Building Resilience to Climate-Change-Related Disruptions in the Global LNG Supply Chain

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Abstract

Liquefied Natural Gas (LNG) supplies one-third of the global natural gas market and is expected to grow in volume in the years to come. The LNG supply chain is faced with many challenges, including (1) increased exposure to climate-change-related hazards like hurricanes, typhoons, storm surges and sea level rise, (2) changes in market structure with opening up of new trade routes, e.g., Panama Canal, and (3) changes in energy prices, development of new energy sources and gas supplies, e.g., Shale Gas. A model of the global LNG supply chain is developed in order to assess vulnerabilities and to help identify measures to build resilience. The global supply chain is simplified with the aggregation of four large regions of the world, where each region produces and consumes LNG. It is found that climate-change-related disruptions in one region can have cascading effects in other regions, that the policy that minimises the effect of the disruption in one region can increase it in other regions, and that a policy best suited to one kind of disruption can be poorly suited to other kinds.

Introduction

The Liquefied Natural Gas (LNG) industry supplies one-third of global natural gas, constituting a US$340 billion industry in 2011. But there exist large uncertainties related to how this industry will develop in the future, due to the influence of politics, global economic growth, cross-border trade and technological change, among others. Estimates for the industry range up to US$725 billion by 2030 [McKinsey, 2014]. Climate change adds another layer of new and not widely recognised risks to the LNG supply chain. Uncertainty is related to the timing, severity and location of climate change impacts and extreme weather events. Therefore there is a need to better understand these vulnerabilities and the potential for building resilience in the LNG supply chain.

Risk assessments which focus on hardening specific system components (*e.g.*, individual LNG export terminals) have proven to be useful when assessing foreseeable and calculable stressors. However, risk management is faced with a number of challenges to identifying and providing guidance to the scale, complexities and uncertainties associated with climate change in global supply chains [Simchi-Levi, 2014]. A resilience perspective enables a wider understanding of the LNG supply chain and its vulnerabilities and can guide companies and governments to move beyond individual risk assessments and envision longer-term, synergetic measures to build resilience.

Various disciplines define resilience in different ways, but in this work we follow the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report's definition of resilience as 'The capacity of … systems to cope …. responding or reorganizing in ways that maintain their essential function, identity, and structure, while also maintaining the capacity for adaptation, learning, and transformation' [IPCC, 2014].

In many resilience-building initiatives the authors are familiar with, it seems that measures are recommended based on intuition about the behavior of the system, based primarily on case studies. However, learning has shown that even in simple systems, non-intuitive behavior is often observed. To further develop the field of resilience sound principles are needed, including models and simulations of socio-economic technical systems. A model addressing all aspects of the LNG supply chain would be extremely large and complex. However, small aggregated system dynamics models can create insightful lessons [Forrester, 1961; Pruyt, 2013]. Therefore, we have developed a model to achieve some general learning objectives, including how climate-change-related disruptions might affect the LNG supply chain and how a disruption in one region can create cascading effects and affect other regions, without attempting to capture the totality of the LNG supply chain dynamics.

Methodology

Using a framework developed in collaboration with member companies in the World Business Council for Sustainable Development (WBCSD), our five-step methodology is:

1. Map the supply chain
2. Outline critical features of the supply chain
3. Determine weather-related hazards
4. Identify vulnerabilities
5. Define and apply resilience-building measures

The first step outlines the principal material flows, stockpiles and locations in the supply chain. The second step distinguishes the features of the supply chain that are critical to understanding the dynamic response to a disruptive event. The third step determines current and future weather-related hazards and scenarios for the individual nodes in the supply chain. The fourth step identifies and gauges the magnitude of vulnerabilities via dynamic simulation, and finally in the fifth step resilience-building measures for the supply chain are identified [WBCSD, 2015].

For the purpose of this study System Dynamics (SD) is used to assess the LNG supply chain. System Dynamics has been widely used to study supply chains [Forrester, 1961; Sterman, 2000] and, in the last decades, increasingly to study climate change [Sterman *et al.*, 2013]. More recently SD has been used to quantify resilience in systems exposed to climate-related hazards [Simonovic and Peck, 2014]. The next sections detail each of the steps in our methodology.

Mapping the LNG supply chain

The liquefied natural gas (LNG) supply chain consists of a number of steps, depicted schematically in Figure 1 below. First, natural gas is transported via pipeline to a liquefaction plant where it is chilled from gaseous form into LNG at an export terminal. Here, LNG is loaded onto a specialised tanker ship. The ship then sails to an import terminal. There, the LNG is unloaded and regasified. Finally, the natural gas is distributed to the customers by pipelines. The liquefaction and regasification steps are capital- and energy-intensive, typically accounting for more cost combined than the cost of the gas at the wellhead.

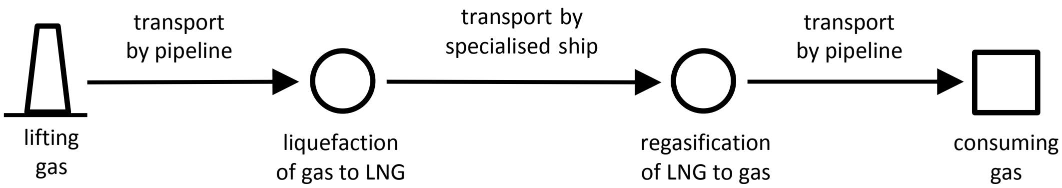

Figure 1. Schematic diagram of the LNG supply chain.

Though natural gas is produced in many locations around the world, the number of liquefaction terminals, plants capable of chilling gas into liquid form, worldwide is currently only about 30. Most of the world's liquefaction capacity is located in the Middle East and Australia. Europe, the United States, Russia and South America currently have only one operational export facility each.

Regasification plants, which turn LNG back into gas for delivery to users, are more numerous, being about 100. Due to its cryogenic nature, LNG requires specialised transport ships, of which there are about 400 worldwide, a number that is rising rapidly. Due to record low gas prices in North America combined with high demand in Asian markets, a number of large export and import terminals are under construction in North America, Africa, Australia and China.

The map in Figure 2 below shows how we have divided the world into major producing and consuming regions.

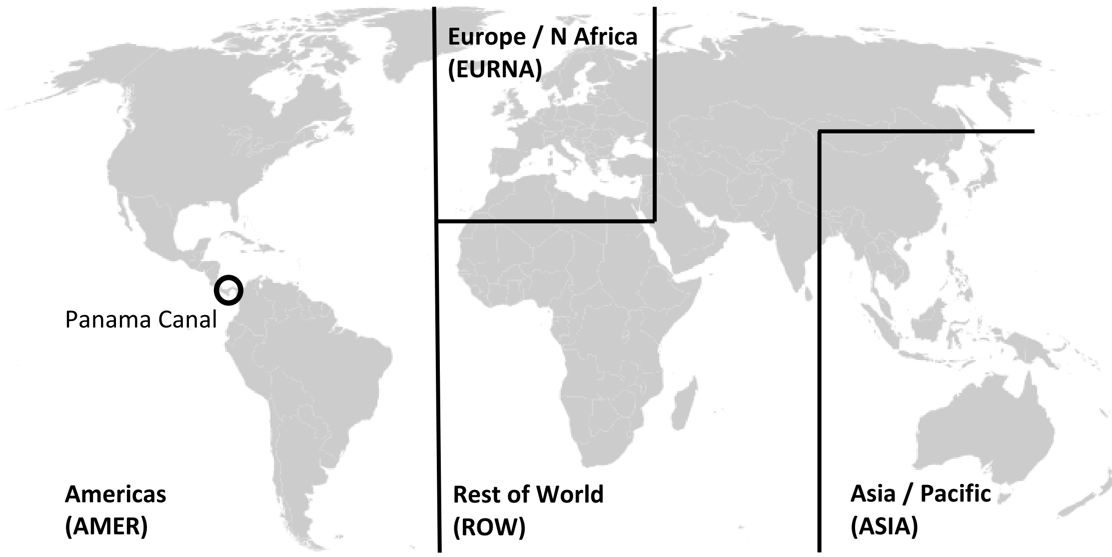

Figure 2. Map of major world regions used in this study.

Because the gas liquefaction and shipping operations are both capital- and energy-intensive, the economics of the LNG industry is only favorable over distances which are prohibitive for pipelines. Currently, about one-third of all natural gas consumed worldwide is transported as LNG and the other two-thirds is transported by pipeline without ever being liquefied. The cost-intensiveness of the LNG industry means that historically LNG trade has operated under long-term export and import contracts, with the price of the product typically indexed to the current price of crude oil. About two-thirds of LNG is currently traded under contract with the remaining one-third via gas spot pricing.

Outlining critical features of the supply chain

In this work, we are concerned with short-term climate-related disruptions and the rate and degree to which the industry recovers in the weeks and months following such disruptions. Therefore, we focus primarily on local production and local consumption in each region of the world, and the inter-region LNG trade and we disregard decade-scale changes in the supply chain, such as the trajectory of the so-called Shale Gas Revolution or long-term cycles in vessel construction and laying-up.

In Figure 3 we represent the global LNG market as a network of 'source' and 'sink' nodes connected by flow pathways. Each node in the model represents the aggregated behavior of one large region of the Earth: the Americas (AMER), Europe/North Africa (EURNA), Asia/Pacific (ASIA) and the Rest of the World (ROW). This work builds on a model of extreme-weather-related disruptions in a manufacturing supply chain [Libby and Christiansen, 2014]. Each region produces and consumes LNG, but two of the regions (AMER and ROW) produce more than they consume while two of the regions consume more than they produce (EURNA and ASIA).

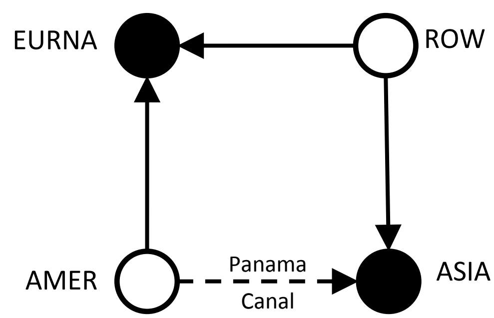

Figure 3. Source-and-sink diagram of regions in the model of LNG trade. Each region, represented by a circle, both produces and consumes LNG. White circles represent net exporters and black circles net importers. Arrows indicate direction of net trade. The dashed arrow is the route through the Panama Canal from the Americas to Asia/Pacific.

A causal loop diagram showing some of the important feedback structure is shown in Figure 4. A central variable is the LNG storage ratio, the ratio of LNG in storage to the 'normal' level of LNG in storage. A shortfall in LNG inventory dampens local gas consumption through presumed higher prices and fuel switching, neither of which are explicitly included in the model but which are implicitly included via the 'availability effect' variable, described in greater detail below. A shortfall in LNG inventory also promotes local LNG production, the desired level for which is governed by the shortfall, by local demand, and the demand for exports from the region (if any).

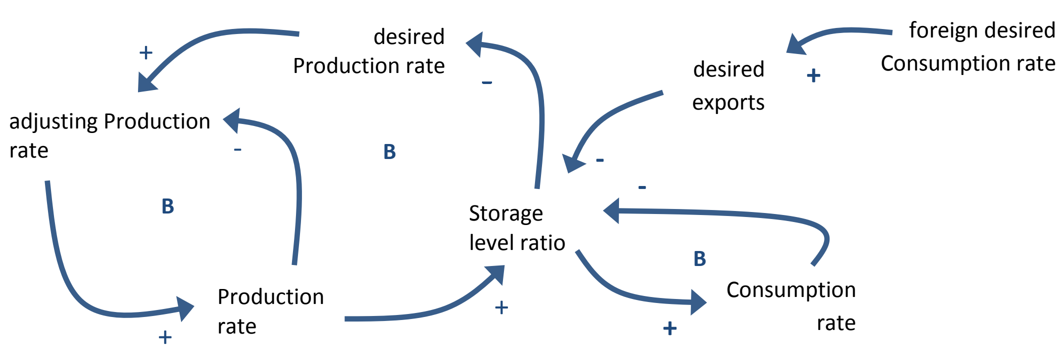

Figure 4. Causal loop diagram showing some of the important feedback structure in the LNG model.

A portion of the SD model representing the structure of the Americas node is shown in Figure 5, below. The structures of the nodes representing the other three regions of the world are conceptually similar. The complete model file is available as supplementary material.

Production of LNG within each region is governed by a first-order negative feedback ('stock adjusting') structure. The Production stock adjustment time constant is 4 weeks for each node. Each region has a local demand for LNG (represented by the sum of desired local consumption plus, in the case of exporter nodes, the sum of the desired demands from the importing nodes). When shipping is available through the Panama Canal, the desired exports from the AMER region is the sum of desired imports from both EURNA and ASIA. In cases where shipping through the Canal is not available, desired AMER exports is only the desired imports by EURNA.

Desired regional Consumption is represented by a first-order negative feedback ('stock adjusting') structure. Price is not explicitly modeled, but the effect of LNG availability (supply) on consumption (demand) is accounted for via a sigmoidal function called the 'availability effect'. When LNG storage levels in a region are high compared to 'normal' stored volumes, consumption will tend to increase. As the regional storage level drops, so too does the desired consumption level. The form of the availability effect function is seen in equation 1 below:

$$\text{availability effect} = 2 / (1 + \text{EXP}(-4*(s-1))) \qquad [1]$$

where 's' is the local storage ratio (LNG in storage / normal LNG in storage)

Each region normally keeps a certain amount of LNG in storage. Production and import of gas increase the stored amount, while consumption and exports decrease it.

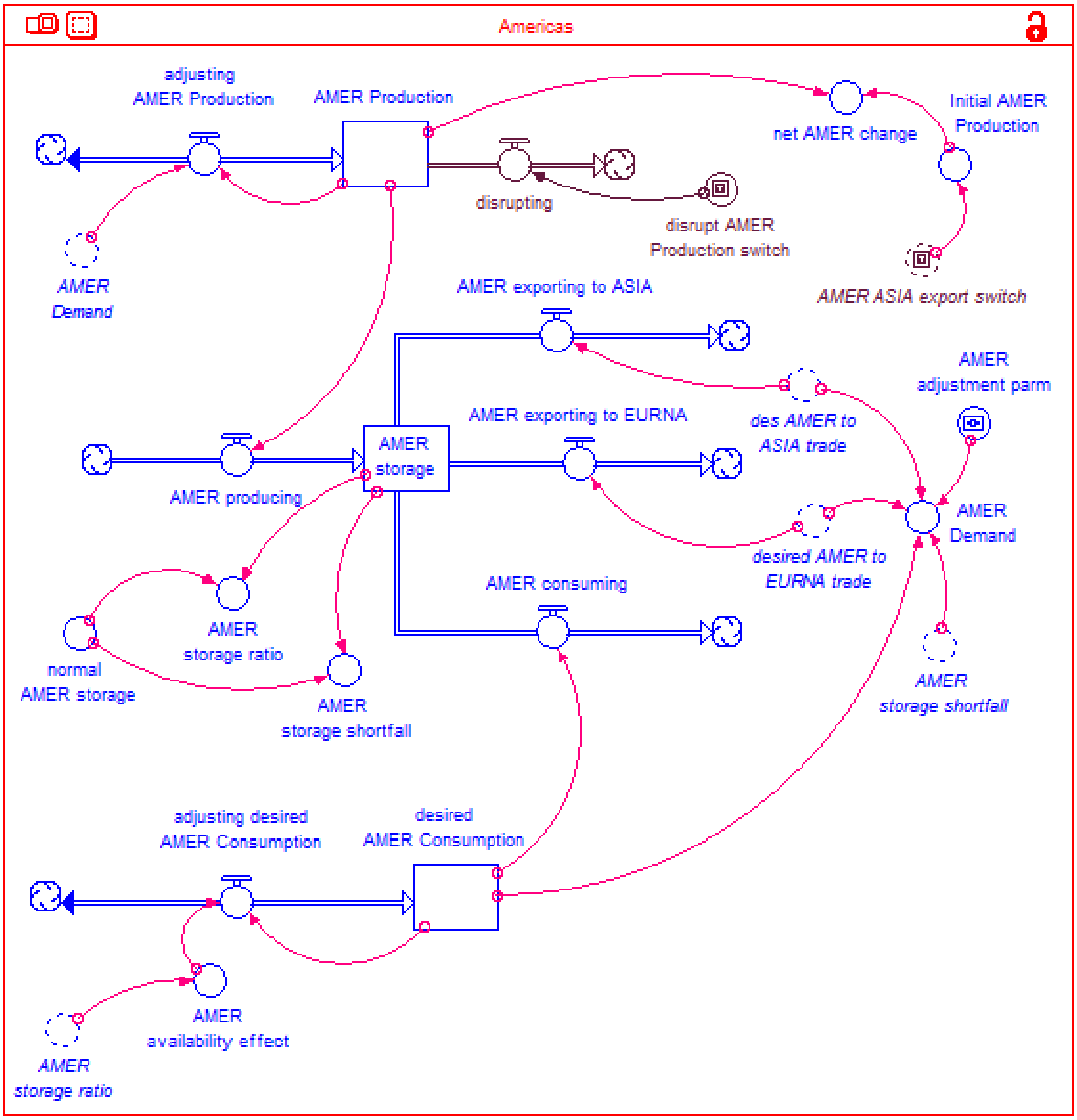

Figure 5. Stock-and-flow map of the Americas node of the LNG market, tracking the production, consumption, storage and trade of LNG. The structure of net importing nodes (EURNA and ASIA) is similar, but with the exporting flows reversed in direction.

The regional demand for LNG is simply calculated as the desired consumption level (plus, for exporters, the volumes desired by the importing regions) combined with some portion of the shortfall between the desired LNG storage level and the current LNG storage level. That is:

$$\text{demand} = \text{desired usage} + a*(\text{desired storage} - \text{current storage}) \quad [2]$$

In equation 2, 'desired usage' is local consumption plus desired exports. (For the importing regions, desired exports is 0.) Thus, each region attempts to maintain a constant amount of LNG in storage and the agressiveness by which a shortfall or overstock in that desired storage level is rectified is governed by the adjustment time parameter, *a*.

	Production	**Consumption**	**Storage**
AMER	110 (before Panama expansion) 120 (after Panama expansion)	100	100
EURNA	40	70	70
ASIA	40	70	70
ROW	60 (before Panama expansion) 50 (after Panama expansion)	10	100

	Pre-disruption Trade Volume
AMER to ASIA	0 (before Panama expansion) 10 (after Panama expansion)
AMER to EURNA	10
ROW to ASIA	30 (before Panama expansion) 20 (after Panama expansion)
ROW to EURNA	20

Figure 6. Initial production, consumption and trade volumes, by region and route.

Rather than attempt to explicitly model the effects of long-term contracts on the LNG trade or to model poltical considerations in gas source diversification, it is instead simply assumed in the model equations that both EURNA and ASIA attempt to get 1/3rd of their LNG from the Americas, if possible, and the remainder from the Rest of the World.

In one variation of the model, we consider the case where the direct export of LNG from AMER to ASIA is not possible. This variation is intended to represent the condition when the Panama Canal was not large enough to accommodate most LNG-carrying vessels. In this case, a disruption in the Americas or ASIA only affects the other region indirectly via the effects on EURNA and/or the Rest of the World.

Another variation allows the direct export of LNG from AMER to ASIA. This variation is intended to mimic the condition where the Panama Canal has been expanded to be large enough to accommodate most LNG-carrying vessels.

The model is intended to be neither quantitative nor predictive in its present form. Rather, it can be viewed as a simplified model whose purpose is to identify the response of production, consumption and shipping levels in different regions to disruptions anywhere in the network.

Determine weather-related hazards

We identify three critical locations in the development of the LNG industry that could be severely affected by extreme weather: (1) Gulf Coast of the USA, which is a hotspot for hurricanes and is also likely to be a net exporting region in the near future, (2) Panama Canal, where a recently-completed expansion provides an additional shipping route for LNG trade, but which is also concerned about droughts and water availability in the long term and (3) Asian markets, particularly China, which are increasing in LNG demand but also susceptible to typhoons and flooding.

Due to the so-called 'Shale Gas Revolution' in the United States, North America has been a dramatically increasing producer of natural gas in recent years, which has led to an oversupply in the local market. Between 2008 and 2012 gas prices in North America fell from about US$9/MMBtu to about US$3/MMBtu [McKinsey, 2014]. In contrast, gas prices have increased substantially in Asia, due both to economic growth and to Japan's decision to shut down nuclear capacity following the disaster at Fukushima in 2011. Thus, there is now a strong economic incentive to export LNG from the Americas to Asia and major LNG liquefaction and export facilities are currently under construction on the US Gulf Coast to address this need. A Panama Canal expansion project finalised in 2015 opens the canal in principle to nearly all existing LNG tankers. However during times of drought, it is possible that the canal's reservoirs may not always be able to supply sufficient water to the locks, making this route vulnerable to disruptions [Christiansen *et al.*, 2014]. For example, in August 2015, due to drought conditions that caused low water levels in the canal, the Panama Canal Authority restricted transit to vessels when laden that extended no more than 39 feet below water level. This coincidentally is the depth (or 'draft') of the largest LNG vessels (so called 'Q-MAX' vessels). In their August decision, the Authority stated that they might make this limit even more restrictive in September 2015 if drought conditions persist [Time, 11 August 2015].

The remainder of this study is concerned with the global effects of a weather-related disruption in LNG production in the Americas, a disruption in the availability of the Panama Canal for shipments from AMER to ASIA, or a weather-related event in ASIA that impacts both production and consumption of LNG.

Identifying vulnerabilities

We now use these three scenarios to stress-test the LNG model, which is constructed in STELLA. Each simulation is intialised in steady-state using the values seen on the tables in Figure 6 above, so that the deviation after the disruptive event can be seen more clearly. The simulation is conducted for 200 time units (days), with the disruption occurring at time=20.

One method of building resilience might be to optimise the storage shortfall adjustment parameter. In these investigations, we primarily consider the effect that the selection of the American adjustment parameter has on the response of production levels throughout the world to several disruption scenarios. For this purpose, we considered three values of the adjustment parameter, 0.5, 1.0 and 4.0.

Scenario 1: A decrease in LNG production in the Americas, before and after the expansion of the Panama Canal

In the first scenario we consider a disruption in production levels in the Americas before the renovation of the Panama Canal permits the transit of LNG vessels. When the disruption occurs, 20 units of production in the Americas are pulsed out of the system, being restored via the 'adjusting AMER Production' flow at the rate of 'AMER Demand – AMER Production' / 4.

The graphs below show the effect of a disruption in American LNG production on production levels around the world when the Panama Canal shipping route is not active (that is, prior to the expansion of the canal).

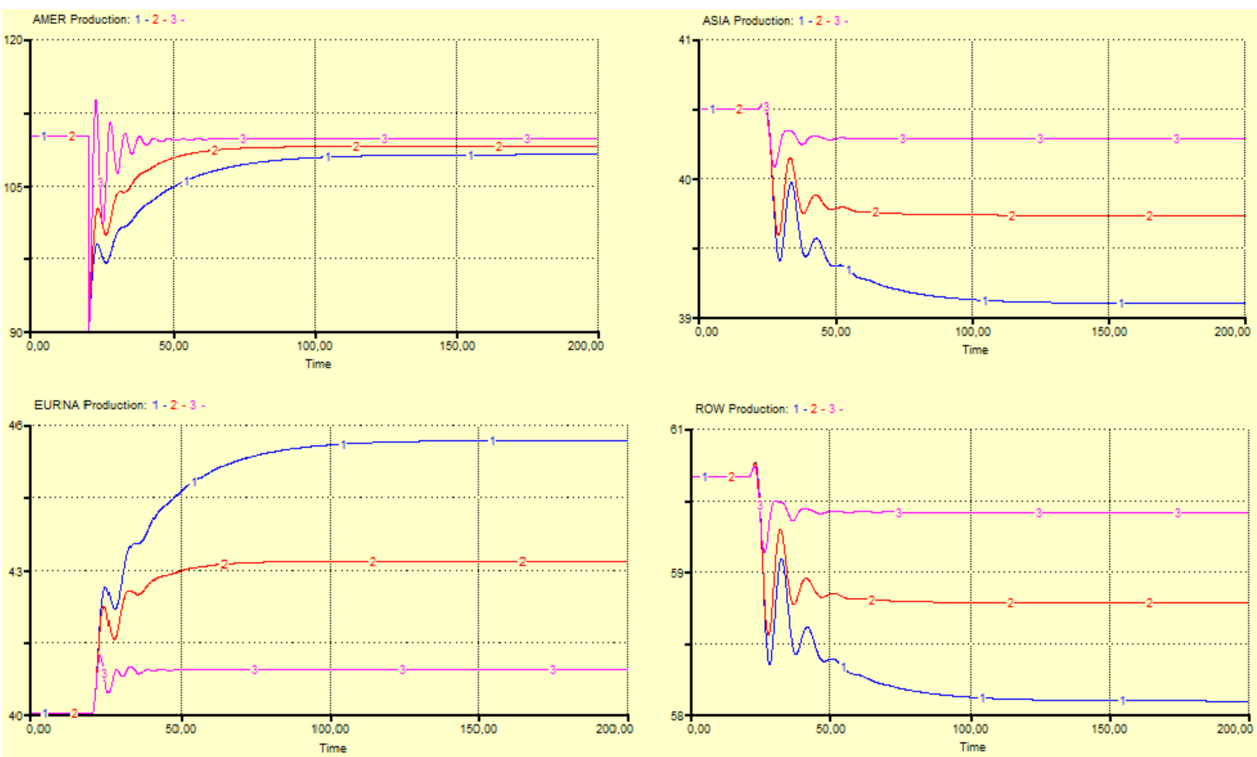

Figure 7. Regional LNG production for a disruption in American production prior to the Panama Canal expansion for three values of the AMER adjustment parameter (blue=0.5, red=1.0, magenta=4.0). The regions are (clockwise from top left): AMER, ASIA, ROW, EURNA.

We can see in Figure 7 that the disruption of American production causes a permanent shift in production levels worldwide, with EURNA favoring more production and the other regions favoring lower production levels.

From a resilience perspective, we consider effects that result in the least deviation from pre-disruption levels to be the most 'resilent'. In this case, when the American adjustment time parameter ('*a*' in equation 2 above) is largest (*i.e.*, fastest), all four regions see the least net effect of the disruption.

We repeat the same analysis with the Panama Canal shipping route activated. (Some of the initial production and shipping volumes have been changed so that the system is in steady-state conditions prior to the disruption).

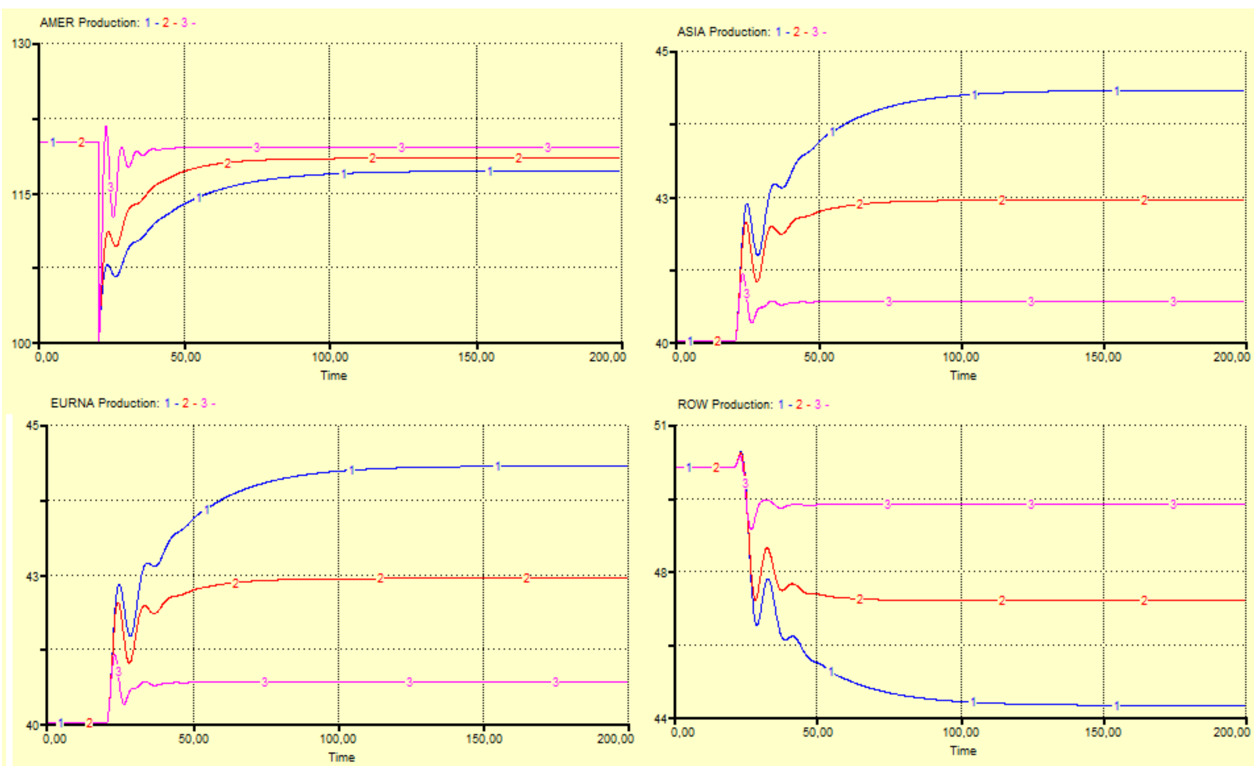

Figure 8. Regional LNG production for a disruption in American production after the Panama Canal expansion. The regions are (clockwise from top left): AMER, ASIA, ROW, EURNA. (adjustment parameter values: blue=0.5, red=1.0, magenta=4.0).

In Figure 8 we see that the effect of a disruption in American production on ASIA is reversed from the previous case. Now, a disruption in American production favors an increase in production in ASIA, rather than a decrease. Production in EURNA and ROW are affected in a qualitatively similar manner to the previous case, though to different degrees. Again, the largest value of the AMER adjustment parameter minimises the effects of the disruption in all regions of the world.

Scenario 2: A disruption in the availability of the Panama Canal shipping route

In the second scenario we consider a disruption in the availability of the Panama Canal to LNG shipping. We initialise the system in the steady-state conditions for the case where the Canal is available for LNG transit. At time=20, the Canal suddenly becomes unavailable for LNG transit for the remainder of the simulation. This mimics the case where, for example, an extended drought pushes the Canal water level below the minimum threshold needed by LNG tankers.

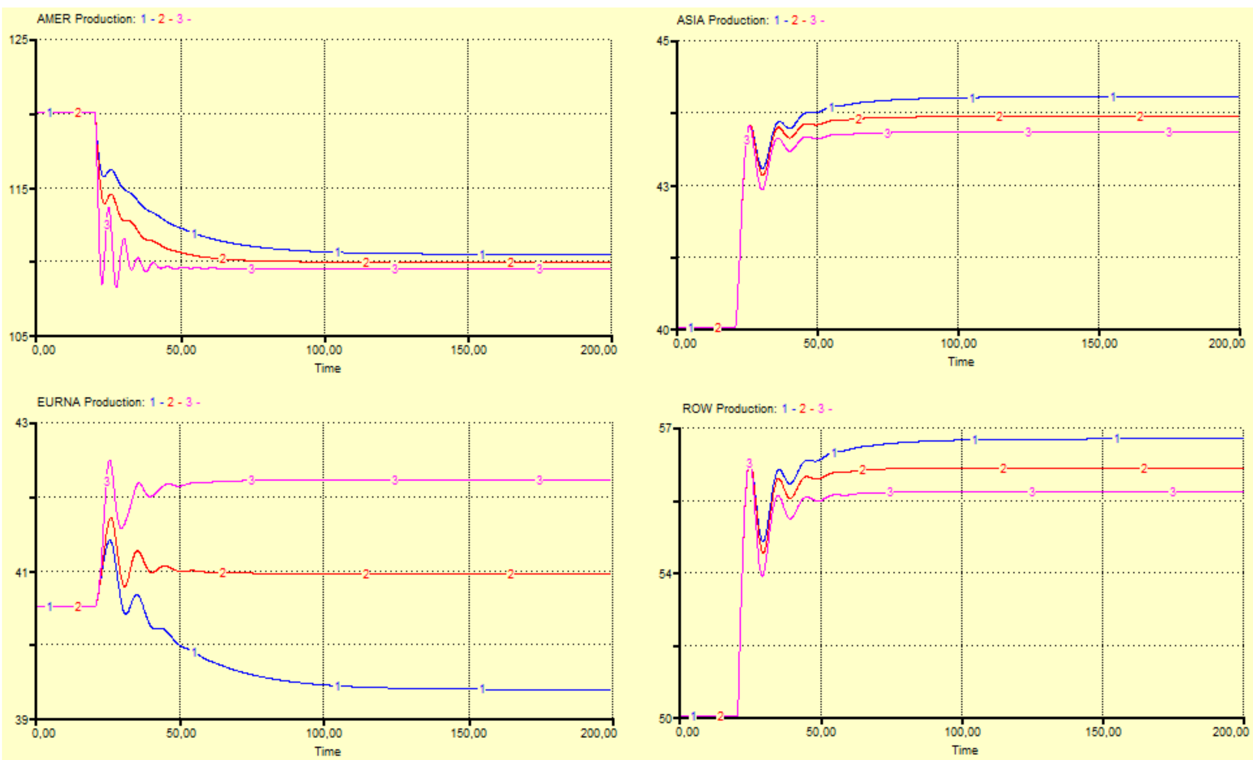

Figure 9. Regional LNG production for the scenario where a disruption in the Panama Canal at time=20 leaves the Canal unusable for LNG transport. The regions are (clockwise from top left): AMER, ASIA, ROW, EURNA. (adjustment parameter values: blue=0.5, red=1.0, magenta=4.0).

In this case we see that the AMER region is relatively insensitive to the adjustment parameter and is best served by a low value of that parameter. However, the other regions are more sensitive. ASIA and ROW see the least effect of the disruption when the parameter value is the highest. The effect in EURNA depends strongly on the AMER adjustment parameter, with a low value favoring reduced EURNA production, a high value favoring increased EURNA production, and an intermediate value resulting in the least effect on EURNA production.

The effect of the disruption in the availabilty of the Panama Canal on global LNG trade and on specfic trade routes is seen in Figure 10 below.

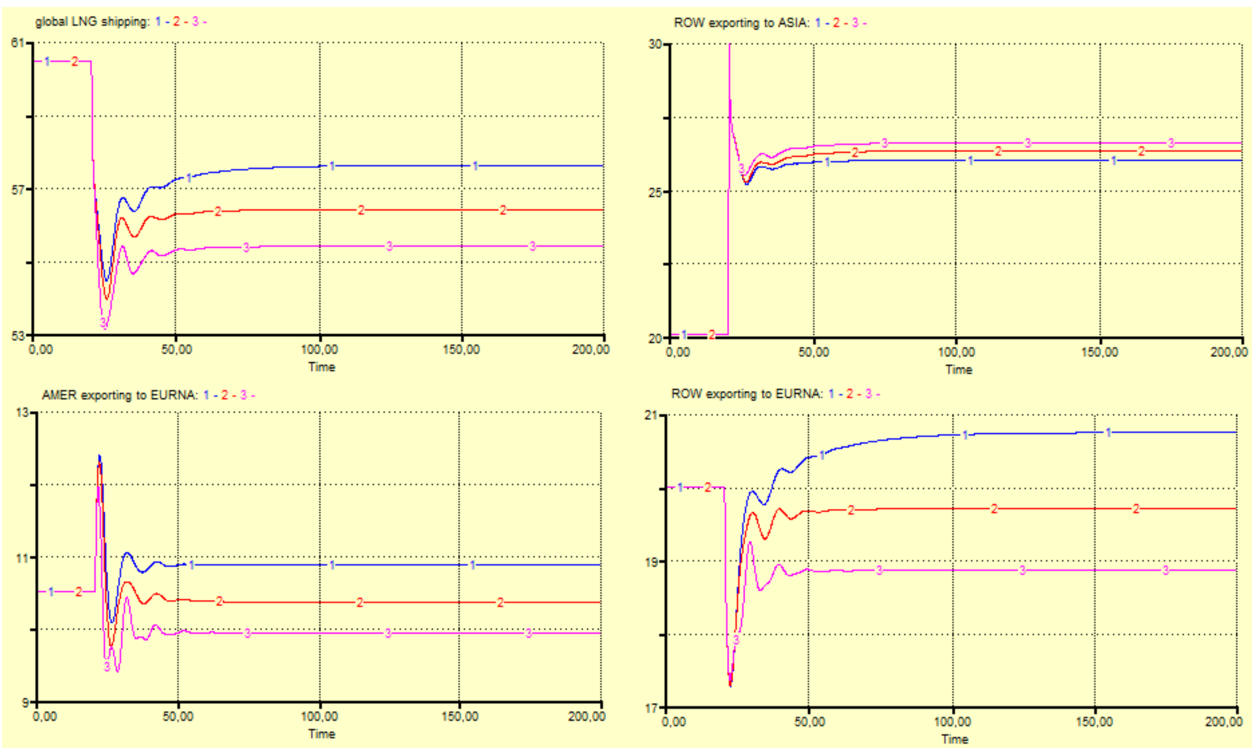

Figure 10. Interregional trade change for the disruption in the Panama Canal scenario. (clockwise from top left): global LNG shipping, ROW to Asia, ROW to EURNA, and AMER to EURNA. The 'AMER to ASIA' route is not shown, as it is constant prior to the disruption and 0 after. (adjustment parameter: blue=0.5, red=1.0, magenta=4.0).

In this case, the loss of the usage of the Canal results in on overall drop in total LNG shipping volumes, as might be expected when shipping becomes more difficult. Both shipping from 'AMER to EURNA' and 'ROW to EURNA' region see volumes rise or fall depending on whether the American shortfall adjustment parameter is small or large. Shipping from ROW to ASIA favors an increase over pre-disruption levels for the parameter values examined.

Scenario 3: An increase in LNG consumption in ASIA combined with a decrease in production

In the third scenario we consider a sudden increase in demand for LNG in ASIA coupled with a decrease in production in the region. This mimics the case where, for example, a powerful typhoon disrupts LNG liquefaction facilities in ASIA while at the same time causing an increase in demand for energy from ASIA consumers. Figure 11 shows the effect of the discontinuity in ASIA production/consumption levels on the production throughout the world.

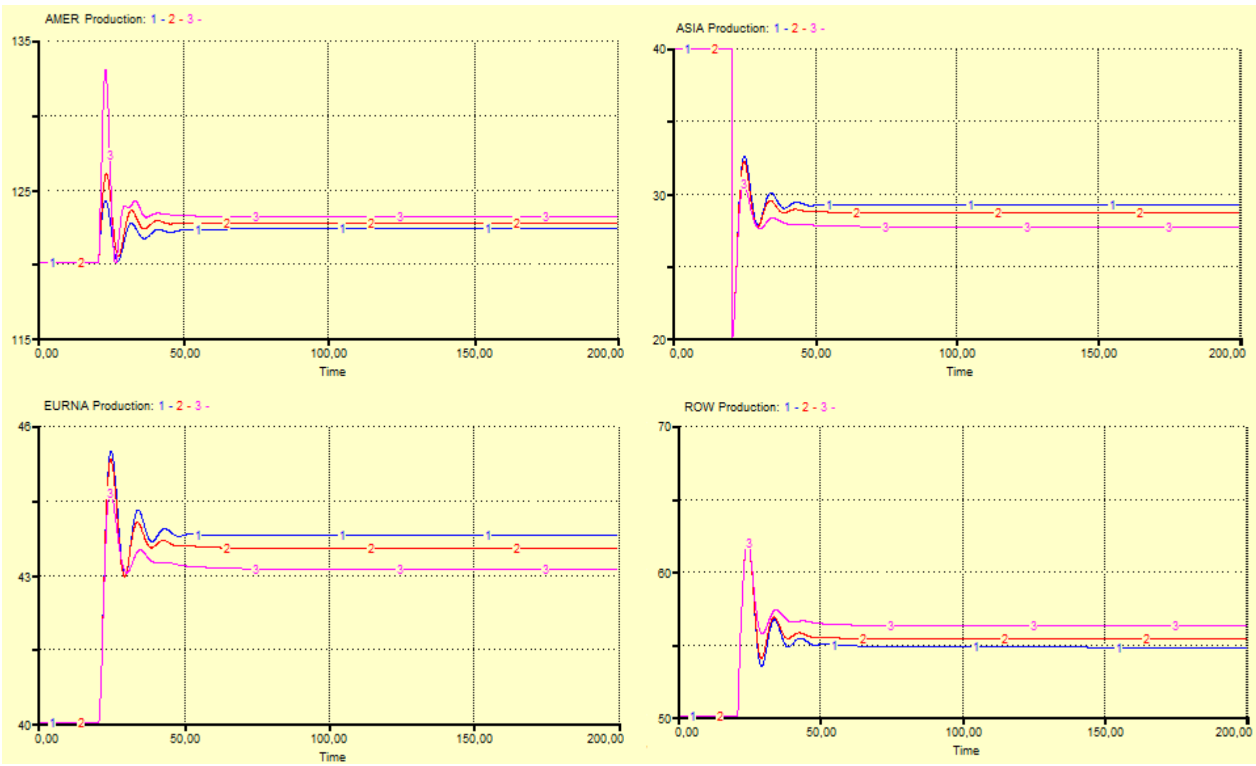

Figure 11. After expansion of the Panama Canal, a disruption in both production and consumption of LNG in Asia. The regions are (clockwise from top left): AMER, ASIA, ROW, EURNA. (adjustment parameter values: blue=0.5, red=1.0, magenta=4.0).

In this scenario, the least effect of the disruption occurs in two of the four regions (AMER and ROW) when the American adjustment parameter is *smallest*, but the least effect occurs in the other two regions (EURNA and ASIA) when the parameter value is the *largest*. This contrasts with the case of the disruption in American production, where the least disruption occurred in all four regions when the adjustment parameter was the largest. Thus, in this case, there is a fundamental trade-off in the American policy that is best for itself (and the ROW) on one hand, and the policy that is best for EURNA/ASIA on the other.

The graphs in Figure 12 below show the effect of the ASIA disruption on LNG shipping patterns. Overall, for the disruption scenario there is greater global demand for LNG shipping, with increased shipping from 'ROW to ASIA' more than compensating for reduced shipping along the 'AMER to EURNA' and 'ROW to EURNA' routes.

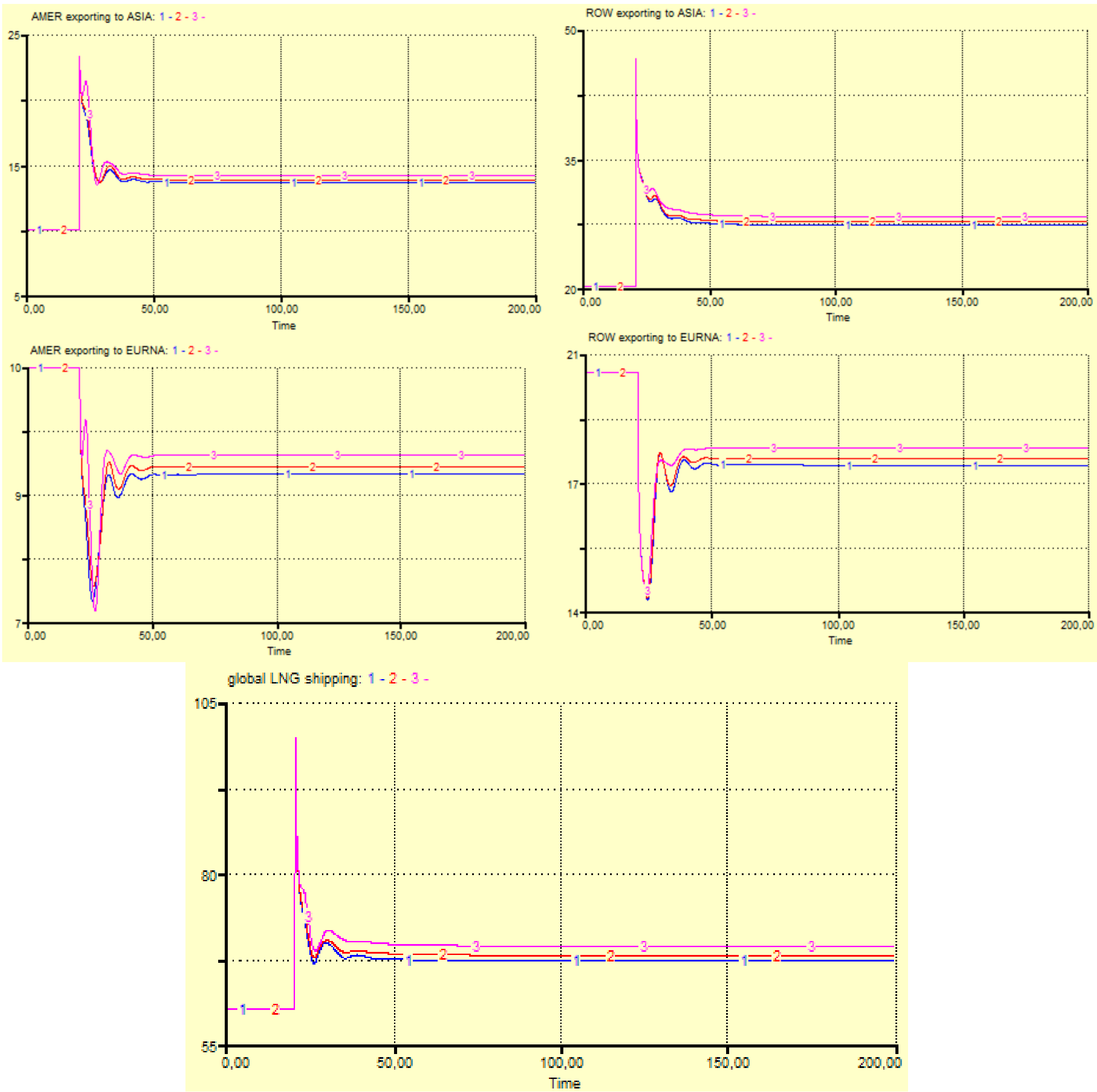

Figure 12. Interregional trade change for the ASIA disruption scenario. The graphs are (clockwise from top left): AMER to EURNA, ROW to ASIA, ROW to EURNA, global LNG shipping, and AMER to EURNA. (adjustment parameter values: blue=0.5, red=1.0, magenta=4.0).

The highest value of the adjustment parameter reduces the effect of the disruption in the 'AMER to ASIA' and 'ROW to ASIA' trade routes, but increases the effect on the other trade routes and in global shipping overall.

Define resilience-building measures

Traditional recommendations for improving the resilience of supply chains include building redudancy into the system and increasing the flexibility or capacity of components of the system to handle unexpected disruptions [Linkov *et al.*, 2014; Sheffi, 2005]. However, for the global LNG system, where capital expenditures are large and the ability to store product is limited, redundancy of core infrastructure and flexibility of the system are difficult to implement. We have used a modeling approach to investigate resilience-building measures in the form of their impact on a time-adjustment parameter in the American market.

Summary

This paper presents a simple multi-node model of LNG production, consumption, storage and transport. Though conceptually simple, the model exhibits persistent changes in production levels (that is, market share) even with temporary disruptions. As well, it shows that the effect of disruptions on different regions of the world is not necessarily intuitive. The stock shortfall adjustment policy that minimises the effects of a disruption in one region of the world can accentuate the effects elsewhere. Additionally, the model shows that the effects of a disruption on the overall system can differ depening on the type and location of the disruption – A production disruption in the Americas, a shipping disruption in Panama, or simultaneous production and consumption disruptions in Asia each have a different effect. The stock shortfall adjustment policy that is most resilient in one disruption scenario (that is, the policy that minimises the effect of the disruption) might be the worst policy in reponse to a different disruption scenario. Consequently, resilience policies must take into account when, where and how a specific disruption occurs.

The model of the LNG industry presented in this work represents a generic economic system with four participants, two of whom are net exporters and two of whom are net importers, subject to discontinuities in production, consumption or shipping ability. Thus, insights from and refinements to this model might also be applicable to other commodities like corn (maize) and lithium, which have been investigated by the authors in other published work.

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