This sector serves as the backbone for downstream industries such as automotive, telecommunications, and healthcare. As a result, any disruptions have a ripple effect across the entire economy.

The electronics and photonics sector has to cope with the pressing problems of continuing production, supply, and exports as the crisis worsens. The study attempts to unravel this complex web of issues, highlighting the sector's specific vulnerabilities and offering insights that may assist policymakers and business leaders in creating sensible solutions amid economic uncertainty. This research aims to support India's growth and development by analysing the varied impacts of the Red Sea crisis on the import and export dynamics of the electronics and photonics sector. The study recognises the urgency and significance of this issue. In light of the sector's crucial importance as a pillar of the Indian economy, this study examines the crisis's subtle impacts on

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India's electronics and photonics sector. This study provides a solid foundation for strategic decision-making and inspires more research in the field of global economic disruptions, in addition to shedding light on the direct effects of the Red Sea crisis on India's electronics and photonics sector. The study offers significant findings for scholars, corporations, and governments. They are essential for managing the complex issues of geopolitical conflicts, building resilience, and strengthening national economies' capacity to adjust to changing international conditions.

1.1. Global impact of the Red Sea crisis

Shipping vessel assaults during the Red Sea crisis have impacted global commerce and shipping, harming many sectors and economies (Notteboom et al., 2024; Yap and Yang, 2024). MSC, Maersk, and CMA CGM halted Red Sea ship activity, disrupting supply networks. Due to this, Tesla, Volvo, BP and Shell had to their manufacturing and shipping operations. According to Notteboom et al. (2024), the crises caused changes in shipping routes, resulting in boats taking a different path around Africa rather than following the Red Sea route (Liyew, 2024). This resulted in higher costs and longer transit times for the movement of commodities, even though it assured safety. In addition, Qatar's decision to stop allowing Liquefied Natural Gas (LNG) ships to pass through the Bab al-Mandeb Strait has caused worries about energy availability, especially during the winter season in Europe, where Qatar is a big supplier of LNG. According to Ashine (2024), the influence of the crises in the Red Sea stretched beyond the realm of trade and affected humanitarian efforts as well (Ashine, 2024; Haralambides, 2024). The delivery of humanitarian assistance to nations such as Sudan was delayed and made more costly, which exacerbated the difficulties already present in areas experiencing wars and disasters. This resulted in higher costs and longer lead times for the distribution of goods, impeding attempts to relieve suffering and meet humanitarian needs. The Red Sea crisis had a major negative effect on commerce, transportation, energy supply, and humanitarian operations overall, which highlighted how linked and vulnerable the global supply chain is to geopolitical events and security threats (Ashine, 2024; Milhiet and Vellayoudom, 2024; Seethi, 2024).

1.2. Impact of Red Sea crisis on India's electronics and photonics sector

The ongoing Red Sea Crisis is causing significant disruptions to worldwide supply networks that are crucial for the electronics and photonics industries. In the electronics sector, shipment delays of essential components such as semiconductors and circuit boards are resulting in reduced production rates and higher expenses. The photonics industry is experiencing shortages of specialized materials, including optical fibres and rare earth elements, which are fundamental to cutting-edge technologies. These supply chain interruptions exacerbate existing vulnerabilities, leading to increased costs and extended production timelines in various sectors, including telecommunications, medical equipment, and defence. Similarly, India's electronics and photonics sector has suffered greatly due to the Red Sea crisis, which disrupted international supply networks and transit routes. Major shipping firms banning travel via the Red Sea have negatively impacted the transfer of vital supplies, such as raw materials, components, and completed goods (He et al., 2023). This has caused shortages and production delays for Indian manufacturers. Longer transit times and higher transportation costs due to rerouting logistics have further reduced profit margins and reduced competitiveness (Hoffman et al., 2023; Hua and Wu, 2024). Additionally, interruptions in export shipments have strained ties with foreign partners and may cost Indian exporters money (Sharma, 2024). Furthermore, the industry's efforts to innovate technologically and conduct research and development might be hampered by delays in delivering essential parts and equipment (Karanam et al., 2024; Raj et al., 2024). To increase resilience in the face of such upheavals in the future, authorities must reevaluate trade strategy, diversify supply sources, and invest in local manufacturing capabilities. By highlighting the top five industries experiencing the most financial losses, this study offers an extensive overview of the sectors most vulnerable to widespread disruptions. To investigate how the crisis has affected various sectors, the research objectives as follows have been developed:

- o RO1 To study and analyse the interdependence of Indian sectors to understand how disruptions in the electronics and photonics sector affect other sectors.
- o RO2 To analyse the effect of the Red Sea crisis on matrices, such as interoperability and economic loss for the Indian economy.
- o RO:3 To identify and rank the most vulnerable sectors that are dependent on electronics and photonics sector in the Indian Economy.

The first research objective (RO1) analyses the Indian sector's interconnectedness. The interconnectedness of electronics and photonics is fundamental to numerous industries, making it essential for policymakers to comprehend their relationship. This understanding enables them to assess how disturbances in these fields, exemplified by the Red Sea Crisis, can have far-reaching impacts on the economy. By recognizing this interdependence, decision-makers can better anticipate and evaluate the potential cascading effects on other sectors, thus highlighting broader systemic vulnerabilities. The second objective (RO2) studies how the crisis affected interoperability and economic loss in electronics and photonics. By estimating economic losses and examining sector interoperability, actionable insights can be gained, allowing for a quantitative understanding of the crisis's impact on the Indian economy and informing mitigation strategies. The third objective (RO3) identifies and ranks India's most vulnerable sectors to guide intervention prioritization and resource allocation. These objectives together provide a comprehensive framework to analyse the Red Sea Crisis's impact on the Indian economy, offering insights into interdependencies, economic vulnerabilities, and prioritization for intervention. To achieve these objectives, the study uses input-output modelling and interval programming approaches to achieve these research objectives. Input-output modelling makes it easier to describe interdependencies between sectors, which aids in quantifying the crisis's impact on the electronics and photonics sector. Interval programming deals with the crisis's uncertainty, allowing for investigating resilient decision-making under different circumstances.

The subsequent sections are organised as follows: Section 2 investigates the Red Sea crisis' economic effects on sectors and interdependency models. Section 3 provides research methods, whereas Section 4 describes Input-Output modelling in this study. Section 5 includes data analysis and outcomes. Section 6 concludes with insights for managers and policymakers and future studies.

2. Literature review

The Red Sea crisis has disrupted the shipping and logistics industries. The unexpected Port route change was most significant in the early weeks of the Red Sea crisis. Rerouting cargo is time-consuming and expensive (Santos and Haimes, 2004). The Red Sea crisis is affecting electric cars (Elkholy et al., 2024). Tesla's Gigafactory Berlin–Brandenburg paused operations from 29 January to 11 February owing to vessel rerouting that disrupted the delivery of components from Asian suppliers. Due to component shortages, Volvo Cars in Ghent, Belgium, halted production for three days in mid-January (Victoria Waldersee and M. M., 2024). Suzuki Motor's Hungary facility halted operations from 14 to 21 January 2024. Longer travel delays also affect the fruit and vegetable industry (Notteboom et al., 2024). Table 1 summarises current studies on how the Red Sea crises affect the global economy.

Table 1
Literature related to Red Sea crises.

Author	Description
Notteboom et al. (2024)	Implications for marine supply chains, transportation networks, and vessel operations.
Ashine (2024)	Examines the Red Sea region's strategic and commercial importance for the main world countries.
Bazoobandi and Talebian (2024)	Examines the nations' historical participation in certain areas.
Milhiet and Vellayoudom (2024)	The effects of Red Sea geopolitical tensions on Réunion Island.
Pietsch (2024)	Houthi attacks on Red Sea ships threaten Israel's economy.
Glauben et al. (2022)	International Response to Red Sea Attacks.
Analytica (2024)	The part India plays in regional marine security.
Das (2024)	Considers the complexity of India-Middle East-Europe Economic Corridor facts.

2.1. Case background

In addition to violating international law, the current increase in the Red Sea crisis poses a threat to the free flow of trade, puts defenceless seamen at risk, and disrupts international law (Notteboom et al., 2024). The confrontation that took place between Israel and Hamas in October 2023, which was then followed by Israel's military reaction in Gaza, was the primary focus of the media (Hokayem, 2023). Subsequently, Houthi Rebels in Yemen attacked foreign ships in the Red Sea and Bab al-Mandab Strait, which resulted in a severe security crisis that affected world commerce and trade (Manea, 2024). Due to the strikes, ships were compelled to alter their routes (Fig. 1), which seriously disrupted the production schedules of the businesses. These issues might result in higher shipping costs, possible shortages of commodities, and delays in imports and exports (Notteboom et al., 2024). Additionally, heightened geopolitical tensions in the region could affect investor confidence and market stability, impacting foreign investment flows and currency exchange rates (Ashine, 2024; Milhiet and Vellayoudom, 2024). Furthermore, if the situation escalates and leads to a broader conflict in the Middle East, it could have implications for global energy prices, affecting India's energy imports and overall economic growth.

2.2. How it is impacting the Indian economy

The interruptions in trade channels have harmed the Indian economy, notably shipping routes through the Red Sea and the Bab al-Mandab Strait. This is one way the Indian economy has been affected. India's shipping industry has been impacted by the rerouting of shipping due to the strikes by the Houthis (Das, 2024). The crisis has impacted Indian exports to Europe, the east coast of the United States, and Latin America (Ashine, 2024). Indian container freight costs rise with global trends. Federation of Indian Export Organisations (FIEO) reports that Indian exporters are holding back 25 % of Red Sea outbound shipments due to rising costs (Bhadana, 2024; Srivastava, 2024).

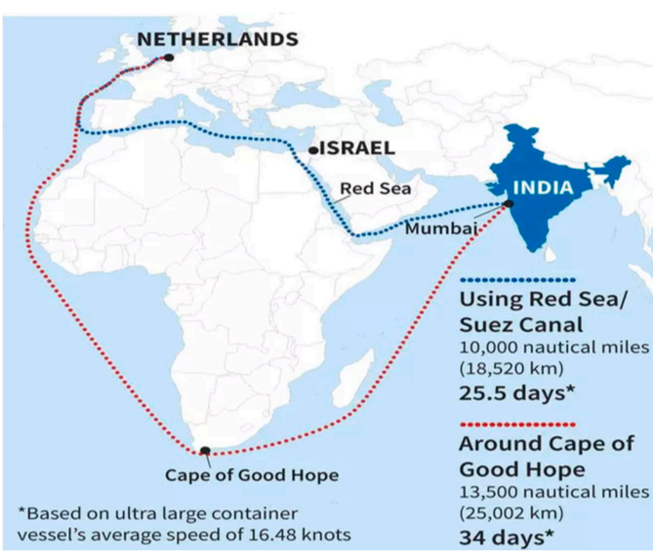

Fig. 1. Change route due to red sea crises (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

India's exports are experiencing considerable challenges, including a huge rise in transportation costs (Janardhan, 2024). The cost of freight has increased by 233 % for exporters of Basmati rice, while delays and uncertainty are being experienced by farmers exporting perishable items like grapes (Global Trade Research Initiative (GTRI), 2024). This situation has an impact on several different industries. Delays in providing pharmaceuticals that may save lives are a problem for the pharmaceutical business, which puts crucial medical supplies at risk (Takawira and Pooe, 2024). Textile producers are experiencing two-month delays in European exports, resulting in missed deadlines and penalties. Steel shipments to Europe and the Middle East are being delayed, prompting fears about order cancellations. In addition, the auto sector is impacted by the rise in freight prices for imported raw materials and delays in delivering essential components (Victoria Waldersee and M. M., 2024).

2.3. Interdependency modelling

Wassily Leontief was awarded the Nobel Prize in Economic Sciences in 1973 for his accomplishments. He is acknowledged as the pioneer of the Input-Output (I-O) methodology. I-O methods are vital for understanding the interdependence of economic sectors informing emergency planning. They are widely used to analyse national accounts and assess the impact of disruptions across sectors. Other methods like Computable General Equilibrium (CGE) and econometric models (regression-based or time-series) were considered for the analysis but not selected due to constraints such as the lack of comprehensive data needed for CGE models, which limits their applicability for immediate assessments. Additionally, CGE models involve complex frameworks that require significant computational resources, making them impractical for timely analysis. Econometric models, while useful for trend predictions, do not effectively capture the interdependencies among sectors as the I-O model does. Given the focus of our study on understanding how disruptions in the electronics and photonics sectors affect other sectors, the Input-Output methodology was deemed the most appropriate tool for providing actionable insights into the economic impacts of the Red Sea Crisis. A suggested Input-Output (I-O) model for each sector is shown in Fig. 2. The system is in equilibrium when its input and output are equal. The model uses resources as input, processes them, and produces final goods for end-users and intermediate consumers.

I/O modelling is versatile. Haimes and Nainis (1974) and Haimes (1977) applied Leontief's approach to water and environmental challenges. Proops (1984) studied energy input-output ratios, whereas Krause (1992) created a non-linear model. Olsen et al. (1997) used Leontief's analysis for flood defence deployment, while Santos and Haimes (2004) suggested the inoperability of input-output modelling—input-output modelling details system disturbances that affect numerous regions, revealing system failure. Matrices measure the negative effects of economic loss and operational complexity. Literature extensively examines the economic consequences of crises on many industries. Park (2008) examined the financial consequences of bombs on Long Beach and Los Angeles ports using a national economic model. Jung et al. (2009) examined issues' economic and infrastructural consequences. MacKenzie et al. (2011) used dynamic Input-Output Modelling (IIM) to evaluate the effects of port closures. Pant et al. (2011) examined the interconnectedness of inoperability in container ports. Caggiani et al. (2014) propose a method for Multi Regional Input-Output model for freight demand estimation. Hiramatsu et al.

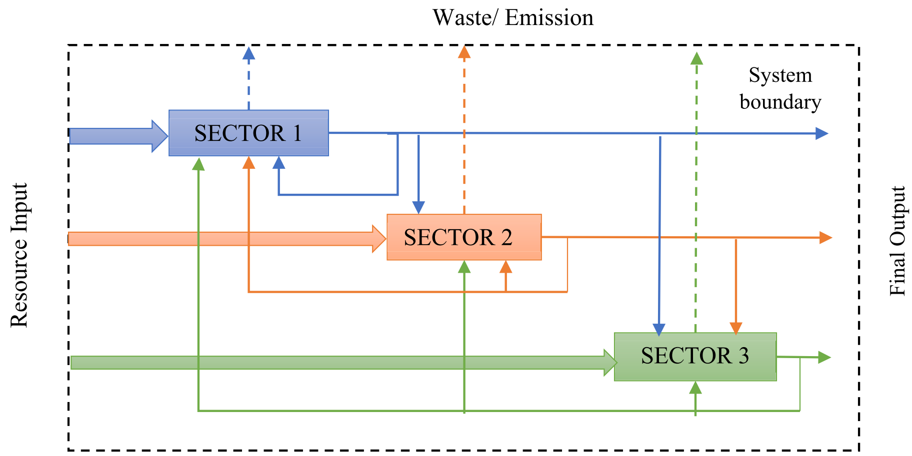

Fig. 2. Input-Output model framework.

(2016) developed a model by combination the RAS method and the real-coded Genetic Algorithm for the interregional I-O table estimation. Further, Balster and Friedrich (2019) developed a multi-scale multi-regional input–output (MSMRIO) model which determines the additionally needed transport capacity in case of a disruption. The recent research includes a range of subjects, such as the evaluation of environmental lifecycle impact, the effects of COVID-19 on port logistics, and the consequences of the Russian-Ukrainian conflict. These studies are referenced in Table 2.

3. Methodology

Data and input-output modelling in this part was examined. The effect of the Red Sea Crisis on India's Electronics and Photonics Sector is examined via a quantitative model using input-output modelling. The inoperability value is used to analyse the interdependence of the sectors, and the economic effect is determined by identifying the sectors with the lowest and greatest priority affected by the Red Sea issues affecting the Indian economy.

3.1. *Data collection & constraints*

This study employed an exhaustive method of gathering data. Fig. 3. illustrates the research flow design to understand the whole procedure to Assess the Red Sea Crisis's economic impact on India's electronics and photonics sector. The study uses India's Input-Output Table for the year 2022 from the Asian Development Bank (ADB) Database. ADB database is considered as a reliable source of comprehensive economic statistics. Table 3 displays the details of these sectors. After initially finding 35 sectors as shown in Table 3, c31 and c35 were excluded from the research due to concerns about data availability. Thirty-three sectors were included in the final study to guarantee a thorough portrayal of the economic environment. The commencement date of the Red Sea Crisis was set as 19 October 2023. During the observation period from 10 November 2023 to 20 January 2024, there were 17 attacks on commercial vessels over a total of 72 days. Subsequently, the observation was extended for an additional 15 days, concluding on 5 February 2024, bringing the total observation period to 87 days, during which there were 23 attacks recorded. Using this the study calculates the upper limit and lower limit for the input output model. The calculated lower limit of attacks per day during the initial 72 days is $72/365 \approx 0.197$, while the calculated upper limit for the extended 87 days is $87/365 \approx 0.238$. Due to its crucial position in India's economic structure, the Electrical and optical equipment sector is considered the Electronics and Photonics Sector in this study. This volatile crisis made the business more vulnerable because it relied on just-in-time manufacturing procedures

Table 2
Literature related to I-O analysis.

Author	Area of research	Description
Weber et al. (2024)	Global inflation	This paper simulates price shocks in an input–output model to identify sectors which present systemic vulnerabilities for monetary stability in the United States.
Aoun et al. (2024)	Centralized vs. Decentralized Electric Grid	This study employs an extrapolation of Leontief's input–output (IO) model, originally designed to study ripple effects in economic sectors
de Mesnard (2024)	Inter-industry inflation	This study uses the Leontief and Ghosh models to determine the price indexes of goods, which is convenient for analysing inter-industry inflation.
Liu et al. (2023)	Drivers of China's carbon dioxide emissions	This study combines the structural decomposition analysis method and the input-output subsystem analysis method to construct a decomposition model of the factors influencing the amount of change of the carbon dioxide emissions in China.
Zhang et al. (2023)	Impact of digital input on enterprises.	This study aims to provide a comprehensive theoretical explanation and micro-level evidence for the impact of digital input on green productivity in manufacturing enterprises.
Pamucar et al. (2023)	Mining and minerals, Agriculture, and Energy	The input-output model illustrates how pandemic-induced perturbations in one sector spread to others.
Sarkar and Gupta (2024)	Russian Ukraine War	Examine how the conflict between Russia and Ukraine affected interoperability and economic losses for the Indian economy.
Sarkar et al. (2022)	Port Logistics	Use I-O modelling and interval programming to examine the impact of COVID-19 on economic loss and inoperability un the Indian economy.
Liu et al. (2020)	Energy and environmental sector	(I-O) modelling to examine how various sectors' life cycles affect the environment.
Wang et al. (2020)	Supply Chain	DEA and I-O models are used to assess sustainability performance.
Goldbeck et al. (2020)	Supply Chain	A scenario tree generation method that uses input-output modelling to take into account the risk of failure propagation.
Ling et al. (2019)	Biomass power plant	Use mathematical modelling to determine the best site for a biomass power plant.

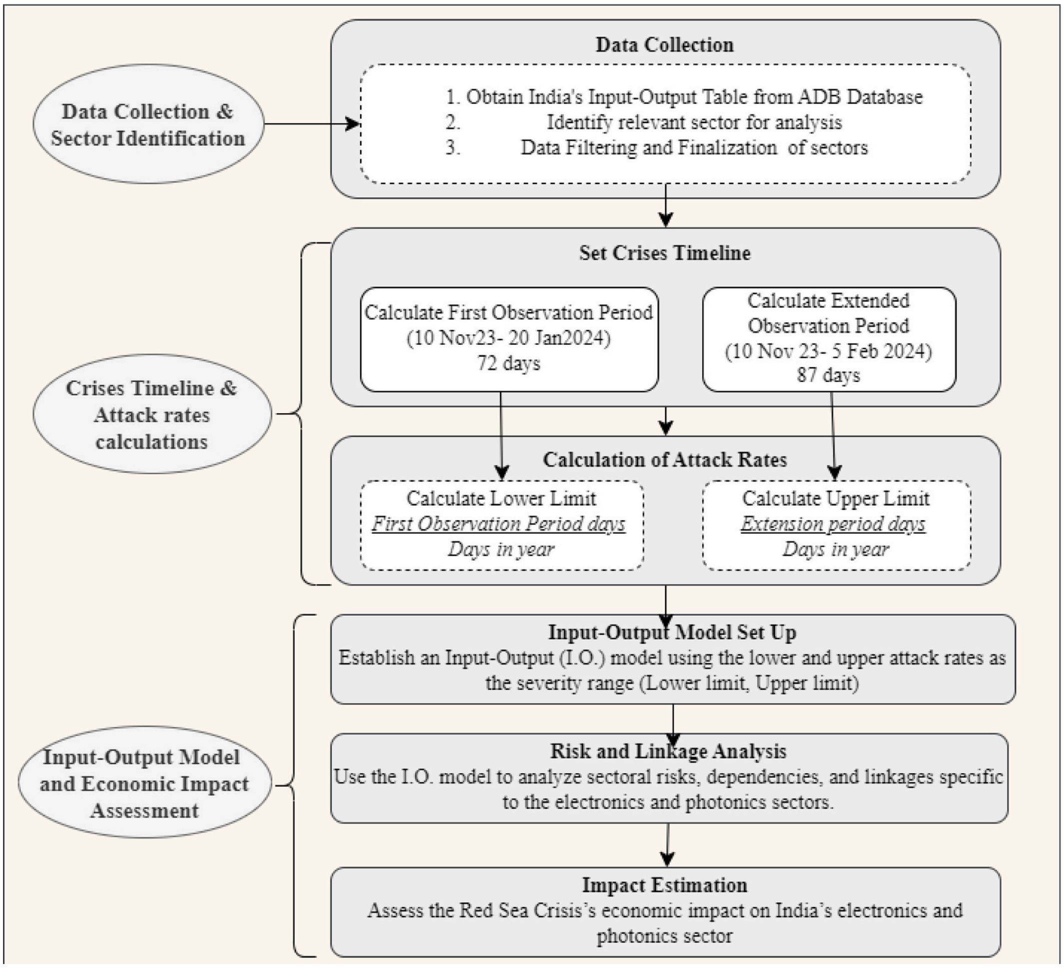

Fig. 3. Research Flow design.

and low inventory levels.

To quantitatively assess the impact, an Input-Output (I.P.) model was established, with a perturbation severity range defined by a lower limit of 0.197 and an upper limit of 0.238. These values were essential for measuring the cascade effects in the electronics and photonics sectors. The model provided a detailed examination of sectoral risks and linkages based on these characteristics. However, data for sectors C31 and C35 was unavailable, underscoring the importance of adhering to a stringent and transparent data inclusion policy. Despite these limitations, the study encompassed 33 sectors, enabling an estimation of the economic impact of the Red Sea Crisis on India's electronics and photonics sector.

3.2. Input-Output modelling

The Input-Output Model (I-O) uses linear equations to analyse economic sector relationships. This model shows the economy's structure and producer-to-consumer exchanges. The following is the formulation of the I-O model that Leontief developed:

$$Y = BY + D \tag{1}$$

$$Y_i = \sum_j B_{ij} Y_j + D_i \tag{2}$$

In the formula below, each sector produces a commodity. Commodities may be commodities or services. The I-O Model uses these notations:

N: number of industrial sectors.

Y_i: total number of output for sector *i*.

Y_j: total number of output for sector *j*.

D_i: final demand for sector *i*.

Y_{ij}: intermediate consumption, input to sector *i* to the production of sector *j*.

B_{ij}: input requirement of sector *j* from sector *i*.

where $i, j = 1, 2, \dots$ N.

I/O coefficient matrix appears to be this:

$$B = \begin{bmatrix} B_{11} & B_{12} & \dots B_{1N} \\ B_{21} & B_{22} & \dots B_{2N} \\ \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots \\ B_{N1} & B_{N2} & \dots B_{NN} \end{bmatrix} \tag{3}$$

It is possible to compute the coefficient of the technology matrix by using the transaction matrix Z and the output Y vector.

$$B_{ij} = \frac{Z_{ij}}{Y_j} \tag{4}$$

$$L = (I - B)^{-1} \tag{5}$$

The fifth equation displays Leontief's inverse matrix. The term "total requirement matrix" also applies to it. Eq. (1) is rewritten as follows after being simplified:

$$Y = BY + D$$

Table 3
Sectors used in the research, listed with codes.

SN	Sectors	SN	Sectors
1	Agriculture, hunting, forestry, and fishing (C1)	19	Sale, maintenance, and repair of motor vehicles and motorcycles; retail sale of fuel (C19)
2	Mining and quarrying (C2)	20	Wholesale trade and commission trade, except of motor vehicles and motorcycles (C20)
3	Food, beverages, and tobacco (C3)	21	Retail trade, except of motor vehicles and motorcycles; repair of household goods (C21)
4	Textiles and textile products (C4)	22	Hotels and restaurants (C22)
5	Leather, leather products, and footwear (C5)	23	Inland transport (C23)
6	Wood and products of wood and cork (C6)	24	Water transport (C24)
7	Pulp, paper, paper products, printing, and publishing (C7)	25	Air transport (C25)
8	Coke, refined petroleum, and nuclear fuel (C8)	26	Other supporting and auxiliary transport activities; activities of travel agencies (C26)
9	Chemicals and chemical products (C9)	27	Post and telecommunications (C27)
10	Rubber and plastics (C10)	28	Financial intermediation (C28)
11	Other non-metallic minerals (C11)	29	Real estate activities (C29)
12	Basic metals and fabricated metal (C12)	30	Renting of M&Eq and other business activities (C30)
13	Machinery (C13)	31	Public administration and defence; compulsory social security (C31)
14	Electrical and optical equipment (C14)	32	Education (C32)
15	Transport equipment (C15)	33	Health and social work (C33)
16	Manufacturing, nec; recycling (C16)	34	Other community, social, and personal services (C34)
17	Electricity, gas, and water supply (C17)	35	Private households with employed persons (C35)
18	Construction (C18)		

$$\mathrm{dD} = \mathrm{Y{-}BY}$$

$$\mathrm{D} = \mathrm{Y.(1-B)}$$

$$Y = \frac{D}{(1-B).}$$

$$\mathrm{Y} = \mathrm{D.(1-B)^{-1}}$$

$$Y = LD \tag{6}$$

3.2.1. Input-Output (I-O) model for inoperability

Inoperability refers to a system's inability to fulfil its purpose. Leontief's Input-Output (I-O) model is widely used across various fields, employing dimensionless numbers from 0 to 1 to denote system conditions. The concept of Inoperability Input-Output Modelling (IIM), introduced by Haimes and Jiang (2001), analyses infrastructure relationships (Haimes and Jiang, 2001). IIM was used by Santos and Haimes (2004) to evaluate the short- and long-term effects of terrorism on the U.S. economy (J. R. Santos and Haimes, 2004). The following is the developed IIM structure:

$$P = B^{*}P + D^{*} \tag{7}$$

where

P: Inoperability vector, which measures the sector's unfulfilled production in relation with planned production. It is also presented in normalised economic loss

B^{*}: Interdependency matrix, represents of the connection of sectors
D^{*}: Perturbation vector, represents final demand

3.2.2. Inoperability

A measurement of inoperability is the ratio of the ideal production level $(\widehat{y}_i)$ to the disrupted production level $\left(\widetilde{y}_i\right)$ with the ideal production level $(\widehat{y}_i)$ serving as the reference point. The scaler representation of P is presented in the following manner:

$$P = [diag(\widehat{Y})]^{-1}[\widehat{Y} - Y] \tag{8}$$

$$\begin{bmatrix} P_1 \\ \vdots \\ P_i \\ \vdots \\ P_n \end{bmatrix} = \begin{bmatrix} \frac{1}{\widehat{Y}_1} & 0 & \ldots\ldots 0 \\ 0 & \ddots & \ddots \vdots \\ \vdots & \ddots & \frac{1}{\widehat{Y}_i} \vdots \\ & \vdots \ddots \ddots 0 & \\ & 0\ldots\ldots 0 & \frac{1}{\widehat{Y}_N} \end{bmatrix} \begin{bmatrix} \widehat{Y} - \widetilde{Y}_1 \\ \vdots \\ \widehat{Y}_i - \widetilde{Y}_i \\ \vdots \\ \widehat{Y_N} - \widetilde{Y}_N \end{bmatrix} \tag{9}$$

Therefore, elements in p vector written as:

$$P_i = \frac{\left(\widehat{Y}_i - \widetilde{Y}_i\right)}{\widehat{Y}_i} \tag{10}$$

3.2.3. Interdependency matrix

Leontief's technology matrix B is related to this matrix. Matrix N*N in this case represents the pairwise evaluation of each sector. This uses the notations from the I-O model.

$$B^{*} = diag(\widehat{Y})^{-1}.B.diag(\widehat{Y}) \tag{11}$$

$$\begin{bmatrix} \frac{1}{\widehat{Y}_1} & 0 & \ldots\ldots 0 \\ 0 & \ddots & \ddots \vdots \\ \vdots & \ddots & \frac{1}{\widehat{Y}_i} \vdots \\ & \vdots \ddots \ddots 0 & \\ & 0\ldots\ldots 0 & \frac{1}{\widehat{Y}_N} \end{bmatrix} \begin{bmatrix} B_{11} & B_{12} & \ldots B_{1N} \\ B_{21} & B_{22} & \ldots B_{2N} \\ \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots \\ B_{N1} & B_{N2} & \ldots B_{NN} \end{bmatrix} \begin{bmatrix} \widehat{Y}_1 & 0 & \ldots\ldots 0 \\ 0 & \ddots & \ddots \vdots \\ \vdots & \ddots & \widehat{Y}_i \vdots \\ & \vdots \ddots \ddots 0 & \\ & 0\ldots\ldots 0 & \widehat{Y}_N \end{bmatrix} \tag{12}$$

The coefficient of interdependency matrix is computed in scalar form using Eq. (13).

$$B^{*}_{ij} = B_{ij}\left(\frac{Y_i}{Y_j}\right) \tag{13}$$

Here, B^{*}_{ij} denotes the increased inoperability provided by sector j to sector i. Santos and Haimes (2004) demonstrate in what manner IIM models use conventional economic I-O data.

3.2.4. Perturbation

Here, D^{*} represents the perturbation vector, which is determined using the provided equation.

$$D^{*} = [diag(\widehat{Y})]^{-1}\left[\widehat{D} - \widetilde{D}_i\right] \tag{14}$$

$$\begin{bmatrix} D_1^* \\ \vdots \\ D_i^* \\ \vdots \\ D_N^* \end{bmatrix} = \begin{bmatrix} \frac{1}{\widehat{Y}_1} & 0 & \ldots\ldots 0 \\ 0 & \ddots & \ddots \vdots \\ \vdots & \ddots & \frac{1}{\widehat{Y}_i} \vdots \\ & \vdots \ddots \ddots 0 & \\ & 0\ldots\ldots 0 & \frac{1}{\widehat{Y}_N} \end{bmatrix} \begin{bmatrix} \widehat{D_1} - \widetilde{D}_1 \\ \vdots \\ \widehat{D_i} - \widetilde{D}_i \\ \vdots \\ \widehat{D_N} - \widetilde{D}_N \end{bmatrix} \tag{15}$$

Here, $\widehat{D}$ represents the final demand, and $\widetilde{D}_i$ denotes degraded final demand. The coefficients of the perturbation vector in scalar form can be computed using the provided equation

$$D_i^* = \frac{(\widehat{D_i} - D)}{\widehat{Y}_i} \tag{16}$$

3.2.5. Economic loss

Here, the vector elements represent the economic loss resulting from sector i's ideal output level (Yi) and inoperability (Pi), which indicates the sector *i*'s monetary value of operational inefficiency.

$$\text{Economic loss} = (Y_i.P_i) \tag{17}$$

4. Results and discussion

The study uses input-output (I.O.) modelling as a crucial methodological tool to investigate the intricate interdependencies across various sectors in the wake of the Red Sea Crisis. I.O. modelling, which helps capture the dynamic links and interdependence within an economic system, enables a more thorough understanding of how shocks in one sector may reverberate throughout the whole network. Given how susceptible India's electronics and photonics sector is to the interruptions caused by the Red Sea Crisis, this modelling technique becomes extremely relevant. Interval Programming (I.P.) is also used to enhance the research's analytical capabilities and thoroughly investigate resilient decision-making across a range of unexpected conditions. I.P. takes into account the inherent unpredictability of economic shocks and geopolitical crises. By considering various potential values within prescribed intervals, the study may assess different scenarios and their associated implications on the electronics and photonics sector. This integrated method allows the research to provide useful insights into the intricate problems highlighted by the Red Sea Crisis by combining interval programming with I.O. modelling. In the face of economic uncertainty, this forms the foundation for risk management, policy creation, and strategic decision-making.

4.1. Perturbation in the electronics and photonics sector

The Red Sea route via the Suez Canal handles approximately 50 % of India's exports and 30 % of its imports, making it a crucial channel for trade with Europe, North America, North Africa, and the Middle East. However, the nature of disruptions resulting from the Red Sea Crisis would depend on the scale and duration of the geopolitical tensions, meaning that a full shutdown of trade is unlikely, but partial disruptions are plausible. The scenarios in Section 4.1 are designed to simulate partial disruptions in the Electronics and Photonics sector and assess how these affect other interlinked sectors, rather than assuming a complete halt in all economic activities. The focus is on the cascading effects such a disruption could have across industries due to delays, increased transportation costs, and potential supply chain bottlenecks. By using the Inoperability Input-Output Model (IIM) with interval programming, the analysis captures the uncertainty in supply fluctuations and variations in trade conditions, thus providing a range of potential economic impacts.

To find out how the Red Sea Crisis affected the Indian economy, the research develops scenarios. In the first scenario, which involves disruptions to the Electronics and Photonics Sector, the study examines significant facets of the ensuing economic landscape and provides informative details on the intricate impacts on other Indian industries. The perturbation study of this important sector shows a comprehensive evaluation of the economic implications, contributing to a more sophisticated knowledge of the ripple effects throughout the economy. To help policymakers and business leaders make informed decisions, it is critical to identify the top five sectors experiencing the most economic losses. Quantifying the overall economic loss is one important statistic that shows the extent of the impact. The findings indicate that industries such as basic metals and fabricated metal, building, financial intermediation, retail trade, motor automobiles and bikes, repair of home items, and inland transportation have been responsible for the greatest economic loss. At the same time, sectors like water transport, air transport, leather, leather products, footwear, other communities, social, personal services, and real estate activities are the least affected. As seen in Table 4, the greatest economic loss for this scenario is ₹ 50,258.4325 (in millions) (605.52 million USD), whereas the least economic loss for this scenario is ₹ 41,600.4672 (in millions) (501.81million USD). Both of these values are shown in the respective tables. For clear understanding Fig. 4 will represent the economic loss in all 33 sectors at minimum and maximum value when perturbation in electrical & optical equipment. Through this graphical representation the sectors which are highly impacted are shown clearly.

This two-pronged strategy also considers the evaluation of five sectors according to their inoperability values, providing a comprehensive

Table 4
Inoperability and economic loss when perturbation in electrical and optical equipment.

Sector Code	Q_{min}	Q_{max}	Initial Output	E.L (Min)	E.L (Max)
C1	0.00033	0.00040	717,241	234.5452	283.3591826
C2	0.00338	0.00408	126,113	426.3812	515.1204031
C3	0.00036	0.00044	361,518	131.0292	158.2992604
C4	0.00091	0.00110	185,399	168.2454	203.2610813
C5	0.00053	0.00064	15,184	8.0291	9.70009949
C6	0.00284	0.00343	16,378	46.5004	56.17812867
C7	0.00244	0.00295	32,261	78.6454	95.0131938
C8	0.00155	0.00187	201,652	312.8576	377.9702576
C9	0.00303	0.00366	253,046	765.8506	925.240937
C10	0.00634	0.00766	88,836	563.3983	680.6537033
C11	0.00403	0.00486	105,731	425.7244	514.3269693
C12	0.01393	0.01682	429,213	5977.3404	7221.3585
C13	0.00723	0.00873	87,780	634.5186	766.5758054
C14	0.21527	0.26007	110,962	23,886.8119	28,858.17584
C15	0.00203	0.00245	172,115	348.9711	421.5996511
C16	0.00288	0.00348	59,440	171.1014	206.7113971
C17	0.00347	0.00419	205,122	711.6177	859.7208645
C18	0.00227	0.00275	712,505	1620.2684	1957.481374
C19	0.00468	0.00565	19,870	92.9166	112.2545119
C20	0.00472	0.00570	154,365	727.9921	879.5032319
C21	0.00469	0.00567	252,067	1182.9000	1429.087303
C22	0.00069	0.00084	88,233	61.1904	73.92543671
C23	0.00268	0.00323	323,167	865.2793	1045.362514
C24	0.00078	0.00094	6086	4.7378	5.723781364
C25	0.00086	0.00104	8477	7.3050	8.825362315
C26	0.00388	0.00469	43,890	170.2075	205.6313652
C27	0.00085	0.00103	128,346	109.0599	131.7576934
C28	0.00570	0.00689	230,688	1314.8941	1588.552402
C29	0.00010	0.00013	249,752	26.0343	31.45266797
C30	0.00058	0.00071	437,215	255.3439	308.4865308
C32	0.00052	0.00063	201,279	104.1830	125.8657568
C33	0.00141	0.00170	103,085	144.9476	175.1144067
C34	0.00039	0.00047	55,480	21.6393	26.14289724
	Total Economic loss (₹)			41,600.4672 (in millions)	50,258.4325 (in millions)
	Total Economic loss (USD)			501.81 (in millions)	605.52 (in millions)

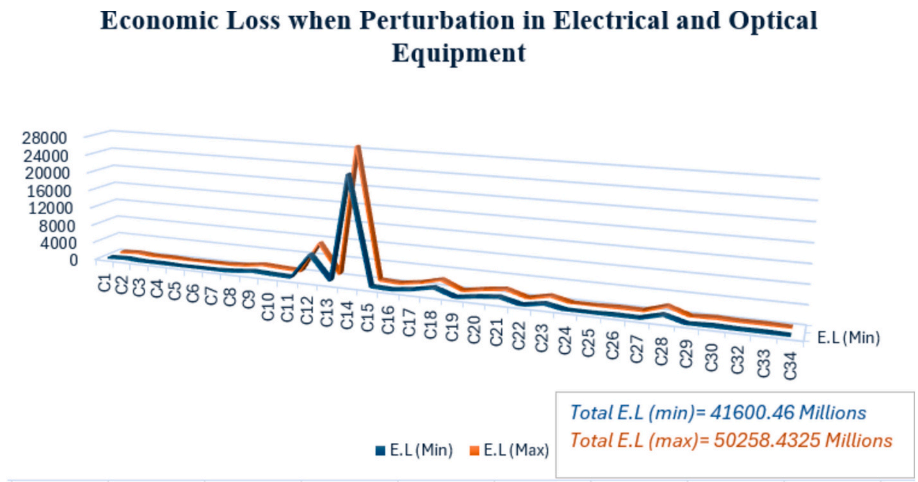

Fig. 4. Total Economic Loss when perturbation in electrical & optical equipment.

view of how susceptible different sectors are to interruptions in the Electronics and Photonics Sector field. The research highlights the significance of considering both inoperability values and economic losses when interpreting the wider impact on India, promoting a thorough comprehension of the intricate dynamics involved. The most impacted industries include basic metals and fabricated metal, machinery, nec (not elsewhere classified), rubber and plastics, financial intermediation, wholesale commerce, commission trade, and motor vehicles and motorbikes. Inoperability-wise, real estate activities, agriculture, hunting, forestry, fishing, food, drinks, tobacco, other communal, social, and personal services, and education are the least impacted. The interplay between these metrics provides a strategic vantage point for stakeholders, aiding in formulating targeted interventions and resilience-building strategies.

Disrupting the Electronics and Photonics Sector has far-reaching effects on various downstream businesses and interrelated sectors, in addition to causing immediate financial losses. Supply chain bottlenecks, production delays, and higher operational costs may be encountered by heavy consumers of products from the Electronics and Photonics Sector. Critical metrics like employment rates, export-import dynamics, and GDP growth overall may be impacted by this cascading effect, which can potentially cause a wider economic downturn. Given the interdependence of the many sectors, disruptions in one important economic node can have far-reaching impacts, making preventive steps necessary to lessen the negative effects and increase the Indian economy's overall resilience to systemic shocks.

4.2. Perturbation in all sectors

When all sectors receive systematic disruption, as in the second scenario, the analysis shows which sectors face the most severe economic difficulties and provides a comprehensive picture of the overall economic loss. The research provides an in-depth depiction of the industries most vulnerable to broad disruptions by identifying the top five sectors suffering the most economic losses. This information is crucial for tactical action. At the same time, the five sectors are arranged according to their inoperability levels, which highlights the significant ramifications for India and provides a more complex view of the overall economic dynamics.

One important measure of the overall effect on India's economy is the economic loss due to the disruption in all industries. As shown in Table 5 the determined total economic loss, which ranges from ₹ 1,906,180.10 (in millions) (22,968.44 million USD) to ₹ 2,300,453.25 (in millions) (27,712.69 million USD), highlights the extent of the Red Sea Crisis's effects on India. Fig. 5. graphically represents the results for inoperability and Economic Loss when Perturbation in all sectors. The report helps governments and businesses establish strategic strategies by providing a focused approach to risk management and emphasising the top five industries with the biggest economic losses. Expanding the perturbation analysis to encompass all sectors concurrently provides a holistic perspective on potential economic losses. Agriculture, hunting, forestry, fishing, building, basic metals and fabricated metal, rental

Table 5
Inoperability and economic loss when perturbation in all sectors.

Sector Code	Q_{min}	Q_{max}	Initial Output	E.L (Min)	E.L (Max)
C1	0.307816	0.37188	717,241	220,778.5	266,727.4
C2	0.453263	0.547596	126,113	57,162.29	69,059.01
C3	0.252189	0.304675	361,518	91,170.68	110,145.3
C4	0.276257	0.333753	185,399	51,217.85	61,877.4
C5	0.234761	0.28362	15,184	3564.611	4306.485
C6	0.430899	0.520578	16,378	7057.256	8526.025
C7	0.40672	0.491367	32,261	13,121.19	15,851.99
C8	0.333654	0.403095	201,652	67,282.08	81,284.95
C9	0.38664	0.467109	253,046	97,837.78	118,200
C10	0.36163	0.436893	88,836	32,125.76	38,811.84
C11	0.428557	0.517749	105,731	45,311.75	54,742.11
C12	0.38735	0.467966	429,213	166,255.7	200,857.1
C13	0.261827	0.316319	87,780	22,983.19	27,766.5
C14	0.271896	0.328484	110,962	30,170.16	36,449.22
C15	0.261502	0.315926	172,115	45,008.33	54,375.55
C16	0.294013	0.355204	59,440	17,476.16	21,113.32
C17	0.401461	0.485014	205,122	82,348.46	99,486.96
C18	0.252124	0.304596	712,505	179,639.3	217,026.1
C19	0.355873	0.429938	19,870	7071.195	8542.866
C20	0.358047	0.432564	154,365	55,269.88	66,772.76
C21	0.356884	0.43116	252,067	89,958.75	108,681.1
C22	0.269584	0.325691	88,233	23,786.21	28,736.65
C23	0.304102	0.367392	323,167	98,275.57	118,728.9
C24	0.22391	0.270511	6086	1362.717	1646.328
C25	0.284197	0.343345	8477	2409.137	2910.531
C26	0.361652	0.43692	43,890	15,872.91	19,176.4
C27	0.319589	0.386103	128,346	41,018.01	49,554.75
C28	0.361397	0.436612	230,688	83,370	100,721.1
C29	0.215653	0.260535	249,752	53,859.69	65,069.06
C30	0.265654	0.320943	437,215	116,148	140,320.9
C32	0.23957	0.28943	201,279	48,220.49	58,256.22
C33	0.2248	0.271586	103,085	23,173.54	27,996.45
C34	0.286103	0.301586	55,480	15,873.01	16,732
	Total Economic loss (₹)			1,906,180 (in millions)	2,300,453 (in millions)
	Total Economic loss (USD)			22,968.44 (in millions)	27,712.69 (in millions)

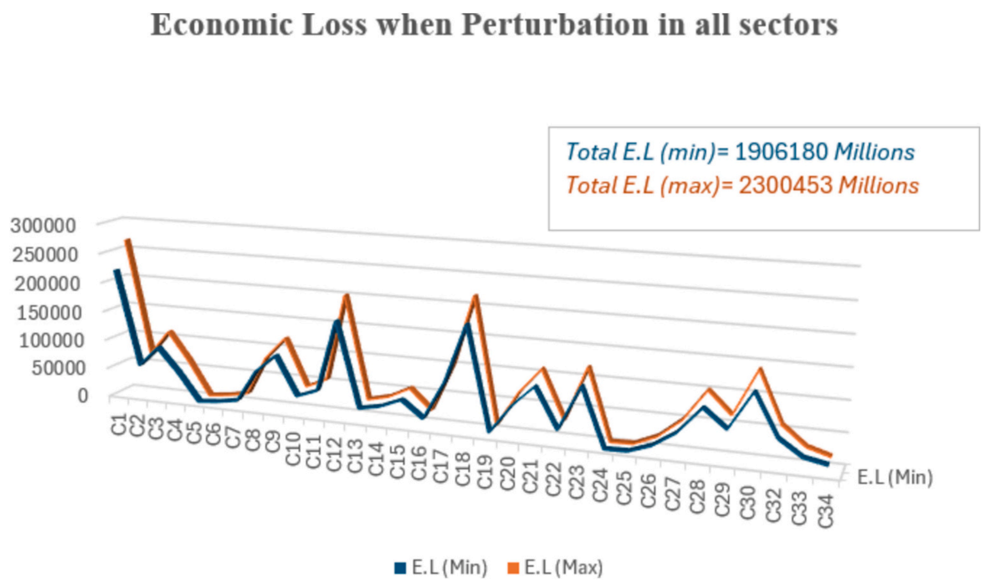

Fig. 5. Total Economic Loss when perturbation occur in all sectors.

M&Eq, other commercial operations, and inland transport are the top five impacted sectors. Water transport, Air transport, Leather, leather items, footwear, Wood and cork products, Sale, maintenance, and repair of motor vehicles and motorcycles, and Fuel retail sales are the least impacted. Strategic planning and action need this understanding, especially when prioritising the top five sectors with the largest economic losses.

The study's emphasis on inoperability values for all sectors further contributes to a robust understanding of vulnerabilities and aids in predicting and mitigating the cascading effects of disruptions. According to the inoperability values, the industries most impacted by the Red Sea Crisis include mining and quarrying; wood and wood products; other non-metallic minerals; pulp, paper, and paper products; printing and publishing; and electricity, gas, and water supplies. The least impacted industries are real estate, water transportation, social work and health, leather goods, footwear, and education. This dual-pronged approach shown in Table 6 allows for informed decision-making, ensuring targeted interventions and enhancing overall economic resilience in the face of complex challenges.

5. Implications of the study

5.1. Theoretical contributions

By employing an innovative analytical model, this research makes a significant contribution to our understanding of the economic effects of the Red Sea Crisis on India. This study represents the first comprehensive attempt, to the best of our knowledge, to examine the intricate interactions across multiple industries during a geopolitical disturbance of this magnitude. The study combines interval programming and input-output modelling (IIM) to produce a strong analytical framework, utilising data from the Asian Development Bank (ADB) Database. The theoretical contribution provides a comprehensive understanding of the ripple effects across the Indian economy. The salient feature of the methodology is the simultaneous assessment of economic losses and interoperability values, providing a sophisticated view of the

Table 6
Decision support conclusion.

	Sector Importance According to Economic Loss		Sector Importance According to Inoperability Value	
	Most Affected Sectors	Least Affected Sectors	Most Affected Sectors	Least Affected Sectors
Scenario 1: Electrical and optical equipment	Basic metals and fabricated metal	Water transport	Basic metals and fabricated metal	Real estate activities
	Construction	Air transport	Machinery, nec	Agriculture, hunting, forestry, and fishing
	Financial intermediation	Leather, leather products, and footwear	Rubber and plastics	Food, beverages, and tobacco
	Retail trade, except of motor vehicles and motorcycles; repair of household goods	Other community, social, and personal services	Financial intermediation	Other community, social, and personal services
	Inland transport	Real estate activities	Wholesale trade and commission trade, except of motor vehicles and motorcycles	Education
Scenario 2: All Sector	Agriculture, hunting, forestry, and fishing	Water transport	Mining and quarrying	Real estate activities
	Construction	Air transport	Wood and products of wood and cork	Water transport
	Basic metals and fabricated metal	Leather, leather products, and footwear	Other nonmetallic minerals	Health and social work
	Renting of M&Eq and other business activities	Wood and products of wood and cork	Pulp, paper, paper products, printing, and publishing	Leather, leather products, and footwear
	Inland transport	Sale, maintenance, and repair of motor vehicles and motorcycles; retail Sale of fuel	Electricity, gas, and water supply	Education

interrelationships across different industries. Policymakers and other interested parties may evaluate the significance and impact of the Red Sea Crisis with the help of this comprehensive methodology. Furthermore, the decision conclusion framework presents four scenarios that model distinct disruptions to further broaden the theoretical perspective. These hypothetical situations provide a dynamic vulnerability analysis and help policymakers develop focused risk management and resilience solutions.

5.2. Managerial implications

The perturbation analysis focused on these sectors provides crucial management insights for those making decisions in the Electronics and Photonics Sector. The findings suggest that strategic prioritization is essential for sectors highly susceptible to both economic loss and inoperability—particularly electrical and optical equipment, construction, and inland transport. Managers should enhance risk mitigation and resource allocation for these sectors, as they are critical to economic stability and are most affected in crisis scenarios. For resilient sectors, like basic metals and real estate, managers might consider allocating fewer contingency resources, allowing for a balanced risk approach. Additionally, understanding sector interdependencies can improve supply chain continuity during disruptions. For instance, for high-risk sectors like electrical and optical equipment, we will recommend enhanced inventory buffers and flexible sourcing strategies to mitigate economic loss. Similarly, for resilient sectors such as real estate, more streamlined resource management practices will be suggested. These focused recommendations will provide actionable guidance tailored to each sector's risk profile.

Taking into consideration both the short-term and the long-term effects, the findings of the research will be of assistance in risk management and strategic planning.

5.2.1. Short-term implications

- Strategic resource reallocation may be important for short-term decisions due to expected economic losses in the electronics and photonics sector. For financial stability, decision-makers may need to assess budgets, prioritize essential projects, and temporarily reallocate money.
- The research emphasises diversifying the supply chain to mitigate potential disruptions. Finding alternate sources may be a short-term option for components heavily dependent on the Electronics and Photonics Sector.
- Inventory management is crucial to prevent production delays and supply chain interruptions. Keep enough key components on hand to minimise unexpected downtime.

5.2.2. Long-term implications

- The Electronics and Photonics Sector may invest in technological innovation to be resilient to future problems. Supply chain digitisation, automation, and innovative manufacturing methods may enhance sector resilience and flexibility.
- Collaborative risk management initiatives including government agencies and supply chain actors are essential to ensure long-term survival.
- Sharing best practices and developing joint risk mitigation strategies may fortify the sector against future crises.
- Long-term strategies may involve market research and diversification to reduce dependency, reduce risk, and mitigate global economic shifts.
- To maintain long-term stability, it is crucial to anticipate and adapt to changing regulatory frameworks. Proactive compliance measures may help the Electronics and Photonics business navigate changing geopolitical circumstances and retain corporate continuity.

When these short-term and long-term plans for the Electronics and Photonics business are combined, a comprehensive approach to risk management and strategic planning is created. This sector-specific perspective offers practical answers to handle the difficulties brought up by the perturbation analysis, which assists decision-makers in maintaining flexibility and sustainability in the face of shocks from the outside world.

6. Conclusion

This research uses an analytical model to unravel the intricate dynamics of geopolitical disruptions. It is a pioneering effort to examine the influence of the Red Sea Crisis on the Indian economy. The research employs a comprehensive analysis integrating Leontief's Input-Output model with Interval Programming to examine sectors crucial to India's economic framework. The disruption scenarios applied to the electronics and photonics sector business and other industries provide a full understanding of the potential financial losses and risks. The study's results highlight the significant importance of the Electronics and Photonics business by exposing substantial financial losses and the extent of inoperability. In addition to the immediate financial impacts, downstream industries must also address issues such as production delays, supply chain interruptions, and increased operational costs. The sophisticated dual evaluation enhances the comprehension of the wider ramifications for India, which considers both economic losses and inoperability values. By concurrently extending the perturbation from Electronics and Photonics to another sector, the impact of the Red Sea Crisis is shown to a greater extent. Strategic interventions focus on agriculture, forestry, fishing, hunting, and construction sectors suffering from the greatest economic losses. These sectors also include renting machinery and other commercial operations, basic metals and manufactured metal, and inland transportation. Sectors with the greatest inoperability scores also highlight important areas vulnerable to disruptions, which is crucial information for focused risk management and strategic planning. Policymakers, stakeholders, and enterprises may benefit greatly from the study's comprehensive approach and findings. Policymakers may devise effective measures to alleviate economic hazards, promote adaptability, and effectively handle the obstacles that arise from geopolitical disputes by pinpointing the susceptible sectors. In an increasingly unpredictable world, this study not only advances the knowledge of the economic effects of the Red Sea Crisis but also paves the way for future investigations into the adaptability of states to complex shocks.

The mathematical models serve as an important tool for evaluating interdependencies among economic systems, although they possess certain limitations that researchers should acknowledge. The study makes the assumption that the interconnections between sectors and industries will remain constant throughout time. Additionally, it assumes that the items produced by a sector are uniform and can be easily substituted for one another. Furthermore, each sector is expected to have predetermined technical coefficients, which represent the input requirements per unit of output. In addition, the study has specifically chosen to include only 33 sectors for the study. Furthermore, the model has been developed using the data from 2022. For the purpose of this study, the analysis has focused solely on two criteria: Inoperability and Economic loss. Subsequent researchers have the option to incorporate other criteria in order to analyse the effects. Furthermore, it is possible to do multi-criteria analysis to establish the priority of the criterion, taking into account their respective weights, and identify the areas that are most significantly impacted.

CRediT authorship contribution statement

Bishal Dey Sarkar: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Laxmi Gupta:** Writing –

review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Sandeep Jagtap:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Funding acquisition, Formal analysis.

Data availability

Data will be made available on request.

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