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Resilience and complexity measurement for energy efficient global supply chains in disruptive events

Esra Ekinci\textsuperscript{a}, Sachin Kumar Mangla\textsuperscript{b,∗}, Yigit Kazancoglu\textsuperscript{a}, P.R.S. Sarma\textsuperscript{c}, Muruvvet Deniz Sezer\textsuperscript{d}, Melisa Ozbiltekin-Pala\textsuperscript{e}

\textsuperscript{a} Department of Logistics Management, Yasar University, Izmir 35100, Turkey
\textsuperscript{b} Operations Management, Jindal Global Business School, O P Jindal Global University, Haryana, 131001, India
\textsuperscript{c} Operations Management, IIM Vishakhapatnam, Visakhapatnam, Andhra Pradesh 530003, India
\textsuperscript{d} Department of Business Administration, Yasar University, Izmir, Turkey

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ABSTRACT

The whole world is faced with the COVID-19 epidemic that causes major disruptions in global supply chains. The aim of study is to evaluate the effects of COVID-19 on energy efficient global supply chains (SCs) and to model the global supply chain resilience and energy management affected during the COVID-19 considering trade between Turkey and China, and Turkey and the EU. In this study, firstly using System Dynamics (SD) model, the behavior of countries against COVID-19 for a certain period of time is observed, subsequently the increase in complexity is analyzed with entropy measurement to determine whether the systems are resilient or not and to mark the differences arising from reporting in the first and second wave of the pandemic in the developed model. It is determined that the second wave reporting differences is less than first wave reporting differences except Turkey. From the learning effect perspective, it has been seen that the effect on the economy and foreign trade are less than first wave of pandemic even though the number of patients originating in the second wave are higher. It means that countries responded to the second wave of COVID-19 in a more resilient way. It is found that as a major finding of this study, perceived complexity of the system decreases in the second wave because of the resilience of supply chain considering learning effect and centralized decision making ensure increasing resilience and resilience measure in global supply chains. The study is highly helpful for governments, decision makers and managers to understand and manage the impacts of COVID-19 on global supply chains being resilient and energy efficient.

1. Introduction

Organizing trade and investment operations around the world causes the expansion of the competitive environment of businesses (OECD, 2020). With the expansion of competitive environments, these businesses have the chance to expand around the world. This view, it has become extremely important for businesses to adopt energy efficient global supply chains (SC), which is an integrated system that covers overseas activities and outsourcing strategies are presented, produced and distributed across national borders (Song et al., 2020a, b; Ivanov & Dolgui, 2020). However, energy efficient global SCs are becoming more vulnerable to risks that may arise as they include global developments, carbon emissions and global competitive environment (Chikaraishi et al., 2020; Chandra and Kumar, 2020; Song et al., 2021).

The environmental/biological events, which are one of the type of disasters consist of climate change, global warming, and epidemic outbreaks such as COVID-19, when whole world strives to overcome (Ivanov, 2020; Romero-Silva & De Leeuw, 2020). In other words, the most important difference of these disruptions because of pandemic from disruptions caused by the other crises is that they are fast, disruptive and large in terms of demand and supply along SCs (Deloitte, 2020) and it causes uncertainties in energy efficient global SCs in the world (Zheng et al., 2021). Moreover, the COVID-19, which caused differences in many sectors, an increase in some sectors and a decrease in some sectors, caused great changes especially for the logistics area (Chikaraishi et al., 2020). One of these changes has been on the SC, which is very important

Abbreviations: SD, system dynamics; SCs, supply chains.
∗ Corresponding author.
E-mail address: esra.ekinci@yasar.edu.tr (S.K. Mangla).

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for world markets and trade (Dunlap et al., 2020).

The most important reason for such huge COVID-19’s impact on SC is that the epidemic started in a country that is important for the world market, China (Ayittey et al., 2020; Balezentis et al., 2021). Even though COVID-19 emerged and spread in China (Martonosi et al., 2021), each country had difficulties in its own economic and health system (Ivanov, 2021; Thakur, 2021). In other words, the pandemic lifecycle situation of each country is different. In addition to being such a large market, China is the main supplier of electronic products in the global automotive industry (Govindan, 2020). Moreover, electrical and electronic devices are the leading products that China exports to the most (Ayittey et al., 2020).

As China is one of the crucial manufacturers for world. Moreover, China’s production spreads to different industries (Govindan et al., 2020). It has become critical point which, lots of countries suffer from disruptions in global SCs (Dunlap et al., 2020; El Baz & Rueel, 2021). In this context, it is critical to consider impact of pandemic on SC based on various sectors.

Besides, COVID-19 has been severely disrupted in Europe due to border closures (Pereira et al., 2021), SCs collapse and production standstills. Notably, 94% of the Fortune 1000 companies have dramatically affected by COVID-19 and its disruptions effects on SC (Fortune, 2020). For example, Boeing, one of the leading aircraft manufacturers, along with transportation and travel restrictions, mentioned that COVID-19 affected demand for transport, production operations and SC, and stated that commercial aircraft production must be decreased to cope with the disruption (Dunlap et al., 2020). Moreover, Fiat Chrysler Automobiles NV have to temporarily halt production at its factories in Serbia, since they have challenges about supply raw materials from China (Fortune, 2020). Besides, trade between the European Union and other countries fell more than 10% in March, according to Eurostat. The unforeseen effects of the COVID-19 crisis have led to the required for more resilient SCs in many industries in Europe such as textile, mining, chemical materials and energy sectors (Bag et al., 2021; Hossain et al., 2021). Foreign trade that is a significant source of technological development, can be considered as a key stimulator for improvement in energy efficiency (Zhao et al., 2020).

Furthermore, Turkey is one of the important emerging economies in the world and China is the second biggest importer of the country (Ayittey et al., 2020). In addition, Turkey is an important country about export to EU especially in textile sectors. For example, Turkey is playing a major role in the European Union’s clothes. 11 percent of the imported clothing from countries outside the EU is going from Turkey (Deloitte, 2020).

Besides, automotive, apparel, machinery and accessories, and raw materials and iron and steel are affected by COVID-19 restrictions (OECD, 2020). These sectors have dramatically demand and supply fluctuations in line with the decreases in raw material supply from China (Onig & Yalikun, 2021). Exports to the European Union, the main importer of automotive sector in Turkey, fall downed drastically by 81% at the end of April due to the pandemic. In addition, China and Turkey are located in countries that perform most imports from EU countries and exports to EU countries (Cameron et al., 2021). Like other countries, Turkey’s global SC and the foreign trade and energy efficiency statistics are affected by COVID-19 as negatively.

Hence, the COVID-19 causes disruptions on the global SC worldwide in terms of energy efficiency. However, there is a lack of decision tool for managers and policy makers to investigate the effects of COVID-19 and evaluate the complexities of the global SCs within the era of COVID-19 in the world. Therefore, the main contribution of this study is to analyze the impacts of COVID-19 on global SCs of countries specifically Turkey and China, and Turkey and EU based on sectors as comparatively. Additionally, one of the main aims is to provide a new perspective for managers and policy makers who encourage the system approach and measure of complexity to make strategic decisions about the prevention effects of COVID-19 or which countries should work.

It has also been argued that there is a strong negative linkage between SC complexity and resilience (Bode & Wagner 2015; Ivanov & Dolgui, 2020). (Ivanov and Dolgui, 2020) stated that complex networks in the SC have become more fragile due to severe disruptions such as pandemics that alter the structures and dynamics of the SC. Further, the simulation techniques such as system dynamics modelling allow developing a variety of resilience measure plans, considering severe interruptions (Moosavi & Hosseini, 2021). Therefore, to help businesses, these approaches are integrated with complexity theories to investigate the impact of COVID-19 on the resilience of countries. To understand how the resilience of energy efficient global SCs be measured to cope with disruptions caused by COVID-19 and what kind of strategies be implemented to improve the resilience of energy efficient global SCs during global crises such as COVID-19 are essential in order to define the problems and propose solutions caused by COVID-19 about the energy efficient global SCs. In line with all of these gaps in the literature and practically, as a result, the research questions of the study are summarized as;

- **RQ1:** How the resilience of energy efficient global SCs be measured to cope with disruptions caused by COVID-19?
- **RQ2:** What type of strategies be implemented to improve the resilience of energy efficient global SCs during global crises such as COVID-19?

To address the 1st research question mentioned above, system dynamics (SD) model is used to analyze how the global SCs of Turkey and China, and Turkey and EU are affected from COVID-19 and investigates the expansion of COVID-19 and its sectoral impacts considering export and import data. Fluctuations in number of cases affects country productivity and capacity utilization which causes changes in export and import rates of countries. Thus, COVID-19 patient sub model is used to show reporting differences and active patient number which indicates that either the reported numbers for pandemic are not totally reflecting the COVID-19 spread and the analyze how controllable it is and investigating reporting problems or health system overload to reveal real burden in country economy caused by COVID-19. Furthermore, lockdowns due to the COVID-19 pandemic have affected the trade and economic and supply chain activities, especially on the peak points of the pandemic, this spread results with disruptions due to lockdowns in related countries. Besides, learning effect is measured in order to understand how countries have adapted to the COVID-19 progress. Moreover, using SD model outputs based on foreign trade statistics and logistics activities between countries, the resilience measurement of countries is employed. Besides, in order to handle 2nd research question, with entropy metrics, it is aimed to evaluate the resilience of energy efficient global SCs during the pandemic period by developing various policies with scenario analyzes.

With COVID-19, it has also become extremely difficult for complex and globalized supply chains to be efficient (Hoang et al., 2021). According to literature review, there are very limited studies about the effects of COVID-19 on energy efficient global SCs of countries (Kikstra et al., 2021; Jiang et al., 2021). Therefore, by considering literature review, this study is unique to make comparative analysis about the effects of COVID-19 on energy efficient global SCs of countries based on system approach using SD modelling and to further investigate the effects of COVID-19 on resilience of energy efficient global SCs with complexity measurement based on complexity theory and resilience measurement. One of the main contributions of the study is that the entropy measure, which is measurement of complexity has been adapted for measuring resilience of energy efficient global SCs. Additionally, the study provides a unique contribution by analysing sectoral impacts of COVID-19 on global SCs of Turkey and China, and Turkey and EU through a comparative study.

The SD model is used to analyze how the energy efficient global SCs of Turkey and China, and Turkey and EU are affected from COVID-19.
Further, the complexity measurement based on complexity theory evaluates the effects of COVID-19 on resilience measure of countries based on foreign trade and energy efficiency statistics and logistics activities between countries.

The remainder of the paper is structured as follows. Section 2 exhibits the literature review description. Section 3 covers research methodology. Section 4 includes a case study, which is comparative study between Turkey and China, and Turkey and EU as an implementation of the study. Section 5 exhibits results of the implementation. Section 6 highlights discussions of the study. Section 7 covers the implications for managers and policymakers. Lastly, Section 8 concludes this study.

2. Literature review

The literature review covers impact of epidemic outbreaks (COVID-19) on global SCs, resilience of global SCs, theoretical background (complexity, system theory etc.), and proposed research techniques used during epidemics in global SCs context.

2.1. Impact of epidemic outbreaks (COVID-19) on global SC

Disaster can be defined as a sudden or chaotic start, significant deterioration that causes loss of people in the society (Gupta et al., 2016). Disaster occurs naturally (geophysical, meteorological and environmental/biological events) or can be caused by human-made (nuclear, technological and chemical) (Davis et al., 2019). In the past years, different disasters have occurred in the world (Gupta et al., 2016; Ye et al., 2019). Instead of other natural disasters, environmental/biological events especially epidemics are most dangerous type of disasters for both human health and SC operations of countries (World Health Organization, 2020). There are various studies, which consider the disruptions causes by past time epidemics such as MERS, mad BSE bovine spongiform encephalitis, SARS, bird flu i.e. (Parvin et al., 2018; Muggy & Heier Stamm, 2020). Recently, all countries in the world have struggled with the COVID-19 pandemic (Muggy & Heier Stamm, 2020). COVID-19 negatively affects health systems, governments and businesses worldwide such as nation-wide lockdowns, shortage, disruptions in global SCs, and cash flow shortages affect (OECD, 2020). The most important reason why the epidemic is having a crucial impact on a global scale is that China, is the leading producer and buyer of raw materials in various sectors and global commodities and industrial products (Deloitte, 2020; International Trade Centre, 2020).

In addition to endangering human health, COVID-19 has caused countries to close their borders, stop import-export activities and production activities in many factories, and close many businesses such as entertainment centres, shopping malls and restaurants i.e. (International Trade Centre, 2020). As a result, many areas such as consumer spending, investments and international trade, global market conditions are affected in a negative way and have disruptions in the global SC (Dunlap et al., 2020). Since the emergence of COVID-19, there has been a critical increase in lead times of products supplied from China, and capacity utilization has been reduced by half in the production facilities in China (Deloitte, 2020). In other words, since the beginning of the COVID-19 epidemic, first of all production processes in China have been seriously disrupted and SCs all over the world have not been able to provide the intermediate and end products they need (OECD, 2020).

Moreover, during global epidemic period, various sector reduces their production, transportation, assembly because of government restrictions (International Trade Centre, 2020). In the epidemic time that affects each sector differently, sectors such as the travel sector, automotive production, manufacturing, retail, energy, high technology have been the most affected in terms of SCs (McKinsey & Company, 2020; Ivanov et al., 2020).

During this epidemic period, it seems that most of the countries, firms and their global SCs are not resilient. Therefore, it is essential to evaluate the resilience of their global SCs to cope with the challenges (Demirel et al., 2019; Harvard Business, 2020).

2.2. Resilience of global SCs

SCs are getting more dynamic and complex with the globalization (OECD, 2020). As the SC becomes more complex and the distance between suppliers and customers increases, decision-making processes in SC management are exposed to uncertainties (Kim et al., 2014; Ambulkar et al., 2015; Freeman et al., 2021). Therefore, global SCs become more vulnerable to risks because of their complex structure (Kim et al., 2014; Ivanov, 2020). Due to natural disasters or pandemics in past years, many companies have learned how to strengthen the resilience of their global SCs (SC) to face disruptions triggered by serious disasters (Ayitety et al., 2020). However, with the COVID-19 that emerged in March 2020, companies’ global SCs started to deteriorate again (OECD, 2020; Golan et al., 2021).

Although some firms manage to survive by placing emphasis on the resilience efforts of global SCs, many companies around the world are having a hard time in SC management due to unprecedented fluctuations in demand, cost increases and labour problems due to the epidemic (Ivanov, 2020). In the past, while the focus was on cost savings and stock optimization in the SC world, today it has become clear that ensuring the resilience of SCs should normally be the top priority of companies (McKinsey & Company, 2020). Recently, the resilience of SCs requires solutions such as the adoption of dynamic and integrated SC systems that improve with smart technologies and constantly optimize itself instantly (Kim et al., 2014).

The COVID-19 outbreak has negatively affected not only the economy and society, but especially global SCs and this has led to testing of global SCs (Ayitety et al., 2020; Xiong et al., 2021). Companies that work for the resilience of global SCs and have solutions such as risk reduction inventories, backup supply and transportation infrastructures, multi-channel distribution systems, flexible production technologies and data-oriented, real-time monitoring and visibility systems can survive and start the process of recovery as soon as possible (Ivanov, 2020).

As seen with the Covid-19 outbreak, there are serious issues faced by industrial sectors related to the resilience of global SCs (McKinsey & Company, 2020). Therefore, appropriate strategies are needed to help businesses to manage such disruptions and to improve the resilience of their value chains.

In the following part, theoretical background about complexity measurement and system theory are explained in detail.

2.3. System theory and complexity measurement

A general systems theory first put forwarded in Ludwig von Bertalanffy’s research in the 1940s-50s. In a complex system, components have the power to both affect cyclically and cause an effect on the system, and so many different relationships arise (Von Bertalanffy, 1972). The system thinking provides problem solving skills in complex systems (Forrester, 1958). A system is a set of interrelated elements whose boundaries are defined (Gröller et al., 2009). The system can also be defined as a set of interconnected components that are coherently organized to arrive at something (Porra, 1999). In other words, the system is a whole consisting of parts that work together and affect each other to achieve a certain purpose (McKelvey, 1999). The change in one part of the system by predicting the system behavior affects both another part of the system and the entire system (Morel and Ramanaum, 1999).

In every system, there is a tendency for activities to deteriorate, to lose balance, to confuse and disrupt, and eventually to cease the system’s activities (Porra, 1999). “Entropy” is the concept expressing this tendency (Sanders and Carpenter, 1998). Entropy is strong in closed systems and it is the most important factor that stops the system after a certain period of time (Porra, 1999). Open systems can negatively affect...
the effects of energy and material and entropy that they receive from their environment (Morel and Ramanujam, 1999).

For a system to be complex and chaotic, it must be sensitive to initial conditions and nonlinear. Because in linear relationships, while cause has a single effect on the result, nonlinear relationships have more than one effect on the result (Fang et al., 2018). Moreover, complexity occurs in uncertain situations in systems and it is related to lack of understanding of the system (Anderson, 1999). Complexity is often defined on the basis of the ‘system’ concept (Kostova and Zaheer, 1999). Most of these concepts admit that complexity reveals the state of the elements in a system and the forms of relationship between these elements (Anderson, 1999). Complexity theory deals with complex systems in which there are no simple cause-effect relationships and reveals that complex systems can produce unexpected results due to choices and interactions (Morel and Ramanujam, 1999).

On the basis of complexity, there are various studies such as general systems theory, infection theory, disciplinary systems subject, genetic algorithms autopoiesis subject, chaos theory (Anderson, 1999). However, the origin of complexity theory is based on the general systems theory (Eisenhardt and Pettigrew, 1999). Contrary to the classical scientific approach, general systems theory allows a two-way relationship between variables or models. Measuring complexity is highly important in order to understand correlation and reveal randomness in complex systems (Doz, 2011). With the measurement of complexity, it is aimed to eliminate the uncertainty in the system by implementing new strategies or decisions by decision makers (Anderson, 1999).

Global SCs contain the characteristics of complex systems due to their global size (Hall et al., 2011). In addition, demand fluctuations in SCs, making different choices between suppliers or aggressive decisions made due to management cause complexity in SCs (Morel and Ramanujam, 1999; Zhan et al., 2021). For example, situations that greatly affect global SCs, such as the COVID-19 era, are also among the most important reasons for complexity to occur.

In order to increase the resilience of energy efficient global SCs, the ability to measure complexity will be a guide for decision makers. Thus, understanding the underlying complexity provides to give decisions in a realistic way and having knowledge how the complexity is measured is essential in SCs.

In the following section, proposed research techniques to reducing effects of disruptions in global SC are illustrated.

2.4. Proposed research techniques used during pandemic in global SCs

Simulation models are a suitable tool for forecasting short and long-term behaviors in the SC (Berends & Romme, 2001; Keskin et al., 2010). However, the literature on investigating the impacts of outbreaks on the global SCs using simulation is scarce (Ivanov, 2020). There are some studies that analyzes the impact of epidemics on the SC, including simulation techniques such as multi-agent, SD and discrete event simulation.

(Vo and Thiel, 2006) investigated the behavior of the entire poultry SC under the avian flu crisis through SD modelling. This model aimed to make effective decisions by indicating possible effects for policy maker. (Buyuktahhatkin et al., 2018) developed a decision support model to estimate their impact on the SC during and after Ebola outbreaks. Ivanov (2020) has stated a new concept of viable SC and discussed its applicability based on the three characteristics of the SC: agility, resilience and sustainability. In this study, the relationships between flexibility, resilience and viability in the SC are revealed. With the viable SC model developed based on dynamic system theory, it is aimed to enable them to create a resilience, sustainable and flexible SC that will guide decision-makers while making short-term and long-term decisions. Besides, Hackl & Dubernet (2019) developed an agent-based transport simulation spread model for the seasonal influenza outbreak for investigating the impacts spread of this epidemic.

(Ivanov, 2020) has investigated the impacts of COVID-19 on the global SC using discrete-event simulation techniques to predict the effects of COVID-19 outbreaks on the supply performance. This study focuses on impacts of epidemic on the SC using various scenarios to indicate behavior of SC over time for decision makers. The manufacturing and logistics activities are aborted temporarily because of the COVID-19 lockdowns (Ayittey et al., 2020). These disruptions have serious effects the demand and supply of various products and also retailers.

Global SC in real world need to tackle with many unidentified risks and disruptions such as pandemics and need to manage them effectively (Reeves et al., 2020). Besides, pandemics bring about many interrelated relations in the global SC.

Therefore, there is still a need for studies focuses on the investigating the effects of countries’ SCs on COVID 19 and how SC resilience is affected by COVID-19 based on import & export operations. Moreover, there is need to see that how the effects of COVID-19 changes from 1st wave to 2nd wave for countries and analyze learning effects of pandemic. Thus, this study is aim to analyze how countries’ energy efficient global SCs and different sectors are affected from COVID-19 by System Dynamics on the basis of the system approach and to investigate the effects of COVID-19 on resilience of energy efficient global SCs with complexity measurement based on complexity theory.

3. Research methodology

The research methodology adopted in this research is discussed in this section. This study aims to analyze how the energy efficient global SCs of Turkey and China, and Turkey and EU are affected from COVID-19. Thus, firstly, causal loop diagram is created to indicate relationship between trade dynamics and SD model is used to investigate the expansion of COVID-19 and its sectoral impacts based on foreign trade and energy efficiency statistics and logistics activities. Besides, by using outputs of system dynamics model, learning effect is measured in order to understand countries behavior against COVID-19 progress and adaptation of SC disruptions. Besides, the resilience measurement of countries is analyzed with the SD model outputs. Finally, different scenario analyzes with the entropy metrics is developed in order to evaluate the resilience of global SCs during the pandemic period. Flowchart of methodology is indicated in Fig. 1.

System dynamics modelling created by Jay Forrester (1961) to analyze complex systems has been applied to many issues in economic, social and environmental dimensions. In addition, it has also been implemented in the global SC, which is complex in nature and has a dynamic structure that includes many interrelated factors (Barratt et al., 2018). Causal relationships between variables determined according to the aims of the system are indicated using causal loop diagrams (Liu
appropriate determination of the variables and the relationships between them in the system is very significant for the system to provide coordination and to present a holistic perspective (Sterman et al., 2015; Darabi & Hosseinichimeh, 2020). The feedback loops that form the main structure of the system dynamics modelling are of two types, negative and positive feedback loops. Loops are a way to reveal nonlinear relationships and complex structures. Thus, the structure of the system can only be accurately defined by these feedback loop mechanisms.

Besides, through system dynamics modelling approach, it can be dealt with unforeseen challenges. Since in systems with high uncertainty environments such as pandemics, it is very important to consider the structure as a whole and to analyze its possible effects. In addition, the analyzed effects are beneficial for decision makers by revealing the analysis of the dynamic structure and investigating the possible effects in the short and long term (Ivanov, 2020). With the system dynamics models, it aims to develop various policies by considering all dynamics in the system, determining the driving factors and defining the leverage points of the systems.

4. A case study–Case of trade between Turkey - China & Turkey-EU

SD model provided in this article aims to represent the impact of COVID-19 on energy efficient global SCs by concentrating on the foreign trade and energy efficiency statistics and logistics activities of Turkey. However, used methodology can be adapted to the foreign trade and energy efficiency statistics of any country by changing the figures, sectors, etc. Implementation stage is beginning with the gathering related data the system under consideration. Different data sources are used in the proposed model. Economic, population, COVID-19 and logistics data are used to build system dynamics model. Turkey import & export, capacity utilization based on sectors for Turkey, Harmonized System Code (HS code) and Broad Economic Categories (BEC) are gathered from Turkish Statistical Institute (TSI). Industrial production based on country and trade in goods and services forecast, industrial production based on country, capacity utilization based on sectors for Turkey are obtained from open databases which indicated in Fig. 2. Active patients’ data is used that represent at a specific time the number of total reported COVID-19 patients actively carrying virus for this study, new patient data and deaths caused by COVID-19 are provided by Ministry of Health and open databases. Population country and total deaths of countries are gathered from Turkish Statistical Institute and related links that shown in Fig. 2. Lastly Logistics data are used in this model such as maritime freight cost, maritime logistics - the amount resulting from Turkey to other countries (tonnes) and country breakdowns on the basis of customs offices which are obtained from different sources - Forefront Company, Ministry of Transport and Infrastructure and Turkish Statistical Institute (TSI), respectively. After providing related information, a causal loop diagram based on Turkey perspective is created to observe relationships between proposed variables and parameters and analyze negative and positive loops in the model. In this study as a case study, which is one of the most important emerging economies is discussed Turkey. Turkey trade flows with China and Europe in particular is a country that is dense and see the bridge with the task of being close to Europe geographically. In addition, it is one of the countries most affected by COVID-19. After this stage causal loop diagram is convert into stock and flow diagram and system dynamics model to investigate the impact of COVID-19 on global SCs by focusing on the foreign trade and energy efficiency statistics and logistics activities of Turkey. With the start of COVID-19 pandemic, foreign trade and energy efficiency statistics of Turkey has been negatively influencing as the disease began spreading in January 2020. In order to represent the impact of COVID-19, countries with the highest import and export values are selected. China is the biggest supplier country of Turkey with 10.3% of total import (88 billion dollars) between 2016-2019 and 86.2% of the imported goods are raw materials or semi-finished products or machinery & equipment (TSI, Foreign Trade Statistics). Therefore, the disruption of import process from China can have detrimental effects on many sectors and various global SCs in Turkey. Similarly, 48.4% of Turkey export is shipped to European Union (EU) and United Kingdom. In Table 1, export value from Turkey to EU countries and United Kingdom are provided.

In SD modelling, among EU countries and United Kingdom, 5 highest

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**COVID-19 DATA**

Source: Ministry of Health Database, https://en.wikipedia.org/wiki/COVID-19_pandemic_in_Turkey, https://en.wikipedia.org/wiki/COVID-19_pandemic_in_Turkey, https://www.worldometers.info/coronavirus, https://covid19.saglik.gov.tr/EN-69532/General-coronavirus-table.html (Turkey, China, Spain, Italy, France, Germany, United Kingdom)

- Active Patients
- New Patients
- Deaths caused by COVID-19

**ECONOMIC DATA**

Source: Turkish Statistical Institute (TSI)

- Foreign Trade and Energy Efficiency Statistics
  - Turkey import & export
    - Country based
    - Harmonized System Code (HS code)
    - Broad Economic Categories (BEC)
  - Capacity utilization based on sectors for Turkey

Source: https://tradingeconomics.com/

- Industrial production based on country

Source: https://data.oecd.org/trade/trade-in-goods-and-services-forecast.htm

- International trade - Trade in goods and services forecast

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**LOGISTICS DATA**

Source: Forwarder Company

- Maritime freight cost

Source: Ministry of Transport and Infrastructure

- Maritime logistics - Handling tonnes from Turkey to other countries

Source: Turkish Statistical Institute (TSI)

- Country breakdowns on the basis of customs offices

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**POPULATION DATA**

Source: Turkish Statistical Institute (TSI), https://ec.europa.eu/eurostat/database/owner/view/DEMO_R_MWK, TX_custom_155620/default/table?lang=en, http://data.un.org/Data.aspx?d=POP&f=tableCode=9&f=5

- Population
- Deaths by country

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Fig. 2. Data of the systems dynamic model.
export countries have been selected. For modelling ease, 5 biggest sectors in export and import data have been selected and provided in Table 2. By considering the effects of COVID-19 on various sectors, these selected sectors, which are electronics, machinery and accessories, textile and raw materials, chemicals and plastics and rubber are the highest affected sector in terms of import value in Turkey (Deloitte, 2020). At the same time, the fact that these sectors, which constitute the most important sector group in the country’s economy (OECD, 2020), are among those most affected by COVID-19, shapes the country’s ability to be affected and manage the effects of COVID-19 (Deloitte, 2020).

Causal loop diagram for the SD model has been provided in Fig. 3 and it is based on Turkey perspective. It is modelled in STELLA graphical version. Causal loop diagram consists of the COVID-19 lifecycles and the impact of pandemic on global SCs. The COVID-19 lifecycles shown in Fig. 3 are the sub model included in the model to represent the impact of the pandemic on global SCs. Export and import activities are negative affected by COVID-19 disruptions. Industry capacity utilization and industrial productivity dramatically are affected by COVID-19 spreads. Thus, model starts with the spread of COVID-19 in China in January 2020. In March, many countries in Europe have been impacted severely by the COVID-19 pandemic. Model has been simulated from January 1st, 2020 to May 31st, 2021. In order to represent pandemic spread, patient and death statistics have been collected. Life cycle of COVID-19 can be most efficiently tracked using active patient counts, since the data is smoother compared to new patient counts or death counts. However, in many countries, data transparency is of an issue and active patient counts are either not visible or not representing the real situation. Therefore, SD model has been adapted based on the available data of each country selected. Available data for each country is shown Table 3. As this article is prepared, all the countries except China is dealing with the second wave of the pandemic. The purpose of the model is to guide countries on estimating when they could go back to work routine and when the impact on global SCs would end by using the most recent available data.

COVID-19 lifecycle in the model shows the load of the pandemic in the country economy; therefore, showing the real impact is critical. In order to represent the real impact, total death numbers are incorporated. In normal conditions, average death rate (total deaths/country population) is quite stable and additional deaths from COVID-19 would increase the total deaths approximately as the reported pandemic deaths. But if the additional deaths in country between years 2019 and 2020 are significantly higher than the COVID-19 reported deaths, this indicates that either the reported numbers for pandemic are not totally reflecting the COVID-19 spread or the health system overload does not permit the support of the other patients. Since the death counts on daily basis show unstable behavior, the numbers are smoothed using moving average over 7 days. In the model, Eq. (1) is used in order to represent the differences in deaths.

\[
\text{Difference}_\text{Deaths}(t) = \begin{cases} 
\text{Death}_\text{Count}_{2020} \times \text{MA7}(t) & \text{if Death}_\text{Count}_{2019} \times \text{MA7}(t) > \text{Threshold} \\
\text{Death}_\text{Count}_{2019} \times \text{MA7}(t) & \text{else 0} 
\end{cases} 
\]

In Eq. (2), COVID-19 reporting difference calculation is provided. Reporting difference will be used a multiplier on the reported active COVID-19 counts of the country (Eq. (3)). Active patient count in a country represents the total reported COVID-19 patients actively carrying virus at time t. As the multiplier on Eq. (2) grows, it shows the real burden in country economy and health system, no matter if there are reporting problems or health system overload, since there are a significantly higher deaths compared to the COVID-19 reported deaths.

\[
\text{Reporting Difference} (t) = \frac{\text{Difference}_\text{Deaths}_\text{MA7}(t)}{\text{COVID}_\text{Death}_\text{MA7}(t)} 
\]

\[
\text{COVID}_{\text{active patient updated}}(t) = \text{COVID}_{\text{active patient}}(t) \times \text{Reporting Difference} (t) 
\]

In Fig. 4, COVID-19 active patient reported counts and updated patient counts are provided. It can be seen from Fig. 4, China had only one wave at the beginning of 2020, but pandemic spread is currently under control. However, at the time of this study (end of November), all the other countries in this study were struggling with the 2nd wave of COVID-19. For United Kingdom, France and Spain since active patient counts are not available at the time of this study, new patient counts are incorporated into the model after smoothing them with moving average over 7 days. New patient count is the number of patients tested positive on COVID-19 test and recently added to the active patients at time t. In SD model, after November 2020, forecasted numbers are provided. Since for China, country total death counts are not available, reporting differences could not be calculated. In the figures, as the updated patient count (red lines) differs from the originally reported patient count (blue lines), this indicates the uncontrollable spread of the virus and overload in the country economy. In Table 4, average reporting difference in the first and second wave of pandemic is shown (based on average values of Eq. (2) output of STELLA). In the table, highest number has been observed in Turkey during second wave, which is reasonable since it is

### Table 1

Export values from Turkey to EU & United Kingdom (TSI, Foreign Trade Statistics-2016-2019).

| Country          | Export value (million $) | Percentage |
|------------------|--------------------------|------------|
| Germany          | 60,680                   | 9.5%       |
| United Kingdom   | 43,262                   | 6.6%       |
| Italy            | 34,914                   | 5.5%       |
| France           | 27,532                   | 4.3%       |
| Spain            | 26,660                   | 4.2%       |
| Netherlands      | 17,658                   | 2.8%       |
| Romania          | 13,535                   | 2.1%       |
| Belgium          | 12,898                   | 2.0%       |
| Poland           | 12,376                   | 1.9%       |
| Bulgaria         | 10,398                   | 1.6%       |
| Greece           | 7,292                    | 1.1%       |
| Sweden           | 5,472                    | 0.9%       |
| Slovenia         | 5,291                    | 0.8%       |
| Austria          | 4,459                    | 0.7%       |
| Hungary          | 4,256                    | 0.7%       |
| Denmark          | 4,021                    | 0.6%       |
| Portugal         | 3,672                    | 0.6%       |
| Czechia          | 3,654                    | 0.6%       |
| Ireland          | 2,377                    | 0.4%       |
| Malta            | 2,075                    | 0.3%       |
| Slovakia         | 1,885                    | 0.3%       |
| Croatia          | 1,425                    | 0.2%       |
| Finland          | 1,256                    | 0.2%       |
| Lithuania        | 1,084                    | 0.2%       |
| Latvia           | 575                      | 0.1%       |
| Estonia          | 454                      | 0.1%       |
| Luxembourg       | 219                      | 0.0%       |
| TOTAL            | 309,378                  | 48.4%      |

### Table 2

Sectors with highest export and import value in Turkey (TSI, Foreign Trade Statistics-2016-2019).

| Top 5 export sectors | %  | Top 5 import sectors | %  |
|----------------------|----|-----------------------|----|
| Automotive           | 26.5% | Electronics          | 29.9% |
| Apparel              | 13.0% | Machinery and accessories | 24.7% |
| Machinery and accessories | 10.6% | Textile and raw materials | 7.2% |
| Textile and raw materials | 9.3% | Chemicals            | 7.0% |
| Iron and steel       | 6.6% | Plastics and rubber   | 6.2% |
known that government reported in start of the second wave only patients that have been accepted to hospitals as new patients. In the first wave, it can be seen that in all of the countries, the pandemic reporting had some difficulties; whereas, in the second wave, reports of Germany, United Kingdom and Italy seem to be under control since reporting differences are approximately 1 (which indicates that reported COVID-19 patient counts are representing the real situation).

COVID-19 lifecycles that are shown in Fig. 3 are the sub model results incorporated into the model to represent the impact of pandemic on global SCs. Especially on the peak points of the pandemic, the spread results with disruptions due to lock-downs in related countries.

Due to the geographical distances between countries, delays on transportation and customs clearance activities are considered in the model. From Turkey point of view, import from China would be delayed by two months. Therefore, the impact of COVID-19 spread in China in January 2020, reflects to Turkey import figures in March 2020. On the other hand, export numbers are impacted by COVID-19 spread with one-month delay. Order planning or production, customs report preparations can take approximately one month; thus, the industrial capacity decrease due to COVID-19, reduces export numbers with one-month interruption. Even though in the second wave of COVID-19 active patient counts in all countries are much higher than the first wave; it has been observed that the impact of pandemic on industrial production has not caused severe damage as in the first wave due to learning effect.

So, all these factors have been represented in the model to calculate export values using the below Eqs. (4-6):

\[
\text{CountryA Export SectorX}(t + 30) = \text{CountryA Export SectorX}(t - 365 + 30) \times \text{SectorX CapacityUtilization_Turkey}(t) \times \text{CountryA Industrial Productivity}(t) \times \text{SlowDown SectorX CountryA}
\]  

Fig. 3. Causal loop diagram.
The use of Shannon’s entropy metric in measuring complexity of a system is common in literature as mentioned earlier. Complexity of a system arises from uncertainty and entropy metric is useful in evaluation of global SCs. In this study, dynamic complexity is considered the level of information sharing and unpredictability hidden in the system. One of the most critical observations is the learning effect of global SCs. As the global SCs and governments become accustomed to the impact of pandemic, they find alternative solutions to handle the disruption such as increasing their productivity, using methods for enhanced technologies to increase automation. In Tables 5–10, export and import figures are shown during COVID-19 pandemic. In order to estimate the impact of 1st wave, period between March to May 2020 have been evaluated since nearly in all countries there had been lockdowns during this selected period. Severe impact of 2nd wave have started to be seen in November and it is anticipated to see the impact of this wave to finalize at the end of February 2021. Therefore, the export trade will be impacted until end of March 2021. All the foreign trade numbers are compared with respect to the same period of 2019 since it was the last observed normal period before pandemic. Last three columns on the table are used for the calculation of “Learning factor” from 1st wave to 2nd wave. This metric is derived from the ratio of foreign trade reductions of 2nd wave and 1st wave. As the metric becomes larger than 1, it emphasizes the fact that import or export grows and sector stays more stable against the severe impact of pandemic. In some sectors, learning factor can increase up to values of 3 to 4, which shows that there is unexpected increasing trend on those sectors. It can happen if there is a special group of products within that sector which becomes demanded for personal use. In Tables 5–10, export and import figures are also provided. With the decrease in the imports from China and in increase in European exports, logistic companies facing difficulties in finding available ships and container in Europe and this increases the freight costs drastically in Turkey. Besides the exchange rate increase in Turkey has an impact on freight costs. Import numbers in Turkey are the materials shipped from China within two months. Therefore, the decrease in import from China in April-2020 reflected to freight costs in March. It is anticipated to observe decrease in freight costs in April-2021.

The results of SD model output will be used in evaluating resilience of global SCs.

5. Resilience measure and its application

The use of enhanced technologies to increase automation. In Tables 5–10, export and import figures are shown during COVID-19 pandemic. In order to estimate the impact of 1st wave, period between March to May 2020 have been evaluated since nearly in all countries there had been lockdowns during this selected period. Severe impact of 2nd wave have started to be seen in November and it is anticipated to see the impact of this wave to finalize at the end of February 2021. Therefore, the export trade will be impacted until end of March 2021. All the foreign trade numbers are compared with respect to the same period of 2019 since it was the last observed normal period before pandemic. Last three columns on the table are used for the calculation of “Learning factor” from 1st wave to 2nd wave. This metric is derived from the ratio of foreign trade reductions of 2nd wave and 1st wave. As the metric becomes larger than 1, it emphasizes the fact that import or export grows and sector stays more stable against the severe impact of pandemic. In some sectors, learning factor can increase up to values of 3 to 4, which shows that there is unexpected increasing trend on those sectors. It can happen if there is a special group of products within that sector which becomes demanded for personal use. In Tables 5–10, export and import figures are also provided. With the decrease in the imports from China and in increase in European exports, logistic companies facing difficulties in finding available ships and container in Europe and this increases the freight costs drastically in Turkey. Besides the exchange rate increase in Turkey has an impact on freight costs. Import numbers in Turkey are the materials shipped from China within two months. Therefore, the decrease in import from China in April-2020 reflected to freight costs in March. It is anticipated to observe decrease in freight costs in April-2021.

The results of SD model output will be used in evaluating resilience of global SCs.
time. Static complexity focuses on the interactions of the elements in a system which is not fitting into our research questions. In Ekinci and Baykasoglu, (2019), the different forms of the adapted entropy metric have been employed in order to understand the overall system complexity and perceived complexity. System complexity is a useful guide for the decision makers to understand overall information flow in the system. Information flow can get larger due to a number of reasons, such as increasing SC size by adding new partners or increasing the information sharing. The increased information flow can be useful if managed appropriately; otherwise, it can threaten the performance of the SC if its size is extremely larger than the capabilities of the users of the system that can handle. On the other hand, perceived complexity evaluates structure of the SC and interrelations of the components of the

Table 4
Average reporting differences of countries showing accuracy.

| Country  | 1st wave reporting difference | 2nd wave reporting difference |
|----------|------------------------------|------------------------------|
| Turkey   | 1.8287                       | 3.0232                       |
| United Kingdom | 1.2991              | 1.0000                       |
| Germany | 1.0727                       | 1.0104                       |
| France   | 1.1427                       | 1.0584                       |
| Italy    | 1.1856                       | 1.0000                       |
| Spain    | 1.1794                       | 1.1552                       |
| China    | N/A                          | N/A                          |

Fig. 4. COVID-19 active patient/new patient counts (The blue curve (1) shows the COVID new or active patients, the red curve (2) shows the updated new or active patients count considering reporting errors for country in the above graphs).
Table 5
Export values from Turkey to Germany.

| Sectors                              | Export to Germany | Change wrt 2019 | 2nd Wave October’20- November’20 (million $) | Change wrt 2019 | Forecast 2nd Wave December’20-March’21 (million $) | Change wrt 2019 | Learning effect 1st Wave Trade Reduction | Learning effect 2nd Wave Trade Reduction | LEARNING FACTOR |
|--------------------------------------|-------------------|----------------|---------------------------------------------|----------------|-------------------------------------------------|----------------|-------------------------------------------|-------------------------------------------|-----------------|
| Automotive                           | 1,519             | -48.0%         | 522                                         | -13.6%         | 483                                             | -54.0%         | 0.52                                      | 0.61                                      | 1.17            |
| Apparel                              | 1,456             | -34.9%         | 464                                         | 11.2%          | 408                                             | -46.4%         | 0.65                                      | 0.74                                      | 1.14            |
| Machinery and accessories            | 1,376             | -34.1%         | 473                                         | 7.7%           | 429                                             | -47.0%         | 0.66                                      | 0.72                                      | 1.10            |
| Textile and raw materials            | 490               | -29.1%         | 190                                         | 5.7%           | 199                                             | -50.3%         | 0.71                                      | 0.67                                      | 0.94            |
| Iron and steel                       | 442               | -36.0%         | 134                                         | 7.2%           | 153                                             | -41.2%         | 0.64                                      | 0.74                                      | 1.16            |

Table 6
Export values from Turkey to United Kingdom.

| Sectors                              | Export to United Kingdom | Change wrt 2019 | 2nd Wave October’20- November’20 (million $) | Change wrt 2019 | Forecast 2nd Wave December’20-March’21 (million $) | Change wrt 2019 | Learning effect 1st Wave Trade Reduction | Learning effect 2nd Wave Trade Reduction | LEARNING FACTOR |
|--------------------------------------|--------------------------|----------------|---------------------------------------------|----------------|-------------------------------------------------|----------------|-------------------------------------------|-------------------------------------------|-----------------|
| Automotive                           | 276                      | -52.9%         | 511                                         | 32.6%          | 679                                             | -20.2%         | 0.47                                      | 0.96                                      | 2.04            |
| Apparel                              | 154                      | -59.5%         | 372                                         | 33.1%          | 324                                             | -24.2%         | 0.40                                      | 0.98                                      | 2.43            |
| Machinery and accessories            | 168                      | -30.3%         | 215                                         | 13.2%          | 207                                             | -40.3%         | 0.70                                      | 0.79                                      | 1.13            |
| Textile and raw materials            | 119                      | -52.0%         | 166                                         | 12.2%          | 191                                             | -35.6%         | 0.48                                      | 0.80                                      | 1.67            |
| Iron and steel                       | 65                       | -58.2%         | 98                                          | 1.4%           | 134                                             | -75.8%         | 0.42                                      | 0.45                                      | 1.09            |

Table 7
Export values from Turkey to Italy.

| Sectors                              | Export to Italy | Change wrt 2019 | 2nd Wave October’20- November’20 (million $) | Change wrt 2019 | Forecast 2nd Wave December’20-March’21 (million $) | Change wrt 2019 | Learning effect 1st Wave Trade Reduction | Learning effect 2nd Wave Trade Reduction | LEARNING FACTOR |
|--------------------------------------|-----------------|----------------|---------------------------------------------|----------------|-------------------------------------------------|----------------|-------------------------------------------|-------------------------------------------|-----------------|
| Automotive                           | 243             | -68.6%         | 498                                         | -1.2%          | 517                                             | -42.5%         | 0.31                                      | 0.72                                      | 2.30            |
| Apparel                              | 86              | -53.1%         | 112                                         | 3.9%           | 131                                             | -43.6%         | 0.47                                      | 0.71                                      | 1.52            |
| Machinery and accessories            | 109             | -50.2%         | 160                                         | 15.2%          | 162                                             | -36.8%         | 0.50                                      | 0.81                                      | 1.63            |
| Textile and raw materials            | 103             | -41.9%         | 123                                         | 8.7%           | 134                                             | -40.9%         | 0.58                                      | 0.76                                      | 1.30            |
| Iron and steel                       | 148             | -54.3%         | 155                                         | 3.6%           | 286                                             | -38.1%         | 0.46                                      | 0.72                                      | 1.58            |

Table 8
Export values from Turkey to France.

| Sectors                              | Export to France | Change wrt 2019 | 2nd Wave October’20- November’20 (million $) | Change wrt 2019 | Forecast 2nd Wave December’20-March’21 (million $) | Change wrt 2019 | Learning effect 1st Wave Trade Reduction | Learning effect 2nd Wave Trade Reduction | LEARNING FACTOR |
|--------------------------------------|------------------|----------------|---------------------------------------------|----------------|-------------------------------------------------|----------------|-------------------------------------------|-------------------------------------------|-----------------|
| Automotive                           | 348              | -61.0%         | 643                                         | 26.4%          | 929                                             | -10.3%         | 0.39                                      | 1.02                                      | 2.61            |
| Apparel                              | 93               | -43.6%         | 111                                         | 4.3%           | 137                                             | -36.5%         | 0.56                                      | 0.77                                      | 1.36            |
| Machinery and accessories            | 113              | -49.3%         | 154                                         | 6.3%           | 185                                             | -31.0%         | 0.51                                      | 0.82                                      | 1.62            |
| Textile and raw materials            | 51               | -48.7%         | 53                                          | -0.7%          | 87                                              | -36.2%         | 0.51                                      | 0.74                                      | 1.44            |
| Iron and steel                       | 57               | -19.2%         | 48                                          | 2.7%           | 62                                              | -31.8%         | 0.81                                      | 0.80                                      | 0.99            |
system. The metrics used in (Ekinci and Baykasoglu, 2019) can be adapted to evaluate the dynamics of the foreign trade between countries. Increase in the complexity of a system increases the probability of disruption. Therefore, decreasing the complexity would increase the resilience of the system by decreasing the probability of failure. Since the results of the SD model is integrated into entropy calculations, timely behavior of the system is evaluated which enables the study to measure dynamic complexity. The results will show the impact of the COVID-19 in foreign trade. As the complexity increases in the calculations, it will show that unexpected pandemic spread could have detrimental effects in the SC, which indicates that SC is not resilient as expected.

An example matrix to be used in calculations is shown in Table 13.

The elements listed below should be repeated for each month that are included into the calculation. Entropy calculation starts with the preparation of a matrix showing inputs and outputs of the system. If there are N elements in the system, the prepared matrix is a NxN matrix showing the flow between these elements. The elements used in the matrix are:

- Monthly export figures for each country and each sector: The actual and forecast numbers from SD results are combined for Germany, United Kingdom, France and Italy on iron & steel, apparel, machinery and accessories, textile and raw materials, and iron and steel sectors.
- Monthly import figures for China: The actual and forecast numbers on electronics, chemicals, machinery, plastics and textile raw material sectors are gathered for China.
- Trade of Turkey: This element receives the import figures from related sector of China and delivers the export numbers to the relevant country and sector.
Table 13
Matrix structure used in entropy calculations.

| Month 1 | Turkey | China | Germany | ... | Italy | ... | Month M | Turkey | China | Germany | ... | Italy |
|---------|--------|-------|---------|-----|-------|-----|---------|--------|-------|---------|-----|-------|
| Sector 1 | ... | ... | Sector 5 Dummy | ... | Sector 1 | ... | Sector 5 Dummy | ... | Sector 1 | ... | Sector 5 Dummy | ... |
| ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| Sector 1 | ... | ... | Sector 5 Dummy | ... | Sector 1 | ... | Sector 5 Dummy | ... | Sector 1 | ... | Sector 5 Dummy | ... |
| ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| Sector 1 | ... | ... | Sector 5 Dummy | ... | Sector 1 | ... | Sector 5 Dummy | ... | Sector 1 | ... | Sector 5 Dummy | ... |
| ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
5.1. Application of resilience measure

Above mentioned entropy metrics can be used to evaluate the resilience of the global SCs in pandemic period. Three cases are analyzed in order to evaluate the resilience of global SCs. In the first scenario, the existing situation during pandemic period have been analyzed by separating the period as first and second wave. In the second and third scenarios, ideas that might be useful to increase resilience are tested. The results are shown in Table 14.

Case 1: Does the impact of COVID-19 pandemic on foreign trade decrease as countries learn to struggle with it?

In order to make a comparison over the same length of period, simulation results are divided into 8-month periods. Impact of 1st wave is covered between February 2020 to September 2020, and 2nd wave is evaluated from October 2020 to May 2021. It has been already explained in the previous section that, in the second wave of the pandemic, due to learning effect, foreign trade figures are better even though the pandemic spread is higher (Tables 5-10). Supporting results are derived from the complexity calculations. In the 2nd wave, with the increased foreign trade, material flow between the countries increases which rises the system complexity. However, since the fluctuation between months reduced compared to 1st wave, system is more stable and perceived complexity is lower. From the resilience perspective, it can be concluded that industries learn to struggle with the pandemic over the time and system becomes more robust. This could be due to a number of reasons like managing manpower, increasing productivity or shifting to automation by decreasing human factor in production.

Case 2: Do the centralized decisions of policy makers increase the resilience of energy efficient global SCs?

To show the effect of centralized decision making, Case 1 results for 1st wave are used for comparison. In the original scenario, if an industry player in any sector cannot achieve to deliver the expected export figure, they will try to find alternative customer on their own or will have economic difficulty which may even end up with bankruptcy due to lost revenue. Therefore, reduced export numbers mean either increased effort for the businesses or economic burden for the industry and country. Similarly, prevented import due to pandemic will force the companies to search for new suppliers or stop production. If the governmental or sector policy makers find alternative solutions to compensate the lost export/import, foreign trade will face with a reduced chance of disruption and will become resilient. As understood from the system complexity reduction, information flow in the system will reduce since decision is made by centralized government. Also, perceived complexity in the system will reduce by the participants since they don’t need to make their own decisions any more.

Case 3: Does using multiple sources for import increase resilience of energy efficient global SCs?

As mentioned earlier, China is the biggest importer country of Turkey and 86.2% of the imported goods are raw materials or semi-finished products or machinery & equipment. This indicates that many sectors in Turkey are closely dependent on the trade with China and any disruption in the foreign trade can impact various producers in Turkey. Again Case 1 results for 1st wave are used for comparison. If Turkey producers start to use alternative suppliers from other countries for sourcing raw material, and half of the import from China can be moved to alternative suppliers, both system and perceived complexity decrease. In case of a pandemic, different countries can have different industrial capabilities, thereby raw materials can be brought from alternative suppliers which are already in use. It is generally easier to continue with an existing alternative supplier rather than searching for a new one and making new contracts in case of an emergency, which can also be interpreted as the decrease in perceived complexity in this scenario.

In this study, COVID-19 life cycle in each country is used to understand their economic burden and global impact on SCs. China, and five European countries are chosen as the most important countries in Turkey’s trade. Using the existing data in first wave and half of second
wave, foreign trade effect has been forecasted using SD model. This impact can guide the researchers to anticipate when each country can go back to work routine and the impact of a third wave or another pandemic that could happen. It has been observed that each country has adapted to the situation in the second wave due to a learning effect since the reported values are more accurate and the impact on global trade is less impacted even though the pandemic spread is larger. In the second part of the study, SD model outputs are evaluated using entropy measures to calculate the resilience of SCs. This measure has supported the learning effect observed in the second wave. Moreover, it has been shown with the results of the entropy measure that resilience increases with the centralized decision making and using multiple resources as supplier in global SCs.

6. Discussions

As mentioned before, providing resilience in SCs has become extremely important today (Oliveira et al., 2019). Especially during COVID-19, companies that took steps to ensure the resilience of their SC survived the devastating effects of COVID-19 with the least damage (Sög et al., 2021). These companies have created action plans to overcome the difficulties in supplying raw materials, sudden demand fluctuations and disruptions in production caused by COVID-19. For example, Amazon has aimed to increase resilience by regulating its supply chains during the COVID-19 process. According to Deloitte (2020), companies adopted digital supply networks to be resilient. In addition, companies have had to act plans not only in their supply chains but also in almost all their processes. For example, Honda has transformed all of its marketing activities into digital during the COVID-19 era (Williams, 2020).

Besides, there are many studies to measure SC resilience in SC. However, these studies evaluated resilience measurement from different aspects (Ayittey et al., 2020). Chen et al. (2019) has been handle with the traditional understanding of SC risk and resilience and these studies are remain restrictive in tackling long-term, global pandemic disruptions. Many studies have evaluated the risk as measured by the SC resilience. These studies are aimed to deal with unprecedented demand fluctuations in and cost increases due to the pandemic. These studies show that resilience of SCs depends on many parameters, and also it is essential to make comparative analysis. However, these studies (Pinho de Lima et al., 2018; Chen et al., 2019; Oliveira et al., 2019) state that there is a gap about measurement of resilience for SCs. In this study, resilience measurement is developed based on the differences arising from the reporting due to the unpreparedness results of the pandemic and the unforeseen consequences for the SC. In other words, the decreases in resilience measure can be seen from the decreases in Table 14. Especially in scenario 1, the resilience was lower because the country was not prepared in the first wave, then the perceived complexity decreased and the resilient increased in the second wave as the countries could cope.

The COVID-19 crisis is substantially affecting regional and global SCs. However, most of the models/studies which is aim to measure the SC resilience in the period of COVID-19 were not covered by geographic analysis. While Oliveira et al. (2019) has been developed resilience measurement modelling during the pandemic period at the organization level. They found that there is gap between risk management in SCs and measurement complexity for these SCs. Besides, El Baz & Ruel (2021) has assessed the role of supply chain risk management to reduce the impacts of disruptions on the supply chain resilience and robustness during pandemic times. Their findings indicated that supply chain risk management at the organization level plays an important role in increasing flexibility and robustness. Pinho de Lima et al. (2018) resilience measurement has been modelled at the regional level. However, in this study, geographic analysis has been performed and the SC resilience measurement is considered globally. They found that SC resilience depends on collaboration, reengineering, visibility, culture, innovation, trust. According to Moosavi & Hosseini (2021) in order to deal with complex supply chain operations, resilience measurement need to be integrated with the simulation models since complexity of supply chain is directly affects on the overcoming disruptions. In general, results of the mentioned studies show that disruption increases as complexity increases in global SCs. If the SCs are resilient, the disruption that will occur is less. Means that being resilient and complexity level are dependent each other.

Most of the studies focus on a single SC based on a single industry and not considered generally SC resilience. Pinho de Lima et al. (2018) has been investigated in one specific SC such as food, bioenergy production, counterfeit medicines, water, and energy. Thus, in this study, it is aimed to analyze the sectors affected by import and export during the pandemic period and in contrast to the mentioned studies. Besides, Negri et al. (2021) stated that more holistic approaches required in order to embrace resilience in the supply chain. This model deals with the global SC since pandemics occur on a macro scale and only a single SC or a specific region is not affected. Based on literature review, there are no studies addressing foreign trade. Therefore, this study is a unique in the literature in terms of handling foreign trade during the COVID-19 pandemic period.

Moreover, another of the unique features of this model, the model complexity measure developed in this study, entropy which is the degree of disorder and uncertainty of the system measure has been adapted to the resilience measure. In this study, whether the impact of COVID-19 pandemic on foreign trade decrease as countries learn to struggle with it, whether the centralized decisions of policy makers increase the resilience of global SCs and whether using multiple sources for import increase resilience of global SCs are analyzed. It is seen that the complexity of the system increases with the increasing foreign trade in the 2nd wave. Moreover, with centralized decisions, resilience of global SCs increases and using alternative suppliers in import operations increases resilience of global SC.

7. Research implications

There are many implications such as theoretical, managerial and policy makers.

7.1. Theoretical implications

The first theoretical implications of this study are that the entropy measure, which is measurement of complexity, has been adapted for the resilience measurement. In global SCs, probability of disruption increases with increasing complexity. However, if a global SC is resilient, it cannot be affected severely by the disruptions due to sudden crisis or events. In this study, dynamic complexity is measured with SD model in order to analyze system’s behavior in a certain time interval and using this measure resilience of the system has been interpreted. Large complex dynamic systems have a critical level at which they suddenly become unstable, and the stability of the system is related to its complexity. According to our study, as the complexity decreases, the stability of the system increases.

Moreover, complexity is measured by using the output of the SD model and incorporating entropy metric. When the behavior of systems against complexity is analyzed, the resilience measurement is carried out. The important point here is that if a single moment was examined in the model application, then information about resiliency would not be obtained. Therefore, with SD model, the behavior of global SCs against COVID-19 are observed over a period of time, and the increase in complexity is analyzed with entropy measurement to determine whether the systems are resilient or not. Proposed SD model is a beneficial to increase supply chain resilience to future crises through developing different policies and strategies.

In addition, learning effects has been calculated in this study and the results were in line with the complexity measurement. As it is shown in
Section 4, in all countries, greater decreases in export & import numbers are observed within the first wave. According to learning effect, countries had been adopted against pandemic disruption over time and it has been observed that countries became more resilient in the second wave, also it has been confirmed by the entropy metric that complexity has decreased and with the increase resilience, their stability increased as well.

For theoretical contribution, the use of SD model is expanded to measure the resilience of global SCs. Moreover, the measure of entropy, which is a measure of complexity, was adapted to the resilience measure. Even though the model has been developed for global SCs by centering the foreign trade and logistics activities of Turkey, used methodology can be adapted to the foreign trade of any country by changing the figures, sectors, etc.

7.2. Managerial implications

There are many implications for managerial and policy makers. For managerial implications, COVID-19 has negative impacts on global SCs and the most important impact is that businesses generally depend on a small number of suppliers. Businesses need to develop and apply enhanced risk management strategies in order to deal with the disruptions. Therefore, there is a need for supplier diversification to prevent disruptions on global SCs as it has been analyzed and revealed in the Case 3, which is seen in the results of the study.

Moreover, with COVID-19, maritime logistics has been in trouble due to the factors such as demand fluctuations, restrictions in ports and borders and lack of adequate number of containers. According to results of the study, the logistics balance is deteriorating. For example; countries started to ship with small ships instead of large ships. This causes the freight and transportation prices to increase. Therefore, to cope with this problem, resilience and complexity should be analyzed by SD based models throughout the global SCs in order to plan their logistics activities. Besides, firms need to take mitigating actions in the supply chain, by investigating impacts on sea, air and land transport due to the restrictions.

In other transport modes, similar problems may occur in maritime, such as in road freight transportation. For example, problems are encountered in the transit of trucks to Europe in road transportation due to the long queues at the borders. These problems also cause delays in shipments. This situation can even be triggered or amplify by the insufficiencies in governmental planning. Thus, in order to cope with these problems, government regulations must be followed regularly to take important decisions rapidly. In addition, it is essential to plan modal and intermodal logistics activities. Hence, the proposed analysis of this study, which is in line with the results of the study can be used by the managers of the global SCs.

Furthermore, the fact that businesses are not prepared for problematic situations such as pandemic that causes fluctuation in raw material and stock levels. Problems in raw material supply affect the SCs of businesses on a global scale. Businesses should create scenario planning for a quick recovery in order to deal with slowdown. In addition, they should infer from key risks from the previous experience across operations and supply chain and should actions on this basis. According to the results of the study related to learning effect, reveals that one of the most important implications at this stage is the necessity of proper stock planning, decreasing human factor and increasing digitalisation in manufacturing sector. In addition, businesses are affected negatively from COVID-19 because of inefficient network design of their global SCs. This is due to the fact that most of global SC managers do not analyze resiliency and complexity of their global SC network.

7.3. Policy implications

For policy makers, as seen in the study, the transparency, reliability and lack of data cause transparency problems and misleading reporting situations. Therefore, databases should be created to encrypt this problem and to ensure transparency in countries.

Another implication is to be prepared against sudden disruptions such as COVID-19 is a major problem. Although there were countries that previously experienced SARS and MERS pandemics, as shown in the study, differences in reporting of various countries shows that countries are still unprepared. Therefore, country policies and management should have action plans against such sudden disruptions. Besides, cross-border cooperation should be conducted by the government by providing response and recovery policies and strategies for the lowdown and pandemic situations. Regional dimensions such as municipalities and local governments should also be integrated into national recovery strategies. The allocation of investment funds for uncertain times such as the pandemic should be effectively planned and organized in order to increase resilience.

Furthermore, the first wave of the COVID-19 pandemic has defeated the economies of the countries in the worldwide. However, as depicted in this study, although the number of patients increased in the second wave of the pandemic, the impact on global SCs decreased. It means that although countries can cope with the negative impact of the pandemic, as mentioned in the results of learning effects analysis of this study, infrastructure and resources can be managed more effectively in the further stages of the pandemic. Moreover, the cooperation of all stakeholders is inevitably collaborated in difficult times in order to provide resource efficiency. To achieve sustainability and resilience and to avoid mistake, government need to be benefit from the previous experience and recovery strategies by using learning effect.

8. Conclusions

Increase in global demand and globalization, global SCs become more vulnerable to sudden disruptions such as epidemics. Recently, COVID-19 pandemic has affected the whole world and caused disruptions in global SCs. The main contributions of the study is determining the COVID-19 effects on global SCs of countries and evaluating resilience level of global SCs of countries, such as Turkey, China, and EU. For this purpose, SD is used for analysing how global SCs of these countries are affected from COVID-19 based on complexity measurement. In addition, by considering foreign trade statistics and international logistics activities, the resilience of mentioned countries global SCs COVID-19 has been evaluated within the scope of the complexity theory.

One of the main contributions of the study is evaluating COVID-19 impacts on Turkey and China, and Turkey and EU’s energy efficient global SCs based on sectoral impacts. Therefore, this research is a kind comparative study, which is beneficial for governments, decision-makers and managers to navigate and manage COVID-19 resilient and energy efficient global SCs. Moreover, the uniqueness of the study is that the measure of entropy, which is a measure of complexity, was adapted to the resilience measure.

As mentioned before, the most affected countries in Europe from COVID-19 are determined as Germany, United Kingdom, Italy, France and Spain. Based on export rates, the highest sector in terms of export value in Turkey, Automotive, Apparel, Machinery and accessories, Textile and raw materials, respectively and Iron and steel are determined, respectively. Furthermore, the highest sector in terms of import value in Turkey, Electronics, Machinery and accessories, Textile and raw materials, Chemicals and Plastics and rubber are determined, respectively.

As main results of the study, it is determined that there are differences between reports of first and second wave of the pandemic and it is shown that first wave reporting differences are more than second wave differences. Because of learning effects, the impact of second wave of COVID-19 on economy and foreign trade of countries are less than impacts of first wave. The other major results of the study are that it is determined that perceived complexity of the system decreases in the second wave which show that the resilience of SC with the learning
effect. As other results of the study, it is shown that countries are more resilient in second wave than first wave. Furthermore, centralized decision making provides increasing resilience and resilience measure in global SCs.

Limitations of the study is to have proper data from countries. Generally, COVID-19 data is not available for the countries. The proposed model has been developed for selected sectors based on the pandemic time and thus obtained results cannot be generalized. In the event of a third wave, according to the course of the pandemic, there may be differences in the estimates, and the discussed sectors which is the most exports and imports may change in the course of time.

For further research, as this study was conducted in the second wave of the disease. In the third wave of the disease or in case of any mutation, the application should be repeated with new data. Used variables in the model are valid for any country and can be derived from national statistical institutions of the countries. After modifying the model, and according to the existing pandemic situation or country specific changes, the resilience and complexity measurement of the SC can be evaluated. Various scenarios for the evaluating resilience measurement can be extended. Besides, selected sectors can be diversified based on the pandemic conditions. This model is developed based on the Turkey perspectives which is one of the emerging countries but this model can be developed for different countries in order to compare and evaluate the impacts of the pandemic.

Authors statement

Dr. Ezra: data curation,methodology; Dr. Sachin: review, editing; Dr. Yigit: supervision and validation; Dr. Sarma: visualization; Muruvvet Deniz: formal analysis, data curation and writing; Melisa: writing, resources, data curation.

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