



Resilience strategies to recover from the cascading ripple effect in a copper supply chain through project management

Vimal K.E.K¹ · Simon Peter Nadeem² · Mahadharsan Ravichandran³ · Manavalan Ethirajan³ · Jayakrishna Kandasamy³

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Abstract

As the supply chains are growing and becoming more interdependent, the vulnerability and the chances of supply chain failure also increases. The supply chain industry is severely affected due to the COVID-19 outbreak and industry practitioners are focusing on minimizing the ripple effect of the disruption made to the economy. Considering the unprecedented situation, the research is motivated to analyse the ripple effect in a multi-echelon supply chain and investigate the performance at various nodes to understand the capability of the supply chain to withstand the disruptions at different levels. Using discrete event simulation, this study analyses the ripple effect in the copper industry by an agent-based simulation software *anyLogistix*, considering various key performance indexes (KPIs) to gauge the magnitude. From the results of the simulation, it is evident that the lack of safety stocks and multi-sourcing of copper facilitate as major causes for the disruptions. The simulation helps to understand the disruption levels and make the supply chain more resilient and robust for any future disruption. Further, the study proposes resilient project management solutions to recover from the cascading ripple effect in the copper supply chain. The scientific contribution of the research is to provide supply chain managers with simulation techniques to understand the ripple effect on the copper supply chain. It helps the stakeholders to understand the importance of project management tools to reduce the cascading ripple effect in a copper supply chain. Further, the findings of this study will support contemporary managers, supply chain allies, project managers, and stakeholders to formulate strategies for recovering from the supply chain disruptions caused due to natural disasters, pandemics such as COVID-19.

Keywords Ripple effect · Multi-echelon copper supply chain · Discrete event simulation · Project management solutions · Resilience strategies · Supply chain disruption

✉ Jayakrishna Kandasamy
jayakrishna.k@vit.ac.in
Vimal K.E.K
vimalkek.engr@gmail.com
Simon Peter Nadeem
s.nadeem@derby.ac.uk
Mahadharsan Ravichandran
maha.dharsan1999@gmail.com
Manavalan Ethirajan
mailtomanav@gmail.com

- ¹ Department of Mechanical Engineering, National Institute of Technology Patna, Patna Bihar - 800005, India
- ² Centre for Supply Chain Improvement, University of Derby, Derby, UK
- ³ School of Mechanical Engineering, Vellore Institute of Technology, Tamil Nadu, Vellore 632 014, India

1 Introduction

In the current pandemic scenario, it can be observed that the immensely interdependent supply chains failed due to the disruptions caused leading to delay in delivery of end products to customers and loss of trust (Zhang and Huo 2013). One of the industries worst affected due to this interdependency is the copper industry, where the entire supply chain is connected, from sourcing the raw material to the delivery of end products (Kinra et al. 2020). In the present global and turbulent environment, as the supply chain of an industry expands, it becomes more vulnerable to various disruptions, incurring huge losses to the companies (Craighead et al. 2007). The impact of these disruptions on the supply chain performance and structural design is described as the ripple effect. *The Ripple effect in the supply chain results from disruption propagation of an initial disruption towards*

other supply chain stages in the supply, production, and distribution networks (Ivanov et al. 2014a, b). For example, a severe drought in Brazil will result in an increase in coffee prices in the world as Brazil is the largest coffee producer in the world. Any disruption to the supply of coffee beans affects the customer demand and scarcity in supply leads to an increase in the coffee price. The event 'severe draught' leads to an 'increase in price'. This phenomenon is called the 'ripple effect'.

The ripple effect has affected various industries due to improper balance between minimalism and complexity (Ivanov et al. 2017; Jüttner and Maklan 2011). Matsuo (2015) focused on how the supply disruption of automotive microcontroller units caused due to earthquakes had impacted the supply chain of Toyota. Hosseini et al. (2019) highlighted various disruptions caused by natural catastrophes in the automobile companies due to the impact on one node of the supply chain that rippled and propagated to the other nodes. Blackhurst et al. (2005, 2011) and Ivanov et al. (2014a, b, 2016a, b) investigated the reason for disruptions and divulged basic reasons for disruptions and their influence on supply chain implementation and performance.

Discrete event simulation studies by Schmitt and Singh (2012), Pettit et al. (2013), Raj et al. (2014) Ivanov (2017a, b, c, 2018, 2019, 2020a), and Hosseini et al. (2019) examined the resiliency of supply chains at various disruption levels. Generally, they focused on evaluating the disruption in the supply chain at the macro level with the help of KPI's and emphasis the need for adapting different recovery policies like backup suppliers, dual sourcing, or large inventory holdings to mitigate the supply chain disruption. Huang et al. (2020a, b) studied the impact of copper due to the boom of the electric vehicle, which emphasises the importance of performing ripple effect analysis on the copper industry. There are not many studies using discrete-event simulation on copper industries taking into account every node in the supply chain. Performing such simulations will enable industrialists to take better decisions resulting in a strong supply chain.

Some of the challenges faced in the supply chain are lack of communication, poor change control and improper execution process. Considering the ripple effect in the supply chain, it is essential to improve the communication, change control and execution process. Communication between two parties in the supply chain is one of the challenging areas. Project managers, subcontractors, regulatory groups, and the internal workforce need to stay connected for the project to go as planned. When something does not go as planned, effective communication can reduce the impact. The copper supply chain is a dynamic environment where the change in requirements is frequent by the customers, and it is imperative to manage the expectation of the customer through a proper change control process. Strategic

planning is key for effective execution. Items not being on time can affect project performance and communication with vendors is key in knowing in time to plan contingencies. Essentially, to tackle the challenges mentioned in the supply chain, an effective project management process is required. Project management involves the planning and organization of resources to move a specific task, event, or duty towards completion based on the defined scope. It can involve a one-time project or an ongoing activity, and resources managed include personnel, finances, technology, and intellectual property (Jain 2021). Project management keeps everything moving smoothly on time and on budget. The recent pandemic situation continues to test the flexibility, agility, leanness with dynamic caveats arising from different levels of disruptions in any supply chain. Project management offers distinct systematized plans, roles, goals, communication channels to increase the efficiency of the systems (Picciotto 2020). Project management solutions can assist by offering solutions to recover from the ripple effect in any supply chain. This research contributes to the supply chain through project management literature by analysing the disruptions levels on the important KPIs and adoption of project management techniques in copper SCs.

In this aspect, the study aims to answer the following research questions (RQs).

RQ1. What are the important KPIs to be assessed to understand the disruption on the copper supply chain?

RQ2. How the KPIs are affected due to the disruption and how project management solutions can aid in recovering from the cascading ripple effect in a copper supply chain?

Therefore, the study aims to address these research questions with the following research objectives (ROs).

RO1. Observing the ripple effect on the supply chain of a copper industry at the micro-level at various disruption levels, quantitatively and identifying bottlenecks in the supply chain.

RO2. Analyse the disruption on the supply chain of various KPIs and propose resilient project management solutions to recover from the cascading ripple effect in the copper supply chain.

The study focuses on examining the supply chain at the micro-level, taking into account every node of the supply chain at different disruption scenarios. By evaluating it at the network level, one can identify the bottlenecks, and various recovery policies can be adapted accordingly. The novelty of this study is that the ripple effect is observed across the copper supply chain considering all nodes by combining analytical optimization approaches and innovative dynamic simulation technologies.

The rest of the study is organized as follows. Section 2 analyses the recent literature on the ripple effect in the supply chain. The ripple effect can be analysed by various tools such as optimization, simulation, etc. The study uses the simulation method to analyze the effect. Section 3 briefs about the simulation and methodology to be used for analysing the ripple effect. The case study to be used for the analysis is formulated in Sect. 4 and also deals with various performing parameters to be considered during the simulation and the assumptions to be made while carrying out the analysis. The simulation of the case study is done in anyLogistix package. The results and output of the same are presented in Sect. 5. Once the comparison is made of different parameters before and after disruption, the performance of the supply chain can be known at various nodes and hence it reveals the potential of each network to withstand the different magnitude of disruptions, thus helping to make resilient changes in the supply chain and making the supply chain stronger for future operations using project management solutions. Section 7 presents the conclusion of this study done and its implications on the copper supply chains in the future.

2 Literature

Various causes of disruptions in the supply chain have been examined in the past few years by researchers. Chaudhuri et al. (2016) studied the impact of performance in the food processing supply chain under risk propagation and found out three categories of risk drivers that the manufacturers need to pay attention to minimize the risks. Deng et al. (2019) studied risk propagation mechanisms in the perishable products supply chain and suggested feasible countermeasures to improve sustainability. Garvey and Carnovale (2020) analysed inventory control under the ripple effect and proposed a new version of the previously available model with its primary focus on supply chain severity. Several studies including Hendricks and Singhal (2005), Craighead et al. (2007), Qi (2013), and Li and Zobel (2020) revealed basic reasons for the increase in disruption impact on the supply chain. Dolgui et al. (2018) reviewed over 70 papers and observed the causes and mitigation strategies for the ripple effect in the supply chain. A study by Dolgui et al. (2018) revealed that disruption in structural dynamics can also be a driver for the bullwhip – effect. Li et al. (2020) investigated how network characteristics and supply chain resilience are related. Chopra and Sodhi (2004) categorised potential supply chain risks into various categories. These potential risks pose a serious threat to the whole supply chain and can be considered as a reason for the ripple effect. COVID – 19 out-break is one of the major disruptions in recent years and an evident

example of the ripple effect in the supply chain. It gives away how susceptible to disruption in the supply chain. Recent studies like Ivanov (2020c), Queiroz et al. (2020), Golan et al. (2020), and Ivanov and Dolgui (2020) discusses how the supply chain is affected during the pandemic and suggested suitable methods that help to overcome the difficulties present in the current supply chain. Thus, reactions to these disruptions should be performed and various recovery measures should be adapted so that the mitigation of disruption takes place in the supply chain (Simchi-Levi et al. 2015; Paul et al. 2017; DuHadway et al. 2019; Ivanov et al. 2019; Pavlov et al. 2019).

Two approaches have been developed, proactive, and reactive to minimise the impact of disruption on the supply chain. The proactive approaches take into account all possible disturbances and deviations while formulating the policy so that it is least impacted in case of disruption. Studies by Peng et al. (2011), Liberatore et al. (2012), Sawik (2016), Mizgier (2017), and Özçelik et al. (2020a, b) examined various proactive strategies to make the supply chains more robust and resilient. The reactive approaches aim at modifying the process and the supply chain structure in case of sudden disruption. Studies by Ivanov et al. (2016a), Ivanov et al. (2016b) belong to the recommendable references on a reactive approach. Recovery policies may also include different elements such as re-routing, transportation reconfiguration, backup suppliers, inventory re-placements (Ivanov et al. 2015). Unnikrishnan and Figliozzi (2011) configured a scenario-based model with an adaptive routing policy. Carvalho et al. (2012) analysed the effects of transportation disruption on lead-time and overall costs in an automotive supply chain. A study by Hosseini et al. (2019) reviewed the literature on quantitative modelling of supply chain resilience, which introduces a structured analysis as to which quantitative methods can be used at different levels of resilience capacity, thereby helping to make the supply chain more vigorous and resistant to disruption. Simchi-Levi et al. (2014) stated the importance of recovery policies in case of disruption. Ivanov and Sokolov (2013) stated that adaptation is the prerequisite of a stable and robust supply chain. But before adopting any policy, the supply chain needs to be thoroughly examined to reform, and structure the operational parameters (Petersen et al. 2005; Li et al. 2017). Though there are various methodologies to evaluate the supply chain, the simulation approaches empower the users for modelling the supply chain with a great level of detail, to study the dynamic disruption, and to observe how a change in design, policies affect the supply chain. Simulation is also considered a validated approach in the modelling of the supply chain (Tako and Robinson 2012; Meisel and Bierwirth, 2014; Oliveira et al. 2016). Schmitt and Singh (2012) performed the discrete-event simulation

and presented the quantitative estimation of the disruption risk at production and supply capacity in a multi-echelon supply chain. Xu et al. (2014) studied the disruption at suppliers and recovery policies of the supply chain service level with the help of anyLogic software.

Ivanov (2017a) considered a four-echelon supply chain comprising of a manufacturer, a central distribution centre, two regional distribution centres, and ten customers in different European cities. The discrete-event simulation was performed using anyLogistix software to analyse the ripple effect in the supply chain. The results suggest that the ripple effect enhances the performance impact of disruptions. In the case of single-source policy, disruption at the upstream facility is more likely to result in a ripple effect. A safety stock increase is recommended at the facilities downstream of disruption-risky supply chain elements. Higher inventory levels in the downstream supply chain dampen ripple effect propagation towards the customers. It has also been observed that the ripple effect has a greater impact on service level and order fulfilment than disruption duration. This implies that dual sourcing at supply chain bottlenecks and large inventory holding points at disruption-risky downstream facilities is much better than hasty investments in quick recovery.

The aforementioned studies performed discrete event simulation on disruption in the supply chain at a macro level taking into account various Key Performance Indicators (KPI's) and focused on adapting different recovery policies which lack the in-depth analysis (examination at the micro-level) of the supply chain at each node and studies related to the supply chain of the copper industry is meagre. To overcome the limitation of current research, this study aims at evaluating the ripple effect at each node of the supply chain focusing on the micro-level with the help of anyLogistix software. Various key performing indicators such as service level, available inventory, fulfilments received (orders received on time), products produced, etc. at each node are simulated against different disruption scenarios that reveal the capacity and capability of each network to withstand the real disruptions of the same magnitude. Performing the simulation on the copper industry which plays a key role in the global economy provides an intimate understanding of its supply chain and helps us prevent mishaps happening soon. Also, the study focuses more on analysing the financial performance for different disruption scenarios to understand how a disruption at an upstream facility propagates and impacts the performance of the whole supply chain and how the performance deteriorates with an increase in disruption. This study also aims to analyse the qualitative effects of economic and social factors on the supply chain and identifying the bottlenecks of the supply chain. It also recommends project management recovery solutions that can be adapted to make them more resilient and robust.

3 Methodology

The ripple effect analysis in a supply chain can be carried out by optimisation as well as by simulation (Dolgui et al. 2018; Özçelik et al. 2020a, b). While analysis of ripple effect via optimisation (Sawik 2016; Levner and Ptuskin 2018) has been governing, the potential of simulation remains unexplored. A simulation is an effective approach for analysing the supply chain (Meisel and Bierwirth 2014; Macdonald et al. 2018). Moreover, the simulation study also offers salient features such as risk analysis, time-dependent disruption duration, duration of the recovery period, number of replications, etc., which has helped to recognise it as one of the most reliable analysis methods in this domain (Ivanov 2020b).

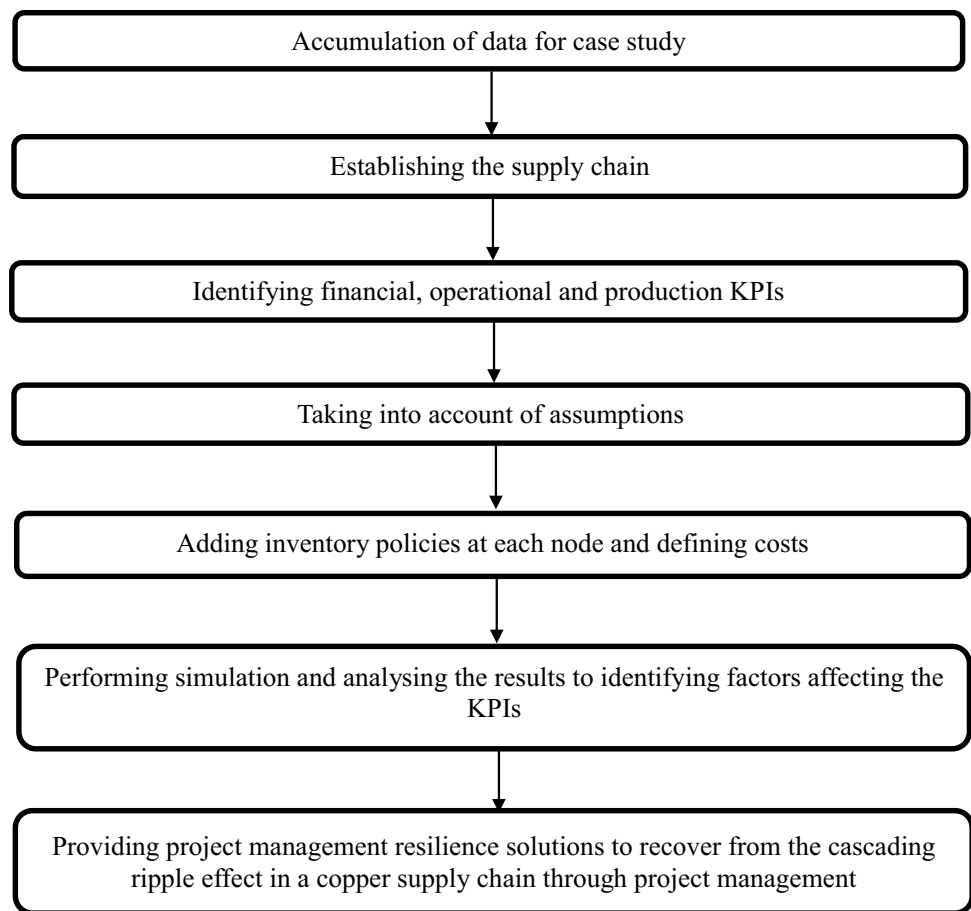
Though there are many methodologies to simulate and analyse the ripple effect, discrete-event simulation can be applied for analysing the ripple effect in a multi-echelon supply chain (Carvalho et al. 2012; Schmitt et al. 2017; Ivanov 2017a). The discrete event simulation can be used to define the sequence of events occurring one after the other. The supply and transportation disruption can be considered while analysing the ripple effect (Hishamuddin et al. 2015). Discrete-event simulation is considered best for resilience analysis concerning severe supply chain disruptions (Dolgui et al. 2018).

The discrete event simulation can be best applied for analysing the disruption propagation in the multi-echelon supply chain as this method is based on one event occurring after the other, all the networks and nodes of the supply chain can be taken into account while analysing the ripple effect. The methodology adopted in the conduct of this study is shown in Fig. 1. The aggregated data is established as a simulation model using the anyLogistix software. Key parameters are identified, and suitable assumptions were made followed by establishing inventory policies at each node and the results are analysed by performing the simulation.

4 Case study

The study reported was conducted to study the ripple effect of a supply chain network of a copper smelting unit, which is located in Tamil Nadu, India. The smelting unit receives its copper ore (chalcopyrite) from Tanzania located in the African continent. The ore is processed into copper metal by the process of smelting. Copper smelting unit further supplies the metal to three major engineering industries namely electrical, transportation, and construction. The quantity of copper used in every industry is taken in tons irrespective of the shape and size of the metal. These factories then further convert copper metal for industrial use and distribute it to various distribution centres located across the globe,

Fig. 1 Flowchart representing the case study



from where the customer fulfilment is met by the various retailers who take the finished goods from the distribution centres. The supply chain consists of the people, organisation, resources responsible for the product flow from the supplier to the end consumer. Any disruption in the chain would impact the performance of the supply chain which leads to poor consumer experience. This disruption propagation in the supply chain is termed the ripple effect. In this study, the supply chain of the copper industry was considered.

The raw material (copper ore), is imported from Tanzania, Africa. It is transported via sea route to the copper smelting unit in India. Many agencies are working at the port who are responsible for loading and unloading the copper ore at the port. Also, the copper ore has to be transported from the port to the smelting unit. It implies the workforce which is involved indirectly with the supply chain of the smelting unit. The smelting unit also has substantial manpower working in the factory, involved directly with the supply chain. Disruption in the smelting unit has impacted the whole network linked directly or indirectly to the smelting unit. Ultimately, the raw material being imported would

decrease exponentially. There would be sudden unemployment in the unit if the company is not able to sustain the disruption. Also, the indirect labours such as the shipping agencies at the port, contract workers, and the logistics company would suffer from the disruption. In short, the local economy surrounding the smelting unit would be devastated.

Due to the current disruption, there is a loss of jobs of workers working in factories due to less profit and overall sales. Now, this outcome will occur at various other levels of the supply chain as a similar decreasing trend of profit to the level of disruption can be seen in all the other levels of the supply chain. Copper is a widely used metal for industrial purposes hence disruption in the supply chain of copper disrupts various other parameters of the economy. It can be inferred that due to disruption in the supply chain of copper, the ripple effect is observed on the G.D.P. of the country. The end product of the smelting unit is refined copper which is exported to different core industries (such as electrical, transportation, construction, etc.) for conversion to end products such as copper cables, automobile parts, or gas pipelines. Any disruption at the smelting unit would have a ripple effect on these core industries as well as on the

logistics companies which are transporting refined copper to the respective industries.

Various core industries are dependent on refined copper to make their product. These industries are price sensitive, depending upon the supply of refined copper. Any disruption in supply would create a situation of low supply and high demand and would ultimately drive up the price of refined copper, and hence the cost of the final product will go up. In this paper, the ripple effect on the entire supply chain of the copper industry caused due to the sudden disruption caused on the smelting unit is observed along with the observation of various effects on all the other nodes in the supply chain. Even though this research field is dominated by stochastic and mathematical optimization techniques, simulation studies play an important role in ripple effect modelling. The simulation also helps in handling complex problems which are time-dependent and based on huge data set. The simulation and modelling of the above case would be performed on anyLogistix version 2.9.1 an agent-based modelling software. All the nodes are loaded and a map is generated in the software. This work also considers the effect that it will cause to the economy, environment, and sociology of the geographical limitations surrounding the smelting unit. This case study includes both quantitative and qualitative analyses of the problem specific to the parameters.

Figure 2 shows the supply chain of the given problem with all of the steps in the supply chain. The supply chain starts

from the copper supplier located in Tanzania and then shipped to a smelting unit which is located in India. The smelting unit extracts copper from its ore then transports the copper to various manufacturers located in Japan (Mechanical), India (Gas), and Taiwan (wire) that use copper. The finished goods are then transported to the distribution centre which delivers the product to the end customer (in this case retailers).

Figure 3 shows the actual location of all the levels in the supply chain on the world map. Figure 4 shows the different points on the supply chain located near the Indian sub-continent.

From Figs. 3 and 4, it can be seen how spread-out the supply chain is from sourcing to end retailers in countries such as Korea, China, India, Oman, Indonesia, Saudi Arabia, Malaysia, the USA, and Japan. Table 1 shows the various analysis parameters, their description, and the inference for analysing the ripple effect described in this study. The KPIs chosen are based on the available data, to analyze the supply chain at the micro-level. Financial performance helps to measure how the ripple effect affects industrial economics which involves transportation, efficiency, effectiveness on factory working conditions, and other crucial factors that measure the health of the industry. Operational parameters indicate how the inventory changes to variation in the supply of copper which helps to assess the ripple effect path. Products and Sourcing is a crucial factor that depicts the magnitude of the ripple effect since it gives insights on to what degree the end customer is content.

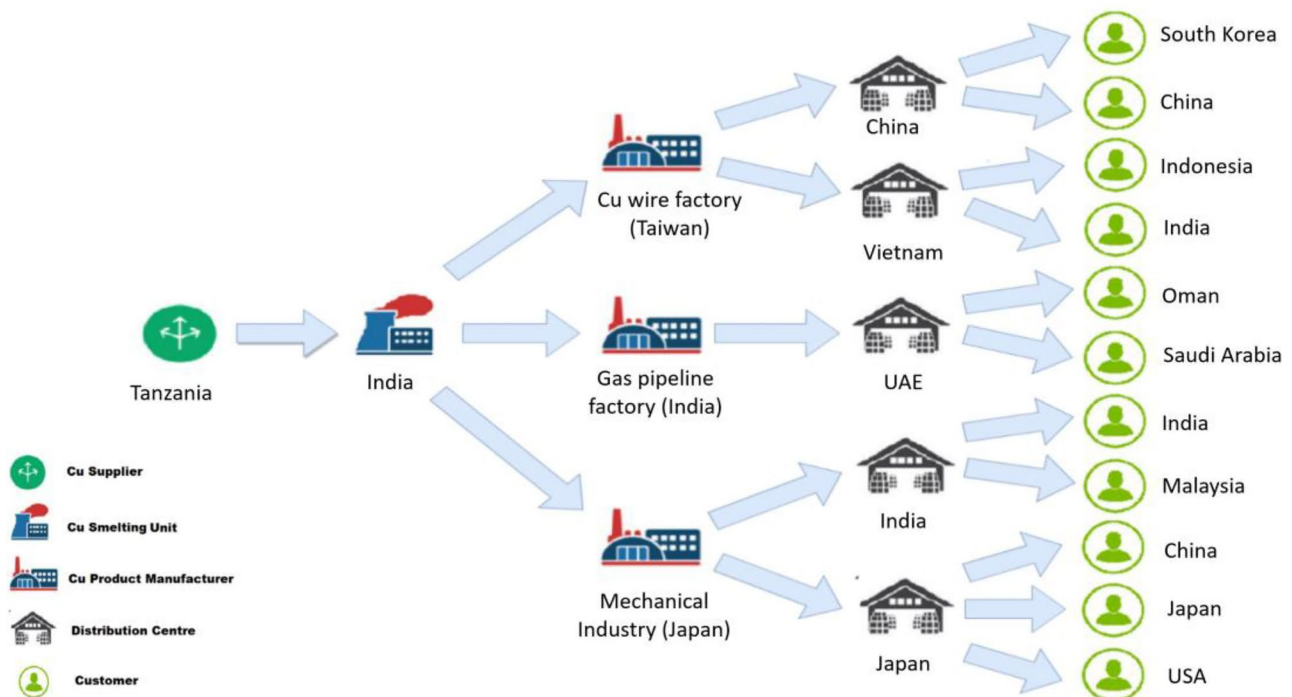
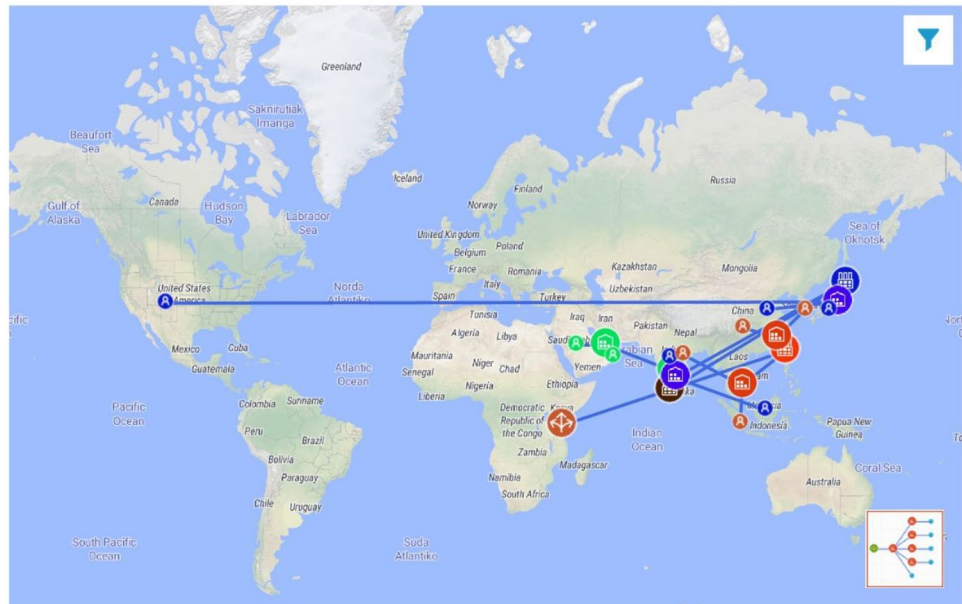


Fig. 2 The supply chain of copper from its ore to the customers

Fig. 3 The supply chain on world map plotted in anyLogistix



4.1 Assumptions and key input data

For making the simulation of the case study feasible few assumptions were made based on the software parameters.

- All the paths connecting the various locations in the case study are considered on a point-to-point basis. The shortest path between the two points is chosen irrespective of the actual path.
- The price of raw material and finished copper (per tonne) remains constant irrespective of the market supply and demand factors.
- Prices of the copper used in end products are considered not the total cost of the product.
- One year is considered for the simulation.
- Less-than-truckload (LTL) condition is considered for the transportation of goods.
- The peak capacity of ship transports is considered 9,000 tonnes with an average speed of 35 km/hr.
- The peak capacity of the truck is considered 20 tonnes with an average speed of 40 km/hr.
- The recovery period is considered one month for all disruption levels.
- Custom duty is neglected in the calculations.

Fig. 4 The supply chain Zoom View over Indian sub-continent

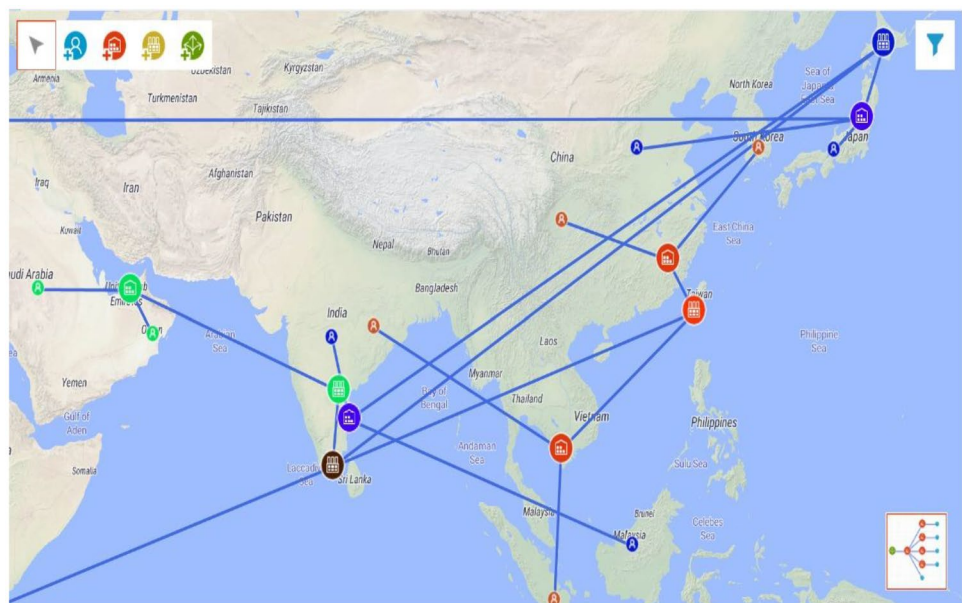


Table 1 KPIs taken into consideration

Criterion	KPIs	Definition	Inference	Reference
Financial	Profit	Profit is a financial benefit that is realized when the amount of revenue gained from a business activity exceeds the expenses, costs, and taxes needed to sustain the activity	It is the measure of efficiency and effectiveness of the working environment	Tseng et al. (2018)
	Production cost	Production costs refer to the costs incurred by a business when manufacturing a good or providing a service	A measure of the production health of the industry	Ha et al. (2017)
	Transportation Cost	The expenses involved in moving products or assets to a different place	Gauges the performance of the transportation and logistics industry under different scenarios	Gurtu et al. (2015)
	Total Cost	Sum of all the direct cost and indirect cost incurred	Used for assessment of ripple effect on the supply chain	Sarkar and Chung (2020)
Operation	Available Inventory	Available inventory is goods held in stock by a company that is available for immediate sale and delivery to customers	Helps in the assessment of tracing the path of the ripple effect	Tao et al. (2019)
Production and Sourcing	Fulfilment Received	Shows statistics on the number of product items delivered within the specific Expected Lead Time	It helps us in determining the degree/amount by which the disruption caused the ripple effect	Turban et al. (2018)

- Inventory holding cost is considered \$1/tonne/day wherever required

4.2 Inputs considered and collected

The inventory policies at each node of the supply chain taking into account two ordering policies order on demand and min–max are indicated in Table 2. The presence of two rows

of the same facility is to indicate the initial arrival station where the products are received and then transported to the facility using locally available transportation. Each manufacturing and smelting unit is defined for minimum, maximum, and initial inventory. The cost value, as well as the selling value of all the copper products tabulated in Table 3, were taken close to their actual international value. The approximation is done for ease of calculation. (Source: <http://www.infomine.com/investment/metal-prices/copper/>).

Table 2 Inventory policies considered at various nodes of the copper supply chain

S.no	Facility	Initial product	Finished product	Ordering policy	Min inventory (tonnes)	Max inventory (tonnes)	Initial inventory (tonnes)
1	Cu Smelting	Cu (ore)	NA	Order on Demand	NA	NA	4,500
2	Cu Smelting	NA	Cu(refined)	Min–Max	0	9,000	4,500
3	Electrical and Electronic Industry	Cu(refined)	NA	Min–Max	2,000	5,000	2,500
4	Electrical and Electronic Industry	NA	Cu Wire	Min–Max	0	5,000	2,500
5	Electrical Industry DC-1	Cu Wire	Cu Wire	Order on Demand	NA	NA	1,500
6	Electrical Industry DC-2	Cu Wire	Cu Wire	Order on Demand	NA	NA	1,000
7	Transportation Industry	Cu(refined)	NA	Min–Max	1,000	3,000	1,500
8	Transportation Industry	NA	Cu (Alloys)	Min–Max	0	3,000	1,500
9	Transportation Industry DC-1	Cu Alloy	Cu Alloy	Order on Demand	NA	NA	450
10	Transportation Industry DC-2	Cu Alloy	Cu Alloy	Order on Demand	NA	NA	1,550
11	Construction Industry	Cu (refined)	NA	Min–Max	400	1000	500
12	Construction Industry	NA	Cu Pipes	Min–Max	0	1000	500
13	Construction DC-1	Cu Pipes	Cu Pipes	Order on Demand	NA	NA	500

Table 3 Selling price and cost prices of various copper products

Name	Selling price (USD/Tonne)	Cost price (USD/Tonne)
Cu wire	10,500	7,300
Cu Alloys	10,700	7,600
Pipes	10,200	7,200
Cu Ore	500	400
Cu (Refined)	6,500	3,600

5 Simulation study setup and analysis

This section discloses the numerical values of each parameter and node at various disruption levels. The setup is done and the inventory policies at each node along with selling prices of each manufactured copper product are given as input into the anyLogistix for simulation. Table 4 shows the ripple effect on the KPIs chosen. Table 4 gives us the results of various parameters considered in this study as simulated by the anyLogistix software. In Table 4, the ripple effect and its severity on various performance indicators concerning the various disruption levels can be witnessed. Financial performance indicates the loss in sales and revenue suffered by various components of the supply chain. Operational performance helps to understand the supply of the product in the market and its disruption caused by the ripple effect due

to disruption on the smelting unit. Production and sourcing parameters give an insight into the movement of products further up the supply chain and how is that movement of products affected by the ripple effect. It is observed that the inventory size of the copper wire increases along with disruption rather than decreasing. This is because the available inventory is the sum of the leftover product and the products produced. The demand goes down due to disruption and hence the inventory increases as the disruption increases. It is also observed that the fulfilments received for the copper pipe are not affected by the disruption. This is because the fulfilment received is the sum of the new products produced during the disruption as well as the leftover stocks. As the demand during the disruption goes down, the inventory would relatively be greater during higher disruptions. So, even if the products produced decrease as the disruption goes higher, it is compensated by the increase in inventory which keeps the constant value of the received Shipments, even during the higher disruptions.

Table 5 shows the various financial parameters consisting of production cost, inventory cost, total cost, and transportation cost at each node of the supply chain to the chosen disruption levels, revealing intricate details on the entire supply chain. Table 5 gives a proper look over the ripple effect on various components of the supply chain like transportation, production, and inventory for different disruption levels. It is observed that copper produced in the smelting unit increased

Table 4 Results of various parameters through simulation

Category	Division	Sub-Division	0%	25%	50%	75%	100%
Financial Performance (\$)	Inventory carrying cost		26,62,108	25,97,245	24,67,519	24,02,656	23,37,793
	Production cost		99,78,27,988	97,62,73,813	93,31,65,463	91,16,11,288	89,00,57,113
	Profit		8,14,82,718	7,94,88,066	7,54,98,761	7,35,04,108	7,18,09,465
	Revenue		1,12,15,50,000	1,10,14,53,000	1,06,12,59,000	1,04,11,62,000	1,02,10,65,000
	Total cost		1,04,00,67,281	99,87,45,642	98,57,60,238	96,76,57,891	94,95,55,543
	Transportation cost		14,17,184	13,93,874	13,47,255	13,23,946	13,00,636
Operational Performance (Tonne)	Available inventory	Copper Ore	0	0	0	0	0
		Copper refine	3,730	3,149	1,987	1,406	825
		Copper Wire	826	848	893	915	937
		Copper Alloy	871	767	560	465	352
		Pipe	1000	900	700	600	500
	Peak capacity		4,75,770	4,37,970	3,62,370	3,24,570	2,86,770
Production and Sourcing (Tonne)	Products produced	Copper refine	99,730	97,419	92,797	90,486	88,175
		Copper Wire	55,826	54,148	50,793	49,152	47,437
		Copper Alloy	32,321	32,007	31,380	31,066	30,752
		Pipe	12,000	11,900	11,700	11,600	11,500
	Fulfilment received (Product on Time)	Copper Wire	59,250	54,100	43,800	38,650	33,500
		Copper Alloy	27,150	24,440	19,620	17,110	14,600
		Pipe	12,000	12,000	12,000	12,000	12,000

Table 5 Value of financial parameters at each node of the supply chain to disruption

Parameter	Object	Disruption Level				
		0%	25%	50%	75%	100%
Production Cost (In USD)	Construction parts manufactured in India	81,60,00,000	80,92,00,000	79,56,00,000	78,88,00,000	78,20,00,000
	Copper produced in Smelting Unit	2,99,19,24,242	2,92,25,90,909	2,78,39,24,243	2,71,45,90,910	2,64,52,57,577
	Electrical and Electronic factory Taiwan	3,90,78,47,222	3,79,04,02,778	3,55,55,13,891	34,83,80,69,447	3,32,06,25,003
	Transportation Equipment Industry Japan	2,262.508,417	2,24,05,44,444	2,19,66,16,498	2,17,46,52,525	2,15,26,88,552
Inventory Carrying Cost (In USD)	Constriction Pipe DC—UAE	75,000	75,000	75,000	75,000	75,000
	Construction parts manufactured in India	42,69,481	42,51,136	42,14,445	41,96,100	41,77,754
	Cu produced in Smelting Unit	75,33,654	78,67,714	85,35,832	88,69,892	92,03,951
	Electrical and Electronic DC- China	2,25,000	2,25,000	2,25,000	2,25,000	2,25,000
	Electrical and Electronic DC-Vietnam	1,50,000	1,50,000	1,50,000	1,50,000	1,50,000
	Electrical and Electronic factory Taiwan	91,69,063	83,57,610	67,34,703	59,23,249	51,11,796
	Transportation Industry DC- India	67,500	67,500	67,500	67,500	67,500
	Transportation Industry DC- Japan	3,08,465	3,08,465	3,08,465	3,08,465	3,08,465
	Transportation Equipment Industry Japan	48,22,922	46,70,032	43,64,251	42,11,360	40,58,470
Total Cost (in USD)	Constriction Pipe DC – UAE	1,77,897	1,77,897	1,77,897	1,77,897	1,77,897
	Construction parts manufactured in India	82,05,82,167	81,37,63,821	80,01,27,131	79,33,08,785	78,64,90,440
	Copper produced in Smelting Unit	3,38,63,07,979	3,35,26,06,681	3,28,52,04,083	3,25,15,02,784	3,21,78,01,486
	Electrical and Electronic DC- China	6,96,025	6,76,399	6,37,147	6,17,521	5,97,895
	Electrical and Electronic DC-Vietnam	7,16,303	7,11,583	7,02,145	6,97,426	6,92,707
	Electrical and Electronic factory Taiwan	3,91,77,09,109	3,79,94,40,230	3,56,29,02,470	3,44,46,33,591	3,32,63,64,711
	Transportation Industry DC- India	2,58,519	2,58,519	2,58,519	2,58,519	2,58,519
	Transportation Industry DC- Japan	12,63,818	12,55,511	12,38,896	12,30,588	12,22,281
	Copper ore Tanzania	47,86,565	47,02,426	45,34,149	44,50,010	43,65,871
Transportation Cost (in USD)	Transportation Equipment Industry Japan	2,26,81,74,428	2,24,60,56,268	2,20,18,19,946	2,17,97,01,785	2,15,75,83,625
	Constriction Pipe DC—UAE	1,02,897	1,02,897	1,02,897	1,02,897	1,02,897
	Construction parts manufactured in India	3,12,685	3,12,685	3,12,685	3,12,685	3,12,685
	Cu produced in Smelting Unit	52,50,082	51,48,057	49,44,007	48,41,982	47,39,957
	Electrical and Electronic DC- China	4,71,025	4,51,399	4,12,147	3,92,521	3,72,895
	Electrical and Electronic DC-Vietnam	5,66,302	5,61,583	5,52,145	5,47,426	5,42,707
	Electrical and Electronic Factory Taiwan	6,92,823	6,79,841	6,53,876	6,40,894	6,27,912
	Transportation Industry DC- India	1,91,019	1,91,019	1,91,019	1,91,019	1,91,019
	Transportation Industry DC- Japan	8,55,353	9,47,045	9,30,431	9,22,123	9,13,816
	Copper ore Tanzania	47,86,565	47,02,426	45,34,149	44,50,010	43,65,871
	Transportation Equipment Industry Japan	8,43,088	8,41,791	8,39,197	8,37,900	8,36,602

ELT SERVICE LEVEL BY PRODUCT(GRAPH)

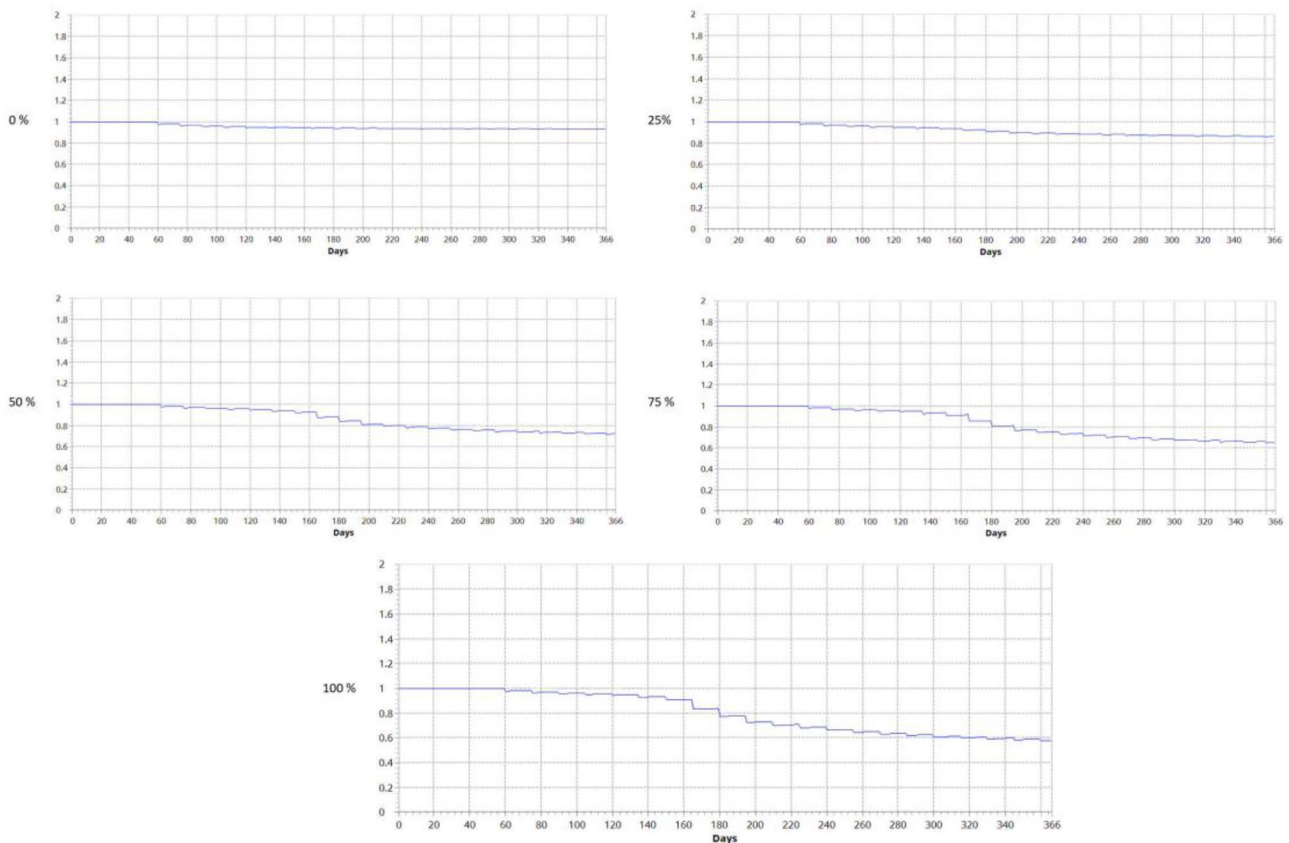


Fig. 5 ELT service level by product at 0%, 25%, 50%, 75%, 100% disruption levels with ration values ranging from 0 to 2

with disruption as opposed to contrary. It is because it is inclusive of the leftover stock and the new ones produced. As the demand goes down due to disruption, the inventory at the smelting unit increases. From Table 5 the impact of the disruption experienced first-hand by the customer, factory, and distribution centres can be inferred. Table 4 and Table 5 presents the various parameters such as financial, operational and production levels during the disruption periods. As the magnitude of the disruption goes up, each corresponding value decreases showing that there is a ripple effect observed in each network of Industry caused due to disruption. Thus, it is inferred that the ripple effect can be observed at every node as well as at the levels of the supply chain at different disruption levels.

Numerical calculation for the simulation is made available in Appendix 1.

6 Results and discussion

The analysis of ELT service level by-products, peak capacity, fulfilments received, available inventory, and products produce helps in analysing the disruption in the supply chain and identify the bottlenecks giving profound insight on the supply chain. ELT tells us how many orders were received on time, indirectly indicating how the disruption affects the supply chain. Peak capacity tells the maximum amount of product items that are in stock along with fulfilments received indicating the uncertainty in the supply chain due to the ripple effect. Available inventory and products produced to reveal the availability of the manufactured goods during the disruption.

Figure 5 compares the ELT service level on various disruption levels (0%, 25%, 50%, 75%, and 100%) to the

PEAK CAPACITY

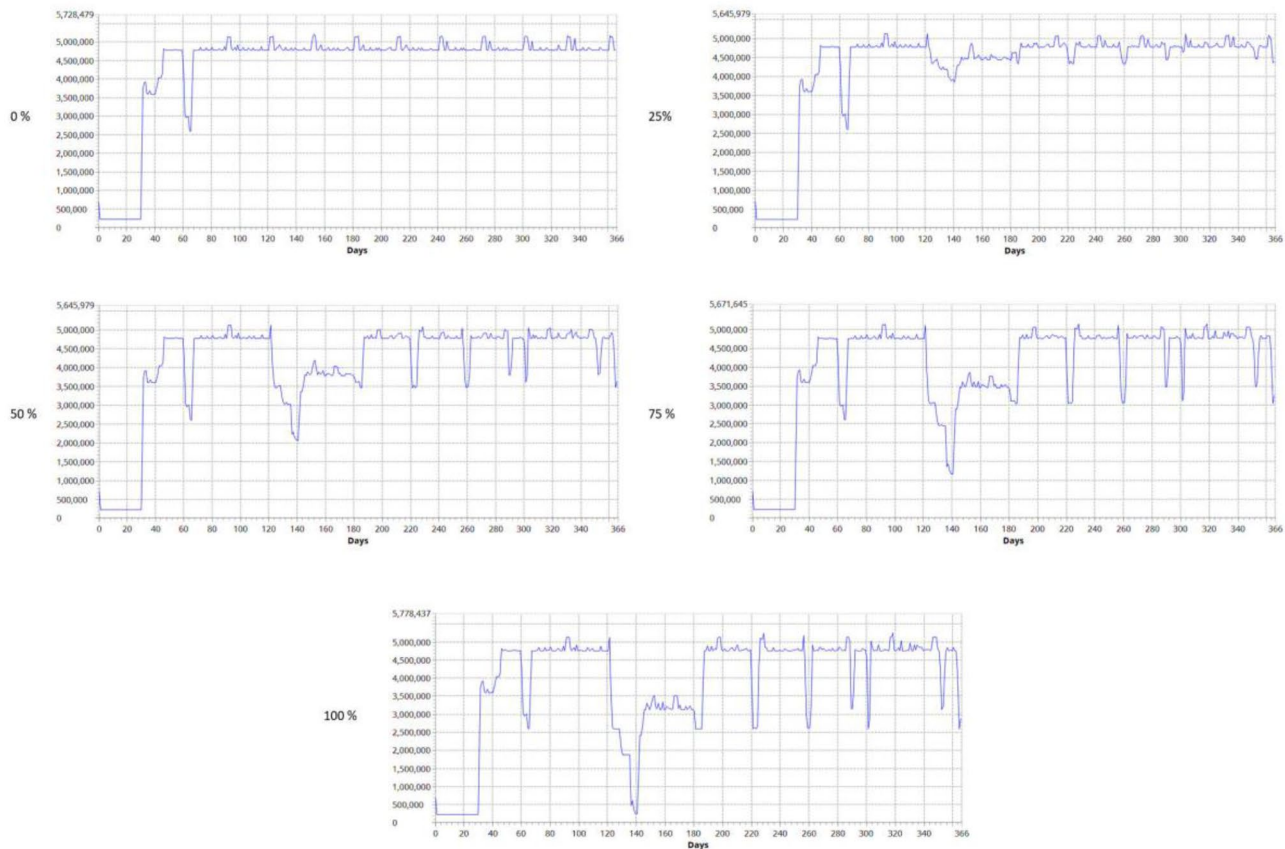


Fig. 6 Peak capacity at 0%, 25%, 50%, 75%, 100% disruption levels with average maximum value of 5.69E6 to minimum value of 0

number of days simulated. ELT service level gives us the ratio of the number of on-time orders to orders to the number of outgoing orders. Typically, a ratio of one is considered as good and anything below that is an indicator of a bad or disrupted supply chain. On observing the graphs, the values of ELT go below one over time with an increase in the percentage of disruption. It is also observed that at ELT service level has a negative trend at 0% disruption. This is because the study has taken into account real-life and practical disturbances. It can be seen that only after few days it shows a minute negative trend. 100% efficiency is almost impossible to be achieved by any organisation. Hence it can be inferred from all the graphs that an increase in disruption causes the ELT service to decrease more. With these results, it can be concluded that the gap between supply and demand is increasing as more orders are in the market and the production unit is not able to meet the demand.

Peak capacity variation (Fig. 6) shows us the effect of disruption levels on the peak capacity of inventory kept at

various parts of the supply chain. On inferring the graph at 0% it is seen that peak capacity is stable and periodic after some time but as the disruption percentage increases the stability and periodicity are replaced with tottering and aperiodic values. Hence, the disruption causes a ripple effect in the inventory which increases with an increase in disruption level. Uncertainty is observed in Peak capacity and that further increases with an increase in disruption level.

Figure 7 shows the Fulfilments received, which gives the data of products received on time for various industries taken in the case study. From Fig. 7, a trend of fulfilment and disruption can be observed. As with no disruption, the graph shows a smooth trend but as the disruption level increases there is a sudden break in that trend and the break is more in the higher disruption level which results in fewer products being delivered at a higher disruption level. It is also observed that the stagnation period (a period where no products are produced) also gets longer to increasing disruption percentage. This is due to some disruption caused at the

FULFILLMENT RECEIVED (PRODUCTS ON TIME)

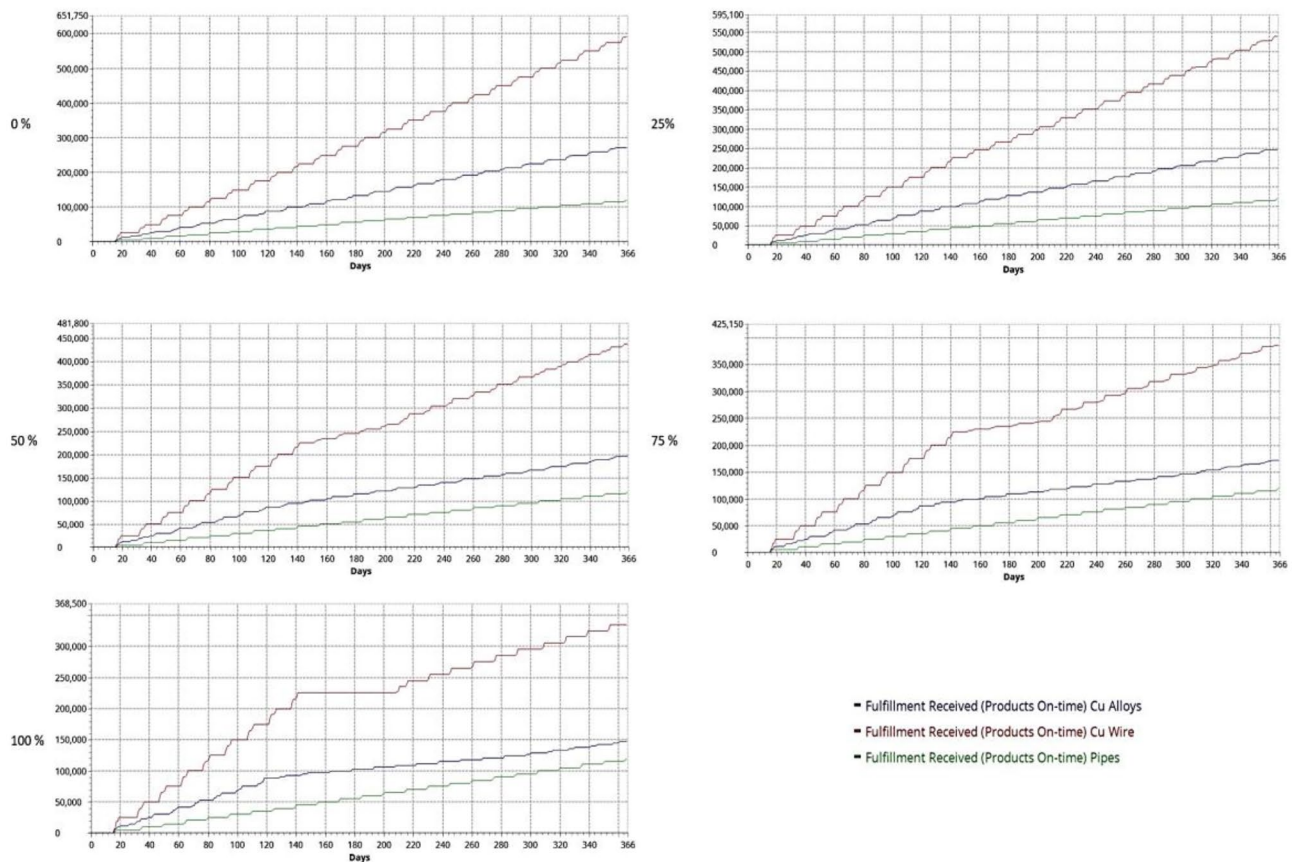


Fig. 7 Fulfilment received analyzed at 0%, 25%, 50%, 75%, 100% disruption levels for Cu Alloys, Cu Wire and Pipes

distribution centre or manufacturing facility. By representing them as cumulative values, the holistic picture of fulfilment received during the disruption period can be predicted and by zeroing it, the facilities that are impacted during the disruption can be forecasted.

Figure 8 serves as a base for the future scope of proactively taking measures at the facility level by analysing both the graphs to mitigate the ripple effect at the various supply chain of the copper industry. The trend in the graph also shows the points of improvement in the supply chain *i.e.*, where and when the changes should be made to reduce the impact of the ripple effect on the end consumer.

Figure 8 shows the available inventory during the simulation period at various disruption levels. Figure 8 gives the pattern of uncertainty created by various disruption levels for no disruption (0%) the graph follows a cyclic repetitive pattern of available inventory. As the disruption level increases it creates an uncertain inventory period which is more vigorous for a higher level of disruption. The cycle

tries to revert to the cyclic stage after the disruption. This is possible for lower disruption levels like 25% as inferred from the graphs above. The higher disruption level creates a ripple effect of higher uncertainty and variability of available inventory which can be spotted in this graphical analysis, the effects of higher disruption level can be observed for a longer duration of time and recovery period for the cycle to its initial cyclic stage is also increased. Hence it can be concluded that a higher level of disruption causes higher uncertainty to the inventory and the effects are more devastating and will last for a longer duration of time.

From the analysis, the production problem that occurred by the entire supply chain can be understood. Figure 9 shows the break between the production period and the number of products produced until that day. The higher level of disruption would bring a higher number of breaks in between production periods hence a smaller number of products are produced at a higher level of disruption. By representing the graph as cumulative values, the holistic

AVAILABLE INVENTORY

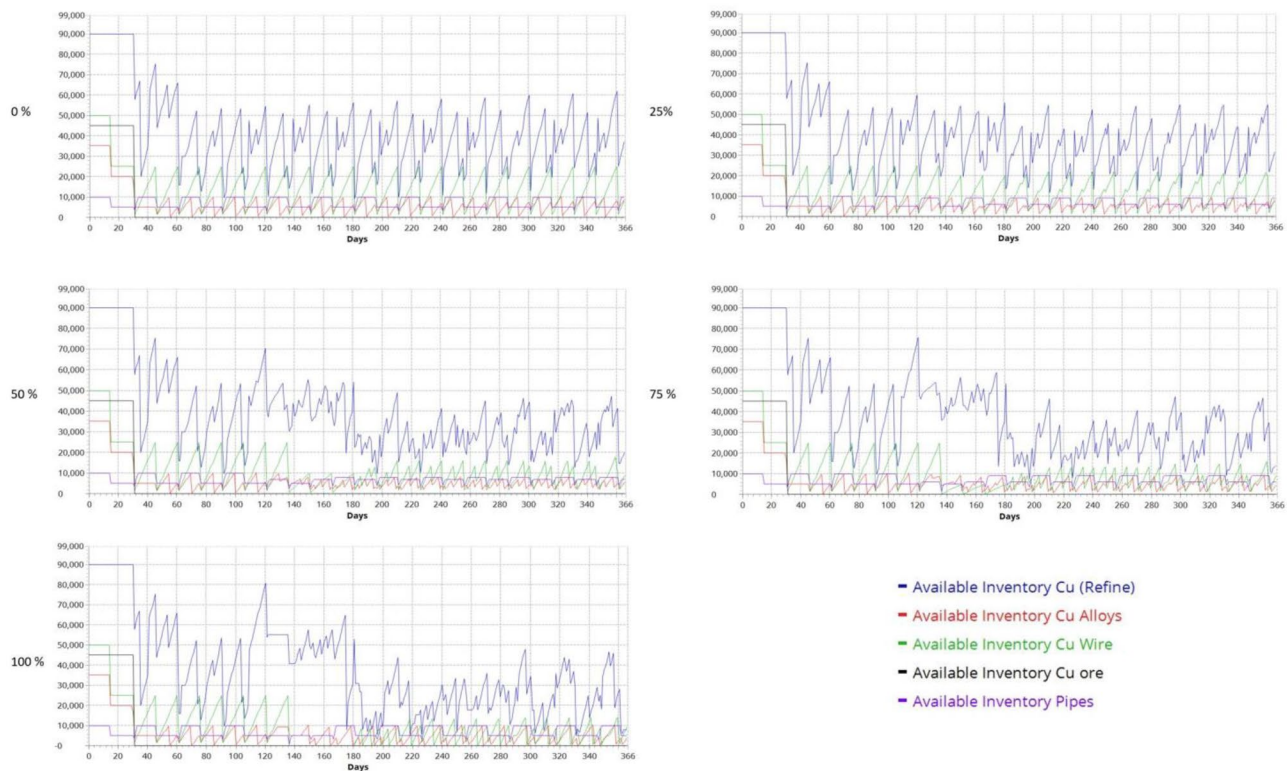


Fig. 8 Available inventory at 0%, 25%, 50%, 75%, 100% disruption levels with values ranging from 0 to 99,000

picture of this KPI's performance during the disruption period is visible. By zeroing it down, during which period, all facilities were impacted severely or moderately depending upon the magnitude of disruption can be known. This graph also serves as a base for the future scope of proactively taking measures at the facility level by analysing both the graphs to mitigate the ripple effect at various supply chain levels of the copper industry.

In the context of project management, collaborative planning, integrated execution, and strategic alignment streamline the copper supply chain. In the contemporary case organization, the acquisition strategy is aligned for project success by sharing procurement plan unifies the stakeholders, sharing the execution strategy on budget, product specification, quality and schedule drives consistent decisions. Use of effective project management methods such as the critical path method used to visualize the sequence of activities with dependencies that minimizes the supply chain disruption in the copper

industry. The project managers are provided with project management dashboards to proactively resolve issues before they impact business as illustrated in Fig. 11.

The stakeholders involved in project management activities are provided with three dashboards namely the procurement operations dashboard, item analysis dashboard, supplier analysis dashboard. The operations dashboard helps to prioritise work, discover, and resolve problems that offer a complete view of inbound and outbound supply chain activities. It also helps to drive a timely and well-informed decision-making process. The item analysis dashboard helps the project managers to quickly access the procurement history of both inventory items and one-time items. It allows them to make an informed item choice by comparing procurement history and performance attributes for each item. The supplier analysis dashboard helps to find the right supplier meeting organizational objectives and business needs. It also helps to manage the overall supplier relationship.

PRODUCTS PRODUCED

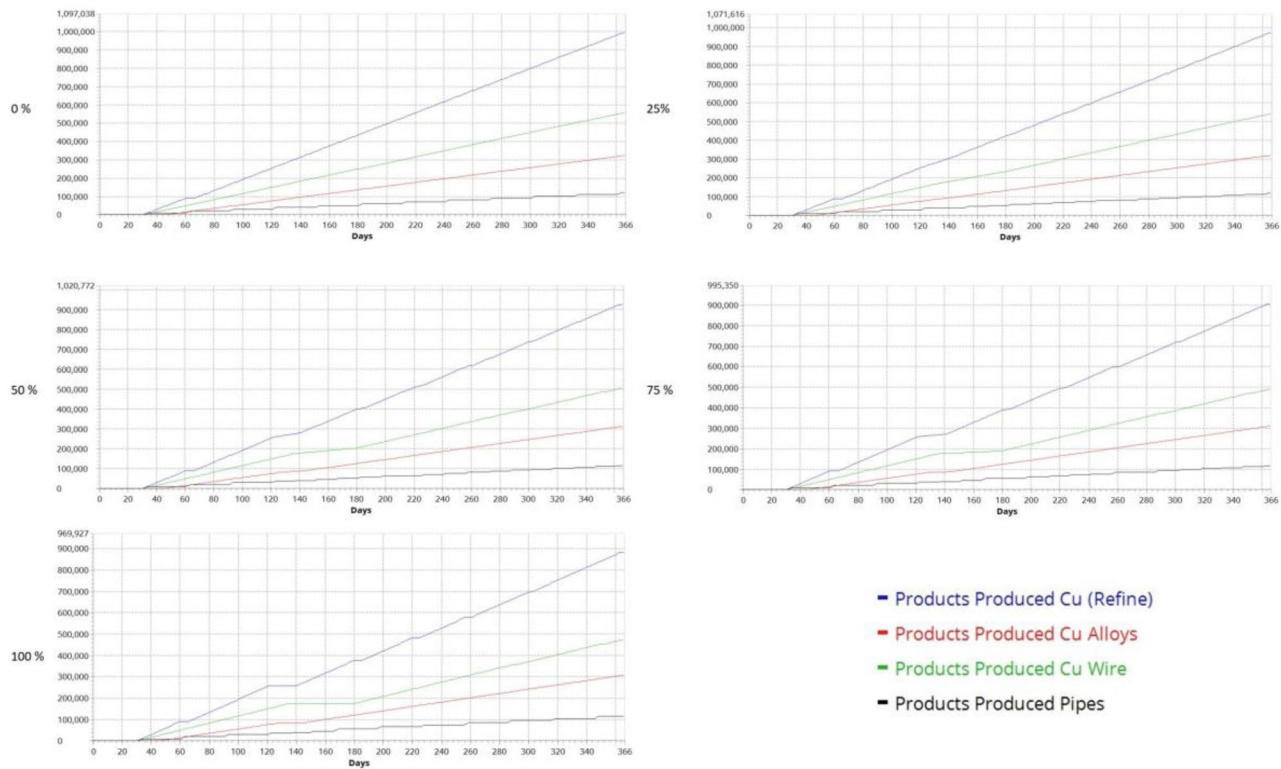


Fig. 9 Products produced at 0%, 25%, 50%, 75%, 100% disruption levels. Refined Cu, Cu Alloys, Cu Wire, and Cu pipes are included in the analysis

7 Managerial and theoretical implications

This research presents several contributions to the present literature on the supply chain through project management. The study is conducted in a copper extracting industry that supplies copper for different industries across geographies. The study provides qualitative analysis due to the disruption caused. It provides insight into the macroeconomic effects caused due to the disruption in a supply chain. Simulation and optimization studies give power to decision-makers to analyse the performance impact on supply chain dynamics and make it resilient to future mishaps. This study considers a large number of parameters that give an in-depth analysis. After analysing the ripple effect in the supply chain, the following insights are provided keeping all the nodes into account.

- Increasing safety stocks at the copper smelting unit ensure that the supply of refined copper to the other

dependent industries is smooth up to a certain extent, even during the disruption phase and that the disruption is not propagated to the other nodes.

- Increasing the minimum inventory level at all the networks ensures that the disruption does not have any effect on the industries dependent and can dampen the ripple effect up to a certain period.
- Consideration of multi-sourcing of refined copper from other/outside units till the primary unit recovers from the disruption so that the dependent industries are not impacted by the disruption and the supply of copper-based end products remains uniform in the market.

From the results, it can be seen that the ripple effect has a higher impact on the products reaching the customer at a higher level of disruption (%) than the duration of the disruption. Hence it is very useful to increase the safety stock, dual or multi-sourcing during supply chain bottlenecks, and checking the alternate way of transportation to dampen the

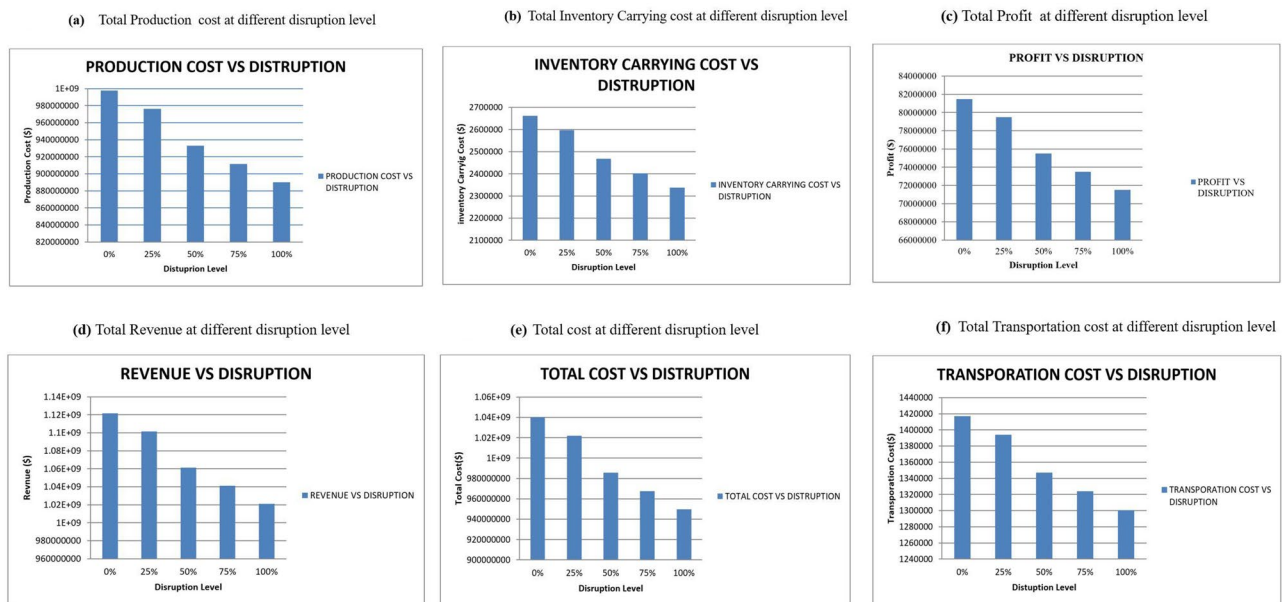


Fig. 10 Financial Performance at 0%, 25%, 50%, 75%, 100% disruption levels analysing (a) Production cost (b) Inventory carrying cost (c) Profit (d) Revenue (e) Total cost (f) Transportation Cost. Financial performance indicates the effect caused by the disruption of the supply chain and its various performance indicators. Figure 10a gives the trend of reduction in production cost which indicates the reduction in the supply of raw materials at every production unit. Hence it can be inferred that increased disruption level causes the number of finished goods to decrease. From 10b it can be inferred that increased disruption level causes inventory to reduce, and inventory cost is directly indicating that loss in inventory as disruption stops the flow of copper from the lower level of the supply chain to the higher level.

els. Figure 10c, d infers the loss of Profit and Revenue (Sales) in the entire supply chain is due to the disruption. From Fig. 10c it can be observed that there is an approximate loss of 12.1% between 0% disruption and 100% disruption. Thus, the higher the disruption leads to increased loss of profit and revenue. Figure 10e indicates that the loss is evenly distributed based on the linearly decreasing graph, on all the other financial parameters as it agrees with the trend which is shown by the other performance indicators thus showing us the ripple effect on each node of the supply chain. Figure 10f helps to understand the loss in the movement of copper further up the supply chain as transportation cost decreases due to the lack of products and it also shows the loss of revenue to the transportation companies.

ripple effect toward the end customers rather than focusing on a faster recovery process. The alternate ways of transportation should be chosen carefully since if the chosen method of transportation is not able to perform an outbound operation (e.g., rough seas), it does not help in reducing the ripple effect.

Building the supply chain with a proper project management tool helps in recovering from the cascading ripple effect in a copper supply chain. The outcome shows that there is a reduced planning time as both the project manager and buyer have better visibility on the in-transit items. When a consignment is delayed due to unforeseen conditions, the project management tool helps to find a

quick alternate supplier to reduce the supply chain disruption. The stakeholders can make a faster and better decision using the objectives set out in the alignment stage, more context to the buyer to improve their decision making and negotiating, and more information to the project manager to improve their planning. It also results in better procurement processes that will reduce wastage and help meet the overall project objectives. With the effective project management tool, all operational decisions are streamlined. The stakeholders can focus on spend analysis, supplier relationship and contract optimization. Further, it improves the interaction with their customers and understands the needs better than before.

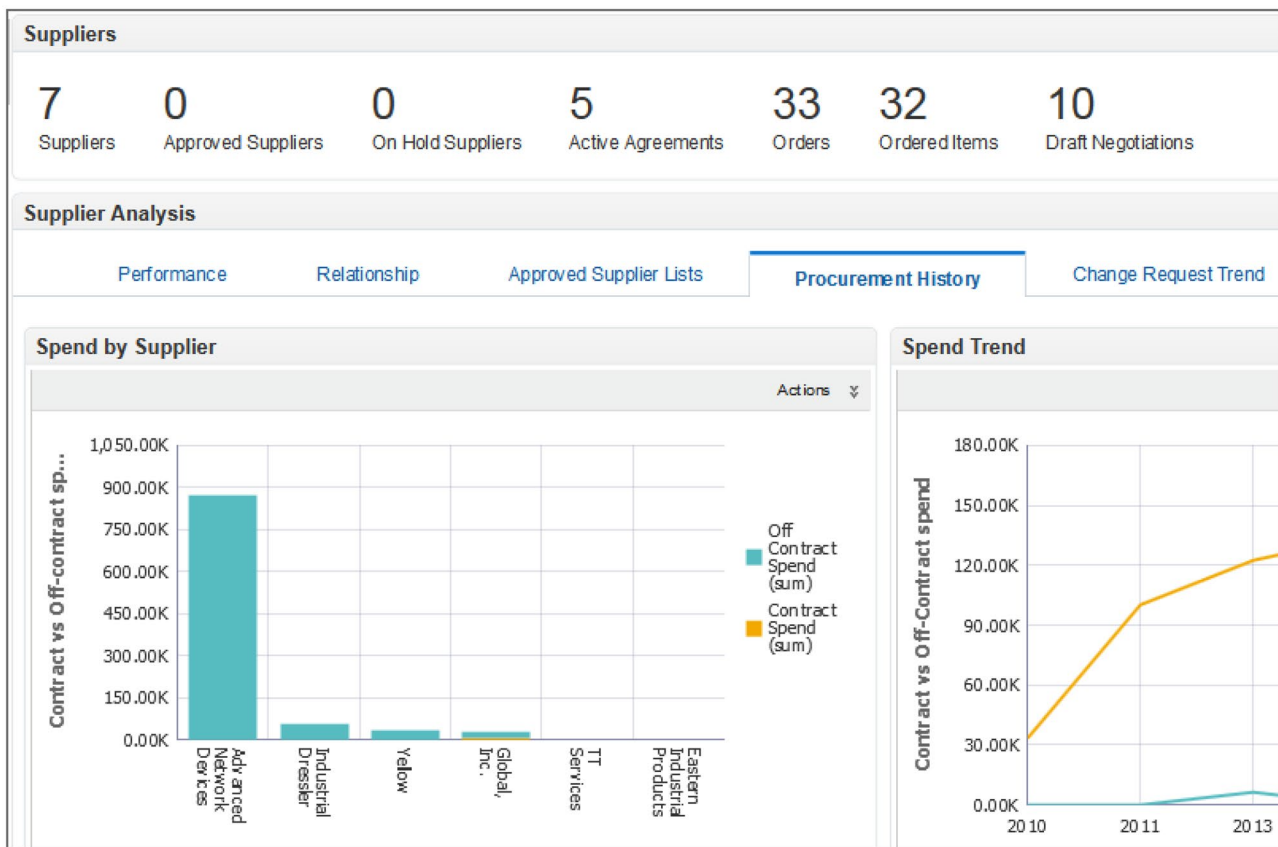


Fig. 11 Supply chain dashboard for project management activities

8 Conclusion and future research direction

Copper is the gold of the technological age that acts as the lifeline for all the major core engineering industries, therefore this study on the supply chain on this metal enables us to look at the engineering market like never before. This paper takes a case study of a copper smelting unit located in south India and is considered as a major producer for the other industries which feeds on copper as a raw material. The case study considers a supply chain starting from the copper ore origin to the retailer who sells the finished goods which contain the copper produced from the smelting unit.

Modelling of the supply chain of the copper smelting unit helped to better understand the industrial network. Modelling with anyLogistix software made the analysis of the ripple effect more effective as well as understandable for future use. This analysis is purely quantitative and qualitative discussion is made concerning values involved in the KPIs parameters. This paper limits the economical quantifiable aspect of the smelting unit to the supply chain. By observing the various levels of disruption of 0%, 25%,

50%, 100% on the smelting unit, various parameters were observed in each case. A sensitivity analysis was made comparing all the results. Sensitivity analysis gives a comparison of all the different values of disruption to all the KPI's and the ripple effect caused due to the disruption concerning the parameters. Thus, the analysis reveals the capacity and potential of each node of the supply chain enabling it to observe at the micro-level thus satisfying the research objectives. Subsequently, changes in the structural design and planning parameters can be done to make the Supply chain more robust and resilient for future operations.

Ramezankhani et al. (2018) investigated the sustainability and resilience factors and performed a case study in the automotive industry. Further, it proposes a framework to demonstrate its capabilities and effectiveness. Dolgui and Ivanov (2021) discussed the new trends and research directions on the ripple effect and supply chain disruption management. This article focuses on the ripple effect and its disruption in a copper supply chain. Using simulation, the various distribution levels are analyzed to overcome the supply chain operational issues in procurement, inventory, and logistics management. Further, it helps to understand the importance

of project management tools to reduce the cascading ripple effect in a copper supply chain.

This paper gives the general idea of disruption in a supply chain of a copper industry and the ripple effects caused due to it. These effects the economy and social aspects of the industry, of the country in a devastating manner no matter how small these effects may seem to be. This study was unable to quantify all the qualitative analyses which could serve as a base for future research. The impact on the local economy (*i.e.*, the ripple effect caused due to disruption) can be made quantifiable for future work. The local economy would inevitably be impacted by the disruption. The reason being, the disruption would create a ripple effect on the jobs and the economic cycle-related directly or indirectly with the disrupted industry. Though it could not be quantified as to how much the economy was impacted, there will be a loss in sales and profits of an industry attributed to the disruption that will impact the local economy. The direct and indirect losses in jobs related to an industry can be quantified and that would vary depending upon the magnitude of disruption and recovery policies. Once the ripple effect is simulated, different recovery policies can be taken into account by the industries. The simulation can again be performed considering these policies, and subsequently, a better and pragmatic overview of their adapted measures would be seen. The selling price of copper and its finished goods is assumed to be fixed hence a more dynamic approach could be made for future work. Work price fluctuations can be considered with respect to the change in market supply and demand of the goods used. This case study does not consider the variability of custom duties of various countries with each other future work could improve this limitation. The selling price of the material is left unaffected by the change in supply which could also be seen as an opportunity for future work.

The role of project management in the supply chain is to align the strategies with customer deliverables, manage the constraints and resolve issues to minimize the ripple effect, drive accountability across the organization with better visibility in the process. In addition, empower the supply chain execution team to make quick decisions and to have better workload management. It enables to reduce wastage and align the delivery of project outputs to the organizational objectives.

Appendix 1

Model Calculations for Production Cost

This section shows model calculations of production cost at different disruption levels.

Production Cost- PC.

0%

$$PC = PC_{refine} + PC_{wire} + PC_{Alloy} + PC_{pipe}$$

$$\begin{aligned} PC_{refine} &= \text{Product produced (in tonne)} \times \text{Cost (per tonne)} \\ &= 99730.81 \times 3000 \\ &= \$ 299192430 \end{aligned}$$

Similarly,

$$PC_{wire} = 5526.39 \times 7000 = \$ 390784730.$$

$$PC_{Alloy} = 32321.55 \times 7000 = \$ 226250850.$$

$$PC_{pipe} = 1200 \times 6800 = \$ 81600000.$$

Hence

$$\begin{aligned} PC &= 299192430 + 390784730 + 226250850 \\ &+ 997827988 = \$ 997827988 \end{aligned}$$

Similarly, for other disruption levels.

25%

$$PC_{wire} = 97419.69 \times 3000 = \$ 292259070$$

$$PC_{wire} = 54148.61 \times 7000 = \$ 379040270$$

$$PC_{wire} = 32007.77 \times 7000 = \$ 292259070$$

$$PC_{wire} = 11900 \times 6800 = \$ 80920000$$

$$\begin{aligned} PC &= 292259070 + 379040270 + 292259070 \\ &+ 80920000 = \$ 9762738130 \end{aligned}$$

50%

$$PC_{wire} = 92797.47 \times 3000 = \$ 278392410$$

$$PC_{wire} = 50793.05 \times 7000 = \$ 355551350$$

$$PC_{wire} = 31380.23 \times 7000 = \$ 219660000$$

$$PC_{wire} = 1170 \times 6800 = \$ 7956000$$

Hence

$$PC = \$ 933165463$$

75%

$$PC_{wire} = 90486.36 \times 3000 = \$ 271459080$$

$$PC_{wire} = 49152.78 \times 7000 = \$ 344069460$$

$$PC_{wire} = 31066.45 \times 7000 = \$ 217465150$$

$$PC_{wire} = 1160 \times 6800 = \$ 7888000$$

Hence

$$PC = \$ 911611288$$

100%

$$PC_{wire} = 88175.25 \times 3000 = \$ 243525750$$

$$PC_{wire} = 47437.50 \times 7000 = \$ 332062500$$

$$PC_{wire} = 30752.69 \times 7000 = \$ 215268830$$

$$PC_{wire} = 11500 \times 6800 = \$ 78200000$$

Hence

$$PC = \$ 890057113$$

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