LIFELINES: The Resilient Infrastructure Opportunity

Transportation and Supply Chain Resilience in the United Republic of Tanzania

Assessing the supply-chain impacts of disaster-induced transportation disruptions

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ABSTRACT

The economy of the United Republic of Tanzania is growing fast but remains vulnerable to disasters, which are likely to worsen with climate change. Its transportation system, which mainly consist of roads, often get disrupted by floods. How could the resilience of the transportation infrastructures be improved?

We formulate a new type of model, called DisruptSCT, which brings together the strength of two different approaches: network criticality analyses and input–output models. Using a variety of data, we spatially disaggregate production, consumption, and input–output relationships. Plugged into a dynamic agent-based model, these downscaled data allow us to simulate the disruption of transportation infrastructures, their direct impacts on firms, and how these impacts propagate along supply chains and lead to losses to households.

These indirect losses generally affect people that are not directly hit by disasters. Their intensity nonlinearly increases with the duration of the initial disruption. Supply chains generate interdependencies that amplify disruptions for nonprimary products, such as processed food and manufacturing products.

We identify bottlenecks in the network. But their criticality depends on the supply chain we are looking at. For instance, some infrastructures are critical to some agents, say international buyers, but of little use to others. Investment priorities vary with policy objectives, e.g., support health services, improve food security, promote trade competitiveness.

Resilience-enhancing strategies can act on the supply side of transportation, by improving the quality of targeted infrastructure, developing alternative corridors, building capacity to accelerate post-disaster recovery. On the other hand, policies could also support coping mechanisms within supply chains, such as sourcing and inventory strategies. Our results help articulate these different policies and adapt them to specific contexts.

CURRENCY MEASURE

Currency Unit – USD

WEIGHT AND MEASURES

Metric system

BASELINE DATA YEAR

Business census – 2016

Macroeconomic data – 2014

Firm survey – 2018

Population census – 2012

Transportation infrastructure data – 2016

ABBREVIATIONS AND ACRONYMS

DisruptSCT model	Disruption-in-Supply-Chains-and-Transportation model
DR Congo	Democratic Republic of Congo
DSM	Dar es Salaam
GDP	Gross Domestic Product
GIS	Geospatial Information Systems
IO	Input–Output
JICA	Japan International Cooperation Agency
km	Kilometers
m	Meters
MT	Metric Tons
OD	Origin-Destination
UN	United Nations
USD	United States Dollars
kUSD	Thousands of USD
mUSD	Millions of USD

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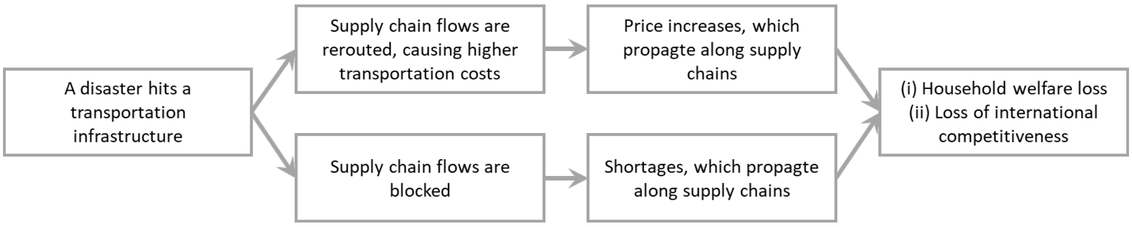
A disaster hits a transportation infrastructure
Supply chain flows are rerouted, causing higher transportation costs
Price increases, which propagte along supply chains
Supply chain flows are blocked
Shortages, which propagte along supply chains
(i) Household welfare loss
(ii) Loss of international competitiveness

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Chapter 1. Introduction

This chapter provides the background, purpose, and scope of the study. It explains the main features of the DisruptSCT model (for Disruption-in-Supply-Chains-and-Transportation model) and outlines the rest of the report.

1.1 Background, purpose, and scope

1.1.1 A new method to assess the resilience of supply chains to transportation disruptions

Transportation systems play a pivotal role in connecting multiple components of an economy. They enable firms to source inputs from distant suppliers and to deliver outputs to customers. They link various regions, channeling agricultural products from countryside to urban centers, and manufactured products from industrial areas to retailers.

Transportation networks are vulnerable to natural disasters, such as floods, landslides, or earthquakes. Roads may become impassable, forcing trucks to take a longer, sometimes busier, itinerary. Railways may get damaged, forcing transporters to switch to other transportation modes. Disasters can even paralyze an entire transportation node, such as a port or an airport, inducing severe delays.

The economic impacts of such disaster can be reduced by resilient transportation systems, which offer multiple and cost-effective options to connect suppliers and customers. How resilience can be quantified and took it into account in infrastructure investment decisions?

Several methods have been designed to quantify the redundancy of transportation networks. They build criticality indicators to rank the nodes and edges of these networks. Such methods focus on the network structure and may quantify some of the direct impacts of disruptions, such as the extra costs induced by detours or the number of blocked vehicles. They leave, however, the economic activities enabled by the network out of the scope. What these extra transportation costs mean for firms and households? Are these blocked vehicles significant for the economy of that region? Who suffer the most from the disruption: importers, exporters, or local businesses?

Here, we propose to quantify these indirect, ripple effects of a disruption on economic agents. We analyze how transportation disruptions propagates along supply chains and lead to losses to firms and households. This assessment rest on a full embedding of supply chains into the transportation system, which is the main innovation of the DisruptSCT model.

Using trade and national accounting data, household and business census, and an ad-hoc firm survey, we spatially map economic flows onto the transportation network, and model how firms and households dynamically adjust their supply and demand behavior to disruptions. That way, roads are linked to the economic activities they enable. We then evaluate the importance of specific transportation infrastructures in connecting two sectors or two regions, or in providing products to households.

1.1.2 The United Republic of Tanzania: a growing economy vulnerable to climate change

The United Republic of Tanzania is a growing economy. Its population has grown from 44.9 million inhabitants in 2012[1] to 55.6 million in 2016[2]. The annual growth rate of its Growth Domestic Product (GDP) has remained between 5 à 8% over the past decades[3]. This economic growth comes with increased transportation needs for domestic and for business purposes.

In addition, the United Republic of Tanzania plays a pivotal role in connecting neighboring landlocked countries with international markets, namely Uganda, Rwanda, Burundi, DR Congo, Zambia, and Malawi. The port of Dar es Salaam is of upmost significance for the whole East Africa region, and rank among the four largest African port on the Indian Ocean, together with Durban in the Republic of South Africa, Mombasa in the Republic of Kenya, and Maputo in the Republic of Mozambique.

Lying just a few degrees south of the Equator, the country is vulnerable to multiple hazards, acutely recalled by the massive destruction of the city of Beira in neighboring Republic of Mozambique after cyclone Idai in March 2019. As its neighbor, the United Republic of Tanzania is prone to tropical storms which typically occur between November and April. Last significant events took place during the 2008–2009, 2009–2010, and 2011–2012 seasons.

Bordered by the Indian Ocean and the three largest African Great Lakes, namely Lake Victoria, Lake Tanganyika, and Lake Malawi, the country is seasonally exposed to large masses of warm and humid tropical air, which can induce heavy rains and convective storms. Floods are frequent and affect almost all regions of the country. They displace people, damage building and infrastructure, and are the main cause of transportation disruptions. As opposed to neighboring Republic of Mozambique though, the country is more elevated, leading to more localized floods.

On top of these water-induced disasters, the United Republic of Tanzania also suffers from their opposite: droughts. Among the wide diversity of ecosystems found in the country, its central regions consist of savannah-covered arid and semi-arid plateaus. Droughts are often triggered by delayed or weak rainy seasons in April and May or in November. In an agriculture-based economy, prolonged droughts, such that of 2008–2009 and of 2011, lead to extremely severe losses.

Located along the East African Rift, the United Republic of Tanzania is, to a large extent, exposed to earthquake and volcanic activities. Over the past decade, the Ol Doinyo Lengai volcano, about 60km from the Kenyan border, has been active. The largest recent earthquake hit the Ugandan border near Lake Victoria in 2016 with a magnitude of 5.9.

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[1] Figures from the 2012 census: National Bureau of Statistics (2013) *Population Distribution by Administrative Areas, 2012 Population and Housing Census*, United Republic of Tanzania, 2013

[2] Estimates from the United Nations: United Nations (2017) *World Population Prospects: The 2017 Revision*. United Nations Department of Economic and Social Affairs, Population Division. Available at : ESA.UN.org.

[3] Figures from the International Monetary Fund, available at https://www.imf.org/en/Countries/TZA

Climate change is likely to increase the exposure of the United Republic of Tanzania to some of these disasters. With the increase in land temperature, longer droughts are expected to hit. Although large uncertainties remain concerning the evolution of the rainfalls, changes in temporal and regional pattern of the rainy seasons are expected. As for storms and floods, the sea surface temperature of the Indian Ocean is growing faster than expected, which tend to increase the intensity of tropical storms. On the longer term, sea level rise is expected to worsen the exposure to floods in coastal regions.

Inside the country, freights are very predominantly transported on roads. The 34,000 km road network is at 65% unpaved. The paved roads are found on the main transportation corridors and in the main urban centers. The 4,000-km rail network supports less than 1% of freights. In a context of growing demand and of increasing exposure to floods, the current transportation system is experiencing frequent failures. As reported by Pant et al. (2018)[4], most floods events not only trigger significant disruption of transportation services, but also induce damages to infrastructure themselves, such as trunk roads, bridges, and urban roads.

Improving the transportation system of the United Republic of Tanzania requires more than building more infrastructure. In the context of climate change, it is crucial to take actions that reinforce the resilience of the system. To that end, it is necessary to adopt a broader view of transportation. We need to look at the resilience of the Tanzanian economy through transportation, instead of only focusing on transportation networks and infrastructure. We propose to study how transportation disruptions ripple to the rest of the economy by modeling supply chains.

1.1.3 Scope of the study

The study focuses on the economy of the United Republic of Tanzania. We model the spatial and temporal dynamics of production, trade, and consumption, and study how the resulting supply-chain flows depend on the transportation network. These supply-chain flows include the trades of intermediary inputs between Tanzanian firms, business-to-consumers flows, imports, exports, and transit flows. The latter are products transported across The United Republic of Tanzania but produced and consumed elsewhere. Firms and households are explicitly modeled, along with their behavior in case of transportation disruptions (e.g., rerouting, delays, price adjustments).

The resulting model, called Disruption-in-Supply-Chains-and-Transportation model, or DisruptSTC model, is used to evaluate the indirect impacts of transportation disruptions. To define such impacts, it is useful to describe the direct and indirect consequences of a disaster.

- The direct consequences of a disaster are the loss of human lives and injuries, environmental degradation, and loss of economic assets.

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[4] Pant, R., Koks, E.E., Russell, T., & Hall, J.W. (2018). Transport Risks Analysis for The United Republic of Tanzania – Systemic vulnerability assessment of multi-modal transport networks. Final Report Draft, Oxford Infrastructure Analytics Ltd., Oxford, UK.

- These consequences have secondary effects, such as the inability of a firm to produce due to damaged equipment or to deliver to clients due to flooded roads.

The study specifically focuses on these indirect impacts. We estimate them by modeling how transportation disruption perturbs firms and how such perturbations propagate along supply chains. The model produces estimates in monetary terms. These figures are produced by measuring economic losses for specific economic agents. In this study, we primarily focus on the losses affecting Tanzanian households.

The study aims to capture the indirect impacts on the short term. Our simulation starts with a perturbation—a transportation disruption—from a steady state baseline and analyze economic recovery back to the pre-perturbation state. We simulate disruptions that last up to four weeks and analyze pathways that span over a maximum of 15 weeks. We also leave out of the scope the simulation of disasters that trigger profound perturbations and transformations of the local economy, such as 2005 hurricane Katrina and its lasting impacts on New Orleans in the USA. Instead, we suppose that the transportation and economic systems remain structurally unchanged and leave out of the scope any transformational capacities of those systems. We do include, however, some major reactive and adaptative behavior which economic agents are likely to exhibit in the short run, such as the adjustment of their orders or the use of inventories

1.2 Model's main features

1.2.1 From transportation disruptions to price increases and shortages

The model includes two mechanisms by which a disaster results in economic losses for households and other agents. Both mechanisms start with the disruption of a transportation infrastructure, such as a road or a bridge. They are summarized in

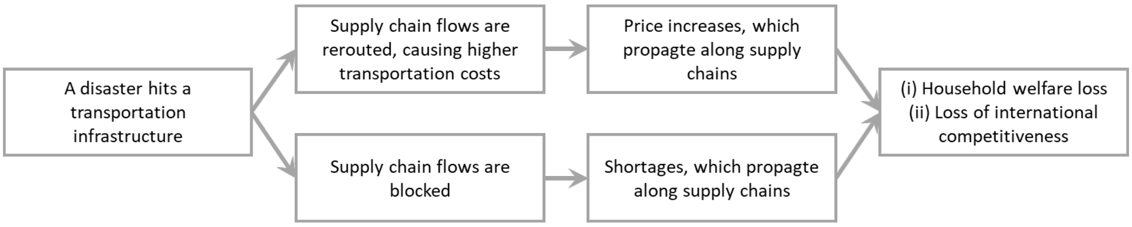

Figure 1-1.

- *Price effect*. A transportation infrastructure is disrupted. Flows ordinarily circulating there are temporarily rerouted. This alternative route is likely to be longer and thus costlier. Congestion may occur. The firms in charge of these flows bear higher costs and increase prices to preserve their margin. Those which are buying those products face higher prices, and, to save their own margin, they themselves increase prices. As a result, households experience higher market prices. To measure this adverse effect, we assume that households keep purchasing the same quantity of products as usual. The extra spending made by households quantifies the economic loss. If products are sold to international buyers, the extra spending made by those buyers is a proxy for a loss of competitiveness.

- *Shortage effect*. A transportation infrastructure is disrupted. Among flows normally travelling through this infrastructure, some have no alternative route. They are held at suppliers' premises. Firms relying on these flows for production inputs need to tap into their inventory to maintain production. When inventory gets exhausted, production declines, and firms are forced to ration their clients. Households may suffer from a loss of consumption, measured by the quantity of unconsumed products at pre-disaster prices. Further firms may in turn run out of inputs and drop production, leading to further consumption losses.

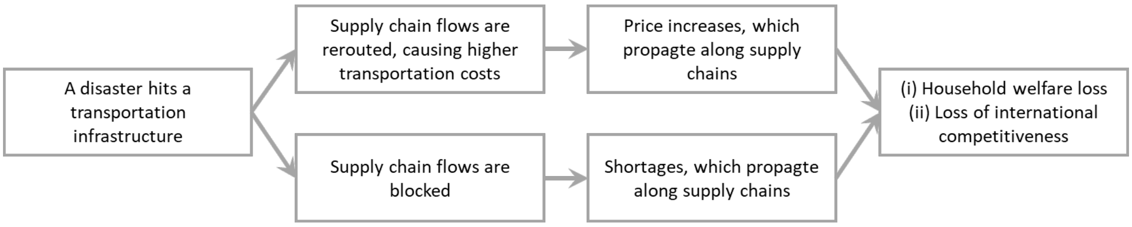

Figure 1-1: Two mechanisms by which a natural disaster results in economic losses for households and international buyers.

Note that these mechanisms are simplifications of real decisions. In fact, there are more than these two pathways through which a disruption turns into indirect costs.

- When a disruption causes a detour, some firms may prefer to hold a shipment and wait for the usual route to reopen instead of rerouting it. Others would not transfer the added transportation costs, or the added input costs, to their clients. When facing higher market prices, some households may adapt their purchase plan, and temporarily reduce their consumption. We argue that these alternative pathways would also generate economic losses to some agents, for instance to firms, transporters, or suppliers, which may ultimately then generate losses to households. For instance, transporters may not be paid a higher price for a long detour, leading to loss of income for them and their workers. Delaying consumptions is a welfare loss. Although the quantification of losses may differ according to the pathways, we argue that the "price mechanism" used in the model is a way to estimate the ultimate indirect impact of detours on households.
- When a disruption causes a shortage, some firms may find a way to continue production by downgrading their product or service quality. Others may be able to reschedule production or to negotiate delays with clients in order to lower their losses. Prices would also be expected to adapt to supply–demand imbalances, influencing households in their purchasing behavior. All these adaptations would ultimately generate losses. The "shortage mechanism" used in the model provides an estimate of the indirect impacts on households.

1.2.2 Spatial mapping of supply-chain flows

The main innovation of the model is the mapping of supply-chain flows onto the transportation network. For each sector, supply and demand are spatially disaggregated, associated to firms and households, and assigned to specific nodes of the transportation network, called *Origin–Destination nodes*, or OD nodes. According to their sectoral production function, firms are assigned suppliers and buyers. These exchanges generate supply-chain flows, which are then associated to pathways in the network by evaluating the least-cost route between supplier and buyers. This section provides a very short summary of the data integration method, which is presented in detail in Chapter 3.

OD nodes are selected using data on transportation infrastructure, on population and GDP; see Figure 1-2. Data sources:

- Transportation infrastructure data collected and prepared by Oxford Infrastructure Analytics[5].
- The 2012 population census of the United Republic of Tanzania[6]
- Satellite-based population[7] and GDP estimates[8].

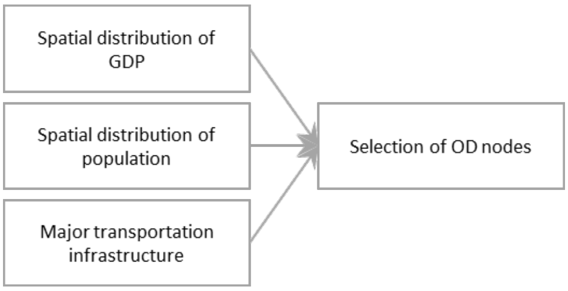

Figure 1-2: The selection of OD nodes of the transportation network is based on spatially explicit infrastructure, demographic, and economic data.

Final demand is composed of household demand, government demand, and exports.

- Household and government demands are spatially disaggregated using the 2012 population census. Major consumption centers are thus identified and associated to the transportation nodes. This procedure is summarized in Figure 1-3.
- Demands from other countries—i.e., exports—are localized by identifying the transportation nodes that connect Tanzanian firms to these countries.
- Data sources:
  - 2012 population census[9] provides the spatial distribution of population.

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[5] Pant, R., Koks, E.E., Russell, T., & Hall, J.W. (2018). Transport Risks Analysis for The United Republic of Tanzania – Systemic vulnerability assessment of multi-modal transport networks. Final Report Draft, Oxford Infrastructure Analytics Ltd., Oxford, UK.

[6] Data provided by the National Bureau of Statistics of the United Republic of Tanzania.

[7] Center for International Earth Science Information Network (CIESIN), Columbia University. 2018. Documentation for the Gridded Population of the World, Version 4 (GPWv4), Revision 11 Data Sets. Palisades NY: NASA Socioeconomic Data and Applications Center (SEDAC). https://doi.org/10.7927/H45Q4T5F Accessed 12/01/2019.

[8] Kummu M, Taka M, Guillaume JHA (2018) Gridded global datasets for Gross Domestic Product and Human Development Index over 1990-2015. Scientific Data 5: 180004.

[9] Data provided by the National Bureau of Statistics of the United Republic of Tanzania.

  - GTAP [10] provides the 2014 shares of household consumption, government consumption, and exports per sector.

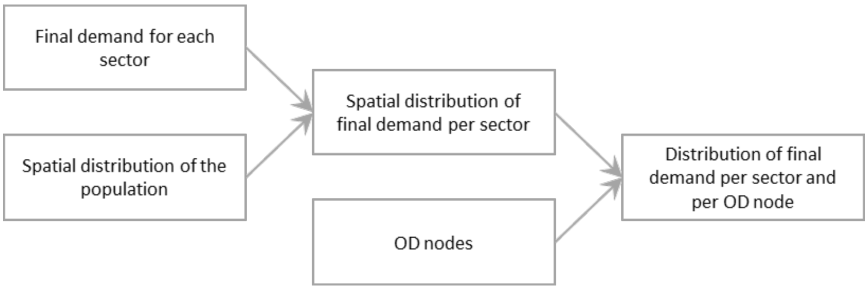

Figure 1-3: Schematic procedure by which final demand is spatially disaggregated and assigned to transportation nodes.

Supply is composed of production from Tanzanian firms and of imports from foreign countries.

- Production is, for each sector, spatially distributed using census and spatial GDP data. Companies from the same sector and located close to the same transportation node are grouped together. This procedure in summarized in Figure 1-4.
- For sectors with a large share of unregistered activities, such as agriculture, we use regional land use data to infer the size and location of productive units.
- Imports are localized by identifying the transportation nodes that connect foreign countries to Tanzanian firms.
- Date sources:
  - The 2017 business registry[9] provides the list of registered companies, their sector (for 100% of them), the administrative district they depend on (for 95% of them), their number of employees (84% of them), their turnover (for 40% of them).
  - Agricultural production is estimated using satellite-based land cover data [11].
  - Satellite-based estimation of the 2015 GDP [12], at a 5 arc-min resolution, are used to increase consistency.

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[10] Aguiar, A., Narayanan, B., & McDougall, R. (2016). An Overview of the GTAP 9 Data Base. *Journal of Global Economic Analysis*, 1(1), 181-208.

[11] Data provided by the Regional Centre For Mapping Of Resources For Development, Nairobi, Kenya.

[12] Kummu M, Taka M, Guillaume JHA (2018) Gridded global datasets for Gross Domestic Product and Human Development Index over 1990-2015. Scientific Data 5: 180004.

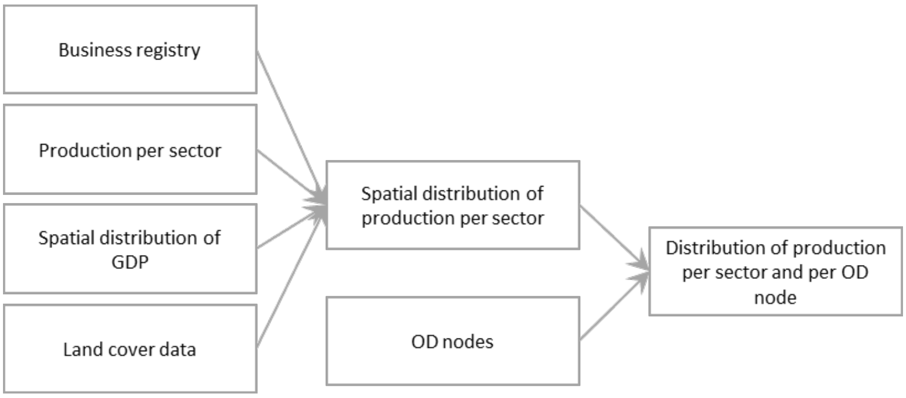

Figure 1-4: Schematic procedure by which production is spatially disaggregated and assigned to transportation nodes.

We infer *commercial links* between the identified hotspots of economic production and consumption using input–output and trade data; see Figure 1-5. Commercial links are associated with actual routes in the transportation network, resulting in supply-chain flows; see Figure 1-6.

- Households get connected to Tanzanian firms to match data on final consumption. We suppose that households only buy from firms located at their transportation node.
- Firms buy input from other firms. Sector-to-sector input–output tables determine the type of suppliers that firms need source inputs from. The actual choice of suppliers depends on firm size and distance. Firms tend to source input from large firms located close to their premises. Firms have one supplier per type of inputs.
- Trade data determine imports from foreign countries. The construction of country-to-firm commercial links depends on countries' importance in trade data. Similarly, the export relationships linking a Tanzanian firm to foreign countries depends on firm size and on country significance as buyers.
- Commercial links are associated with routes in the transportation network. As several routes may connect two locations, the least-cost one is chosen.
- Data consist of sector-to-sector input–output and international trade data provided by the 2014 release of the GTAP project[10].

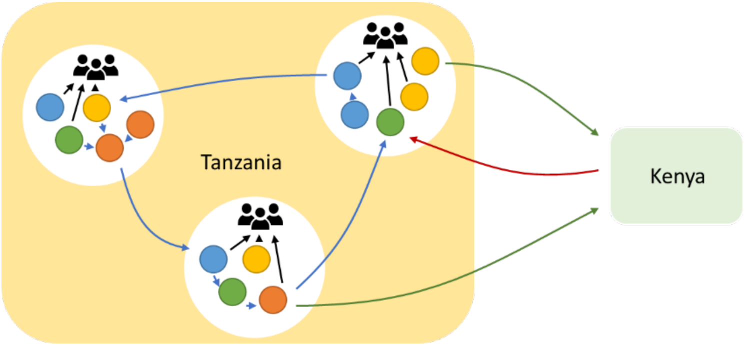

Figure 1-5: Schematic diagram of the supply chain linkages in the model. The three circles represent transportation nodes. Each node hosts households, symbolized by black silhouettes, and firms, represented by colored bubbles. Each color is a sector. Households buy products from local firms (black arrows). Firms purchase inputs from other firms, either located in the same node on in other nodes (blue arrows). Some firms sell products to Kenya (green arrows), while other buys inputs from it (red arrows). Each of these elements are spatially located (not shown).

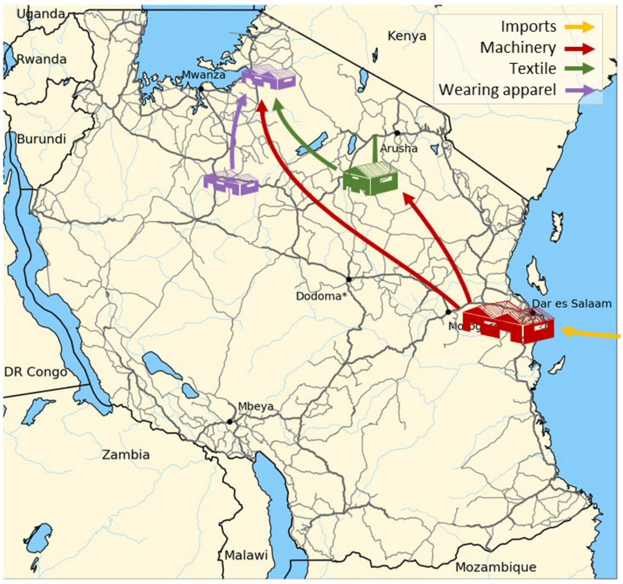

Figure 1-6: Schematic diagram of a supply chain. A wearing apparel manufacturer located in the north of the United Republic of Tanzania sources textile and other wearing apparels from firms in nearby regions and buys imported machinery from a trading firm in Dar es Salaam.

1.2.3 Dynamical adaptation of flows

In its static version, the model maps the supply-chain flows onto the transportation network. It estimates, for each transportation infrastructure, the value of freight flows per sector. To evaluate the impact of a disruption, the static model is made dynamic. Flows evolve through time in response to changes in the transportation network. Households, firms, and trading countries have a supply and demand behavior, which allow them to adapt to potential disruption. This section provides a short summary of various modeling components. They are presented in detail in Chapter 2.

Baseline supply-and-demand dynamics.

- Households and international buyers place orders in order to fulfil their demand. Firms plan their production and future purchases in response to these orders and their current inventory. They produce and deliver outputs to clients using the transportation network. Payment are made upon reception of products.
- The cycle of orders, production, and deliveries makes a time step, which represents a week. In the absence of disruption, this supply and demand dynamics produces constant supply-chain flows. We do not model seasonal variations, and these weekly flows correspond to a 52^{th} of the annual flows.

Reaction and adaptation to disruptions.

- *Reaction to route unavailability.* Firms react to route unavailability by rerouting deliveries and changing their selling prices, or by holding production at their premises. Specifically, each supplier checks the availability of routes before shipping an order. If the normal route is disrupted, it looks for the least-cost alternative and evaluates the associated increase in transportation cost, which is immediately added to the order price. If no other route is available, it holds the shipment at its premises.

- *Reaction to price increase.* If input prices change, they readjust their own selling prices. Specifically, upon reception on an input whose price is higher than usual, a firm evaluates its marginal loss. At the next time step, it compensates this loss by raising its selling price accordingly.
- *Adaptation to delivery failure.* If, following a disruption, they hold too much or too little inventories, they adapt their production, delivery, and purchase plans. Specifically, when a supplier fails to deliver an input, firms use their inventory. If inventory is insufficient, they ration their clients. When the transportation services are back to normal, firms restore inventory by ordering more than usual.

1.3 Applications: estimate indirect costs, identify bottlenecks, test policies

Applied to the United Republic of Tanzania, the DisruptSCT model has three objectives:

- Estimate the indirect costs of specific disasters
- Identify critical infrastructures by simulating a wide range of scenarios
- Evaluate the potential of selected policies to enhance resilience

1.3.1 Estimate the indirect costs of specific disasters

Specific disasters are translated into disruption scenarios of transportation infrastructures. Scenarios are defined by the disrupted edges and nodes of the transportation networks and by the sequence and duration of these disruptions. We can look at past disasters. In this case disruption scenarios are inferred from observations. We can also assess hypothetical disasters, and use, for instance, flood maps to infer the affected infrastructure. The model allows us to test the disruption of any transportation infrastructures, such as a bridge, a crossing, a port. Disruptions may occur in isolation, sequentially, or simultaneously. They can last from one to four weeks.

In Chapter 5, the DisruptSCT is used to estimate the indirect costs associated with such disruption scenarios. These costs correspond to the price and shortage effects described in Section 1.2.1. They correspond to two observables: (i) the extra expenditure incurred by households and (ii) their missed consumption due to shortages. These two quantities are measured until spending and consumption are back to pre-disruption values. The sum of the two quantities is a measure of the indirect economic impacts of the disruption.

In addition to these end-of-chain impacts, the DisruptSCT allows us to analyze how these impacts cascade along supply chains, across sectors and regions. Moreover, the model allows us to measure other observables, such as the impacts on international buyers of goods produced in the United Republic of Tanzania or that transited through it, the increase in generalized transportation costs, the amount of disrupted flows, in monetary terms or in tonnages.

1.3.2 Identify critical infrastructures

In Chapter 6, we select about 3,000 nodes and edges on the transportation network and simulate the isolated disruptions of each one of these infrastructures. This systematic assessment allows us to compare their significance in supporting supply chains that matters for Tanzanian households. We generate criticality maps, which facilitate the identification of the most critical infrastructures.

Criticality maps are not unique. They show different patterns, whether we investigate short, frequent disruption or long, rare events, whether we focus on Tanzanian households or international buyers, whether we look at food products or any types of goods.

1.3.3 Evaluate the impact on resilience of several policies

Multiple policies may be designed to increase economic resilience. Supply-side policies target the transportation system itself and aim to improve the resistance of infrastructure, the redundancy of the network, and to accelerate post-disaster recovery. Demand-side policies support coping strategies from the transportation users, mostly firms, such as strengthening the supply strategies or enabling safety stocks.

Chapter 7 builds and tests alternative scenarios based on these policies and informed by criticality maps. We discuss the effectiveness of these interventions in different geographical and economical contexts. We show how the DisruptSCT model can help decision makers adapt and articulate these multiple policies.

1.4 Structure of the report

The remainder of the report is structured as follows:

- Chapter 2, p. 29, provides a technical description of the model. First, it presents the input–output and agent-based bases of the model and how economic flows are associated with transportation infrastructure. Next, it describes the dynamical components of the model, and how agents react and adapt to disruptions.
- Chapter 3, p. 41, explains in detail how data were integrated into the model. It presents data on transportation infrastructure and explains how major transportation nodes are selected. Next, it explains integration of spatial data on businesses and households with country-wide input–output data. Last, it shows how the commercial linkages are built.
- Chapter 4, p. 56, shows the distribution supply-chain flows generated by the model and discusses its robustness.
- Chapter 5, p. 65, presents estimates of indirect costs of disruptions scenarios. First, two disruption scenarios are studied: the first corresponds to a one-week hypothetical floods affecting the Tanga region, the second simulate a four-week floods that affected the Morogoro region in 2016. Next, we discuss the salient features of these costs estimates and the key parameters influencing their magnitude. Finally, we compare these estimates with those resulting from the input–output method generally used to evaluate the economic impact of natural disasters.

- Chapter 6, p. 76, exposes the criticality maps resulting from the model. Criticality to short and long disruptions are presented. Next, we show how the criticality patterns depends on the supply chains under study. We contrast these results with existing methods of transportation criticality analyses.
- Chapter 7, p. 87, assesses the effectiveness of several resilience policies, both on the supply and on the demand side of transportation. We discuss how these policies can be adapted to different contexts.
- Chapter 8, p. 97, identifies the most crucial steps to improve the analyze and proposes further areas of application of the model.
- The Appendices, p. 99, gathers data tables, figures, and additional model outputs.

Chapter 2. Model formulation

The chapter provides a technical description of the model. First, it presents two major building blocks: the input–output equilibrium and the agent-based construction of the model. Next, it explains how economic flows are associated with transportation infrastructure. Last, it describes the dynamical components of the model, and how agents react and adapt to disruptions.

2.1 Input–output equilibrium of economic flows

This first building block of the model is the input–output structure. We define three types of agents: households, firms, and countries. Firms produce using inputs from other firms—domestic flows—and from countries—imports. Given the final demand of households and given exports, the input–output equilibrium determines the productions of each firm and the flows between each agent. This building block provides a static snapshot of the economy, which is not yet spatially localized. Section 2.2 will show how these economic flows are mapped onto the transportation network.

2.1.1 Firms, countries, and households

The model consists of economic agents connected through commercial relationships. Each commercial relationship involves a supplier and a buyer. There are three classes of agents:

- F Tanzanian firms, denoted by $f_1, \dots, f_F$,
- C foreign countries $c_1, \dots, c_C$, and
- H Tanzanian households, $h_1, \dots, h_H$.

There are S domestic economic sectors, denoted by $s_1, \dots, s_S$. Each firm belongs to a single sector and produce a single type of product. There are S types of products, in one-to-one correspondence with the sectors. For ease of notation, countries are formally grouped into sector s_0, and produce products that are of another type of that of domestic firms.

All the firms of a sector have the same production process. We model production using Leontief functions, with one set of technical coefficients per sector. Specifically, firm f_i from sector s_k produce a quantity x_i of output as follows:

$$x_i = \min(a_{0,k}\phi_0, a_{1,k}\phi_1, \dots, a_{S,k}\phi_S), \tag{2-1}$$

where

- $a_{0,k}, \dots, a_{S,k}$ are the technical coefficients, and
- $\phi_0, \dots, \phi_S$ is the quantity of product from each sector that the firm has access to. Note that $\phi_1, \dots, \phi_S$ corresponds to products from domestic sectors while ϕ_0 corresponds to imports.

The technical coefficients define the input mix of the firm. They form a $(S+1) \times S$ matrix $\mathbb{A}$, with input types as rows and sectors as columns. Matrix $\mathbb{A}$ will be directly inferred from data; see Section 3.2.1. Leontief functions assume a strict complementarity between inputs. Only the type of input matters, not the firm or country that produced it. It follows that, for each coefficient $a_{j,k}$ that is non-null, any sector-s_k firms need at least one supplier from sector s_j, or one supplying country if $j = 0$.

2.1.2 A network of commercial relationships

The three classes of agents are linked together through commercial relationships, forming an economic network. We decompose this network into five subnetworks.

- The final consumption network connects firms to households. It is represented by the $F \times H$ matrix $\mathbb{D}^{\mathrm{FH}}$, in which element $d_{i,j}^{\mathrm{FH}}$ is the amount of goods produced by firm f_i purchased by household h_j. Its calibration from data is explained in Sections 3.3.3 and 3.5.1.
- The domestic network connects firms. It is represented by the $F \times F$ input–output matrix $\mathbb{W}$, in which element $w_{i,j}$ is the so-called input–output coefficient. If firm f_i is supplying to firm f_j, then it is equal to the technical coefficient of f_i's sector relative to inputs from f_j's sector, weighted by the share of inputs of f_j's sector purchased from f_j. If firm f_i is not supplying to firm, then $w_{i,j}$ is null. We assume that no firm supplies to itself. The construction of matrix $\mathbb{W}$ and calibration from data is explained in Sections 3.3.1, 0, and 3.5.2.
- The import network connects countries to the firms that buy their products. It is represented by the $C \times F$ matrix $\mathbb{Y}$. Element $y_{i,j}$ is strictly positive if firm f_j imports good from country c_i, it is null otherwise. If country c_i is supplying to firm f_j, then $y_{i,j}$ is equal to the technical coefficient of f_j's sector relative to imports, weighted by the share of imported inputs purchased from c_i. The calibration of matrix $\mathbb{Y}$ is explained in Sections 3.2.2, 3.2.3, and 3.5.3.
- The export network connects exporting firms to countries that buy their products. It is represented by the $F \times C$ matrix $\mathbb{Z}$. Element $z_{i,j}$ is the amount of goods produced by firm f_i purchased by country c_j. Its calibration from data is explained in Sections 3.2.2, 3.2.3, and 3.5.4.
- The transit network connects countries, other than the United Republic of Tanzania, which trade together and whose trade flows, at least in part, circulate through the United Republic of Tanzania. It is represented by the $C \times C$ matrix $\mathbb{V}$, in which element $r_{i,j}$ is the amount of goods produced by country c_j and purchased by country c_i that goes through the United Republic of Tanzania. Its calibration from data is explained in Sections 3.2.2, 3.2.4, and 3.5.5.

2.1.3 The input–output equilibrium

The five matrices described in the previous section allow us quantity the production of each firm and all economic flows between households, firms, and countries.

First, we evaluate the final demand per firm. Each row of matrix $\mathbb{D}^{\mathrm{FH}}$ contains household purchase for each firm, and each row of matrix $\mathbb{Z}$ contains country purchase for each firm. We sum, row by row, the elements of each matrix, yielding two F-length vectors. The first is represent final consumption per firm, the second the total export per firm. We sum these two vectors and obtain the vector of final demand per firm, D.

Next, we evaluate the intermediary demand per firm, which is the demand from the other firm. We denote by X the F-length vector of total production per firm. Input—output relationships impose that, to produce a quantity X of outputs, firms need to buy inputs from the other firm. A property of the input—output matrix $\mathbb{W}$ is that the amount of intermediary inputs that needs to be produced by each firm is $\mathbb{W}X$.

Last, we can evaluate the production of each firm, vector X, using the equation of input–output equilibrium, in which total production equates to final and intermediary demand:

$$D + \mathbb{W}X = X. \tag{2-2}$$

The production vector that satisfies this equation is $X = (\mathbb{I} - \mathbb{W})^{-1}D$, where $\mathbb{I}$ is the $F \times F$ identity matrix. Knowing productions, we can deduce all flows in the network.

- Flows from firms to households are already given by matrix $\mathbb{D}^{\mathrm{FH}}$.
- The flow from firm f_i to firm f_j is given by $w_{i,j}x_j$.
- The flow from country c_i to firm f_j is given by $y_{i,j}x_j$.
- Flows from firms to countries are already given by matrix $\mathbb{Z}$.
- Flows between countries are already given by matrix $\mathbb{V}$.

We denote by $\varphi_{i,j}$ the flow of products from agent i to agent j, whereby indices i and j point to any agents $h_1, \ldots, h_H, f_1, \ldots, f_F, c_1, \ldots, c_C$, i.e., to any households, firms, or countries. Similarly, we denote by $\theta_{i,j}$ the monetary flows from agent i to agent j.

2.1.4 Stock and inventories

Firms hold inventories. We denote by $\phi_{i,j}$ the amount of inventory from sector s_i held by firm f_j from sector s_k. Quantity $p_{j,k}$, defined by

$$p_{j,k} = \frac{\phi_{i,j}}{a_{k,i}x_j}, \tag{2-3}$$

can be interpreted as the duration over which firm f_j can maintain its production without ordering more sector-s_i inputs, assuming that no other inputs would lack. For instance, if a wearing apparel factory has two weeks of inventory of textile, it means that, if there is no shortage of other inputs (e.g., electricity), it can keep producing at a normal pace for two weeks without new supplies of textile.

For each input type, firms have a fixed inventory target $p_{j,k}$, expressed in time duration. Firms start with this amount of inventory, that may decrease if a disruption occurs. All the firms of a sector have the same target per input type. Targets $p_{j,k}$ form a $S + 1 \times S$ matrix $\mathbb{P}$, with sectors as columns and input type as rows. Inventories of sector s_i products held by firm f_j, which belongs to sector s_k, is:

$$\phi_{i,j} = p_{j,k} a_{j,k} x_i. \tag{2-4}$$

Firms also hold a stock of output, denoted by q_i. It will be used in the dynamical version of the model to store any output that, because of disruption, cannot be delivered; see Section 2.3.4. At initialization, this stock is set to 0.

2.1.5 Costs, revenues, and margin

The flows of products determined in Section 2.1.3 are associated with monetary flows. To each product flow correspond a monetary flow of the same amount but of opposite direction.

- Monetary flows going to firm f_i correspond to its revenues from sales, denoted by $\mathcal{R}_i$. They come from its buyers, which can be households, countries, and other firms.
- Monetary flows going out from firm f_i are its inputs costs. We isolate the flows corresponding to transportation costs, $\mathcal{C}_i^T$, and denote by $\mathcal{C}_i^I$ the other input costs.
- We add another financial category, called "other costs", which does not correspond to the commercial links of the model. Other costs aggregate any other monetary flows other than sales, input and transportation costs, such as labor and capital costs, tax, and subsidy. We assume that the portion of other costs relative to the firm's total revenue is the same for any firm of the same sector.

With these financial items, we can analyze the overall profit margin of the firms. We can also measure margins associated with specific clients, by linearly rescaling costs and revenues according the share of those clients in total sales. Table 2-1 summarizes these financial variables.

Table 2-1: Definition and description of the financial variables.

Symbol	Definition	Description
$\mathcal{R}_i$	$\sum_j \theta_{j,i}$	Sales of firm i
$\mathcal{C}_i^I$	$\sum_{j\mid\mathcal{S}(j)\neq 48,49,50} \theta_{i,j}$	Input costs of firm i except transportation, which corresponds to sectors 48, 49, and 50; see Table 3-2.
$\mathcal{C}_i^T$	$\sum_{j\mid\mathcal{S}(j)=48,49,50} \theta_{i,j}$	Transportation costs of firm i
$\mathcal{C}_i^O$	$c^O_{\mathcal{S}(i)}\mathcal{R}_i$	Other costs for firm i, which are a fixed fraction of sales. Ratio $c^O_{\mathcal{S}(i)}$ is a constant and sector-dependent parameter.
$\mathcal{M}_i$	$\frac{\mathcal{R}_i - \mathcal{C}_i^I - \mathcal{C}_i^T - \mathcal{C}_i^O}{\mathcal{R}_i}$	Margin of firm i
$\alpha_{i,k}$	$\frac{\theta_{k,i}}{\sum_j \theta_{j,i}}$	Share of client k in firm-i's sales
$\mathcal{C}_{i,k}^T$	$\alpha_{i,k}\mathcal{C}_i^T$	Transportation costs of firm i for delivering to firm k
$\mathcal{M}_{i,k}$	$\frac{\alpha_{i,k}\mathcal{R}_i - \alpha_{i,k}\mathcal{C}_i^I - \mathcal{C}_{i,k}^T - \alpha_{i,k}\mathcal{C}_i^O}{\alpha_{i,k}\mathcal{R}_i}$	Margin of firm i in relation to client k

2.2 Integrating the economic and the transportation network

The edges of the economic network are commercial relationships, linking a supplier and a buyer. As long as the supplier is able to produce, goods and services can flow along those edges without any constraints. Here, we embed commercial relationships into the transportation system, and products can only flow if there are functioning transportation infrastructure between suppliers and buyers. This reliance of commercial relationships on transportation systems also allows us to link the transportation costs described in Section 2.1.5 with the actual route taken by the flows.

2.2.1 Defining the transportation network and transportation costs

The transportation network is composed of nodes and edges.

Transportation nodes are:

- Road crossings,
- Railway stations,
- Ports,
- Airports,
- Multimodal nodes.

Transportation edges are:

- Roads,
- Railways,
- Airways,
- Waterways,
- Multimodal links.

We call transportation infrastructure these nodes and edges, denoted by u. We assign a cost to each infrastructure, denoted by Γ_u. It represents the average direct cost that firms need to pay to transporters to channel a one-USD-worth of material good through infrastructure u. This cost depends on the average transportation price on paved and unpaved road, and on the length of paved segments:

$$\begin{aligned} \Gamma_u = {} & UnitTransPrice_{paved} PavedLengh_u \\ & + UnitTransPrice_{unpaved} UnpavedLengh_u, \end{aligned} \tag{2-5}$$

where:

- $UnitTransPrice_{paved}$ is the average market price of transporting one-USD-worth of material good through one km of paved road,
- $UnitTransPrice_{paved}$ is the average market price of transporting one-USD-worth of material good through one km of unpaved road,
- $PavedLengh_u$ is the length of paved road on infrastructure u,

- $UnpavedLengh_u$ is the length of unpaved road on infrastructure u.

On top of these direct costs, we also estimate, for some specific purposes, the so-called generalized costs of transportation. They represent the direct and indirect costs of transporting goods between two points. We use a slightly simplified version of the costing model adopted by Pant et al. (2018) based on World Bank (2015)[13] and its associated parameter values. Generalized costs are the sum of direct costs, calculated in Eq. (2-5), and of monetized indirect costs, namely waiting time, travel time, and unreliability.

The rest of the Section succinctly describes the generalized transportation costing model; see Pant et al. (2018) for more details. The generalized transportation costs $\widetilde{\Gamma_u}(x)$ of transporting x USD-worth of material good through infrastructure u

$$\widetilde{\Gamma_u}(x) = \Gamma_u * x + CostOfTime * \left(Wait_T + Trvl_T(1 + unreliabilityFactor)\right), \quad (2\text{-}6)$$

Where:

- $CostOfTime$ is a monetization of time, in USD per hour. It is set to 0.49 USD/hour.
- $Wait_T$ is the waiting time associated with carrying one USD-worth of material good through transportation infrastructure u. It is a fixed value for
- $Trvl_T$ is the average travel time associated with carrying one USD-worth of material good through transportation infrastructure u. For roads, it is equal to:

  $$Trvl_T = Speed_{paved} PavedLengh_u + Speed_{unpaved} UnpavedLengh_u, \quad (2\text{-}7)$$

  where

  - $Speed_{paved}$ is the average speed of trucks on paved road, in km/h. It is set to 30 km/h.
  - $Speed_{unpaved}$ is the average speed of trucks on unpaved road, in km/h. It is set to 18 km/h.
- $unreliabilityFactor$ is a unitless measure of the unreliability of transportation infrastructure u. It is expressed in percentage of the average travel time. For paved roads, this factor is equal to 1%, and to 7.5% for unpaved roads.

2.2.2 Assigning routes to commercial relationships

We assign a transportation node, which is spatially localized, to each household and to each firm. Countries may be associated to several transportation nodes, which correspond to border crossings. For instance, Kenya has four terrestrial border crossings with the United Republic

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[13] World Bank (2015) Building a Reform Consensus for Integrated Corridor Development in the East African Community: Pillar 1 – A Strategy and Action Plan for Intermodal Development. *World Bank, Washington DC, USA*.

of Tanzania, while Europe mostly trades with the United Republic of Tanzania through the port of Dar-es-Salaam.

Each commercial relationship is associated with a route, which is a path in the transportation network linking the node of the supplier—or one of the nodes if the supplier is a country—to the node of the buyer—or one of the nodes if the buyer is a country. There are generally several paths linking two nodes. We select the least cost route.

We denote by $\mathcal{P}_{i,j}$ the ordered list of transportation infrastructures in the least cost route linking agent i to agent j. Route cost $\mathcal{D}_{i,j}$ is computed by summing the unitary cost of each transportation infrastructure included in the route, i.e.,

$$\mathcal{D}_{i,j} = \sum_{u \in \mathcal{P}_{i,j}} \Gamma_u. \tag{2-8}$$

The flows evaluated in Section 2.1.3 can now be mapped onto the transportation network. On each transportation infrastructure, we compute the quantity of products that flows through it. This total flow defines the normal traffic condition on infrastructure u, denoted by Ψ_u. It will be used to evaluate congestion costs in case of rerouting; see Section 2.3.5.

2.2.3 Linking balance sheet transportation cost and actual transportation costs

The route cost described in the previous section is not meant to directly represent the financial flows paid by firms to transporters. It allows us to identify least-cost routes, and to evaluate the relative increase in transportation cost in case of rerouting. Rerouting refers to a dynamical feature of the model and will be described in Section 2.3.

We link the financial transportation costs $\mathcal{C}_{i,k}^T$ described in Section 2.1.5 with the route costs $\mathcal{D}_{i,k}$ defined in Section 2.2.2. We suppose that route costs are supported by suppliers, not by buyers. There is a linear function $\mathcal{T}_{i,k}$, specific to each commercial link, that maps route cost $\mathcal{D}_{i,k}$ into transportation cost $\mathcal{C}_{i,k}^T$, i.e., $\mathcal{T}_{i,k}(\mathcal{D}_{i,k}) = \mathcal{C}_{i,k}^T$.

The form of $\mathcal{T}_{i,k}$ matters when the route costs vary, which may happen in the dynamical version of the model. We will describe this function in greater detail in Section 2.3.5.

2.3 From static to dynamical modeling

Sections 2.1 and 2.2 described a static model. We now build a discrete-time dynamic model on this static basis, which we will use to evaluate response to disruptions. Each time step corresponds to one week. At each time step, agents order, produce, buy, sell, and adjust their operation in response to current situation.

2.3.1 Overview of agent behavior

At each time step, agents retrieve orders from their clients, plan their production and purchases, send their orders to their suppliers, produce and deliver their products to their clients, receive their orders and pay.

Table 2-2: Actions of agents occurring at each time step. They are listed in chronological order.

Class of agents	**Actions**	**Description**
Firms	Retrieve orders	Aggregate the orders placed by clients.
Firms	Plan production	Set the target level of production for this time step.
Firms	Plan purchases	Evaluate how much inputs should be purchased
Firms, Households, Countries	Place order	Place orders to suppliers to satisfy the purchase plan
Firms	Produce	Produce outputs using inventoried inputs
Firms, Countries	Evaluate price	Evaluate the price of each delivery
Firms, Countries	Deliver	Deliver products to clients who ordered
Firms, Households, Countries	Collect orders	Collect the products that were ordered to suppliers
Firms, Households, Countries	Pay	Pay the suppliers

2.3.2 Production planning

Firms aggregate all the orders placed by their clients at the last time step. We denote by $g_{j,i}(t-1)$ the order placed by agent j—which can be a firm, a country, or a household—on firm f_i at the last time step. The initial value of these orders corresponds to the equilibrium flows determined by the static equilibrium model in Section 2.1.3. The sum of all orders defines their delivery target for this time step, denoted by $\xi_i(t)$, i.e., $\xi_i(t) = \sum_j g_{j,i}(t-1)$.

Firm f_i may hold some stock of already produced outputs, $q_i(t-1)$. To fulfill its order, it needs to produce a quantity $\xi_i(t) - q_i(t-1)$ of output. But firms have a fixed production capacity they cannot exceed, denoted by $\overline{x_i}$. In this context, the production target $\widehat{x_i}(t)$ of firm f_i is $\widehat{x_i}(t) = \min(\xi_i(t) - q_i(t-1), \overline{x_i})$.

We assume that, at initialization, firms have 80% utilization rate. In other words, they produce at 80% of their production capacity.

2.3.3 Purchase planning

The static model defined the amount of inventory for each firm, $\phi_{i,j}$; see Section 2.1.4. In the dynamic model, these values become targets $\widehat{\phi_{i,j}}$. Firms dynamically adjust the orders it places to maintain inventory $\phi_{i,j}(t)$ at its target level.

Take firm f_i from sector s_j. Its production target is $\widehat{x_i}(t)$ and its inventory target of sector-s_k product is $\widehat{\phi_{k,i}}$. It currently holds $\phi_{k,i}(t)$ for this type of input and anticipates the consumption of a quantity $a_{k,j}\widehat{x_i}(t)$ of it at this time step. The rules followed by firm f_i to decide how much sector-s_k product it will order to its suppliers are described in Table 2-3. We denote by $\gamma_{k,i}(t)$ the quantity of sector-s_k product that firm f_i will order at time t.

Table 2-3: Decision rules for planning purchases. Case of firm i purchasing a type-k input with production target $\widehat{x_i}$.

Condition on the current inventory, $\phi_{k,i}(t)$	Resulting quantity to purchase, $\gamma_{k,i}(t)$	Description
$\phi_{k,i}(t) \geq \widehat{\phi_{k,i}} + a_{k,j}\widehat{x_i}(t)$	0	Even after using the input at this time step, inventory would still exceed the target. Firm i decides to not purchase this input.
$\phi_{k,i}(t) \geq \widehat{\phi_{k,i}}$ $\phi_{k,i}(t) < \widehat{\phi_{k,i}} + a_{k,j}\widehat{x_i}(t)$	$\widehat{\phi_{k,i}} + a_{k,j}\widehat{x_i}(t) - \phi_{k,i}(t)$	Inventory is already larger than the target but would fall below the target if no input is purchased. Firm i decides to buy the exact quantity that will bring the inventory to the target after production.
$\phi_{k,i}(t) < \widehat{\phi_{k,i}}$	$a_{k,j}\widehat{x_i}(t) + \rho\left(\phi_{k,i}(t) - \widehat{\phi_{k,i}}\right)$, where $0 \leq \rho \leq 1$	Inventory is already under the target. Firm i decides to buy the quantity that will be used at this time step ($a_{k,j}\widehat{x_i}(t)$). On top of that, it also buys extra inputs to compensate the low level of inventory and get back to the target. However, it does not buy all the necessary quantity ($\phi_{k,i}(t) - \widehat{\phi_{k,i}}$) at once. Instead, it only buys a portion ρ of it. Parameter ρ is the reactivity rate. It allows firms to not overreact to a lack of inputs, which generally leads to instabilities. Such overreactions are well known in supply chains and are called *bullwhip effect*.

These rules allow firms to evaluate its product-level purchase plan, i.e., how much of each types of product will it orders, $\gamma_{0,i}(t), \ldots, \gamma_{S,i}(t)$. This plan is then split into a supplier-level purchase plan, i.e., how much product will it orders from each of its suppliers, $g_{j,i}(t)$. To that end, the share of inputs of a sector purchased from each supplier of this sector, contains in the input–output matrix $\mathbb{W}$, is used.

Countries and households have no inventory. They always order the same quantity given by matrix $\mathbb{D}^{\mathrm{FH}}$, $\mathbb{Z}$, and $\mathbb{V}$; see Section 2.1.2.

2.3.4 Production and delivery

Firms try to reach their production targets, $\widehat{x_i}(t)$. For that, they evaluate the largest output they can produce given their current inventories, $x_i^{\max}(t) = \mathcal{P}\left(\phi_{0,i}(t), \ldots, \phi_{S,i}(t)\right)$. Production is then $x_i(t) = \min\left(x_i^{\max}(t), \widehat{x_i}(t)\right)$. The quantities of inputs consumed, $a_{0,k}x_i(t), \ldots, a_{S,k}x_i(t)$ are removed from the inventory. The stock of produced output ready to be delivered is now $q_i(t) = q_i(t-1) + x_i(t)$.

Firms then decide on the quantity that should be delivered to its clients. If they do not have enough to deliver, rationing may take place.

- If the amount of produced output, $q_i(t)$, is equal to or larger than the delivery target $\xi_i(t)$, no rationing will take place. The quantity to be delivered to agent j, denoted by $\widehat{\varphi_{i,j}}(t)$, is equal to the order placed by clients, i.e., $\widehat{\varphi_{i,j}}(t) = g_{i,j}(t-1)$.
- If $q_i(t)$ is smaller than the delivery target $\xi_i(t)$, the firm is not able to satisfy all customers. It needs to ration. Priority is given to households. The amount ordered by households is $g_{i,H}(t-1)$.

- If $q_i(t) \geq g_{i,H}(t-1)$, then all households can be satisfied.
    - $\widehat{\varphi_{i,j}}(t) = g_{i,j}(t-1)$ if agent j is an household.
    - The other clients $j \notin H$ are then rationed:

$$\widehat{\varphi_{i,j}}(t) = g_{i,j}(t-1)\left[\left(q_i(t) - g_{i,H}(t-1)\right)/\left(\xi_i(t) - g_{i,H}(t-1)\right)\right] \tag{2-9}$$

- If $q_i(t-1) + x_i(t) < g_{i,H}(t-1)$, then not all households can be satisfied.
    - Households $j \in H$ are rationed:

$$\widehat{\varphi_{i,j}}(t) = g_{i,j}(t-1)\left[q_i(t)/g_{i,H}(t-1)\right] \tag{2-10}$$

    - The other clients $j \notin H$ will not be served at all: $\widehat{\varphi_{i,j}}(t) = 0$

After deciding the quantity that should be deliver, firms do the actual delivery. Before shipping to client j, the firm checks whether the usual route associated with this client is passable.

- *Normal route*. It the route is passable, then the shipment is delivered, i.e., $\varphi_{i,j}(t) = \widehat{\varphi_{i,j}}(t)$ and $q_i(t) = q_i(t) - \widehat{\varphi_{i,j}}(t)$.
- *Rerouting*. If the route is impassable, then it looks for an alternative route. If there are such routes, it chooses the least costly. In that case, the shipment is delivered, i.e., $\varphi_{i,j}(t) = \widehat{\varphi_{i,j}}(t)$ and $q_i(t) = q_i(t) - \widehat{\varphi_{i,j}}(t)$.
- *No route*. If the route is impassable and if there is no alternative route, then the shipment is hold at the firm premises. No flow is associated to this commercial link at this time step, i.e., $\varphi_{i,j}(t) = 0$, and the quantity that were supposed to be shipped remains in the firm's output stock.

Countries also deliver. We assume that they always produce the among that need to be delivered, so that there is no rationing. They have the same behavior as firms regarding rerouting.

2.3.5 Transportation-induced price adjustment

When delivering to clients, firm can choose to adjust selling price. There are two additive price adjustment mechanisms: the transportation-cost-induced mechanism and the input-cost-induced mechanism.

Through both mechanisms, firms aim to maintain its current margin to the baseline level $\mathcal{M}_i$ evaluated in the static input–output equilibrium model; see Table 2-1. For each delivery, firms compute their anticipated margin and compare it to the corresponding client-specific baseline margin $\mathcal{M}_{i,k}$. If the anticipated margin is smaller than the baseline one, then the firm adjusts the selling price to compensate these potential losses. We assume that buyers do not adapt their level of purchase to prices.

If the delivery is rerouted, it will generally go through a route that is costlier than the normal one. We denote by $D'_{i,k}$ the cost of this alternative route, which is higher than the usual cost, i.e., $D_{i,k} \geq D'_{i,k}$. We use the linear mapping $\mathcal{T}_{i,k}$, introduced in Section 2.2.3, to evaluate the corresponding transportation cost, denoted by $\mathcal{C}^{T\prime}_{i,k}$.

$$\mathcal{C}^{T\prime}_{i,k} = \frac{D'_{i,k}}{D_{i,k}} \mathcal{C}^{T}_{i,k}. \tag{2-11}$$

Rerouting leads to extra costs for supplier. To mitigate the anticipated loss, it will adjust its selling price. The extra cost of supplier f_i related to client k is $\mathcal{C}^{T\prime}_{i,k} - \mathcal{C}^{T}_{i,k}$. Firm f_i increases its price by a factor β, such that its anticipated revenue related to client k become $\beta\alpha_{i,k}\mathcal{R}$. The anticipated margin related to this client, denoted by $\mathcal{M}'_{i,k}$, is:

$$\mathcal{M}'_{i,k} = \frac{\beta\alpha_{i,k}\mathcal{R}_i - \alpha_{i,k}\mathcal{C}^{I}_{i} - \mathcal{C}^{T\prime}_{i,k} - \alpha_{i,k}\mathcal{C}^{O}_{i}}{\beta\alpha_{i,k}\mathcal{R}_i}. \tag{2-12}$$

Factor β is set such that the anticipated profit $\mathcal{M}'_{i,k}$ equals baseline profit $\mathcal{M}_{i,k}$, i.e.,

$$\beta = 1 + \frac{\mathcal{C}^{T\prime}_{i,k} - \mathcal{C}^{T}_{i,k}}{(1 - \mathcal{M}_{i,k})\alpha_{i,k}\mathcal{R}_i}. \tag{2-13}$$

2.3.6 Input-induced price adjustment

As described in the previous section, prices may vary in response to transportation disruptions. Firms whose suppliers have increased prices face higher input costs, which may reduce their margin. Upon reception of more expensive inputs, they transfer these added costs to their clients by increasing their price, thereby preserving their margin.

The baseline input costs of firm f_i is $\mathcal{C}^{I}_{i}$. Suppose that suppliers have increased their prices, such that the actual input costs of firm f_i is $\gamma\mathcal{C}^{I}_{i}$. Then, similarly to the procedure described in the previous section, firm f_i increases its price by a factor δ, such that,

$$\delta = 1 + \frac{\gamma\mathcal{C}^{I}_{i} - \mathcal{C}^{I}_{i}}{(1 - \mathcal{M}_{i,k})\alpha_{i,k}\mathcal{R}_i}. \tag{2-14}$$

In both cases of price increase, the actual flow of products $\varphi_{i,j}(t)$ from agent i to agent j is unchanged. In contrast, the monetary flow, which corresponds to the payment made by agent j to agent i, grows from $\varphi_{i,j}(t)$ to $(1 + \delta)(1 + \beta)f_{i,j}(t)$.

2.4 Disruption analyses

2.4.1 Dynamical behavior

The model is initialized at the static equilibrium described in Sections 2.1 and 2.2. In the absence of any disruptions, the model stays at equilibrium. If a utilized transportation infrastructure gets disrupted, then flows may be rerouted or blocked. Price may increase due to increased transportation costs, or household consumption may be missed due to shortages.

A disruption scenario is defined by a list of disrupted transportation infrastructures and the duration of the disruptions, denoted by τ. The model is initialized at $t = 1$. Disruptions occur at time $t = 2$. We monitor the flows of products between all the agents over time, $\varphi_{i,j}(t)$, as well as the flows of products at each transport infrastructure, denoted by $\varphi^{[u]}(t)$. We stop the simulation when flows are back to pre-disruption values.

2.4.2 Indicators

We focus on households, which are located at different nodes of the transport networks. We follow their consumption, $\varphi_{i,j}(t)$ and spending $\theta_{i,j}(t)$, for $j = h_1, \dots, h_H$. We denote by $\varphi_{F,H}(t)$ the total consumption of households at time t, and by $\theta_{F,H}(t)$ their total expenditure at time t.

We build an aggregate indicator, called *indirect loss* and denoted by R, to summarize the impact of a disasters on the consumption of Tanzanian households:

$$R = R[\text{PRICE}] + R[\text{SHORTAGE}]. \tag{2-15}$$

It consists of two terms.

- $R[\text{PRICE}]$ measures the aggregate impact on consumption due to price increases. It the total amount of extra expenditure made over the whole time period relative to expenditure in pre-disaster time:

$$R[\text{PRICE}] = \frac{\sum_t \left(\theta_{F,H}(t) - \theta_{F,H}(1)\right)}{\theta_{F,H}(1)}. \tag{2-16}$$

- $R[\text{SHORTAGE}]$ measures the aggregate impact due to lost consumptions. It the total amount of consumption missed over the whole time period relative to consumption in pre-disaster time:

$$R[\text{SHORTAGE}] = -\frac{\sum_t \left(\varphi_{F,H}(t) - \varphi_{F,H}(1)\right)}{\varphi_{F,H}(1)}. \tag{2-17}$$

By looking at factor β and δ, described in Sections 2.3.5 and 2.3.6, as well as firms' margin, we study the propagation of price increases on the network.

A criticality analysis consists of disrupting one-by-one each transportation infrastructures and measuring the associated indirect loss. The resulting criticality map is:

$$u \rightarrow R(u). \tag{2-18}$$

Multiple criticality maps can be generated by varying model parameters, such as the duration of the disruptions, the number of inventories, the number of suppliers, etc., or by changing the definition of indirect impact R, for instance by focusing of specific agents or sectors.

Chapter 3. Data integration

This chapter explains how the model described in Chapter 2 is calibrated. A variety of dataset is used: infrastructure data, population census, firm survey, business registry, pre-analyzed satellite data containing gridded land cover, population, and GDP. The data preparation procedures are described.

3.1 Transportation infrastructure

3.1.1 Tanzanian transportation infrastructure

Pant et al. (2018) compiled and structured a dataset of the multimodal transportation infrastructure of the United Republic of Tanzania, represented on Figure 3-1. We checked this dataset and performed multiple corrections; see Appendix A.

Pant et al. (2018) gathered estimates of freight flows. They concluded that airways had a negligible shares of freight flows, with less than 0.015% of the imports, exports, and transit flows. We decide to exclude airways and airports from the study. According to Pant et al. (2018)'s estimates, rails account for less than 1% of freight flows. We leave rails out of the scope in this version of the study.

The transportation cost associated with each infrastructure, Γ_u, is calibrated using Pant et al. (2018)'s costing model.

- The cost of transportation services is 0.07 USD per ton per km on paved roads, and 0.1 USD per ton per km on paved roads.
- Average speeds are 18 km/h on unpaved road and 30 km/h on paved roads.

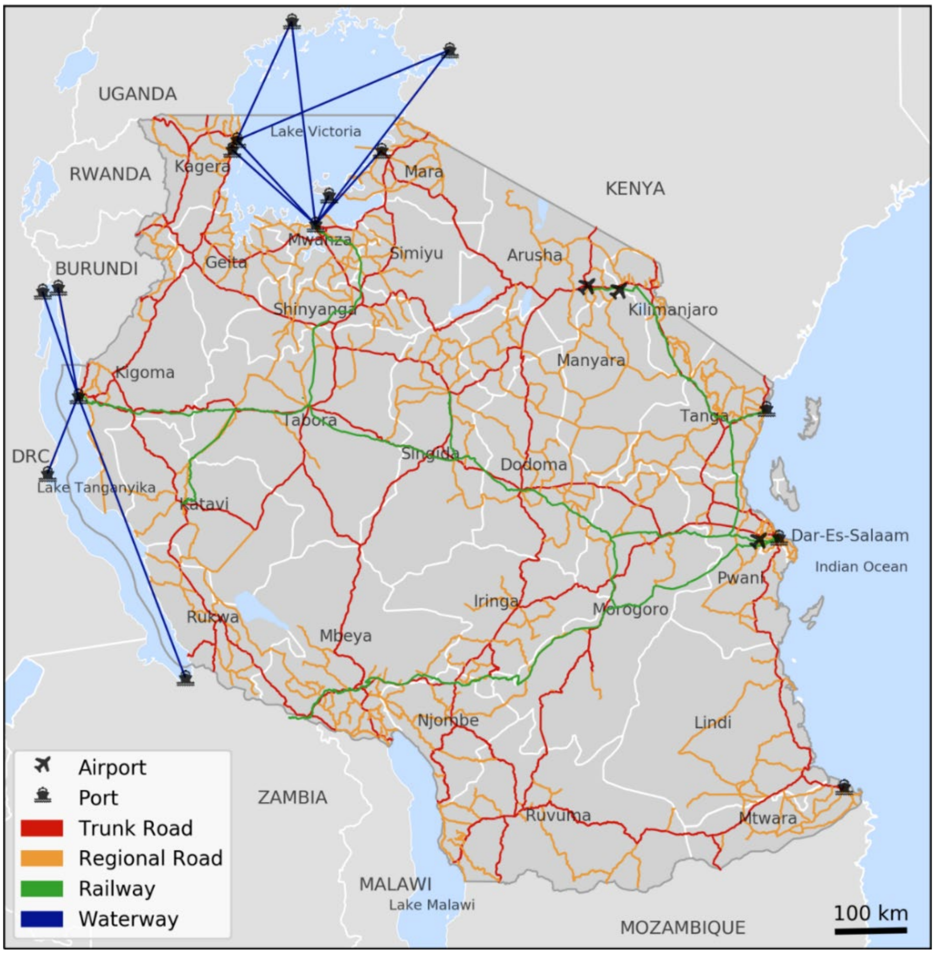

Figure 3-1: Map of the main transportation infrastructure of the United Republic of Tanzania. Figure taken from Pant et al. (2018)

Several transportation nodes are the entry and exit points for imports, exports, and transit flows; see Table 3-1.

Table 3-1: Transportation nodes connecting the Tanzanian transportation network to other countries

Type of nodes	Node names
Seaport	Dar-es-Salaam port, Tanga port, Mtwara port
Inland port	Mwanza, Kigoma
Road border crossing	Horohoro, Holili, Namanga, Sirari, Mutukula, Rusumo, Kabanga, Kigoma, Tunduma, Kasumulu, Mkenda, Ruvuma river, Mtambaswala
Railway station	Tunduma station

3.1.2 Identification of the main origin-destination nodes

Pant et al. (2018) analyzed the spatial distribution of population using data from the WorldPop project available at worldpop.org.uk. They identified the most significant transportation nodes based on population criteria. They provided a list of 311 OD nodes.

We amended this list of OD nodes, using pre-analyzed satellite data on GDP and population, and the population census data at the ward level. Wards are, in the United Republic of Tanzania, the third administrative units in size after regions and districts. We superimposed these data to select OD nodes located areas with significant population and economic activity. OD nodes in districts of less than 40,000 inhabitants were eliminated. In populated districts, we selected multiple OD nodes, such that no OD nodes should represent more than 300,000 inhabitants.

We finalized a list of 324 OD nodes. From the original list of 311 OD nodes, we removed 95 nodes and added 113 new nodes.

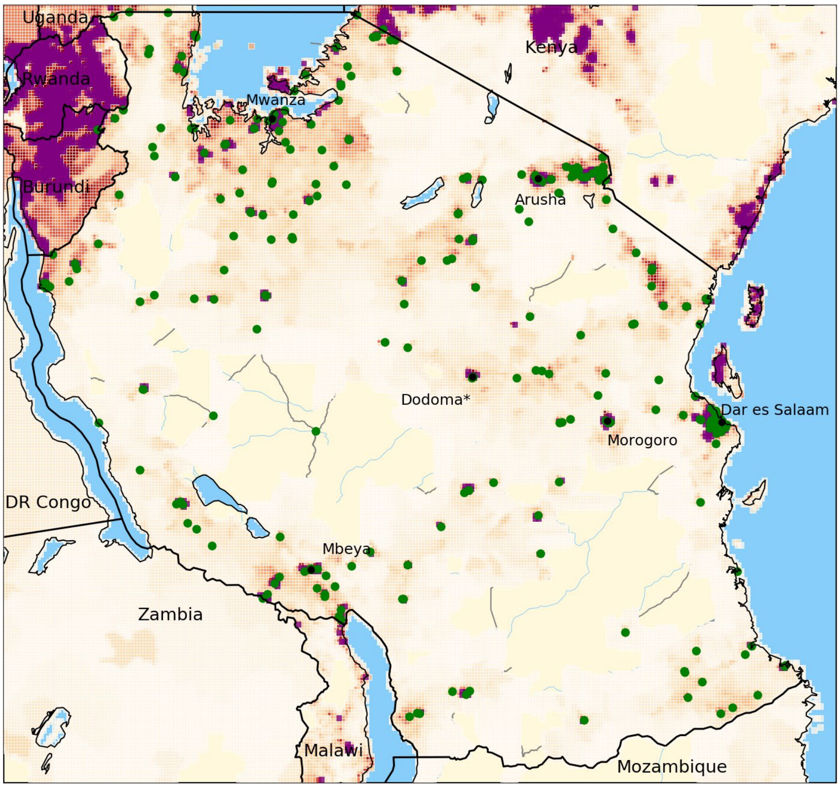

Figure 3-2: We model supply-chain-flows between 324 origin–destination nodes. On the map a color-coded layer of population data, the GPWv4 dataset [14], is shown.

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[14] Center for International Earth Science Information Network (CIESIN), Columbia University. 2018. Documentation for the Gridded Population of the World, Version 4 (GPWv4), Revision 11 Data Sets. Palisades NY: NASA Socioeconomic Data and Applications Center (SEDAC). https://doi.org/10.7927/H45Q4T5F Accessed 12/01/2019

3.2 Country-wide input–output and international trade data

3.2.1 Input–output data connecting sectors

We use input–output data for the United Republic of Tanzania from the Global Trade Analysis Project (GTAP). The 2014 release contains data on 57 sectors, listed in Appendix B, Table 8-4. The number of sectors used in the model, S, is 42. We applied several changes to this list of sectors to obtain a classification that is consistent with other data sources. For instance, the business registry, which is our main source of information for the spatial distribution of production, is built using the ISIC Rev. 4 sector coding, and lacked data on agricultural sector. The final list of sectors used in the model is shown in Table 3-2. The procedure by which the number of sectors was reduced from 57 to 42 is described in Appendix A.

Table 3-2: List of the 42 sectors used in the model.

Id	Sector name	Id	Sector name
1	Agriculture, except forestry and fishing	36	Metals nec
13	Forestry	37	Metal products
14	Fishing	38	Motor vehicles and parts
15	Coal	39	Transport equipment nec
16	Oil & Gas	40	Electronic equipment
18	Minerals nec	41	Machinery and equipment nec
19	Meat products	42	Manufactures nec
21	Vegetable oils and fats	43	Electricity
22	Dairy products	44	Gas manufacture, distribution
23	Food products nec	45	Water
24	Sugar	46	Construction
26	Beverages and tobacco products	47	Trade
27	Textiles	48	Transport nec
28	Wearing apparel	49	Sea transport
29	Leather products	50	Air transport
30	Wood products	51	Communication
31	Paper products, publishing	52	Financial services nec
32	Petroleum, coal products	53	Insurance
33	Chemical, rubber, plastic prods	54	Business services nec
34	Mineral products nec	55	Recreation and other services
35	Ferrous metals	56	PubAdmin/Defence/Health/Educat

GTAP data are used to fill a sector-to-sector input–output table, whose structure is given in Table 3-3. Note that only selected data were compiled, leaving out of our scope accounting fields such as compensation of employees, taxes and subsidies on production, consumption of fixed capital, gross fixed capital formation, etc. Technical details on input–output accounting can be found in the UN Handbook of Input–output Table Compilation and Analysis (1999) [15].

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[15] United Nations (1999), *Handbook of Input-Output Table Compilation and Analysis*, Department of Economic and Social Affairs, Statistics Division. Studies in Methods, Handbook of National Accounting, Series F No. 74. ISBN 92-1-161416-3. United Nations, New York, USA

Table 3-3: Structure of the input–output table filled with GTAP data.

		Buying sectors									
		1	**2**	**3**	**…**	**56**	**57**	**Exports**	**Government consumption**	**Households consumption**	**Total output**
Supplying sectors	**1**										
	2										
	3										
	…										
	56										
	57										
	Imports										

The $(S+1) \times S$ technical coefficients of matrix $\mathbb{A}$ are derived from this input–output table. The “total output” column is transposed into a S-length “total output” row. Then, the first S columns of the table—those headed by buying sectors—are isolated, and each of the rows of this $(S+1) \times S$ table are divided by the “total output” row. The resulting table contains the technical coefficients: the top 57 rows corresponds to coefficients $a_{i,j}$ for $i, j = 1, \dots, S$. The bottom row, which is labelled “imports”, corresponds to coefficients $a_{0,j}$ for $j = 1, \dots, S$. We discard coefficients that are below a threshold $\beta_a = 1\%$, i.e., there are set to 0.

Matrix $\mathbb{A}$ describes the reliance of Tanzanian economic sectors on other Tanzanian economic sectors and on imports. It is shown in Appendix B, Table 8-5. We observe expected interdependencies, such as, the reliance of the processed rice sector on the paddy rice sector ($a_{1,25}$), of the textile industry on plant-based fibers producers ($a_{7,27}$), or of wood producers on forestry ($a_{13,30}$). The dependence of all sectors on trade is also well marked (row 47).

GTAP provides household consumption at the sectoral level for the whole country, forming a length-S vector $\mathbb{D}^{\mathrm{H}}$. It is shown in Appendix B, Table 8-9. Tanzanian households spend most in food products and vegetables, as well as product from the trade sector. Government consumption is very low compared to household consumption. We aggregate government and household consumption.

To ease the interpretation of the results, we group the remaining GSC sector into five larger sectors: Agriculture, Food, Manufacturing, Trade, and Others; see Table 3-4. This level of aggregation is not used in the model itself, only for the presentation of the results.

Table 3-4. Definition of the five most aggregated sector grouping used for the interpretation of the results.

Sector grouping	Grouped sector id and name
Agriculture	1 – Paddy rice 13 – Forestry 14 – Fishing
Food	19 – Meat: products 21 – Vegetable oils and fats 22 – Dairy products 23 – Food products 24 – Sugar 26 – Beverages and tobacco products
Manufacturing	27 – Textiles 28 – Wearing apparel 29 – Leather products 30 – Wood products 31 – Paper products, publishing 32 – Petroleum, coal products 33 – Chemical, rubber, plastic prods 34 – Mineral products nec 35 – Ferrous metals 36 – Metals nec 37 – Metal products

	38 – Motor vehicles and parts 39 – Transport equipment nec 40 – Electronic equipment 41 – Machinery and equipment nec 42 – Manufactures nec
Trade	47 – Trade
Others	43 – Electricity 44 – Gas manufacture, distribution 45 – Water 46 – Construction 48 – Transport nec 49 – Sea transport 50 – Air transport 51 – Communication 52 – Financial services nec 53 – Insurance 54 – Business services nec 55 – Recreation and other services 56 – PublicAdmin/Defense/Health/Education

The shares of household consumption in each of these larger sectors are as follows: 44% in Agriculture, 33% in Food, 10% in Trade, 6% in Manufacturing, and 7% in Others; see Figure 3-3.

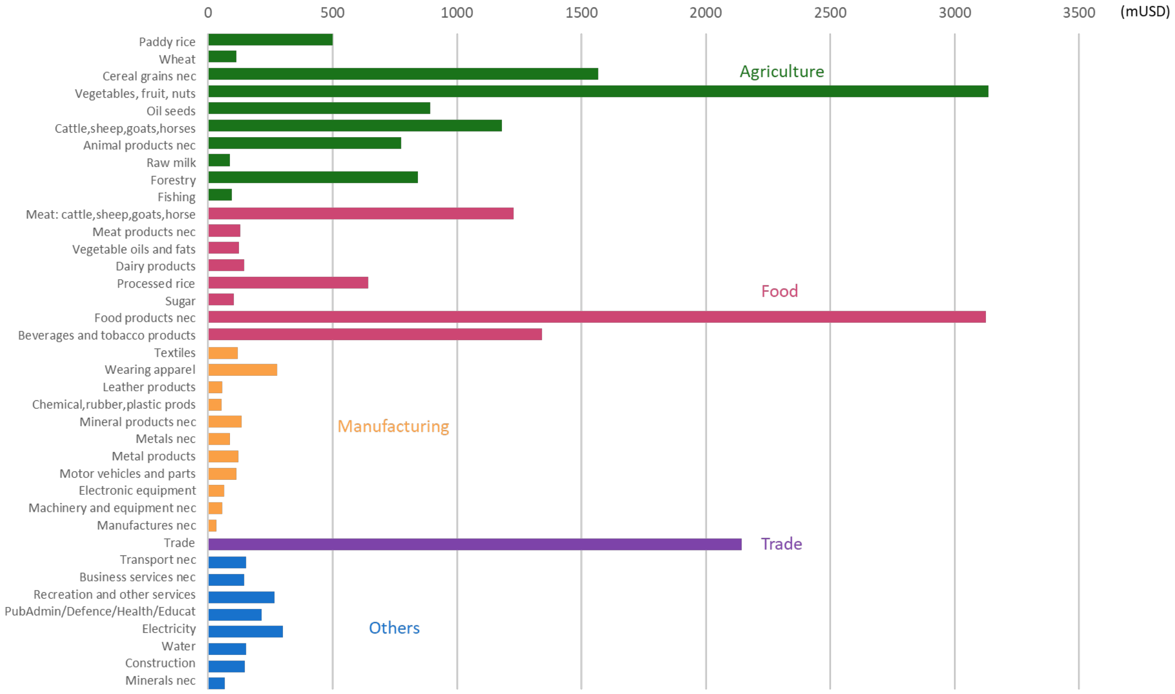

Figure 3-3. Final demand per GTAP sector, grouped into five larger sectors: Agriculture, Food, Manufacturing, Trade, and Others.

3.2.2 Selection of trading countries

The imports and exports data are disaggregated at level of countries or group of countries. We isolate the 8 neighboring countries, i.e., Burundi, Democratic Republic of Congo (abbreviated by DR Congo), Kenya, Malawi, Mozambique, Rwanda, Uganda, and Zambia. We group all other trading countries into 6 global regions: America, Asia, Europe, Middle East, Oceania, Other Africa. These 14 countries or regions corresponds to 14 countries in the model, $c_1, \dots, c_C$.

As described in Section 2.2.2, each agent is, in the model, associated to one or several nodes of the Tanzanian transportation network. These nodes are the origin or destination of the modeled trade flows. Table 3-5 lists the countries and their associated countries.

Table 3-5: List of the country or global regions modeled and their associated transportation nodes.

Id	Country and global region	Transportation node
c_0	Burundi	Kabanga (road border crossing), Kigoma (inland port)
c_1	DR Congo	Kigoma (inland port), Rusumo, Kabanga (road border crossing)
c_2	Kenya	Sirari, Namanga, Holili, Horohoro (road border crossing), Tanga (seaport)
c_3	Malawi	Kasumulu (road border crossing)
c_4	Mozambique	Mkenda, Ruvuma river, Mtambaswala (road border crossing), Mtwara (seaport)
c_5	Rwanda	Rusumo (road border crossing)
c_6	Uganda	Mutukula (road border crossing), Mwanza (inland port)
c_7	Zambia	Tunduma (road border crossing), Tunduma station (railway station)
c_8	America	Dar-es-Salaam port (seaport)
c_9	Asia	Dar-es-Salaam port (seaport)
c_{10}	Europe	Dar-es-Salaam port (seaport)
c_{11}	Middle East	Dar-es-Salaam port (seaport)
c_{12}	Oceania	Dar-es-Salaam port (seaport)
c_{13}	Other Africa	Dar-es-Salaam port (seaport)

3.2.3 Imports and exports

GTAP data provide import and export flows from each one of the 57 economic sectors of the United Republic of Tanzania to 141 countries or regions. We group these data according to the 14 selected countries or global region of Table 3-5. We obtain the sector-to-country export table, whose shape is described in Table 3-6 and whose values are shown in Appendix B, Table 8-6. The export matrix $\mathbb{Z}$, described in Section 2.1.2, is directly derived from Table 8-6.

Table 3-6: Structure of the sector-to-country export matrix filled with GTAP data.

		Buying countries						
		c_0	c_1	c_2	…	c_{12}	c_{13}	**Total exports**
Supplying sectors	**1**							
	2							
	3							
	…							
	41							
	42							
	Total purchases							

We observe that the metal-producing sector is the most exporting (sector 36), especially to Asia and the Middle East. Large quantities of gold, copper, and other precious metals are exported each year. It is followed by the export of fruits (sector 4) and of mining ores (sector 18). European countries are also significant destinations of Tanzanian products. Among neighboring countries, Kenya is the largest importers of Tanzanian products, especially of cereal other than wheat and rice (sector 3), of various food products (sector 25) and textile (sector 27).

We also obtain the country-to-sector import table, whose shape is described in Table 3-7 and whose values are shown in Appendix B, Table 8-7. For each buying sectors (columns), we evaluate the share of imports coming from each country. This value, called *importance*, will be used in the construction of the country-to-firm import network $\mathbb{Y}$ in Section 3.5.3. We denote by $\mathcal{I}(c_i, s_j)$ the importance of country c_i in supplying sector s_j.

Asian countries are the main exporters to the United Republic of Tanzania, with large quantity of refined petroleum (sector 32) coming from India, and of plastic products coming from China (sector 33).

Table 3-7: Structure of the country-to-sector import matrix filled with GTAP data.

		Buying sectors						
		1	**2**	**3**	**…**	**41**	**42**	**Total imports**
Supplying countries	c_0							
	c_1							
	c_2							
	…							
	c_{12}							
	c_{13}							
	Total purchases							

3.2.4 Transit flows

Transit flows are international trade flows that are neither produced nor consumed in the United Republic of Tanzania, but that go through its transportation system.

- First, we build a trade matrix between the 14 countries and global region using the GTAP data; see Table 3-8 (a).
- Next, we estimate, for each flow, the share that goes through the United Republic of Tanzania; see Table 3-8 (b). These estimates are derived from the study of transit flows of JICA (2013) 16. In Volume 3, Chapter 1 of the JICA report, the authors analyzed the routes taken by trade flows between selected neighboring countries. In addition, we use common sense assumptions to fill remaining unknown values of Table 3-8 (b). For instance, we assume no trade flows between non-African countries goes through the United Republic of Tanzania. For neighboring countries that share a common terrestrial border, e.g., Burundi and Rwanda, we assume that no flows go through the United Republic of Tanzania.
- Last, we perform an element-wise multiplication of table Table 3-8 (a) and Table 3-8 (b) to obtain the transit flow matrix $\mathbb{V}$ described in Section 2.1.2. It is shown in Appendix B, Table 0-5.

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[16] Japan International Cooperation Agency (2013) *Comprehensive Transport and Trade System Development Master Plan in the United Republic of Tanzania*. This report was produced by the Japan International Cooperation Agency for the Ministry of Transport of The United Republic of Tanzania and released in 2013.

Table 3-8: Structure of (a) the country-to-country trade table and (b) the table displaying the share of each flow that goes through the United Republic of Tanzania.

(a)

		Buying countries					
		c_0	c_1	c_2	…	c_{12}	c_{13}
Supplying countries	c_0						
	c_1		Trade flows				
	c_2						
	…						
	c_{12}						
	c_{13}						

(b)

		Buying countries					
		c_0	c_1	c_2	…	c_{12}	c_{13}
Supplying countries	c_0	Share flowing through the United Republic of Tanzania					
	c_1						
	c_2						
	…						
	c_{12}						
	c_{13}						

We observe significant transcontinental trade flows coming from Asia, Europe, and the Middle East and going to Burundi, DR Congo, Rwanda, Uganda, and Zambia. Significant exports from the DR Congo and Zambia are flowing to Asia, Europe, and the Middle East through The United Republic of Tanzania. Trade flows between neighboring countries are dominated by Kenyan imports and exports with Burundi, DR Congo, Malawi, Rwanda, and Zambia.

3.3 Geographical distribution of production and consumption

3.3.1 Evaluating the significance of sectors in districts

To evaluate the significance of each sector in each district, we use merged three metrics:

- The employment of each sector in each district
- The importance of a sector at the country level
- The GDP of each district

In theory, knowing the employment of each sector in each district, which is a satisfactory proxy for size, would have been enough to evaluate the significance of each sector in each district. In practice, this approach did not deliver reasonable estimates, because the main data source for employment at the district level, which was the business registry, was lacking consistency. Some regions seem to overrepresented, other underrepresented, leading to inconsistent estimates. We used satellite-based estimates of GDP per district along with nationwide sectoral metrics to correct such inconsistencies.

To begin with, we had to produce estimates of employments in agriculture. This sector was nearly absent from the business registry, although it represents the main economic occupation of the Tanzanian workforce.

We used the 2010 dataset from the Regional Centre For Mapping of Resources for Development (RCMRD)[17], which provides a classification of land cover at a 30-meter-by-30-meter resolution. We analyzed the dataset that uses the Scheme II classification and counted as agricultural land any pixel labeled as Planted Forest, Closed Grassland, Closed Bushland, Perennial Cropland, and Annual Cropland. Using administrative boundaries, we obtain estimates of the surface of land used for agriculture per district.

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[17] https://www.rcmrd.org/

Next, we use these data to evaluate the number of workers in agriculture. According to the World Factbook (2017)[18], the Tanzanian workforce amounts to 24.89 million workers, 68% of which are in agriculture. The business registry built and maintained by the National Bureau of Statistics of the United Republic of Tanzania provides a list of about 257,894 companies. The main activity is indicated for 246,833 firms and the employment for 217,785 firms, i.e., for 84.4% of them. The total number of workers in these registered firms is 1,725,793. If we suppose that the registry should contains all nonagricultural employees, a number of employees in agriculture that is consistent with the registry is 1,725,793*0.68/(1-0.68) = 3,667,310. We use the estimates of the surface of land used for agriculture per district to downscale this number of workers in agriculture in each district.

We obtain the number of employees per sector and per district, denoted by $E_{s,d}$. Because this value does not satisfactorily represent the production per sector per district, we used GDP per district, GDP_d, and production per sector, P_s, to build an indicator that will be used as input in the DirsuptSCT model, called importance of production per sector and per district, $\mathcal{J}_{s,d}$. GDPs per district are built by analyzing the satellite-based dataset of Kummu et al. (2018) together with the administrative boundaries of the United Republic of Tanzania. Productions per sector are given in the GTAP database.

The importance of production per sector and per district are calculated as follows:

$$\mathcal{J}_{s,d} = \left(E_{s,d}\right)^{\alpha} (GDP_d)^{\beta} (P_s)^{\gamma}, \tag{3-1}$$

where α, β, and γ are factors such that $\alpha + \beta + \gamma = 1$. If the employment data were comprehensive and fully consistent, we would use $\alpha = 1$. If we had no data on employment at all, i.e., $\alpha = 0$, our estimates will suppose that the sectoral mix is the same in all district, which only differs by the economic importance. If this study, we use $\alpha = \beta = \gamma = 1/3$.

3.3.2 Creating representative firms on OD nodes

Based on the importance of production per sector and per district, we deduce the importance of production per sector and per OD node, called $\mathcal{J}_{s,OD}$, simply by dividing $\mathcal{J}_{s,d}$ by the number of OD nodes in district d. From these values, we build one representative firm per sector and per OD nodes, whose importance is $\mathcal{J}_{s,OD}$.

Firms from utilities and services, i.e., from sectors 43, 44, 45, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, and 58, are modeled differently. We suppose that their outputs do not need the transportation network to move from supplier to buyer. In the model, firms from these sectors do not need to be localized on any OD nodes. We still need to represent them, because they play a role in supply chains. We model two representative firms for each one of these sectors. These firms are not localized and represent any firms in the country. We create two firms per sector instead of one to allow them to source their same-sector inputs.

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[18] https://www.cia.gov/library/publications/resources/the-world-factbook/index.html

In all other sectors, we create one firm per sector and per OD node, if the importance is larger than 0. Doing so on the 324 OD nodes, we would model 5,072 firms. Computational time grows at least quadratically with the number of agents in the model. We set cut-off values to reduce the number of firms to 1,861. We only model firms whose importance are over 0.003, except for agriculture and forestry, for which the threshold is set to 0.0015. In these two sectors, the spatial distribution of importance $\mathcal{J}_{s,OD}$ is much more spread that in the other sectors, forcing us to adapt the threshold in order to avoid eliminating all firms. In addition, if all firms of a sector fall below the threshold, we keep the firms of the most important district for this sector.

The 1,861 representative firms, simply called firms, are denoted by $f_{i,j,k}$, where i indicates the index of the OD node they are in, u_i, j the index of the sector they sector they belong to, s_j, and $k = 1,2$. The importance of firm $f_{i,j,k}$ is denoted by $\mathcal{I}(f_{i,j,k})$. There is a one-to-one correspondence between the notation $f_{i,j,k}$ introduced in this Section and the notation f_i introduced in Section 2.1.1, in which $i = 1, \ldots, F$. We introduce the mapping $\mathscr{i}$, such that each combination (i, j, k) gets a unique index $\mathscr{i}(i, j, k)$ in $1, \ldots, F$.

3.3.3 Assigning consumption to OD nodes

We now use population data to spatially distribute household consumption across the country. We build on the work of OIA and their identification of 324 OD nodes—see Section 3.1.2—and model 324 household $h_1, h_2, \ldots, h_{311}$.

To determine the demand of each of them for each sector, we evaluate the share of population on each OD node, denoted by $\omega_1^H, \omega_2^H, \ldots, \omega_{311}^H$. To that end, we use the latest population census, which was collected in 2012 by the National Bureau of Statistics of the United Republic of Tanzania. Weight ω_i^H is equal to the population of the district in which h_i is located, divided by the total population of the districts that contains an OD node, and again divided by the number of OD nodes in the district.

We generate a $S \times H$ matrix $\mathbb{D}^{\mathrm{SH}}$, in which element $d_{i,j}^{\mathrm{SH}}$ is the consumption of household j of sector-s_i products. It is equal to $d_{i,j}^{\mathrm{SH}} = \omega_j^H d_i^H$. The sum of each row yields the final demand vector $\mathbb{D}^{\mathrm{H}}$. It is possible, however, that some OD nodes have no firm from some sectors. Because we assume that household only consume from local firms, matrix $\mathbb{D}^{\mathrm{SH}}$ need to be adjusted to the local absence of some sectors.

For instance, household h_1 only buys from firms that are located on the 1st OD node. Say that there are no firms from sector s_9 on OD node 1. The consumption of sector-s_9 products from this household, $d_{9,1}^{SH}$, should have been $\omega_1^H d_9^H$; it is set to 0. This lost consumption is transferred to the other households $h_2, h_3, \ldots, h_{311}$. For instance, the consumption of sector-s_9 products of household h_2 increase from $d_{9,2}^{\mathrm{SH}} = \omega_2^H d_9^H$ to $d_{9,2}^{\mathrm{SH}} = \omega_2^H d_9^H + (\omega_2^H/(1 - \omega_1^H))\omega_1^H d_9^H$. In this transformation, the row sum of matrix $\mathbb{D}^{\mathrm{SH}}$, $\sum_j d_{9,j}^{\mathrm{SH}}$, is unchanged.

3.4 Calibrating inventories using survey data

In section 2.1.4, we defined quantity $p_{j,k}$ by the duration over which firm f_j can maintain its production without ordering more of sector-s_k inputs, assuming that no other input would lack. In the model, these quantities are expressed in weeks. There is one parameter per combination of supplying sector i – buying sector j for which the technical coefficient $a_{i,j}$ is positive. Given the cut-off value applied to the matrix of technical coefficient, we need 218 values; see Section 3.2.1.

To calibrate these parameters, we use the 2018 firm survey of the World Bank carried out in the United Republic of Tanzania over the summer 2018. In three regions, 837 firms were surveyed. They were asked, inter alia, to report their five main types of input, and, for each them, how much inventories they keep. The sector of the surveyed firms and their suppliers were collected using ISIC Rev. 4 coding. For each combination of sectors, after translating ISIC Rev. 4 codes to our selected sectoral classification, we calculate the average reported inventory.

With this method, we directly identified 88 inventory parameters. The remaining combinations were not directly accessible in the data, i.e., we did not have data on how much a firm from that particular sector keeps inventory of that particular input. For them, we use the average inventory of the input kept by any firms, whatever their sector. If this value was missing, we use the average inventory for any combinations of input–sector. Overall, the average inventory for each combination of sector is 4.5 weeks. Note that this value is the average over input–sector combinations and is not weighted with the actual inventories hold by firms.

3.5 Connecting households, firms, and countries

The previous sections have defined the three classes of agents: households h_i, countries c_i, and firms $f_{i,j,k}$. We now build the commercial links between these agents leading to the construction of the five networks introduced in Section 2.1.2.

3.5.1 Final consumption network

In Section 0, we created firms on OD nodes. In Section 3.3.3, we created one household per OD node, and evaluates household consumption on OD nodes for each sector. We generated matrix $\mathbb{D}^{\mathrm{SH}}$ to store this information.

On each OD node, we now link the household h_i to local firms $f_{i,j,k}$. We thereby transform the $S \times H$ matrix $\mathbb{D}^{\mathrm{SH}}$ in the $F \times H$ matrix $\mathbb{D}^{\mathrm{FH}}$ introduced in Section 2.1.2. We assume that, for each sector, households buy from the two local firms, $f_{i,j,1}$ and $f_{i,j,2}$. The share of purchase to each firm is proportional to firm importance. Specifically, for each nonzero element (i,j) of $\mathbb{D}^{\mathrm{SH}}$, corresponding to OD node j and sector s_i:

- Two commercial links are drawn: one from $f_{j,i,1}$ to household h_j, another from $f_{j,i,2}$ to household h_j.
- The final consumption matrix $\mathbb{D}^{\mathrm{FH}}$ is updated as follows:

- $d^{\mathrm{FH}}_{\imath(j,i,1),j} = d^{\mathrm{SH}}_{i,j}\, \mathcal{I}(f_{j,i,1}) / [\mathcal{I}(f_{j,i,1}) + \mathcal{I}(f_{j,i,2})]$, and
- $d^{\mathrm{FH}}_{\imath(j,i,2),j} = d^{\mathrm{SH}}_{i,j}\, \mathcal{I}(f_{j,i,2}) / [\mathcal{I}(f_{j,i,1}) + \mathcal{I}(f_{j,i,2})]$,

  where $\mathcal{I}(f_{j,i,k})$ is the importance of firm $f_{j,i,k}$ calculated in Section 0, and $d^{\mathrm{SH}}_{i,j}$ are calculated in Section 3.3.3.

Note that no route is associated to these commercial links. We assume that households buy directly at the firms' premises. No transportation infrastructure is needed for the delivery of final products.

3.5.2 Interfirm network

The interfirm network is represented by the $F \times F$ input–output matrix $\mathbb{W}$ defined in Section 2.1.2. It is built by having each firm selecting other firms as suppliers, based on their technical coefficients, the weight of and the distance to the other firms.

Firm $f_{i,j,k}$ is located at OD node u_i and belongs to sector s_j. The nonzero technical coefficients of sectors_j provides the list of sectors supplying products to firm $f_{i,j,k}$. For each one of these, the firm selects one supplier. This selection is a weighted random choice, in which the weights of the firms is based on their importance and their distance.

Say the technical coefficient $a_{4,8}$ is strictly positive. Firm $f_{1,8,1}$ needs a supplier from sector s_4. All firms $f_{i,4,k}$, where $i = 1, \ldots, 311$ and $k = 1,2$, if any, are eligible to be a supplier of $f_{1,8,1}$. Firm $f_{1,8,1}$ select one supplier among them. In this context, we define the weight of firms $f_{i,4,k}$ as follows:

$$\mathcal{N}\left[\frac{\mathcal{N}[\mathcal{I}(f_{i,4,k})]}{1 + \mathcal{N}[\mathcal{D}(f_{1,8,1}, f_{i,4,k})]}\right], \tag{3-2}$$

where:

- $\mathcal{I}(f_{i,4,k})$ is the importance of firm $f_{i,4,k}$ calculated in Section 0.
- $\mathcal{D}(f_{1,8,1}, f_{i,4,k})$ is the distance between firm $f_{1,8,1}$ and firm $f_{i,4,k}$, which is equal to the distance between OD node 1 and OD node i.
- Operator $\mathcal{N}$ is a normalization operator, which linearly transforms a list of values $x_1, \ldots x_n$ into a list between 0 and 1.

Once a firm has been selected, say $f_{10,4,2}$:

- A commercial link is drawn from $f_{10,4,2}$ to $f_{1,8,1}$.
- A route is associated to this commercial link, as described in Section 2.2.2. It is the least-cost route linking OD node 10 and OD node 1.
- The input–output matrix is updated as follows: $w_{\imath(10,4,2),\imath(1,8,1)} = a_{4,8}$.

3.5.3 Import network

The import network is represented by the $C \times F$ matrix $\mathbb{Y}$ defined in Section 2.1.2. It is built by having firms select countries as suppliers, based on the import technical coefficients, the importance of countries, and their distance to countries.

The technical coefficient related to imports is the first row of matrix $\mathbb{A}$, which was calibrated in Section 3.2.1. Only firms belonging to sectors whose import technical coefficient is nonzero do import.

The procedure for selecting countries as supplier is the same as the one for selecting firms as supplier, described in Section 3.5.2. Suppose that sector s_4 has a nonzero technical coefficient related to imports, i.e., $a_{0,4} > 0$. Each sector-s_4 firm selects one country as supplier. Selection is a weighted random choice. For firm $f_{1,4,1}$, the weight of each country c_i is:

$$\mathcal{N}\left[\frac{\mathcal{N}[\mathcal{I}(c_i, s_4)]}{1 + \mathcal{N}\left[\mathcal{D}\left(f_{1,4,1}, c_i\right)\right]}\right], \tag{3-3}$$

where:

- $\mathcal{I}(c_i, s_4)$ is the importance of country c_i in supplying sector-s_4 firms of the United Republic of Tanzania, calculated in Section 3.2.3.
- $\mathcal{D}\left(f_{1,4,1}, c_i\right)$ is the distance between firm $f_{1,4,1}$ and country c_i. Because several OD nodes may be associated by a country---see Table 3-5, we need to decide which OD node should be selected when evaluating the distance. We select the OD node of country c_i that is the closet to OD node 1.
- $\mathcal{N}$ is the normalization operator defined in Section 3.5.2.

Suppose that country c_9 was selected. It follows that:

- A commercial link is drawn from country c_9 to firm $f_{1,4,1}$.
- A route is associated to this commercial link, as described in Section 2.2.2. It is the least-cost route linking OD node 1 and the OD node associated by country c_9 that is the closest to OD node 1.
- The import matrix $\mathbb{Y}$ is updated as follows: $y_{9,\imath(1,4,1)} = a_{0,4}$.

3.5.4 Export network

The export network is represented by the $F \times C$ matrix $\mathbb{Z}$ defined in Section 2.1.2. It is built by having each country buying products from Tanzanian firms selects Tanzanian firms as suppliers. Table 8-6 shows which country is buying from which sector.

The selection process is based on firm importance and distance. In contrast to the selection process for the interfirm and import networks, more than one firm is selected. We suppose that each country buys, for each sector, from 10% of the firms of this sector.

Say that country c_9 is buying from sectors s_4. It selects 10% of the sector-s_4 firms using a weighted random-choice procedure without replacement. The weight of each firm $f_{i,4,k}$ is:

$$\mathcal{N}\left[\frac{\mathcal{N}[\mathcal{I}(f_{i,4,k})]}{1+\mathcal{N}[\mathcal{D}(f_{i,4,k}, c_9\,)]}\right], \tag{3-4}$$

where:

- $\mathcal{I}(f_{i,4,k})$ is the importance of firm $f_{i,4,k}$ calculated in Section 0.
- $\mathcal{D}(f_{i,4,k}, c_9\,)$ is the distance between firm $f_{i,4,k}$ and country c_9. Several OD nodes may be associated by a country; see Table 3-5. We select the OD node of country c_9 that is the closet to OD node i.
- $\mathcal{N}$ is the normalization operator defined in Section 3.5.2.

We suppose in this example that there are 20 sector-s_4 firms, and that firm $f_{3,4,1}$ and firm $f_{9,4,2}$ were selected. Country c_9 has to decide how much it buys from each of the two firms. Purchases are shared among the firms proportionally to their importance. In this case, country c_9 buys $\mathcal{I}(f_{3,4,1})/[\mathcal{I}(f_{3,4,1})+\mathcal{I}(f_{9,4,2})]$ from firm $f_{3,4,1}$ and $\mathcal{I}(f_{9,4,2})/[\mathcal{I}(f_{3,4,1})+\mathcal{I}(f_{9,4,2})]$ from firm $f_{9,4,2}$. It follows that:

- Two commercial links are drawn: one from firm $f_{3,4,1}$ to country c_9, another from one from firm $f_{9,4,2}$ to country c_9.
- The route associated with the first commercial link is the least-cost route linking OD node 3 and the country-c_9 OD node that is the closest to OD node 3.
- The route associated to the second commercial link is the least-cost route linking OD node 9 and the country-c_9 OD node that is the closest to OD node 9.
- The export matrix $\mathbb{Z}$ is updated as follows: $z_{i(3,4,1),9}=\mathcal{I}(f_{3,4,1})/[\mathcal{I}(f_{3,4,1})+\mathcal{I}(f_{9,4,2})]$, and $z_{i(9,4,2),9}=\mathcal{I}(f_{9,4,2})/[\mathcal{I}(f_{3,4,1})+\mathcal{I}(f_{9,4,2})]$.

3.5.5 Transit network

The transit network results from matrix $\mathbb{V}$, defined in Section 2.1.2 and calibrated in Section 3.2.4. Matrix $\mathbb{V}$ already contains the details country-to-country relationships. There is no need for country to select other country as supplier. It follows that, for each nonzero flow $v_{j,i}$,

- A commercial link is drawn from country c_j to country c_i.
- A route is associated to this commercial link. It is the least-cost route linking the country-c_j OD node and the country-c_i OD node that are the closest.

Chapter 4. Simulation of supply-chain flows

This chapter presents the main features of the supply-chain flows resulting from the data-integration procedures presented in Chapter 3. These results are produced by the static version of the model, formulated in Sections 2.1 and 2.2. The sectoral and spatial distributions of production, consumption, and freight flows are shown, along with their robustness to modeling assumption.

4.1 Main features of the simulated supply chains

4.1.1 Sectoral shares of production, consumption, and exports

The United Republic of Tanzania has an agriculture-based economy. This sector concentrates represents 37% of the country's total economic output; see Figure 4-1. More than half of this agricultural production is directly consumed by households, without intermediaries. Spending in this sector represents 44% of their expenditure. The whole food sector, which, in our sectoral aggregation shown in Table 3-4, groups processed foods, beverages, and tobacco, is the second largest portion of the economy. Its output is primarily consumed locally.

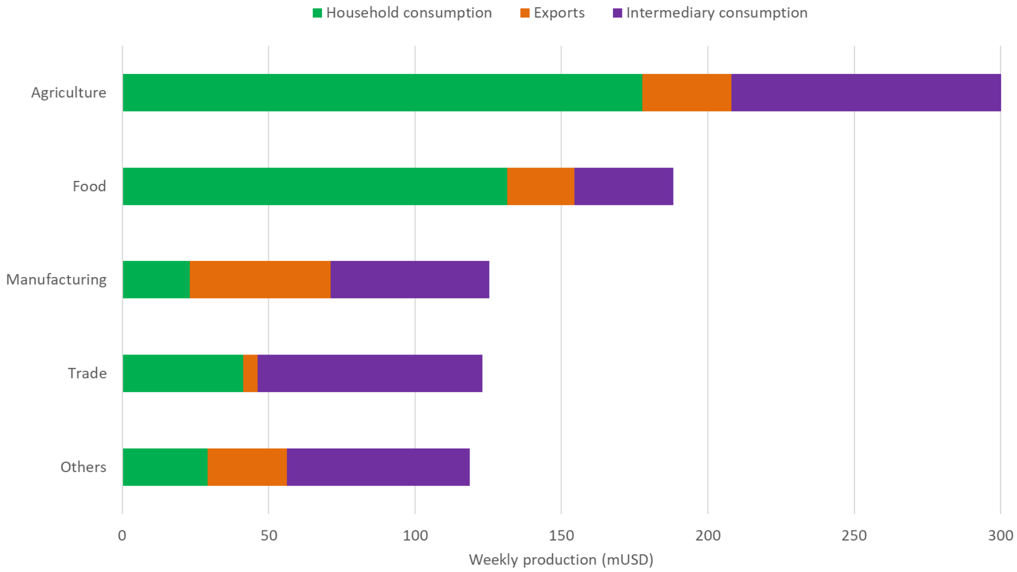


Figure 4-1. Weekly production per groups of sectors defined in Table 3-4. Colors of the bar indicate the quantity purchased by households (green), exported (orange), and purchased by other Tanzanian firms (purple).

The trade sector, which groups retailers and wholesalers, plays a pivotal role in the economy. Its outputs are mainly used as inputs of other sectors. Manufacturing is mostly export-oriented, driven by the production of gold, copper, and other precious metals sold to India and the Middle East; see the "Minerals nec" and "Metals nec" sectors in Figure 4-2. The "Others" sector groups activities that serve as inputs of others, e.g., business services, communication, and transportation, as well as household-oriented services such as education, health services, and recreational activities.

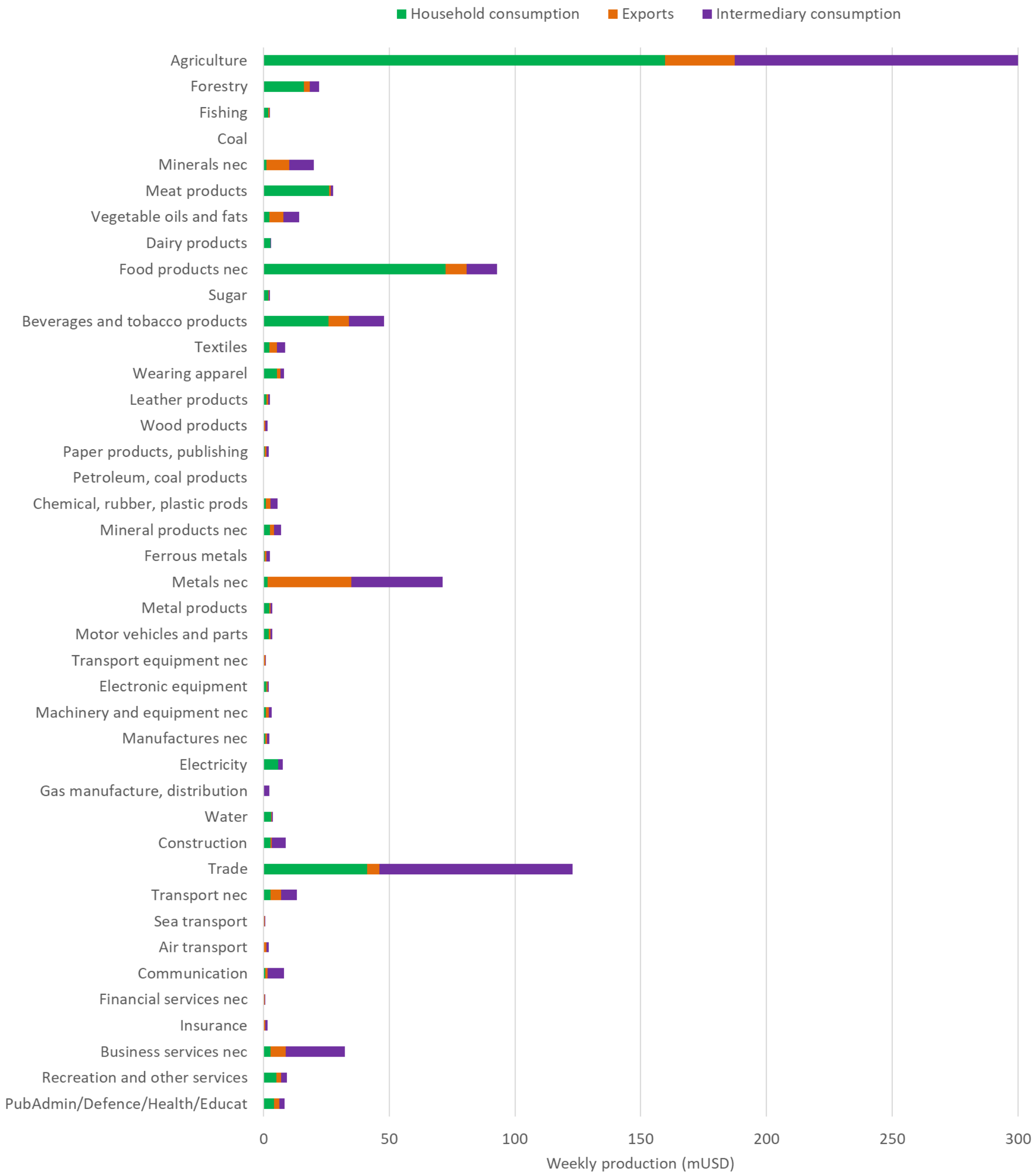


Figure 4-2: Weekly production per GTAP sector. Colors of the bar indicate the quantity purchased by households (green), exported (orange), and purchased by other Tanzanian firms (purple). Note that some GTAP sectors have been grouped together; see Table 8-1 and Table 8-2.

As in most economies, the distribution of production and that of profit are highly concentrated. About 90% of the production is made by the top 10% firms; see Figure 4-3. We expect that the supply-chain impacts of the disruptions of transportation infrastructure will be equally uneven.

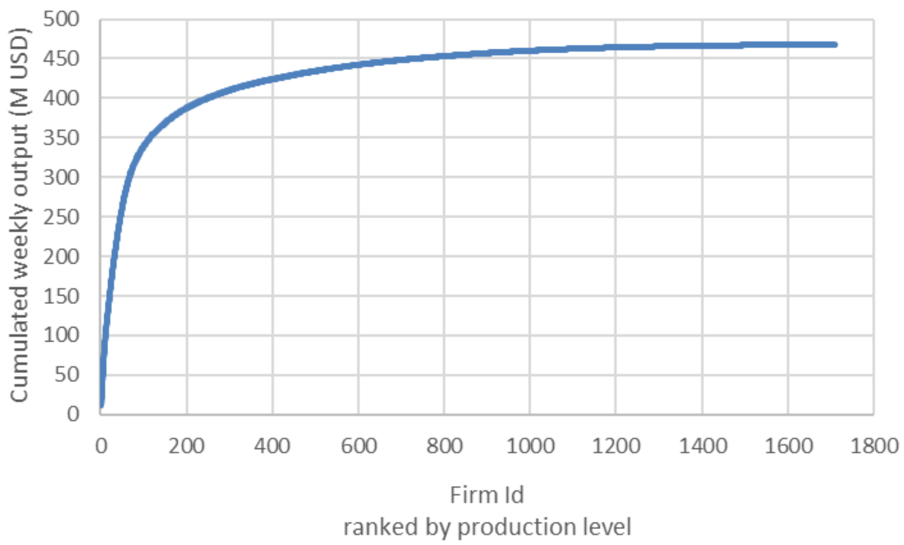
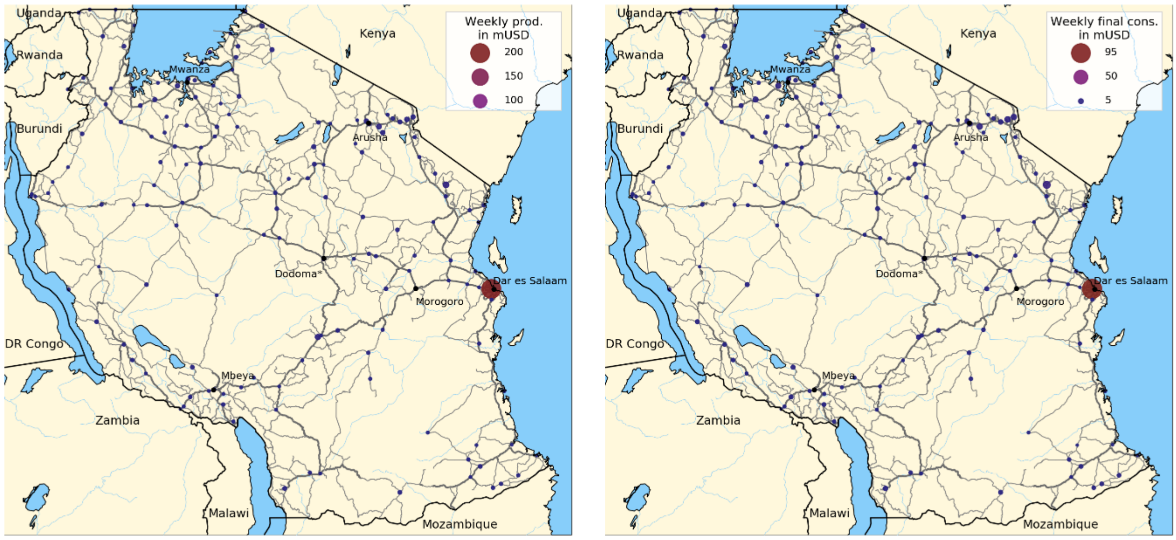


Figure 4-3: Cumulated distribution of weekly output. Firms are ranked by their equilibrium production level.

4.1.2 Spatial distribution of production and consumption

In the model, production and consumption are primarily concentrated in Dar es Salaam; see Figure 4-4. The three districts of the Dar es Salaam region represent 30% of total production and 26% of total demand. About 50% of exports are produced in this region.



(a) Production **(b) Population**

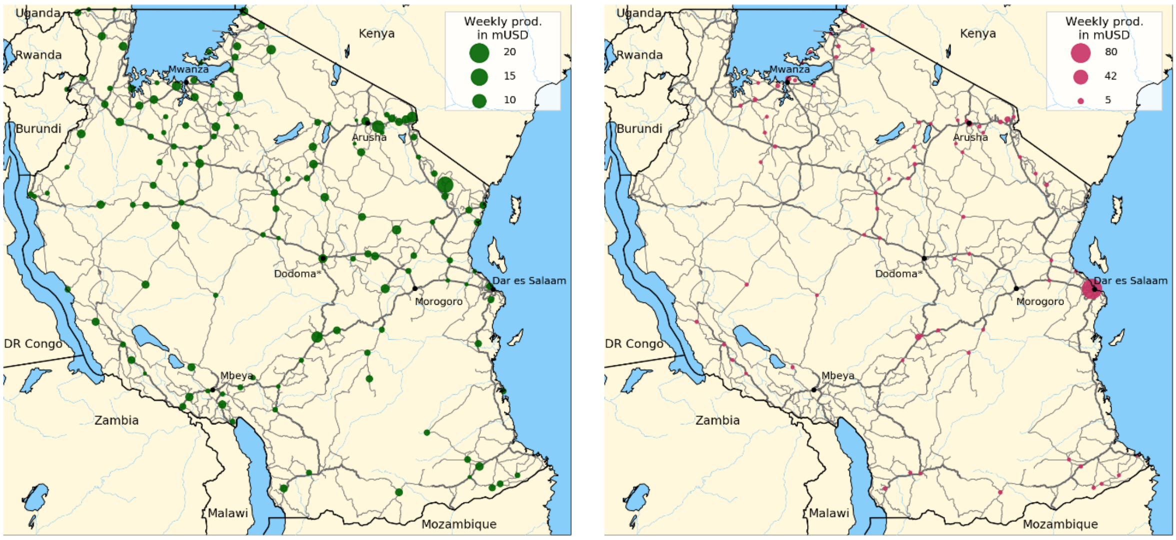
Figure 4-4. Weekly production (a) and population (b) assigned to OD node. To improve readability, nodes located within 30 km of each others are grouped together.

These figures reflect the data:

- According to the 2012 population census, Dar es Salaam represents 10% of Tanzania's mainland population.

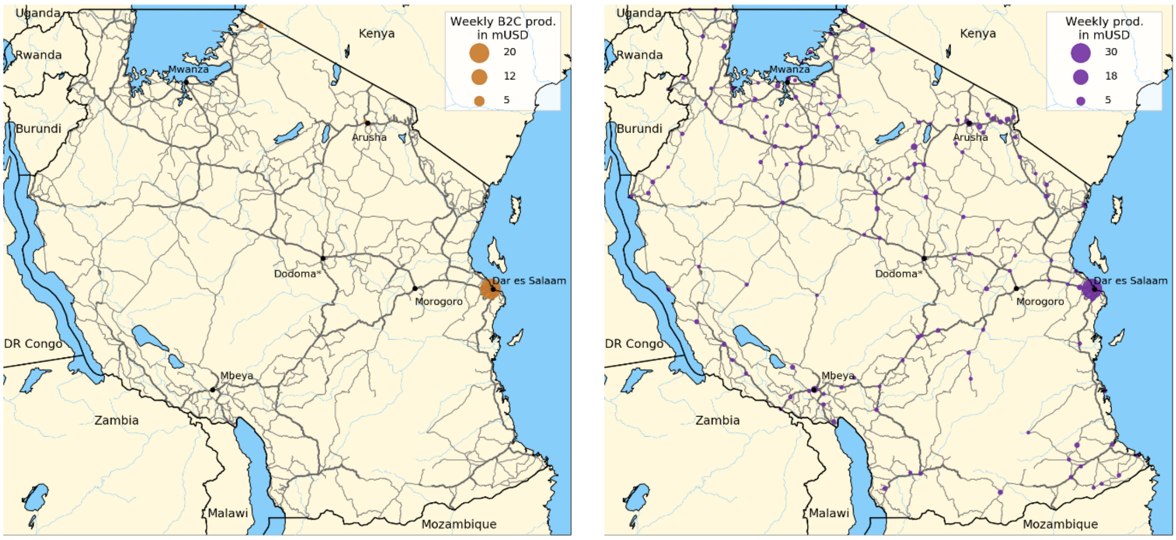
- According to the global gridded dataset produced by Kummu et al. (2018) [19], Dar es Salaam concentrates 26% of Tanzania's mainland GDP.
- According the to business registry, 24% of employees are in Dar es Salaam.

Figure 4-5 maps production between the four main sectors. Agriculture shows a very different pattern than the other sectors. Its production, which has been calibrated using land cover data, is scattered across the country. Manufacturing exhibits the opposite pattern, with 95% of the production concentrated in Dar es Salaam. The remaining 5% of production mostly corresponds to textile manufacturing in Arusha.



(a) Agriculture

(b) Food



(c) Manufacturing

(d) Trade

Figure 4-5: Weekly production assigned to OD nodes per sector. To improve readability, nodes located within 30 km of each others are grouped together.

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[19] Kummu M, Taka M, Guillaume JHA (2018) Gridded global datasets for Gross Domestic Product and Human Development Index over 1990–2015. *Scientific Data* **5**, 180004.

4.1.3 Mapping of supply chains flows on the transportation network

Figure 4-6 presents the distribution of supply-chain flows on the transportation network. The largest flow is located on the T1 trunk road connecting the Dar es Salaam port to Morogoro. There, about 224 mUSD worth of products transit every week, which corresponds to a third of all flows in the model. Pant et al. (2018) estimated that 23% of freight flows were transiting on that road.

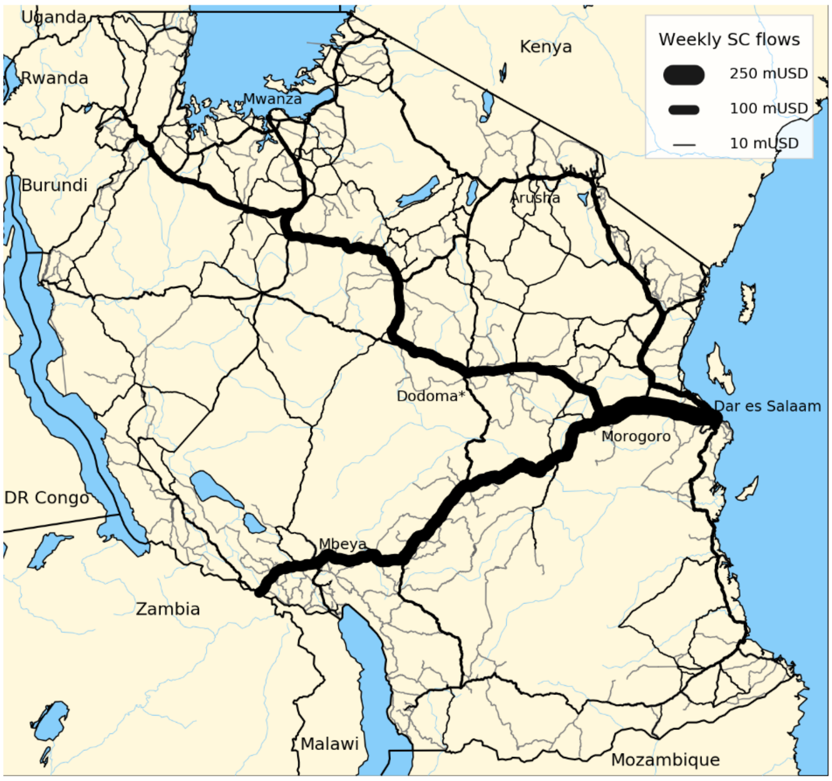
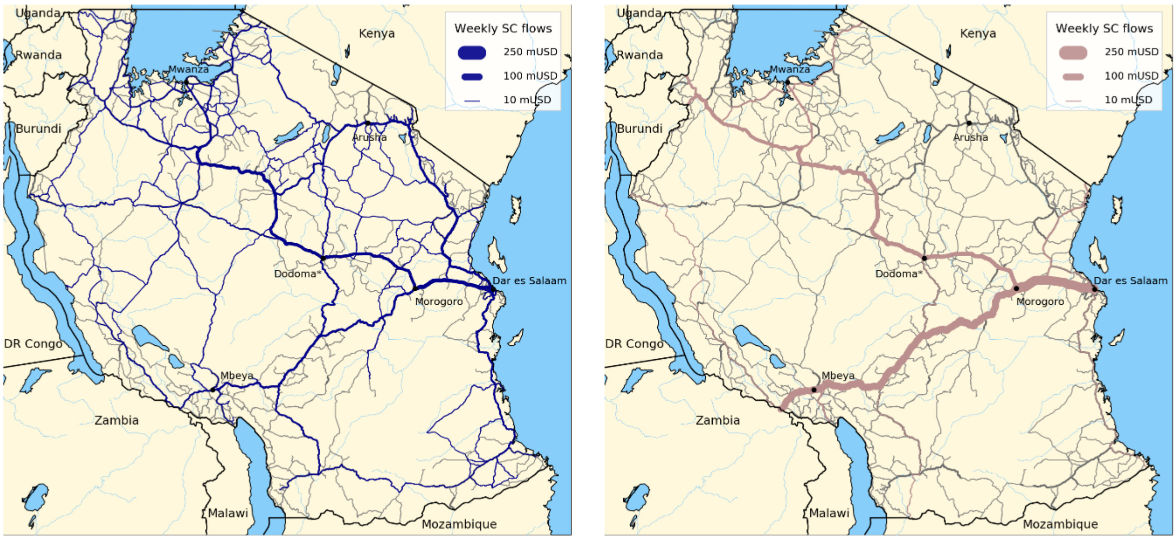


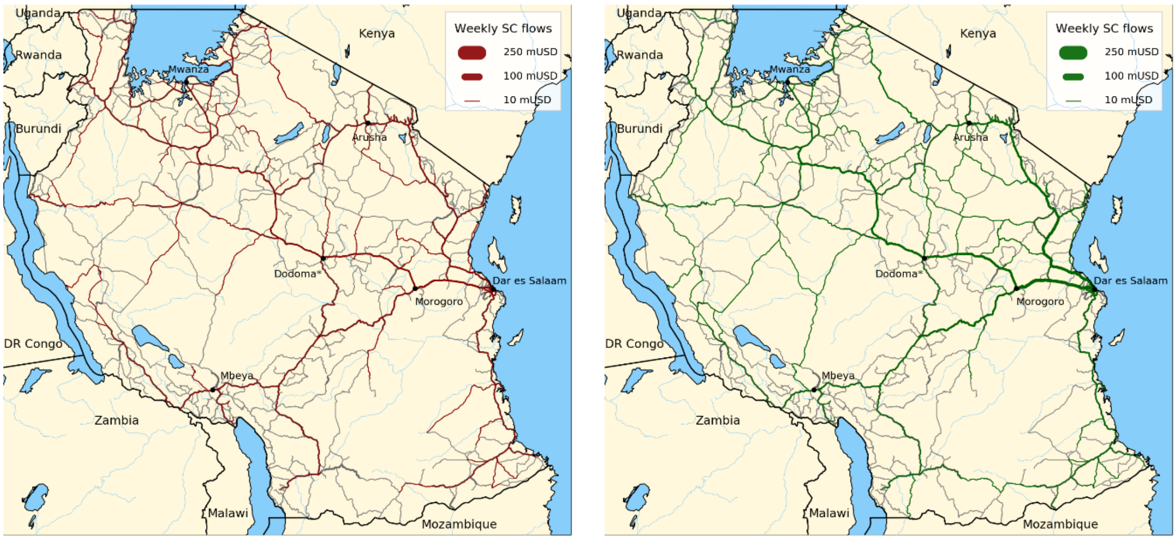
Figure 4-6: Weekly supply-chain flows mapped on the road network. The width of the black lines is proportional to the monetary value of the flow. The widest lines are found on the T1 trunk road connecting Morogoro and Dar es Salaam. It amounts to 224 mUSD per week.

Figure 4-7 breaks down the total flows into domestic, transit, import, and export flows.

- Domestic flows connect the main populated areas: Dar es Salaam on the oceanic coast, Lake Victoria and the Kilimanjaro region in the north with cities such as Mwanza and Arusha, Dodoma in the center and Mbeya in the south east.
- We observe two main transit routes:
  - The Dar es Salaam – north west corridor, which serves Uganda, Burundi and DR Congo.
  - The Dar es Salaam – south west corridor, which mostly serves Zambia.
- Imports and exports flow in and out Dar es Salaam port. Kenya, the main trade partner among neighboring countries, is primarily connected via the Kilimanjaro border. The border crossing close to Lake Victoria (Sirari) and the one close to the Indian Ocean (Horohoro) serve are secondary connection points between the two countries.



a) Domestic interfirm flows **b) Transit flows**

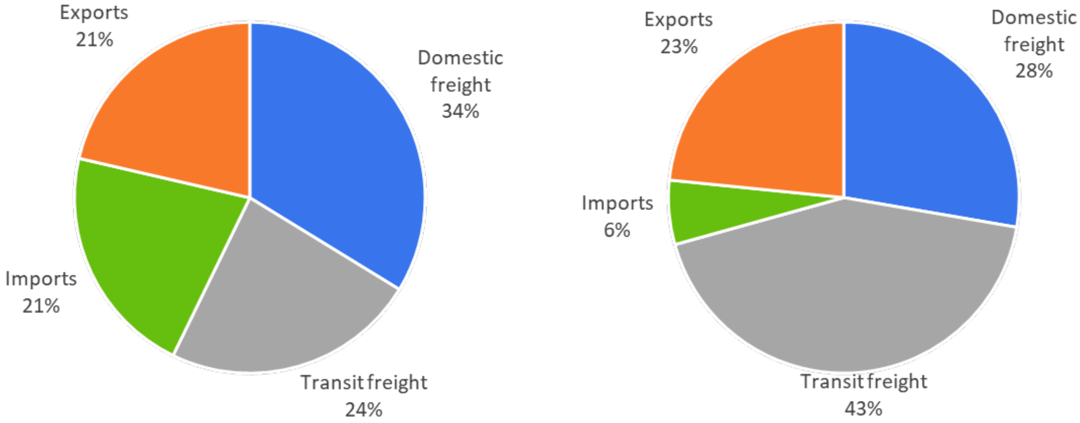


c) Imports **d) Exports**

Figure 4-7: Weekly supply-chain flows mapped on the road network per type of flows: domestic interfirm flows (a), transit flows (b), imports (c), and exports (d). The width of the lines is proportional to the monetary value of the flow. Grey lines indicate roads.

Import and export flows fade out as we move away from Dar es Salaam. They originate or terminate at transportation nodes spread across the country. In contrast, transit flows maintain their size along the corridors, occupying a large share of the transportation network. Transit flows travel much more distance than the other types of flows, a feature captured in Figure 4-8. Panel (a) counts each flow once between its origin and its destination, disregarding the distance travelled, while panel (b) integrate distances. The share of transit flows doubles, from a quarter to almost a half.

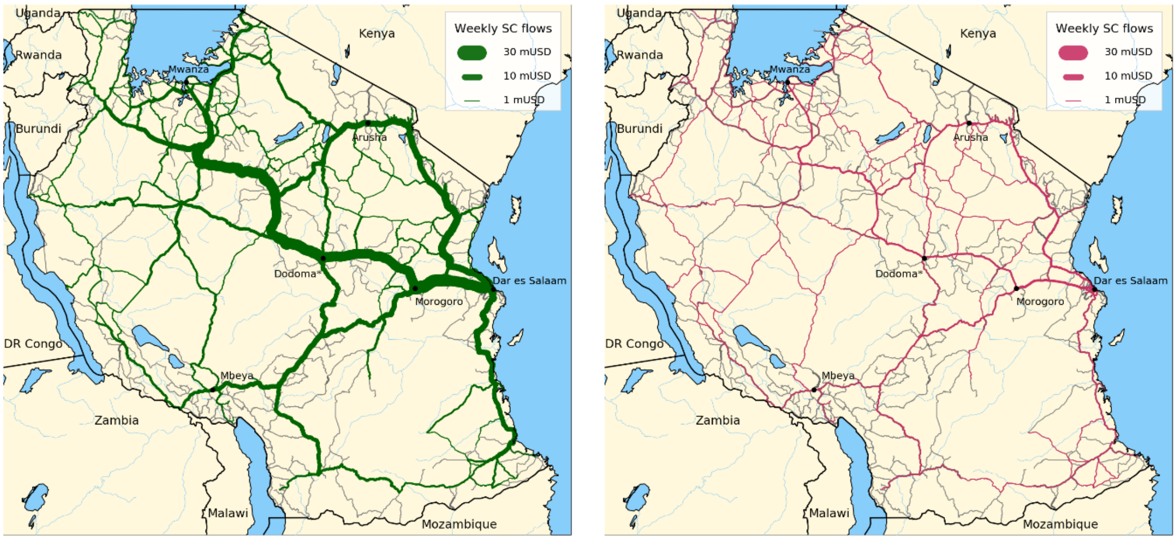
Compared to transit freight, supply-chain flows between Tanzanian firm tend to travel short distances. According to Figure 4-8, imports and exports have a very different transportation footprint. Imports travel much less, suggesting that, in comparison to other Tanzanian firms, businesses located in Dar es Salaam tend to use more production inputs coming from abroad. In contrast, exports have a much larger transportation footprint. Large quantities of mineral and metal ores coming from hinterland are transported over long distances to the port of Dar es Salaam.



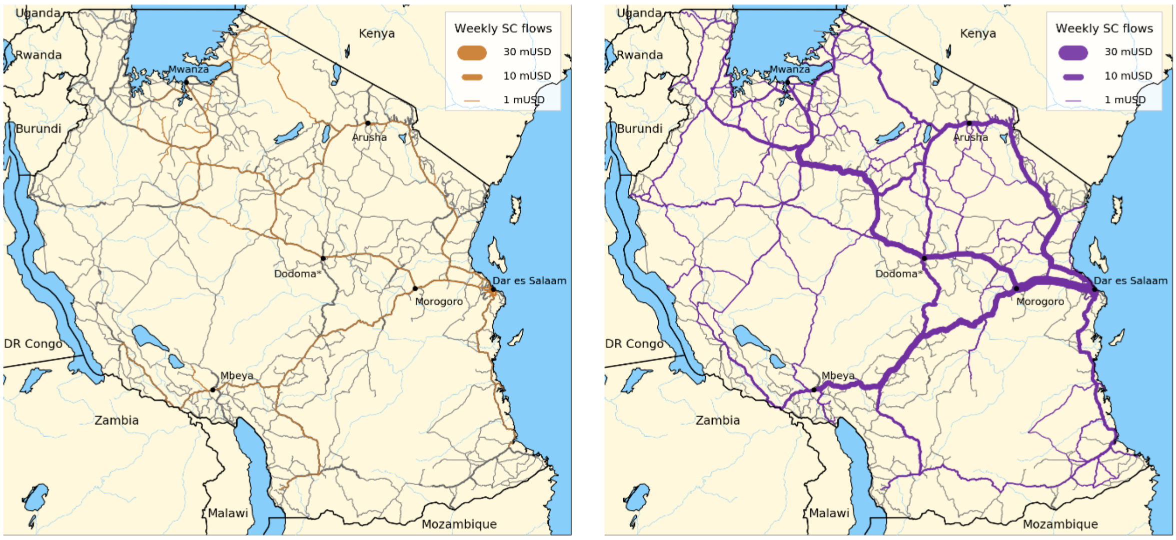
a) Origin-destination flows (USD) **b) Flows times distance (USD*km)**

Figure 4-8. Shares of supply-chain flows per type of flows: domestic freight, transit freight, imports, exports. In panel (a), the monetary value of the flow is counted once between its origin and its destination. In panel (b), the monetary value of each flows is multiplied by the distance travelled. The corresponding indicator is called the transportation footprint.

Figure 4-9 shows the supply-chain flows per types of products. Flows of agricultural products are very large. Production is spread across the country, while the consumption of food products is localized in populated areas, inducing large transportation needs. Trade products also have a relatively large transportation footprint, because they often serve as intermediary outputs of other industries. In contrast, food products are mainly end-of-chain products. Based on agricultural products, they are produced and consumed locally, leading to fewer transportation needs.



a) Agriculture **b) Food**



c) Manufacturing **d) Trade**

Figure 4-9: Weekly supply-chain flows mapped on the road network per type of products: agriculture (a), food (b), manufacturing (c), and trade (d). The width of the black lines is proportional to the monetary value of the flow. See Table 3-4 for details of a definition of this four sectoral groups.

4.2 Robustness to the choice of supplier–buyer pairs

The construction of the supplier–buyer networks is, in part, stochastic; see Sections 3.5.2, 3.5.3, and 3.5.4. Random choices are made by agents—firms and countries—when they choose their suppliers. Although these choices are constrained by the sectors of the firms and influenced by the size and distance of the suppliers, degrees of freedom remain in the process. Multiple run of the model may therefore generate a dispersion of the output.

In fact, some flows are directly plugged into the model and are not subject to variation.

- Household consumption per sector, export per sector and transit flows remain unchanged. In the model, these flows correspond to the final demand. They are directly plugged in and are not subject to random processes.

- Production per sector and sector-to-sector flows result from the input–output equilibrium and remain constant.

Specific imports flows, interregional flows, and flows per transportation segment varies. Variation is limited for large flows but becomes relatively larger of small flows.

- The amount imported by each sector per country depends on network construction. The average standard deviation is 30 kUSD for weekly flows. For country exporting large quantities to the United Republic of Tanzania (over 100 mUSD per year), the coefficient of variation of total trade —standard deviation divided by the mean—is below 2%.
- The interregional flows vary with similar features. The coefficient of variation of interregional flows exceeding 3 mUSD per week is 0.1 in average and the maximum coefficient is below 0.3. For flows smaller than 1 mUSD per week, the average coefficient of variation is 0.7.
- The estimated flows per road segment show limited variations for the main trunk roads. They may vary more widely for secondary roads. Using 10 different network constructions, the rank of the 50 most used roads remain unchanged. The coefficient of variation of domestic flows per road in 0.15 in average for flows larger than 3 mUSD per week. It is 0.7 in average for flows lower than 1 mUSD.

We conclude that the network construction procedures used in the model enable to generate robust estimates of the main supply-chain flows. Quantitative conclusions on fine-grained flows should however be interpreted more carefully.

Chapter 5. Assessment of the indirect costs of disasters

This chapter presents estimates of the supply chain impacts of disasters. First, it describes two specific simulations which illustrate the mechanisms by which the consequences of transportation disruptions propagate along supply chains. Next, the most salient features of the disruption-induced losses are presented, using a comprehensive set of disruption scenarios.

5.1 Simulating the supply chain impacts of disasters

We present two case studies. They illustrate how transportation disruptions are modeled, how their adverse economic impacts propagate along supply chains, and how indirect losses are evaluated.

- *One-week floods in Tanga.* The first case study analyzes a hypothetical flood event occurring for a week in Tanga region in the north west of the country.
- *Four-week floods in Morogoro.* The second case study focuses on an actual flood event that occurred in Morogoro region in the center of the country.

5.1.1 One-week floods in Tanga

Pant et al. (2018) analyzed historical flood data produced by the World Bank. They identified Tanga, located in the north of the United Republic of Tanzania, as a region whose transportation infrastructures are vulnerable to fluvial floods. From their analysis, we inferred two vulnerable transportation nodes: the Mombo village, located along the T2 trunk road (the left red star on Figure 5-1), and the Chumbageni junction, located close to Tanga city (the right red star on Figure 5-1).

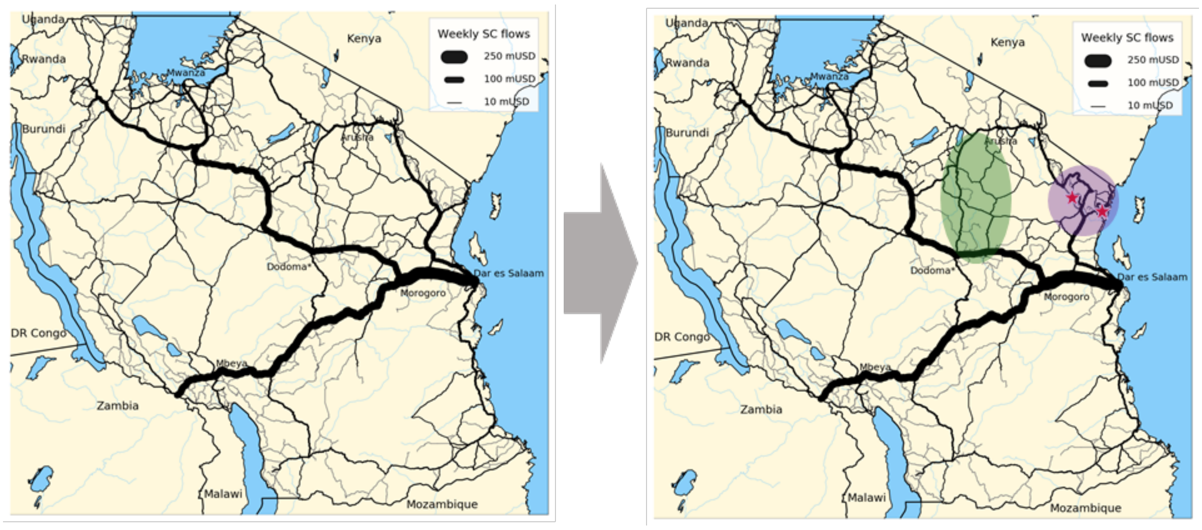


Figure 5-1: Simulated supply-chain flows before (left) and during (right) floods in Mombo and Chumbageni, Tanga region. Flooded locations are indicated by red stars: Mombo on the left and Chumbageni on the right. The purple circle highlights local rerouting, the green one highlights national rerouting; see text for details.

We simulate a week-long disruption of both nodes. Figure 5-1 and Figure 5-2 show how the pattern of supply-chain flows changes during the flood. We observe two major modifications.

- *Local adaption of flows.* Flows that used to go through these nodes are locally rerouted. Figure 5-2 shows how secondary roads are used to go around Mombo. Such rerouting concerns regional flows, whose origin and destination are in Tanga region.
- *National adaption of flows.* Larger interregional flows are rerouted differently. Instead of approaching the disruption and going around it through secondary roads, which may be very costly, they markedly change itineraries and are transferred to alternative trunk roads. This behavior is observed for flows between Dar es Salaam and the Arusha and Kilimanjaro regions. Instead going through the Tanga region, they take the central corridor to Dodoma and then turn north to reach their destination.

A week before the floods During the floods

Figure 5-2: Local rerouting of supply-chain flows during a flooding in Mombo, Tanga region. The location of Mombo is indicated by a red star.

Rerouting induces an increase in transportation costs, which is transferred to clients. Products become more expensive, some of which are intermediary inputs of production. As a result, some firms face a loss of income. To preserve their margin, they raise their selling price. This price effect ripples down to households, which face higher prices. We estimate this adverse impact by measuring, in monetary units, the extra expenditure that households would need to make in order to buy the same quantity of products as usual.

The impact on households is shown on Figure 5-3. We observe that, although the flood takes place in Tanga, most price increases occur in other regions, especially Arusha and Kilimandjaro. Some economic activities of regions, located in the north of the country, depend on supplies from Dar es Salaam, which normally goes through Mombo. To maintain their delivery, transporters takes longer roads leading to higher transportation costs.

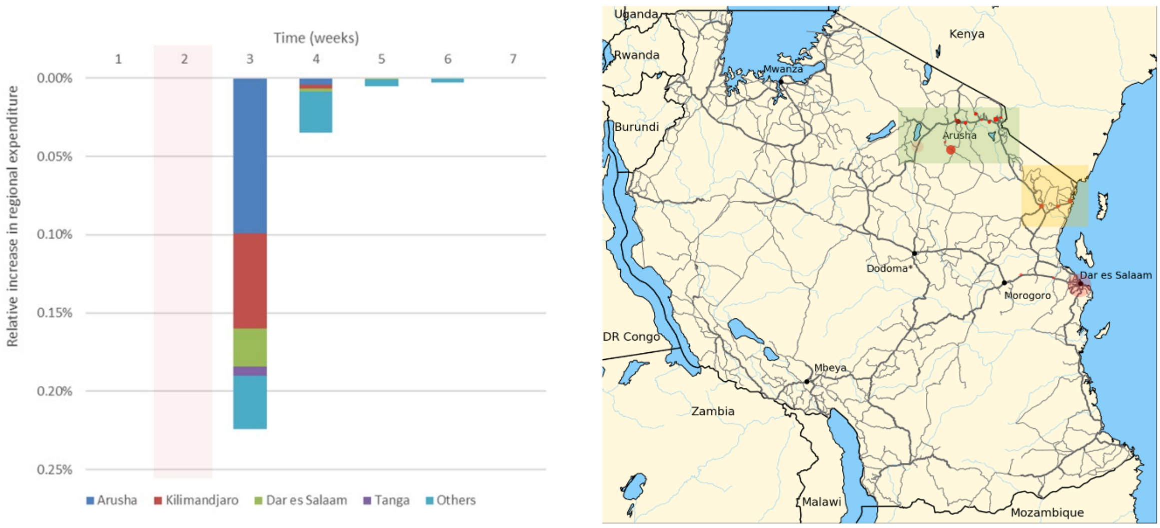


Figure 5-3: Impact on regional household expenditure of a one-week floods in Tanga. Panel on the left shows the time evolution this impact. Each bar corresponds to the relative increase in household expenditure of a specific region or groups of regions. The red rectangle indicates the occurrence of the floods. Panel on the right shows the price increases at time 3, i.e., 1 week after the flood. Red dots indicate OD nodes in which prices are higher than usual. Dot size is proportional to final consumption and color intensity is proportional to price increases. The yellow rectangle highlights Tanga region, the green one highlights the Arusha and Kilimanjaro regions.

Prices increase rapidly fade out after the flood. They are almost completely back at their pre-flood level two weeks after the flood in Arusha, Kilimanjaro, Dar es Salaam and Tanga. In regions whose firms buy from firms which have first increased their prices, prices are still being adjusted to compensate higher input costs. Three weeks after the flood, almost all prices are back to pre-disaster values. Overall household expenditure rises by about 450 kUSD over the whole period.

5.1.2 Four-week floods in Morogoro

Floodlist[20] reported a flood event that took place in 2016 from April 22 to May 31 in Morogoro and that was caused by prolonged heavy rainfall. It is one of the largest floods in Tanzania that year. Reported damages were 5 fatalities, 3,095 building damaged and 14,000 people displaced. The affected districts were Kilosa, Kilombero, Morogoro and Malinyi.

To build a road disruption scenario consistent with these reports, we identify the most vulnerable infrastructures in these four districts. We suppose that, in each district, roads in the immediate vicinity of water stream, and with the lowest elevation, got disrupted. As a result, our scenario consists of the disruptions of nine transportation nodes:

- In Kilosa: node #2344 (Wami)
- In Kilombero: node #2310 (Ifakara)
- In Malinyi: nodes #2338 and #2360 (Malinyi)

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[20] FloodList (http://floodlist.com) is a non governemental organization gathering information on flood events at a global scale. It is funded by the Copernicus program (https://www.copernicus.eu/en), a European Union programme dedicated to the monitoring of Earth's environment.

- In Morogoro: nodes #2359, #2358, #2346, #2340, #2325, #2302 (Morogoro)

These four groups of nodes are shown on Figure 5-4. FloodList reported that the flood events lasted for five weeks and three days. We consider that the roads were not disrupted during the entire duration of the event. We suppose that transportation disruptions lasted for four weeks.

Shipments were rerouted, delayed or blocked, leading to price increases. Disruptions were long enough to induce shortages in several local supply chains. On top of the direct damages brought by the disaster, households in the flooded area also suffer from losses due to local businesses falling short of supplies; see in Figure 5-4 the large red and purple nodes near the flooded areas. Due to cascading shortages and costlier transportation, even households located in Dar es Salaam, where the flood did not hit, felt the effect of the disaster.

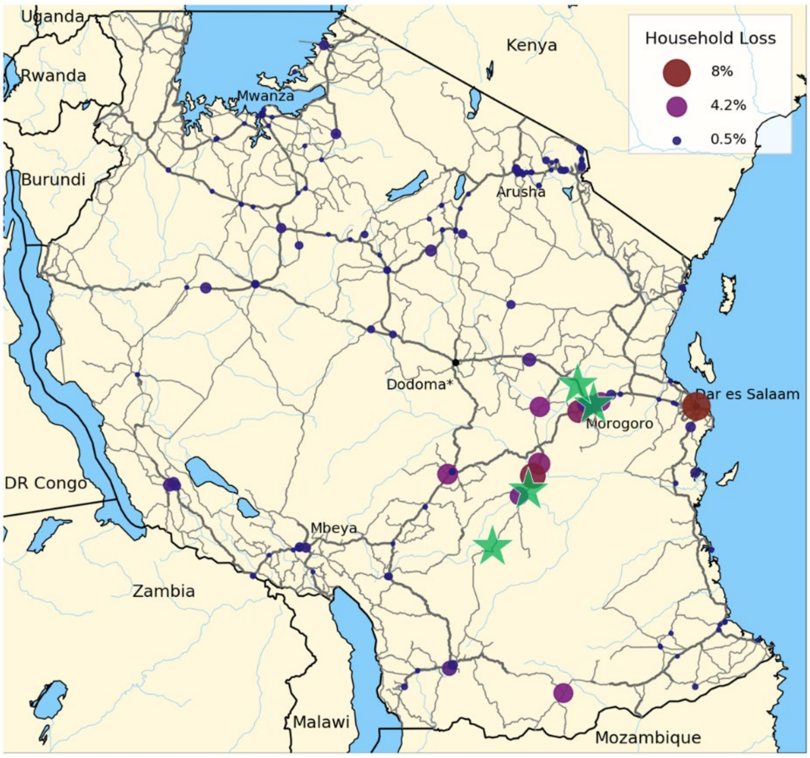


Figure 5-4. Simulating the indirect impact of the 2016 Morogoro flood. The location of the disrupted roads is indicated by green stars. The size and color of the bubbles represent household loss at OD points. Unit are in percentages of weekly household consumption. The OD nodes of Dar es Salaam are grouped together.

Overall, the estimated indirect costs on households amount to about 0.5% of the annual consumption, mostly due to shortages in three of the largest sectors in Tanzania: agriculture, food (i.e., processed food and food-related services), and wholesale and retail trade. Figure 5-5 presents how these impacts evolve through time and ripple across these sectors. First, consumption losses pile up during the flood. Blocked shipments of agricultural products trigger production delays in the food sector and induce product unavailability for wholesalers and retailers. After the flood, losses remain sizeable for another two weeks. In the flooded area, production recovery in agriculture and in the food, sectors are slowed down by missing inputs from wholesalers and retailers.

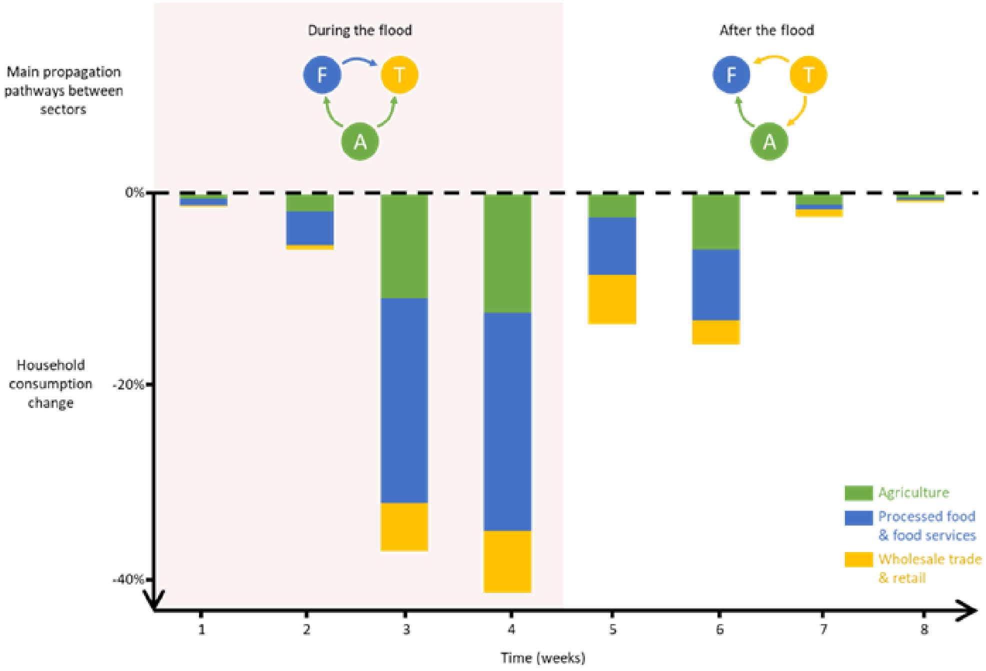


Figure 5-5. The 2016 Morogoro flood triggered disruptions with cascading impacts on supply chains and households. The bar chart shows the time series of household impacts, measured in percentage of weekly consumption that is lost due to shortages. Each bar shows the share of products from Tanzania's three main sectors: agriculture (A), food (F), and wholesale and retail (T). Over the 0% line, the two 3-node graphs show the three main propagation pathways between the three sectors during and after the flood

5.2 Stylized facts of supply-chain amplifications of disasters

Simulating a large range of scenarios provides several insights on the propagation of transportation disruptions through supply chains.

5.2.1 Nonlinear increase of indirect loss with duration

The two case studies of Section 5.1 suggest that the indirect costs for households following a long disruption is different in nature of that following a short disruption. Prolonged floods are likely to create shortages, which are very costly for households, while short floods generate limited price increases.

This behavior is confirmed by analyzing a large set of simulations. We disrupt each node, one by one, during an increasing amount of time: one, two, three, and four weeks. In Figure 5-6(a), we observe that the overall impacts on households increase nonlinearly with the duration of the disruption. This nonlinear behavior is driven by shortages in the supply chains which cascade down to households. As the duration of a disruption gets longer, inventories get exhausted, triggering shortages; see Figure 5-6(c). Extra expenditures, which are induced by transportation-cost-driven adjustment of prices, increase almost linearly; see Figure 5-6(b). Each new week of disruptions maintains prices higher, leading to additive losses, with little compounding effect.

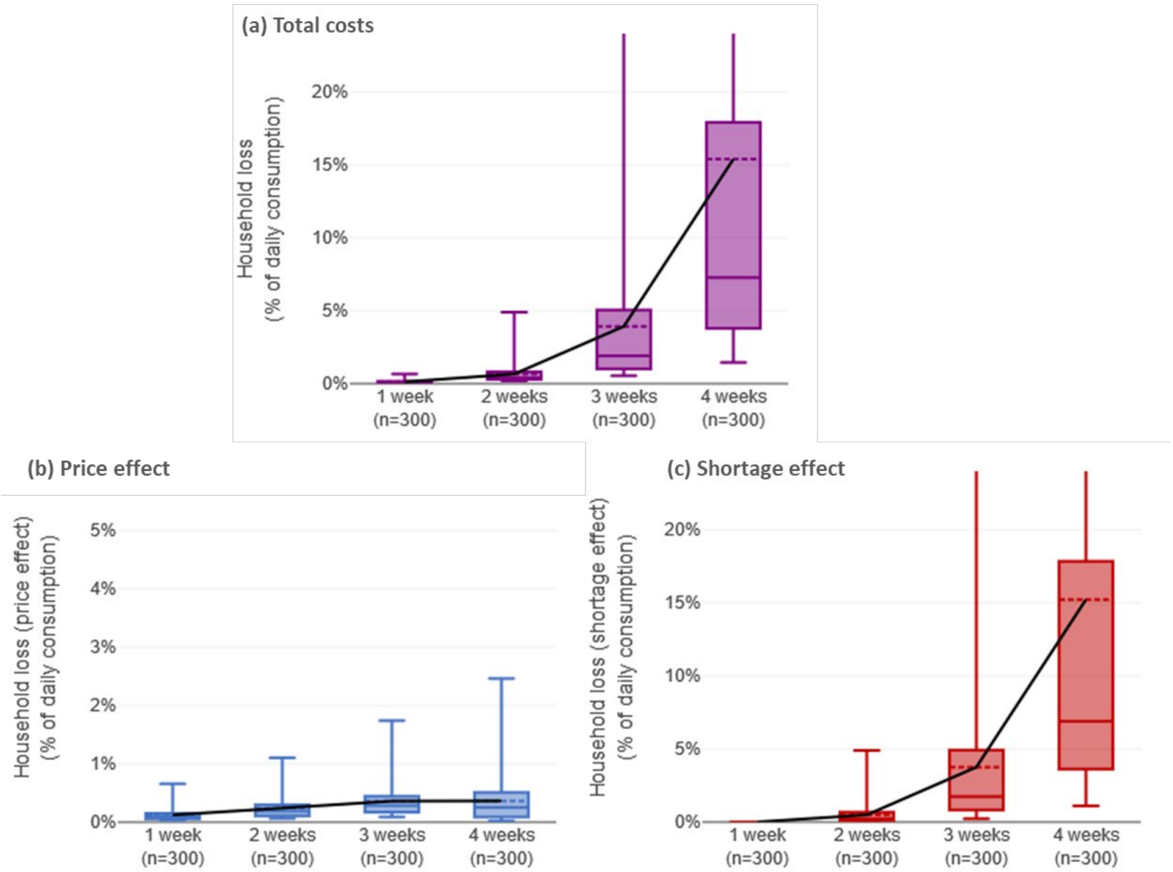


Figure 5-6. Supply-chain impacts on households triggered by disruptions of various durations. Panel (a) shows the total losses. Panels (b) and (c) disentangles two kinds of losses: those attributed to an increase in transportation costs (b), and those due to shortages. Each bar represents a distribution of impacts obtained by disrupting the 300 most critical transportation nodes per category duration. The filled rectangle indicates the interquartile interval, the solid horizontal lines indicates the median, the dash horizontal line indicates the mean. Mean values are joined together with a black curve. The vertical line extends to the minimum and maximum of the distributions; when the maximum lies outside the plotting area, as in (a) and (c), the upper part of the vertical line is not capped.

The increase in mean loss with disruption duration is not quadratic but exponential; see Table 5-1. A doubling of the disruption duration, from one to two weeks, multiplies mean loss by 5.3. From two to four weeks, mean loss is multiplied by 24. The doubling rate growth with duration, which suggest that the growth of losses is exponential.

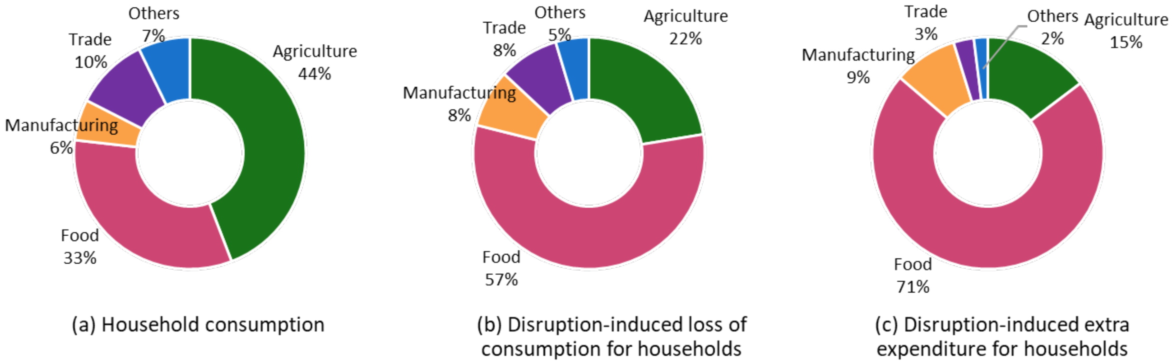
Table 5-1. Nonlinear increase in mean and median losses with the duration of the disruption. Each figure is the ratio between the mean (resp. median) loss triggered by the 300 most critical nodes of a duration, and the mean (resp. median) loss for the 300 most critical nodes of one-week disruptions.

Impacts of the 300 most critical nodes	Multiplication factor relative to 1-week disruptions			
	1-week disruptions	2-week disruptions	3-week disruptions	4-week disruptions
Mean	1	5.3	32	125
Median	1	4.2	20	78

5.2.2 Amplification is stronger for nonprimary products

We now disaggregate the impacts per type of products, as done in Figure 5-5 for the 2016 Morogoro flood in Section 5.1.2. We use long disruptions, in order to include the shortage effects. Figure 5-7 shows that, for both types of impacts—extra expenditure and consumption loss—their sectoral shares differ from the sectoral consumption pattern. In other words, the consumption of some type of products is more likely to get disturbed by transportation disruption than other.

Agricultural products, which are the most consumed goods, are primary products, and therefore less dependent on other supply chains. As a result, they are relatively less affected by disruptions. The impacts on food products are, in contrast, largely magnified by supply chains for both types of impacts. Food production rely on the supply of agricultural products. Any perturbation of farm production and delivery ripples onto the food sectors. Manufacturing products also significantly suffers from supply-chain amplifications.



(a) Household consumption

(b) Disruption-induced loss of consumption for households

(c) Disruption-induced extra expenditure for households

Figure 5-7. Some sectors are more vulnerable to the supply-chain impacts of transportation disruption. Panel (a) shows the sectoral shares of household consumption in the United Republic of Tanzania. Panel (b) presents the sectoral shares of consumption losses due to supply-chain shortages following four weeks-disruptions. Panel (c) presents the sectoral shares of extra expenditure due to costlier transportations in the supply chains. Panels (b) and (c) are based on the simulations of four-week disruptions of 500 distinct transportation nodes.

5.2.3 Supply chains propagate impacts across regions

Not only do supply chains transfer disruption from one sector to another, they also spread perturbations from one region to another. This behavior was illustrated in the case study of Tanga floods in Section 5.1.1, in which households in Arusha, Kilimandjaro, and Dar es Salaam incurred larger price increases than those in Tanga.

By simulating the four-week disruption of all transportation nodes, one by one, we found that only 10% of the total indirect losses affect households located on these nodes. Through supply-chain amplification, most losses occur in other locations. Note that, relative to their own consumption, impacts on local households are in general more severe than those on distant one. But, even if their relative loss is lower, there are often more distant households affected than local one, such as, overall, most losses occur outside of the disrupted area.

5.3 Comparison with input–output models

5.3.1 Main innovations: transportation disruption and spatial disaggregation

The way the DisruptSCT model estimates the indirect economic costs of disasters differs from existing input–output methods, such as those used in Haimes and Jiang (2001)[21], Okuyama (2004)[22], Santos and Haimes (2004)[23], Santos (2006)[24], and Steenge and Bockarjova (2007)[25]. For the latter, a disaster is translated into a demand or a supply drop in one or several sectors. Next, input–output tables are used to propagate this initial shock into the whole economy. In the DisruptSCT model, however, a disaster is only disrupting one or several transportation infrastructures. Firms and households then react to this new setting by adjusting their price, purchases, and production plan.

Another major difference between classical input–output models and the DisruptSCT model is the spatial disaggregation of production, consumption, and of intersectoral flows. Sectors are usually represented by representative entities, in one-to-one correspondence with the input–output tables used as input data. In our model, we use a range of additional data, such as a population census, a business registry, spatial GDP data, and land use data to spatially disaggregate production and consumption into distinct firms and households. In fact, disaggregating sectors into firms or production units was originally proposed by Henriet et al. (2012)[26], whose contributions has provided the basis of the DisruptSTC model.

In the absence of specific data describing the supplier-buyer network, which, for instance, exists for Japan (e.g., Fujiwara and Aoyama, 2010[27]), we rely on simple assumptions to connect firms and sectors described in Section 3.4. This network reconstruction procedure is characterized by very large degrees of freedom that we capture by running simulations on multiple networks and averaging the outputs.

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[21] Haimes, Y. Y., Jiang, P., 2001. Leontief-Based Model of Risk in Complex Interconnected Infrastructures. *Journal of Infrastructure Systems* 7 (1), 1–12.

[22] Okuyama, Y., 2004. Moldeling spatial economic impacts of an earthquake: input–output approaches. *Disaster Prevention and Management: An International Journal* 13 (4), 297–306.

[23] Santos, J. R., Haimes, Y. Y., 2004. Modeling the Demand Reduction Input–output (I-O) Inoperability Due to Terrorism of Interconnected Infrastructures. *Risk Analysi*s 24 (6), 1437–1451.

[24] Santos, J. R., 2006. Inoperability input–output modeling of disruptions to interdependent economic systems. *Systems Engineering* 9 (1), 20–34.

[25] Steenge, A. E., Bockarjova, M., 2007. Thinking about Imbalances in Post-catastrophe Economies: An Input–Output based Proposition. *Economic Systems Research* 19 (2), 205–223.

[26] F. Henriet, S. Hallegatte, and L. Tabourier, “Firm-network characteristics and economic robustness to natural disasters,” *Journal of Economic Dynamics and Control* 36, 150–167 (2012).

[27] Fujiwara, Y., Aoyama, H., 2010. Large-scale structure of a nation-wide production network. *The European Physical Journal B* 77 (4), 565–580.

The modeling of production processes and of economic behavior in DisruptSTC is based on the adaptive regional input–output (ARIO) model of Hallegatte (2008[28], 2014[29]) which focuses on the short-term reaction to disasters, and has been applied to hurricane Katrina (Hallegatte 2008), to the Wenchuan earthquake (Wu et al. 2011[30]), and to assess the potential impacts of flooding in Copenhagen and Mumbai (Hallegatte et al. 2010[31]; Ranger et al. 2011[32]). Firms have limited production capacities, hold inventories, and rationing takes place in case of supply–demand unbalances. In that respect, the ARIO and DisruptSCT models differ from Computable General Equilibrium models (CGEs) in which simultaneous price adjustments enabled by inputs substitutability ensure the immediate rebalancing of supply and demand (e.g., Rose and Liao 2005[33]; Rose et al. 2007[34])

5.3.2 Modeling supply chains leads to larger indirect loss estimates than sector-level input–output models

We compare the estimates of disaster-induced indirect losses generated by our model with those produced by classical input–output model. The DisruptSCT model can be adapted to simulate the behavior of such model in which a local disaster is translated into country-wide and sector-level decrease of production and demand.

To that end, we translate the disruption of a transportation infrastructure into a drop of production in the sectors represented near that infrastructure. Specifically, for each one of these sectors, we decrease the production capacity of all firms in proportion of the production taking place on that node. In other words, we suppose that the disruption reduces production, but instead of being applied locally, this reduction is evenly shared across the country. The production capacities remain impaired for as long as the disruption lasts.

For short disruptions, DisruptSCT leads to similar average estimates as its input–output (IO) counterpart, but the shape of their distribution is very different; see Figure 5-8(a). The loss

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[28] Hallegatte, S., 2008. An Adaptive Regional Input–output Model and its Application to the Assessment of the Economic Cost of Katrina. *Risk Analysis* 28 (3), 779–799.

[29] Hallegatte, S., 2014. Modeling the Role of Inventories and Heterogeneity in the Assessment of the Economic Costs of Natural Disasters. *Risk Analysis* 34 (1), 152–167.

[30] Wu, J., Li, N., Hallegatte, S., Shi, P., Hu, A., Liu, X., 2011. Regional indirect economic impact evaluation of the 2008 Wenchuan Earthquake. *Environmental Earth Sciences* 65 (1), 161–172.

[31] Hallegatte, S., Ranger, N., Mestre, O., Dumas, P., Corfee-Morlot, J., Herweijer, C., Wood, R. M., 2010. Assessing climate change impacts, sea level rise and storm surge risk in port cities: a case study on Copenhagen. *Climatic Change* 104 (1), 113–137.

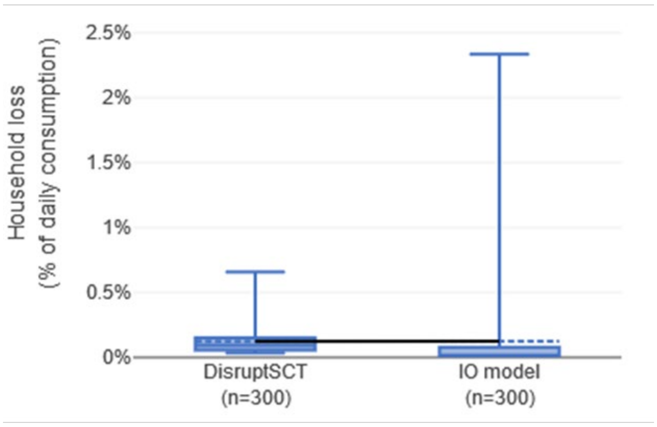
[32] Ranger, N., Hallegatte, S., Bhattacharya, S., Bachu, M., Priya, S., Dhore, K., Rafique, F., Mathur, P., Naville, N., Henriet, F., Herweijer, C., Pohit, S., Corfee-Morlot, J., 2011. An assessment of the potential impact of climate change on flood risk in Mumbai. *Climatic Change* 104 (1), 139–167.

[33] Rose, A., Liao, S.-Y., 2005. Modeling Regional Economic Resilience to Disasters: A Computable General Equilibrium Analysis of Water Service Disruptions. *Journal of Regional Science* 45 (1), 75–112.

[34] Rose, A., Oladosu, G., Liao, S.-Y., 2007. Business Interruption Impacts of a Terrorist Attack on the Electric Power System of Los Angeles: Customer Resilience to a Total Blackout. *Risk Analysis* 27 (3), 513–531.

distribution is more balanced in our model, and more skewed in the IO model. In the DisruptSCT model, short disruptions perturb transportation and generate some price increases for most OD nodes. Inventories damped shortages, which prevent any extreme losses from occurring. In IO models, in contrast, sales loss immediately breaks out because of the exogeneous drop of production capacity, while transportation disruptions are not accounted for. Because production capacities are very unevenly distributed across OD nodes, some nodes lead to large costs whereas most of them does not generate any losses. This behavior accounts for the very unbalanced distribution of losses of the IO model in Figure 5-8(a).

(a) One-week disruptions



(b) Four-week disruptions

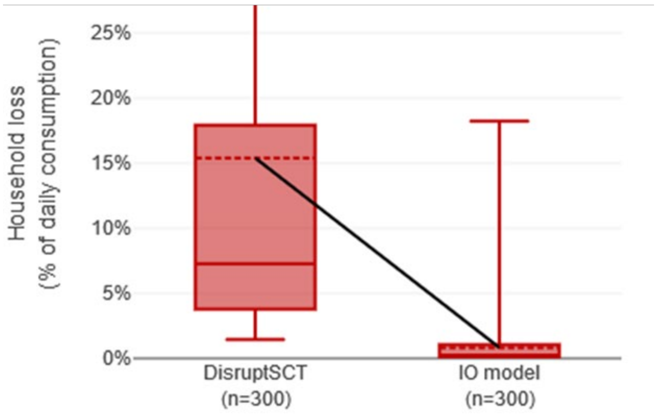


Figure 5-8. Comparison between the disaster-induced indirect impacts on households estimated by the DisruptSCT model and a classical input–output model. In panel (a), all transportation nodes are disrupted one by one for one week. In panel (b), the duration is set to four weeks. Each bar represents a distribution of impacts obtained by disrupting the 300 most critical transportation nodes. The filled rectangle indicates the interquartile interval, the solid horizontal lines indicates the median, the dash horizontal line indicates the mean. Mean values are joined together with a black curve. The vertical line extends to the minimum and maximum of the distributions; when the maximum lies outside the plotting area, as in (a) and (c), the upper part of the vertical line is not capped.

The DisruptSCT model clearly estimates larger losses for large events than IO models. In the latter, drops in production capacities are equally distributed among all firms of a sector. With their inventories, firms cope with most reduction in input supplies. Only extremely large events can generate shortages. Overall, the IO model produces estimates that scales linearly with disruption duration. In DisruptSCT, in contrast, indirect costs grow nonlinearly with disruption duration, already shown in Figure 5-6. Shortages are likely to occur when a node gets inaccessible for a long time because of unpassable roads. With the explicit modeling of supply chains, these shortages propagate and get amplified, leading to potentially high losses.

This major difference is consistent with the findings of Henriet et al. (2012). Shocks lead to higher indirect losses when they are concentrated on a few firms, rather than spread across whole sector. When firms are aggregated, bottlenecks, such as limited inventories or production capacities occurring at local levels, disappear. They are, however, those causing the domino effect reported in many case studies of supply chains disruptions (e.g., Sheffi 2005[35], Fujimoto 2011[36]). This result demonstrates the potential of firm-level modeling to reproduce the nonlinearities and cascading impacts sparked by disasters.

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[35] Sheffi, Y., 2005. *The Resilient Enterprise: Overcoming Vulnerability for Competitive Advantage*. MIT Press, Cambridge, MA.

[36] Fujimoto, T., 2011. *Supply chain competitiveness and robustness: a lesson from the 2011 Tohoku earthquake and supply chain "virtual dualization"*. Manufacturing Management Research Center (MMRC) Discussion paper Series (362).

Chapter 6. Identification of critical infrastructures

Criticality analyses quantitatively compare the significance of each transportation infrastructure for the economic resilience of supply chains. This chapter presents the resulting criticality maps for the United Republic of Tanzania. It shows how criticality patterns change according to the type of supply chains under scrutiny. The criticality of transportation infrastructures is economically contextualized, which is a central innovation of this study that contrasts with traditional assessments of transportation systems.

6.1 Criticality analyses

We simulate the disruption of all transportation infrastructures, one by one. They are then ranked according to their estimated indirect costs. Such criticality analyses allow us to identify bottlenecks. They are run for short disruption—a week—as well as long ones—four weeks.

6.1.1 Criticality to short disruptions

Figure 6-1 is the criticality map for one-week-long disruptions. It represents the extent to which the disruption of each one of the road infrastructures leads to adverse supply-chain effects for Tanzanian households. Note that we simulated the disruption of road nodes—road crossings, access to port or airport, bridge—as well as edges—road segments.

No shortages occur after short disruptions. Losses are entirely due to price increases. Here, criticality is closely related to redundancy.

The seven mostly critical infrastructure are commented in Table 6-1. The most one is the N–S costal trunk road T7 in north Lindi, indicated by number 1 in Figure 6-1. Its disruption provokes very long rerouting through the T1 trunk road in Iringa, located 500km West. Along this road, there are two bridges that are vulnerable to floods: Mkapa bridge over Rufji river and a brige over Matandu river.

Table 6-1. Comments on the seven most critical road infrastructures to one-week disruptions.

Point on Figure 6-1	Infrastructure name	Comments
1	N–S costal trunk road T7 in north Lindi	There is no regional alternative to this corridor. Its disruption provokes very long rerouting through the T1 trunk road in Iringa, adding several hundreds of kms to the journey. Along this road, there are two bridges that are vulnerable to floods: Mkapa bridge over Rufji river and a brige over Matandu river.
2	E–W T1 trunk road between Chalinze and Morogoro	This 86km road carries the largest amount of freight flows in Tanzania. Its closure leads to a 200km detour using secondary unpaved roads, or over a 1,000km detour using paved road. Some local tertiary dirt ways may be passable for some vehicles but were not included in the model. There are two bridges, in Bwawani and Darajani.
3	N–S T4 trunk road between Lamadi and Bunda	Located 130km east from Mwanza, this 25km-long segment is located in a narrow corridor between the Serengeti National Park and Lake Victoria. It crosses five water streams. This road is the only one linking Mara region with Mwanza and Simiyu regions.

4	NE–SW trunk road T1 south of Iringa, between Ihemi and Mafinga	This 40km segments is of national importance for transits flows between DR Congo and Zambia and the port of Dar-es-Salaam. There is no paved alternative in the region, apart from a 100km journey using mountainous dirt roads, which were not included in the model.
5	E–W T3 trunk road between Gairo and Pandambili	This 20km segment lack paved alternatives. There are many dirt roads in this area which were not included in the model.
6	E–W T3 trunk road between Chalinze and Chamwino junction.	This 15km segment lack paved alternatives, but there may be passable dirt roads in this area which were not included in the model.
7	T1 and T16 crossing at Mikumi	Large transit freight flows are carried through this town. There are several national park in this region, and few alternative roads.

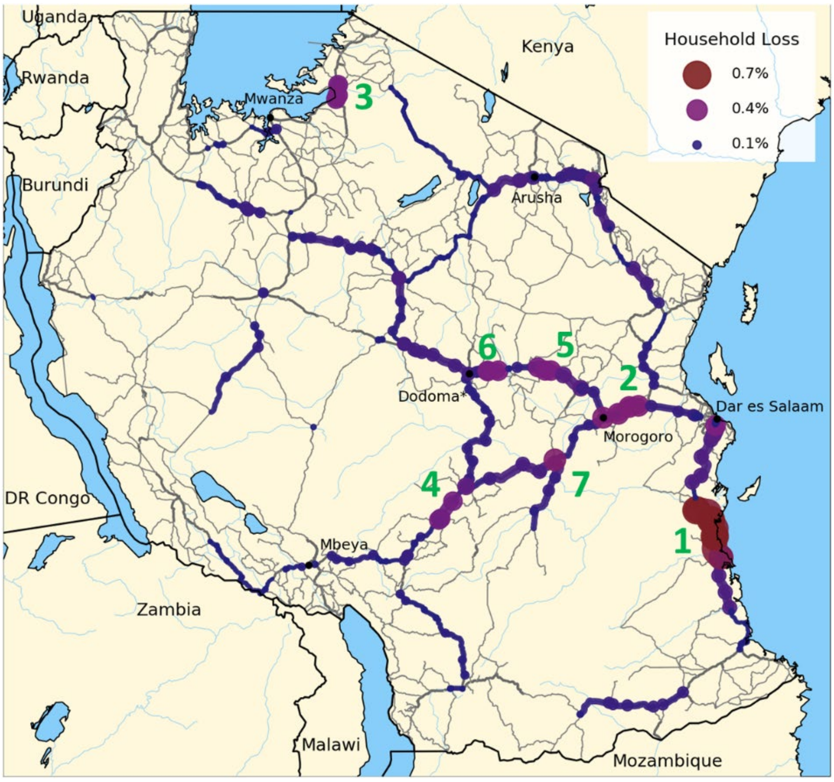


Figure 6-1. Supply-chain criticality to short disruptions of the road network of the United Republic of Tanzania. Each infrastructure is highlighted according to the amount of indirect economic loss for households triggered by its disruption. Indirect loss is made of extra expenditure and consumption loss; see

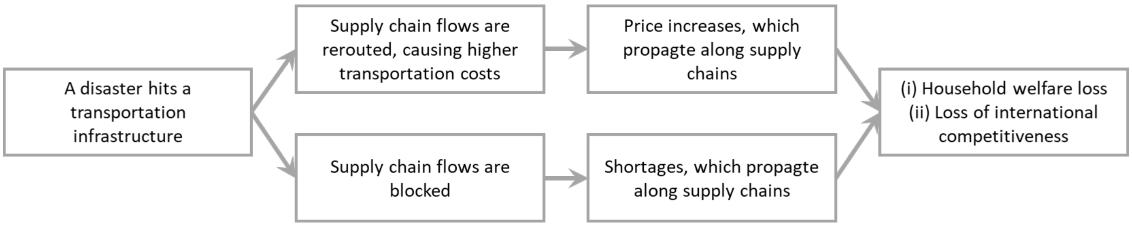


Figure 1-1. It is measured by the relative loss in daily country-wide consumption. Infrastructures that trigger a loss over 0.05% of country-wide daily consumption are shown. The green numbers are associated with the most critical infrastructures; see main text for comments.

6.1.2 Criticality to long disruptions

Figure 6-2 is the criticality maps generated by simulating four-week-long disruptions. Dar es Salaam stands out by far as the most critical area, followed by Tanzania's second and third largest cities: Arusha and Mwanza.

The most critical node is the port of Dar es Salaam; see the left panel of Figure 6-4, which shows a zoom onto the city. Its disruption blocks imports of intermediary inputs from overseas, which many industries, especially the manufacturing sectors, are relying on. When the disruption is short, firms keep on producing using their inventory. A four-week-long disruptions, however, is long enough to create shortages. After the port, the most critical infrastructures are located in the district of Temeke and Ilala, in which most industrial and manufacturing activities of the country take place.

The prolonged disruption of some transportation infrastructures in Arusha, the second largest city, creates shortages in local markets but can have also nationwide consequences. According to the business registry, Arusha's urban area hosts production facilities of national significance in the textile and electronic equipment sector. A few transportation node stand out in the nearby Kilimanjaro region. Their prolonged disruptions may perturb the operations of large sugar production facilities which, according to the business registry, are located there. Other critical infrastructures are identified in Mwanza, the third largest city, as well as in Iringa and Lindi.

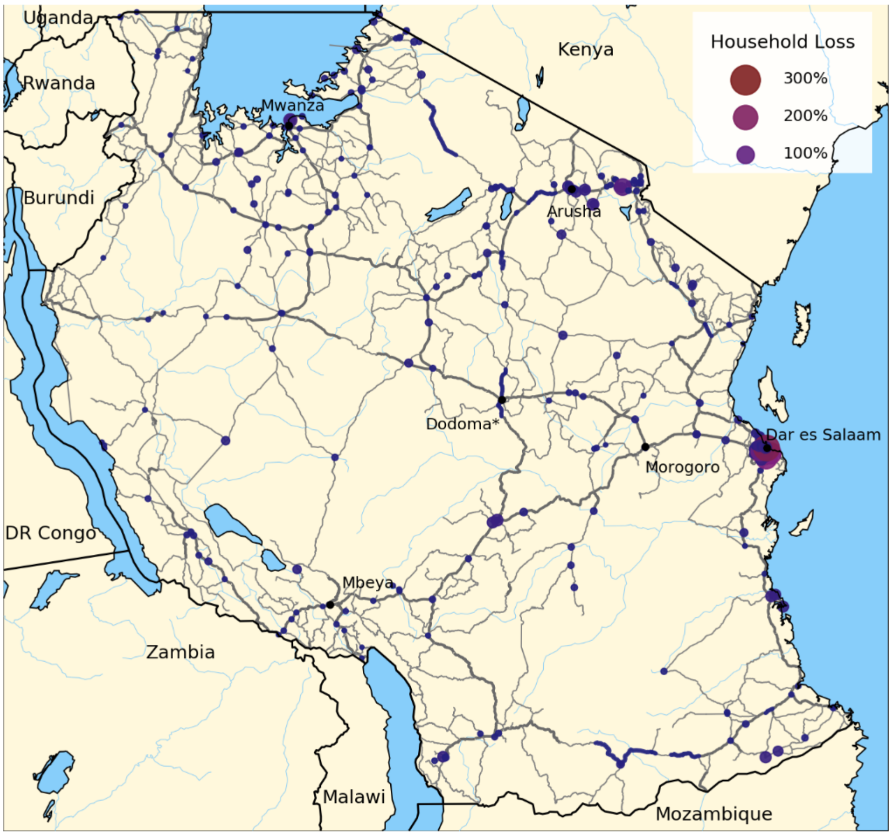


Figure 6-2. Supply-chain criticality to long disruption of the road network of the United Republic of Tanzania. Each infrastructure is highlighted according to the amount of indirect economic loss for households triggered by its disruption. Indirect loss is made of extra expenditure and consumption loss; see Figure 6-4. It is measured by the relative loss in daily country-wide consumption. Infrastructures that trigger a loss over 0.01% of country-wide yearly consumption are shown.

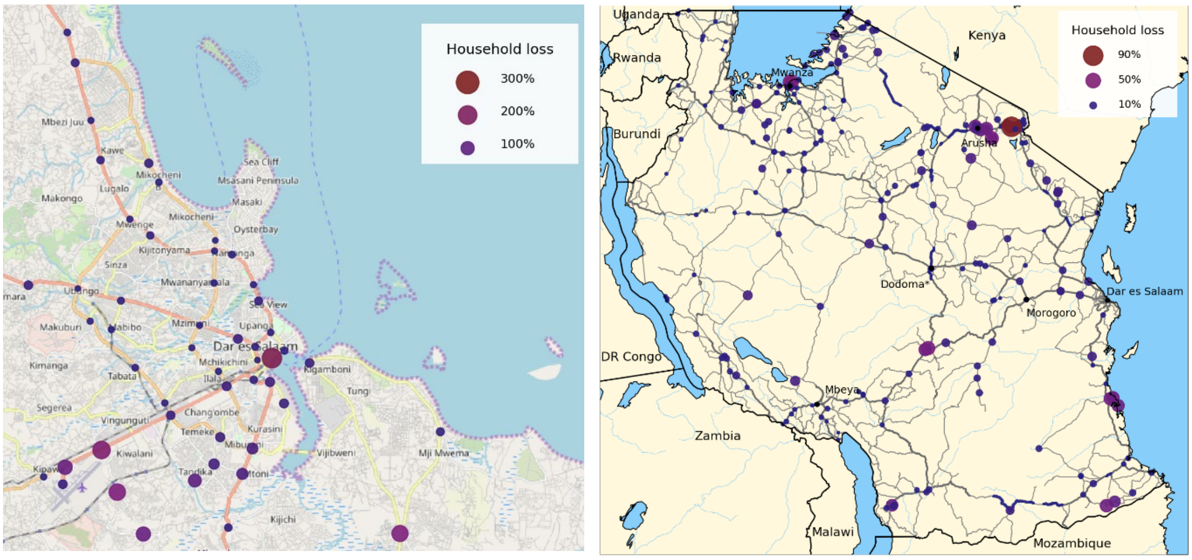


Figure 6-3. Supply-chain criticality of Tanzania's road network to four-week disruptions — zoom on Dar es Salaam (left) and results without Dar es Salaam. Units of household losses are in percentage of daily consumption.

As opposed to short disruptions, the main type of losses for households are due to shortages that propagate along supply chains; see Figure 6-4. As shown in Section 5.2.1, shortages scales nonlinearly with disruption duration, leading to very large impacts. In contrast, the effect of costlier transportation due to rerouting increase linearly, and moderately, with disruption duration.

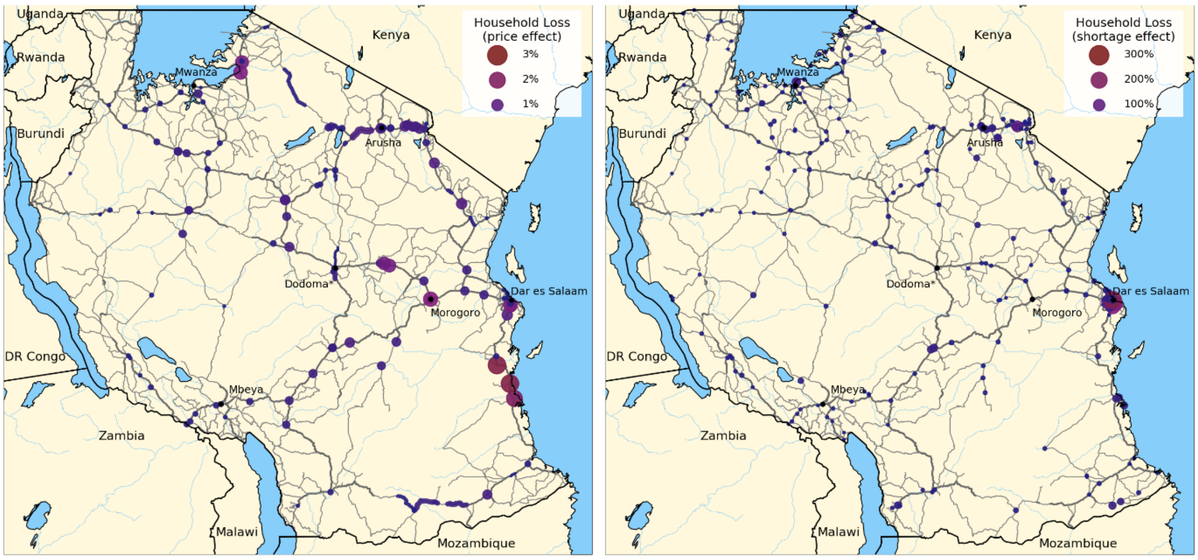


Figure 6-4. Supply-chain criticality of Tanzania's road network to short disruption— Contributions of the price (left) and shortage effect (right). Units of household losses are in percentage of daily consumption.

6.2 Criticality depends on policy objectives

Transportation infrastructures serve multiple supply chains and, thereby, support a variety of functions. Some infrastructures may be important to some users, and of little use for others. Consequently, investment priorities may change depending on the policy objectives, e.g., support health services, improve food security, promote trade competitiveness. By measuring impacts on selected products and supply chains, we can generate criticality maps that are relevant to a specific objective.

6.2.1 Priorities depend on targeted supply chains

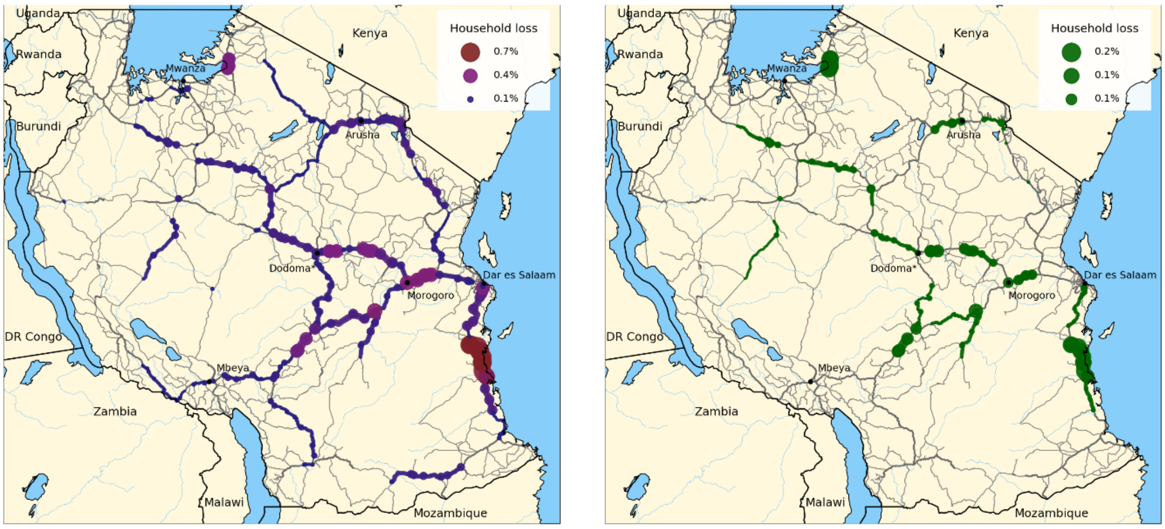
The criticality maps of Section 6.1 are built on estimates of losses to Tanzanian households. In fact, this indicator aggregates all types of products consumed by households. We generate further maps by using losses of selected products only. Figure 6-5 shows five new maps that concern criticality to one-week disruption; each one corresponds to the products of the five groups of sectors defined in Table 3-4, namely, Agriculture, Food, Manufacturing, Trade, Others. Doing so, we can appraise the criticality of transportation infrastructure in relation to specific issues, such as food security or manufacturing competitiveness.

Note that, even if we measure the impacts on a subset of products, we are still simulating the interactions between all supply chains. For instance, the consumption of food products is enabled by firms from different sectors, such as agriculture and trade. We maintain the supply-chain complexity and only reduce the scope of the end-of-pipe indicator.

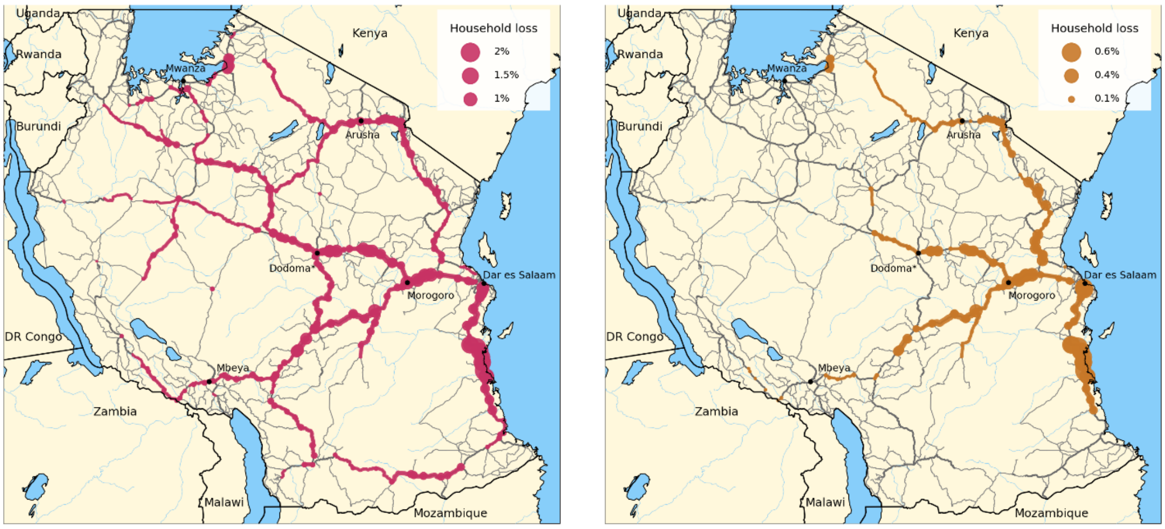
These maps allow us to draw several observations.

- Impacts of transportation disruptions on the consumption of agricultural products are very low; see the scale of Figure 6-5(b). Production and consumption of such products do not depend much on transportation. Households mostly buy agricultural products from local farmers.
- The production and consumption of food products, instead, rely much more on transportation. A one-week disruption of some roads can lead to a decrease in up to 2% of national daily consumption of food products; see Figure 6-5(c). Food products are secondary products. They are made of agricultural products which are carried from the countryside to urban centers. This pattern reflects the role of supply-chain amplification, which, as shown in Section 5.2.2, is the strongest for food products. As a result, food products are the main contributor of supply-chain-driven household loss, its criticality map, Figure 6-5(c), is very similar to Figure 6-5(a), which consider all types of products. Transportation criticality of products sold by wholesalers and retailers, shown on Figure 6-5(e), has a similar behavior to that of food products.
- As nonprimary products, manufacturing products are also subject to supply-chain amplification. Its criticality map, on Figure 6-5(d), shows reliance to transportation corridors in and out Dar es Salaam, where production is concentrated.

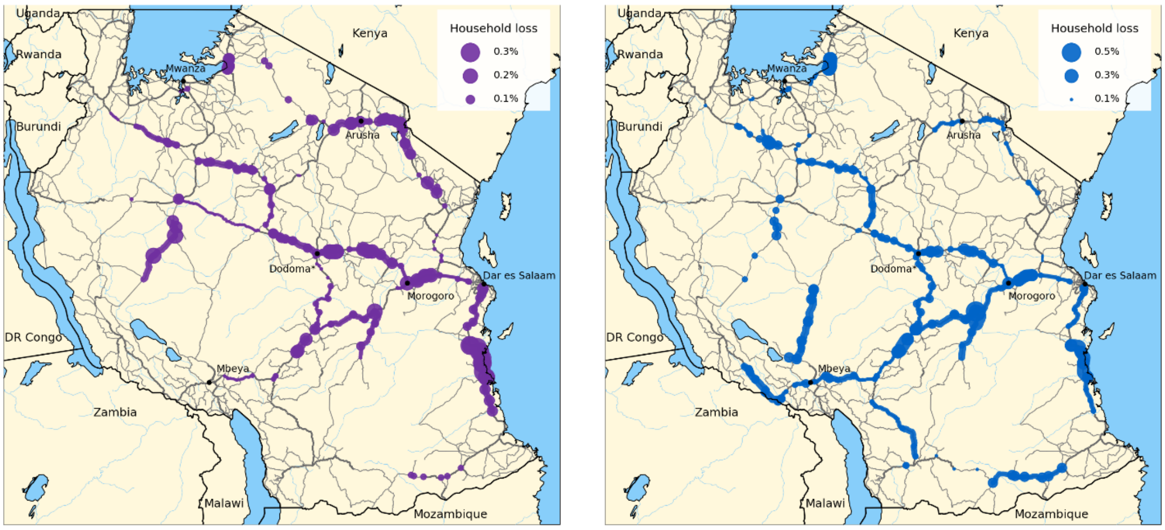
We can produce a similar analysis for four-week disruptions.



(a) All products (b) Agriculture



(c) Food (d) Manufacturing

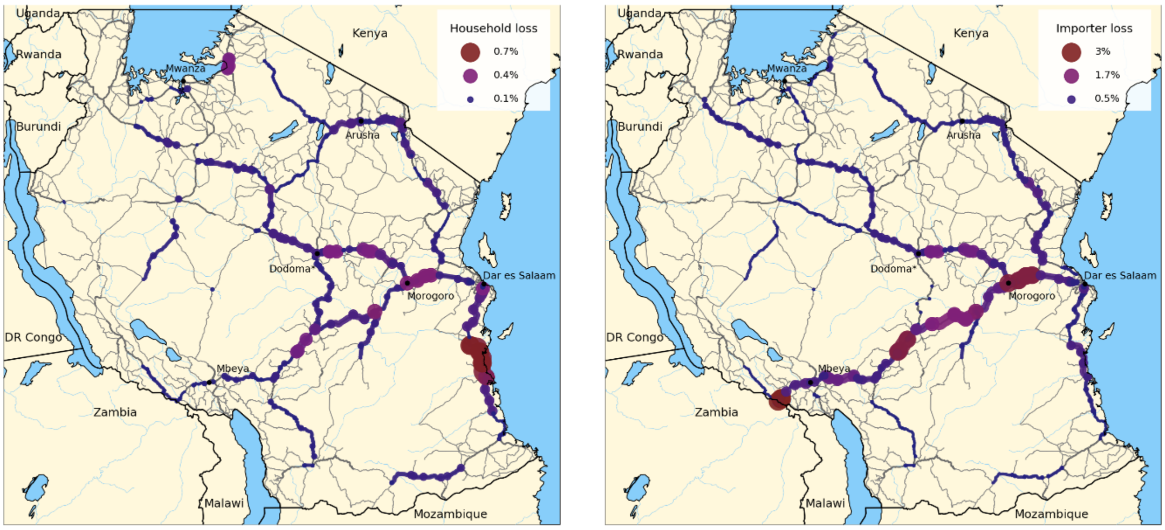


(e) Trade (f) Others

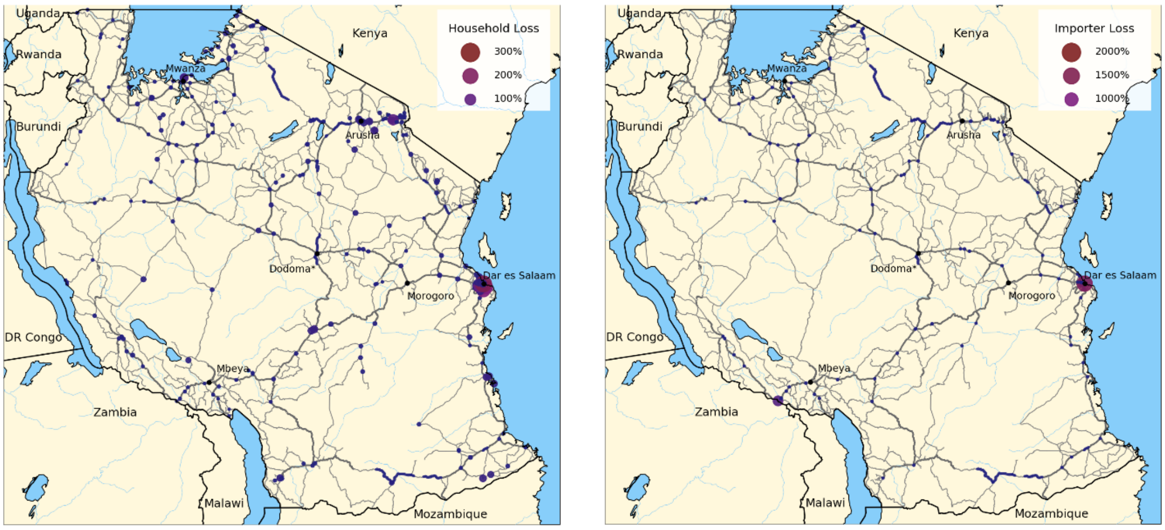
Figure 6-5. Criticality patterns change with the type of product under scrutiny. The six criticality maps are based on the impact of short disruptions on Tanzanian households. They differ by the product basket considered. The map of panel (a) consider the indirect losses of any types of products. In panels (b) to (e), instead, the scope is limited to, respectively, agricultural products, food products, manufacturing products, and products sold by wholesalers and retailers. Panel (f) groups products not included in panels (b) to (e). See Table 3-4 for a definition of these sectoral groups. Units are in percentage loss of daily consumption of the corresponding basket of products.

6.2.2 Priorities depend on end-users: domestic vs. international supply chains

Transportation infrastructures not only support the activity of local businesses but are also pivotal for international trade. The port of Dar es Salaam is an economic asset of very high significance for the whole East Africa region. Large trade flows transit across the United Republic of Tanzania. They are transported between the port of Dar es Salaam and landlocked countries, namely Uganda, Burundi, Rwanda, the Democratic Republic of Congo, Malawi, and Zambia. Our analysis, which so far focused on domestic consumption, can be readily adapted to assess the criticality of transportation infrastructures for the resilience of international trade; see Figure 6-6(b).



(a) Domestic households, one-week disruptions (b) International buyers, one-week disruptions



(c) Domestic households, four-week disruptions (d) International buyers, four-week disruptions

Figure 6-6. Criticality maps vary according to the end-users. Both maps relate to one-week disruptions. Maps of panels (a) and (c) are based on the indirect loss incurred by Tanzanian households, expressed in loss of daily consumption. Those of panel (b) and (d), instead, focus on international buyers of products produced in the United Republic of Tanzania or of products transiting through the country. In the latter, loss are expressed in percentage of daily imports.

Figure 6-6(b) suggest that policy makers interested in the resilience of international supply chains should primarily focus on the T1 trunk roads. This NW–SE corridor carries very large amount of freight between, on one hand, the Democratic Republic of Congo and Zambia and, on the other end, the port of Dar es Salaam. This corridor is of upmost importance for international trade. The T2 trunk road that connects Dar es Salaam with Arusha is more critical in the international-buyer-centric map of Figure 6-6(b) than it appears in the domestic-household-centric map of Figure 6-6(a). This corridor conveys exports from Arusha to the port of Dar es Salaam.

As for long disruptions, the criticality map related international buyers, in Figure 6-6(d), only highlights border crossings and ports. In Figure 6-6(c), instead, more scattered infrastructure are critical to domestic households.

6.3 Comparison with transportation criticality analyses

6.3.1 Main innovation: evaluating how disruptions propagates along supply chains

The present study produces criticality maps which compares to that of existing methods of transportation-network assessments used, for instance, by Rozenberg et al. (2017)[37] and Espinet et al. (2018)[38]. In fact, the output of the DisruptSCT model differs from that of those study. The latter estimate the direct consequences of transportation disruptions in terms of added costs or blocked flows, whereas we model how these direct consequences propagate along supply chains and turn into indirect costs for domestic households and international buyers.

Technically, transportation network analyses rely on static models that simulate two states of the economy: a baseline state and a disrupted state. The impacts of a disruption are measured by measuring the change of certain variables from the first state to the second. The two main variables measured are:

- the amount of products delivered and the corresponding sales generated,
- an estimates of the generalized costs of transportation. This total cost is divided into direct and indirect costs. The direct costs are the prices paid to transporter. The indirect costs are monetized costs of time and of capital associated. Note that the terms “direct” and “indirect” do not refer to the context of disaster impact assessment but should be interpreted in an accounting sense.

The differences of these variables between the undisrupted and the disrupted states quantifies direct impacts of a transportation disruption: how much costlier transportation become, and how much goods are being undelivered.

The DisruptSCT model, in contrast, is essentially dynamics. It can measure the same variables, but, on top on them, it simulates the propagation of these direct impact along supply chains and

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[37] Rozenberg J, Briceno-Garmendia C, Lu X, Bonzanigo L, Moroz H (2017) *Improving the Resilience of Peru’s Road Network to Climate Events*. Policy Research Working Paper 8013, The World Bank Group, Washington DC, USA

[38] Espinet X, Rozenberg J, Singh Rao K, Ogita S (2018) Piloting the Use of Network Analysis and Decision-Making under Uncertainty in Transport Operations — Preparation and Appraisal of a Rural Roads Project in Mozambique under Changing Flood Risk and Other Deep Uncertainties. Policy Research Working Paper 8490, The World Bank Group, Washington DC, USA

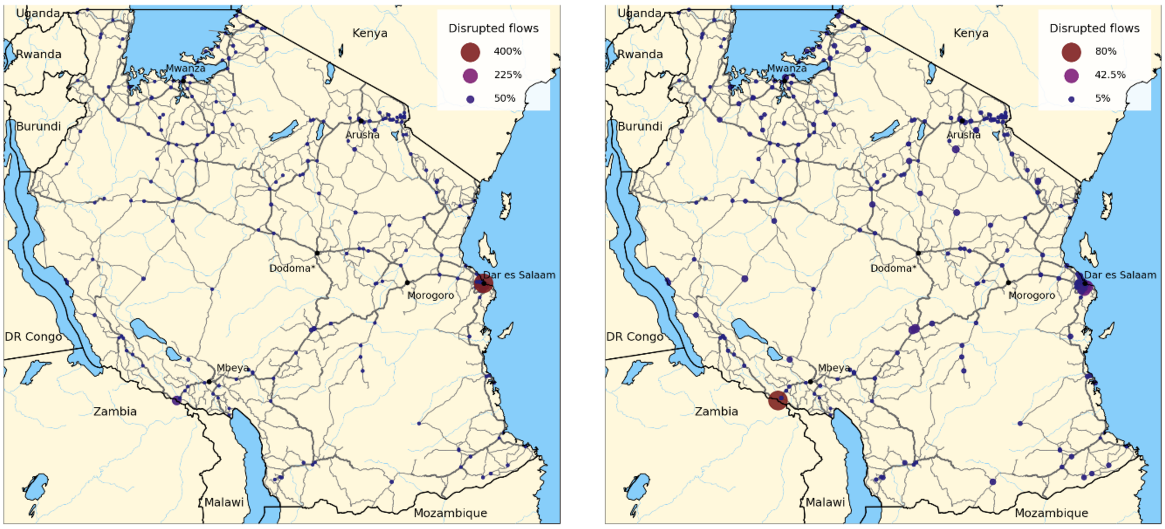
their resulting impacts on economic agents. As seen in Section 6.2, we can contextualize these impacts by looking at specific products.

Table 6-2. Summary of the main differences between the DisruptSCT model and classical method of transportation-network analysis

Transportation network analyses	DisruptSCT model
Static model with two states: functioning or disrupted	Dynamic model with disruption and recovery pathways
Each origin–destination flow is independent from the other flows	Origin–destination flows interact: the existence of a flow depends on the delivery of others
No explicit modeling of production and consumption	Explicit modeling of production and consumption

6.3.2 Quantitative comparison of the indicators

To better grasp the added information brought by the DisruptSCT model, we use it to generate the two main indicators produced transportation network analyses: (i) amount of disrupted supply-chain flows and (ii) generalized transportation costs. We produce the corresponding criticality maps; see Figure 6-7 and Figure 6-8.

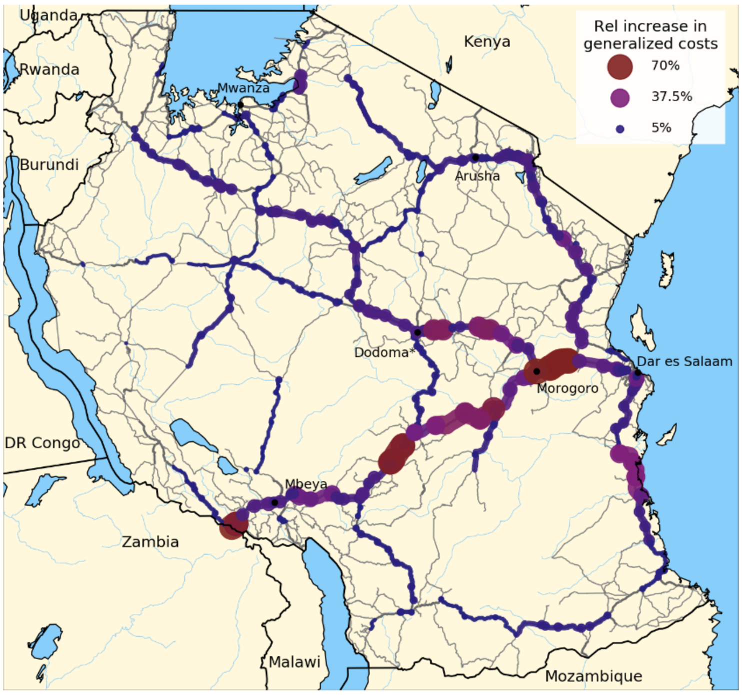


(a) With the port of Dar es Salaam **(b) Without the port of Dar es Salaam**

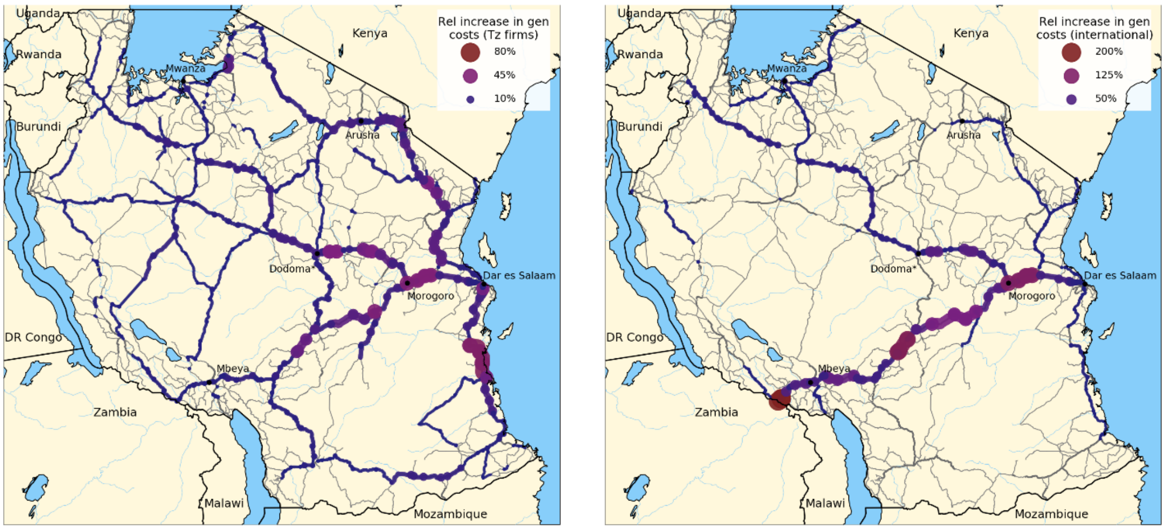
Figure 6-7. Criticality maps based on the amount of disrupted supply-chain flows. Unit is in percentage of normal daily supply-chain flows, measured in monetary terms.

Figure 6-7 presents criticality maps based on the amount of disrupted supply-chain flows. The port of Dar es Salaam stands out by far as the most critical node; see Figure 6-7(a). Its disruptions block about 30% of all freight flows.

By excluding the port from the map, other nodes appear; see Figure 6-7(b). The other main freight-blocking node is the border crossing between Zambia and the United Republic of Tanzania at Tunduma. This node is of the highest significance because most transit flows from and to Zambia and DR Congo, two major landlocked countries, are transported through it. Very few edges stand out are, because roads that completely isolate significant production or consumption areas are very rather rare in the United Republic of Tanzania.



(a) Global increase in generalized transportation costs



(b) Increase for Tanzanian firms

(c) Increase for international firms

Figure 6-8. Criticality maps based on the relative increase in generalized transportation costs. Panel (a) shows the increase for all firms using the transportation network of the United Republic of Tanzania. Panels (b) and (c) disentangle the increase undergone by Tanzanian firms (b), which concerns domestic trade flows and exports, from those faced by international firms, which corresponds to imports and transit flows.

Figure 6-8 shows the criticality map based on the relative increase in generalized transportation costs. This pattern shows many similarities with the criticality map based on increased household expenditure. In the generalized transportation cost model, the indirect costs, which corresponds to the cost of time, is strongly correlated to the direct costs of transportation, which then propagates down to households. It clearly highlights the T1 NE–SW trunk road, which connect Dar-es-Salaam, Morogoro, Iringa, Mbeya, and Zambia, as the most critical corridor.

Secondarily critical roads are the T3 E–W trunk road between Dodoma and Morogoro and the T7 N–S coastal trunk road in Lindi, about 200 km south of Dar-es-Salaam. It is possible to disentangle the increased costs bore by Tanzanian firms from those faced by international partners; see Figure 6-8(b) and (c).

Chapter 7. Resilience strategies

How to address the bottlenecks identified in Chapter 6? Multiple approaches can improve the resilience of the transportation–supply-chain system. One is to enhance the supply-side of transportation, by improving the quality of targeted infrastructure, by developing alternative corridors, and by building capacity to accelerate post-disaster recovery. On the other hand, policies could support resilience of supply-chain, i.e., of the demand-side of transportation. This chapter estimates the potential of these policies in reducing the indirect costs of disasters. It discusses how they can be articulated together and adapted to specific contexts.

7.1 A framework to articulate demand-side and supply-side policies

To enhance the resilience of the transportation–supply-chain system, one can either support the supply side of transportation—i.e., how efficient, robust, redundant is the movement of goods and services on the transportation infrastructures—or work on the demand side—i.e., how supply chains are using these infrastructures[39]. Table 7-1 summarizes policies for both sides and shows how they relate to three main features of resilience: resistance, redundancy, responsiveness.

A policy, such as developing redundancy in the transportation network, may not be cost effective in all kind of geographical, ecological, and socioeconomical contexts. Think of building an alternative highway in a mountainous or an ecologically fragile ecosystem. The choice of one policy or a combination thereof is context-dependent, and the framework presented in Table 7-1 can help envision different solutions. Based on results for the United Republic of Tanzania, the present chapter discusses some of these resilience strategies.

Table 7-1. Strategies to improve supply-chain resilience can complementarily target the supply side and the demand side of transportation.

Resilience dimensions	Supply side	Demand side
Resistance	Improve infrastructures through engineering work and maintenance to reduce their vulnerability to disasters	Promote safety stocks to allow users to sustain their activity during transportation disruptions
Redundancy	Develop alternative transportation corridors and modes	Facilitate supplier and client diversification
Responsiveness	Enhance capacity to react quickly to disruption and restore services	Support the development of business continuity plans

7.2 Supply-side policies

Supply-side policies are meant to increase the resilience of transportation services. We assess such policies by applying them to two corridors, which are the most critical for domestic

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[39] This approach is more commonly used in the energy sector. Demand-side management, such as dynamic pricing, has become a prominent pillar of energy policy.

households in a context of one-week disruptions: (i) the NE–SW trunk road T1 in Iringa and (ii) the N–S costal trunk road T7in Lindi; see Section 6.1.1.

We use the DisruptTSC model to evaluate the benefits of the three policies listed in Table 7-1:

- Reduce vulnerability to disruptions
- Develop alternative roads
- Restore service quicker

Benefits are evaluated in terms of reduction in the indirect impacts of disruptions.

7.2.1 Targeted investments to reduce road vulnerability

We suppose that the roads networks highlighted in Figure 7-1 cannot be disrupted at all. It represents 77 km of T1 paved road in Iringa, 104 km of T7 paved road in Lindi. This assumption of complete undisruptability is strong, and very unlikely in practice because it would require very large investments. Testing this assumption remains interesting to evaluate the potential of such resistance-oriented policies.

With these undisruptable roads, for one-week disruptions, loss on households of the 100 most critical nodes is reduced by 17% for short disruptions. These figures are percentages of relative decrease in impact, evaluated by simulating the disruptions of the 100 most critical road nodes. Making the T1 trunk in Iringa and the T7 in Lindi invulnerable decreases losses by 6.2% and 11%, respectively.

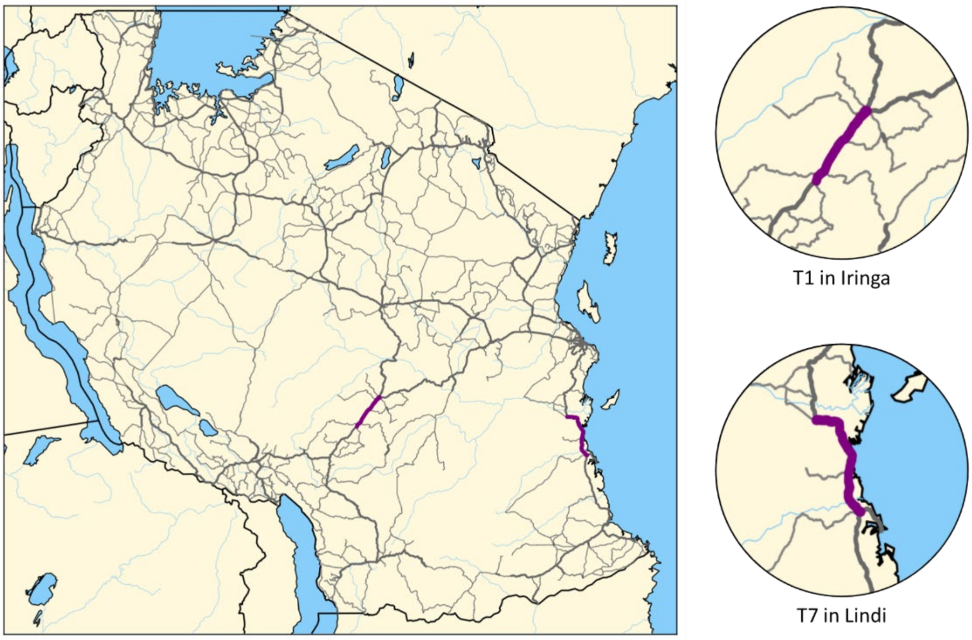


Figure 7-1. Making roads invulnerable. The map highlights in purple the location of the two segments of roads made invulnerable.

7.2.2 Targeted investments to increase redundancy

Instead of making critical segments undisruptable, we may develop alternative corridors. Such policy could be achieved by improving existing alternative roads to make them suitable for freight transportation, or by building new roads. We generate a hypothetical scenario, shown in Figure 7-2, in which new roads enable alternative routes around the three most critical corridors. For simplicity, we designed straight roads between existing transportation nodes. In Lindi, we partly use existing ways documented by OpenStreetMaps. Overall, we created 329 km of new roads: 187 km around T1 in Iringa, 142 km around T7 roads in Lindi.

With these new roads, household loss is reduced by 11% for short disruptions. Redundancy has a lower potential than undisruptability for short disruptions, because the alternative roads are still costlier than the normal ones.

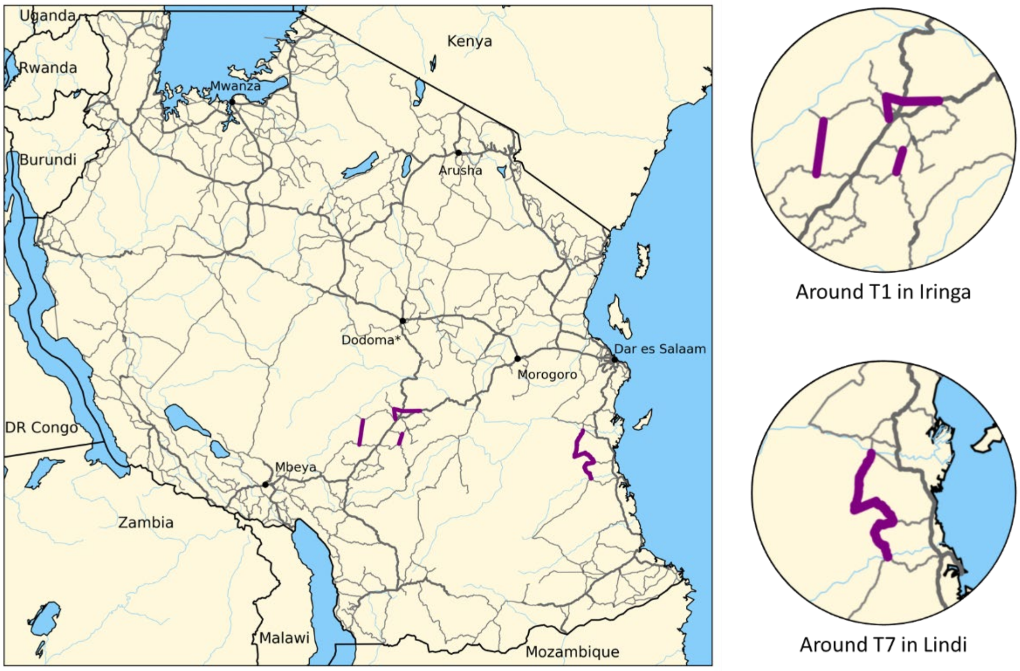


Figure 7-2. Building redundancy in the transportation network. Alternative roads are created or improved to allow rerouting of freight flows along two critical corridors: T1 in Iringa, T7 in Lindi.

7.2.3 Accelerating recovery of critical roads

Instead of investing in fixed capital, either in the form of improved—Section 7.2.1—or new infrastructure—Section 7.2.2, resilience can be improved by accelerating post-disruption recovery. This policy can take various forms: improved monitoring systems, investing in and prepositioning repair equipment and material, training recovery teams, etc. Here, we turn back to the baseline scenario, but suppose that the roads highlighted in Figure 7-1 always get back to a normal service within a week, whatever the length of the disruption.

This "back-quicker" policy does not reduce the impact of one-week disruptions. But, on the 77 km of targeted roads in Iringa, this policy reduces loss triggered by four-week disruptions by 80%, and by 93% of the 104 km of roads in Lindi. Given the exponential growth of losses with disruption time, accelerating recovery significantly alleviate losses.

Since the T1 in Iringa and the T7 in Lindi were selected because of their criticality to one-week disruptions, the impact of the "back-quicker" policy on those segments remains moderate in absolute terms. It represents 0.8% reduction of the losses induced by four-week disruptions of the 300 most critical nodes. In comparison, applying the 'back-quicker" policy only to the access to the port of Dar es Salaam represents a 5% drop in losses of the 300 most critical nodes.

7.3 Demand-side policies

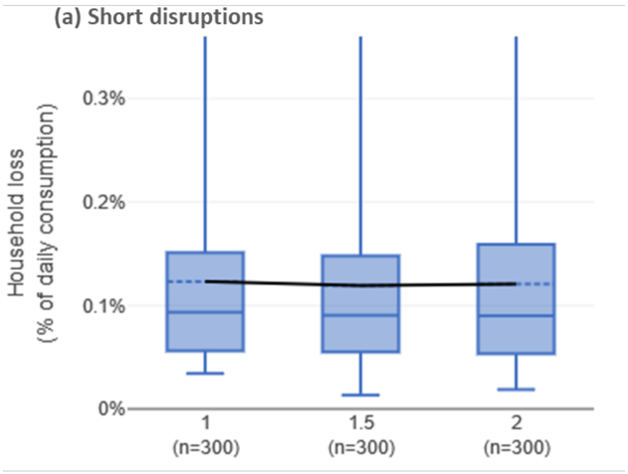
Resilience may also be improved by supporting coping strategies of businesses.

7.3.1 Diversifying sourcing

Many examples show that single-sourcing strategies are a classical cause of supply chain disruptions. Maintaining a diversity of suppliers, is, in turn, a powerful safeguard against disruption, when it combines both local and distant partners. To evaluate the potential of this resilience strategy, we model alternative scenarios in which firms have, in average, 1.5 or 2 suppliers per type of inputs instead of one. Results are shown on Figure 7-3

Supplier diversity does not change much the consequences of short disruptions. In average, having two suppliers per input instead of one even slightly increase indirect losses by 1%. On the one hand, firms are less dependent on one specific transport route, leading to less acute price increases after a shock. On the other hand, they become more dependent on transportation, therefore more often exposed to disruptions.

For long, shortage-inducing disruptions, have multiple suppliers markedly alleviate the indirect costs, which drop by 52% from single to double sourcing. When one supplier is affected by a disaster, they still receive the supply from the other, allowing them to only reduce, instead of completely stop, production. This ability to keep producing has a compounding effect along supply chains, such that consumption loss for household significantly decreases.



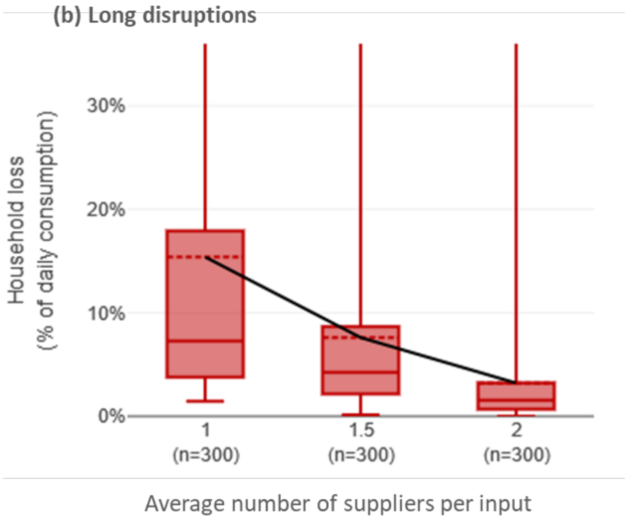


Figure 7-3. Having more suppliers help coping with long disruptions. Both panels show how the indirect impacts on households of transportation disruptions change with the number of suppliers per production input. Panel (a) show the results for one-week-long disruptions, panel (b) for four-week-long ones. They are based on a comprehensive set of model runs, which simulate the disruption of each transportation nodes, one by one. The filled rectangle indicates the interquartile interval, the solid horizontal lines indicates the median, the dash horizontal line indicates the mean. Mean values are joined together with a black curve. The vertical line extends to the minimum and maximum of the distributions; here all maxima lie outside the plotting area.

7.3.2 Short vs. long supply chains

Increasing or reducing the distance between suppliers and buyers has a mixed effect on supply chains.

- On the one hand, sourcing from local partners decreases the reliance on transportation, and significantly reduces the risks of incurring the indirect consequences of a distant disruption.
- On the other hand, maintaining relationships with distant partners helps firms recover when their facilities are directly hit by a disaster.

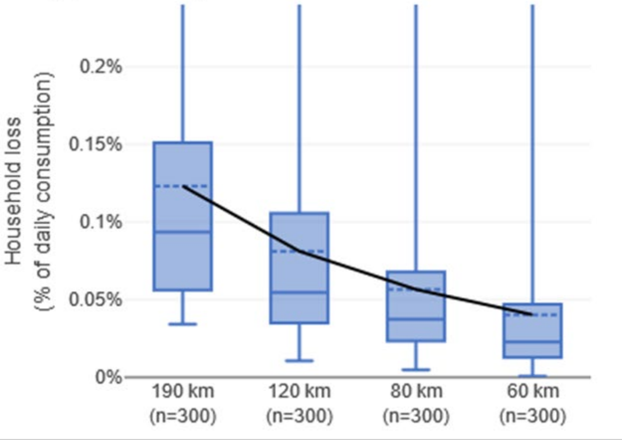
To evaluate the effect of local sourcing on resilience, we design alternative scenarios in which firms use more local suppliers. Specifically, in the baseline, the probability for firm A to choose firm B as a supplier varies with the inverse of the distance between firms A and B, $1/D_{AB}$. In the alternative scenarios, this probability varies with the inverse of distance to the power of 2, 3, and 4, i.e., $1/D_{AB}^2$, $1/D_{AB}^3$, and $1/D_{AB}^4$, respectively. As a result, the average supplier–buyer distance goes from 190 km, to respectively 120 km, 80 km, and 60 km.

For short disruptions, impacts on households decrease by 67% for short disruptions between the 190-km scenario and the 60-km one; see Figure 7-4(a). Firm are much less dependent on transportation services. Prices are consequently much less impacted by transportation disruptions.

On the other hand, we observe in Figure 7-4(b) an increase in losses for four-week long disruptions. Households losses in the 60-km scenario are in average 24% larger than in the 190-km scenario. This figure rises to 66% for the households directly impacted by the disruption. Local sourcing makes large disasters more severe for the directly impacted population.

To conclude, having local suppliers reduce on the day-to-day disruptions. But an overreliance on local suppliers can be detrimental when large disasters hit. Having suppliers located outside the affected regions helps firms recover.

(a) Short disruptions



(b) Long disruptions

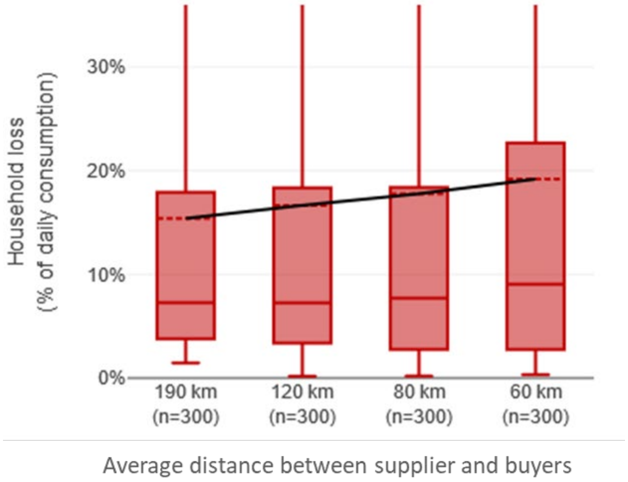


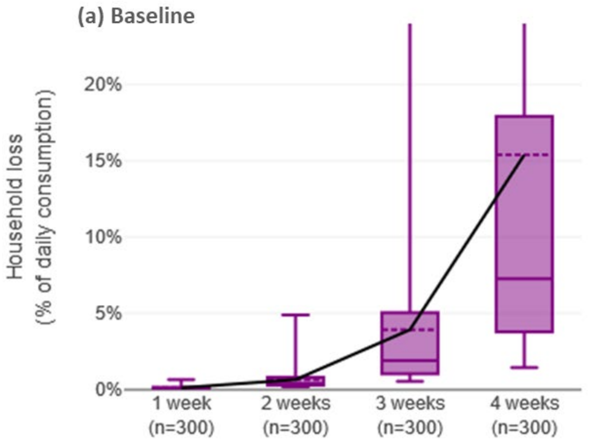
Figure 7-4. Local sourcing strongly reduces the impact of small disruptions, but it increases vulnerability to large shocks. Both panels show how the indirect impacts on households of transportation disruptions change with the average distance between suppliers and buyers. Panel (a) show the results for one-week-long disruptions, panel (b) for four-week-long ones. They are based on a comprehensive set of model runs, which simulate the disruption of each transportation nodes, one by one. The filled rectangle indicates the interquartile interval, the solid horizontal lines indicates the median, the dash horizontal line indicates the mean. Mean values are joined together with a black curve. The vertical line extends to the minimum and maximum of the distributions; here all maxima lie outside the plotting area.

7.3.3 Safety stocks

Holding safety stocks is the most widespread measure to cope with supply-chain disruptions. In the baseline scenario of our model, inventories of material goods—i.e., from the following groups of sectors: agriculture, food, trade, manufacturing—represent 6% of the final consumption in the corresponding sectors. In average, firms hold 4.5 weeks of inventories.

To estimate the effect of safety stocks, we analyze an alternative scenario in which all firms hold one more week of inventory of any inputs, i.e., the average amount of inventories reaches 5.5 weeks. Results are shown in Figure 7-5.

Holding larger inventories markedly reduce indirect impacts on households for long disruptions. Average losses triggered by four-week disruptions of the 300 most critical nodes are divided by 4.9 when firms have one more week of inventories for all inputs. The reduction potential is very limited lower for short disruption, whose impact are dominated by transportation costs. Although excessive inventories are financial burdens and unpracticable for perishable goods, holding safety stocks remain a powerful risk-mitigating measure.


(a) Baseline

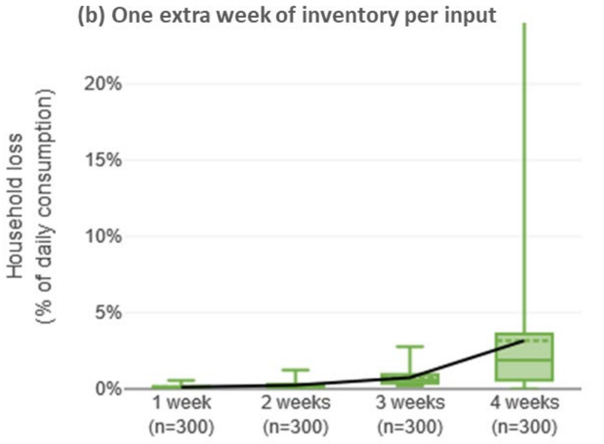

(b) One extra week of inventory per input

Figure 7-5. Having larger inventories help coping with long disruptions. Both panels show how the indirect impacts on households of transportation disruptions change with the duration of the disruptions. Panel (a) corresponds to the baseline scenario, in which firms hold, in average 4.5 weeks of inventories. In panel (b), firms hold an extra week of inventories for all inputs. These figures are based on a comprehensive set of model runs, which simulate the disruption of each transportation nodes, one by one. The 300 most critical are shown. The filled rectangle indicates the interquartile interval, the solid horizontal lines indicates the median, the dash horizontal line indicates the mean. Mean values are joined together with a black curve. The vertical line extends to the minimum and maximum of the distributions; when the maximum lies outside the plotting area, the upper part of the vertical line is not capped.

7.4 Identifying adapted policies

Sections 7.1 to 7.3 presented a variety of measures which can enhance the resilience of supply chains to transportation disruptions. Policies can target either the supply or the demand side of transportation, and, for each side, play on resistance, redundancy, or responsiveness. Some measures may be more adapted than other depending on the context. Comprehensive cost-benefit analyses, which are out of the scope of the present study, are necessary to identify the most adequate measures, or combinations thereof. Before turning to such detailed analysis, the DisruptSCT model provides general results that can help articulate these various policies.

As presented in Section 5.2.1, the nature and extent of the indirect costs change with the severity of a disasters. Small disruptions primarily trigger rerouting and delays, which generate proportionate increases in transportation cost and market prices. Large events may, in turn, generate shortages which get amplified as they propagate along supply chains. Criticality maps thus vary with the extent of disruption; see for instance Figure 6-1 and Figure 6-2. Some infrastructures may be very critical when looking at small disruptions, but not so much in case of a large event, and conversely.

Figure 7-6 shows, for each infrastructure, how the indirect impacts of disruptions varies between short and long disasters. Among critical infrastructures, we distinguish three groups.

A. High along the y-axis, we identify infrastructures whose prolonged disruptions lead to acute losses, but that are not particularly critical when it comes to short disruptions.
    - Such infrastructures concentrate large economic activities but are not situated on a major transportation corridor. During a disruption, very few freight flows need to be rerouted. Using safety stocks, business located close to these infrastructures, or firms that source inputs from them, can sustain small disruptions. Longer disruptions however become problematic.
    - For these infrastructures, policies should enhance capacities for rapid post-disaster recovery, provided local businesses have minimal safety stocks. Building redundancy or improving resistance are not likely to be cost-effective.

B. High along the x-axis, we identify infrastructures which are critical as for short disruptions, but whose prolonged disruptions do not lead to disproportionately high costs.
    - Such infrastructures are supporting major transportation corridors but are not an absolute necessity for any businesses. When they are disrupted, firms can find alternative routes in the short term, which are however much more expensive to use.
    - It is recommended to improve the resistance of these infrastructures, or, if more cost-effective, to develop alternative corridors.

C. On the upper right corner stand infrastructures that are critical in case of both short and long disruptions.
    - They both host noteworthy industries and support transportation corridors.
    - To address their criticality, a combination of policies is necessary. Two options should be looked at: (i) improve their resistance and ensure their rapid recovery, or (ii) develop high-quality redundant pathways.

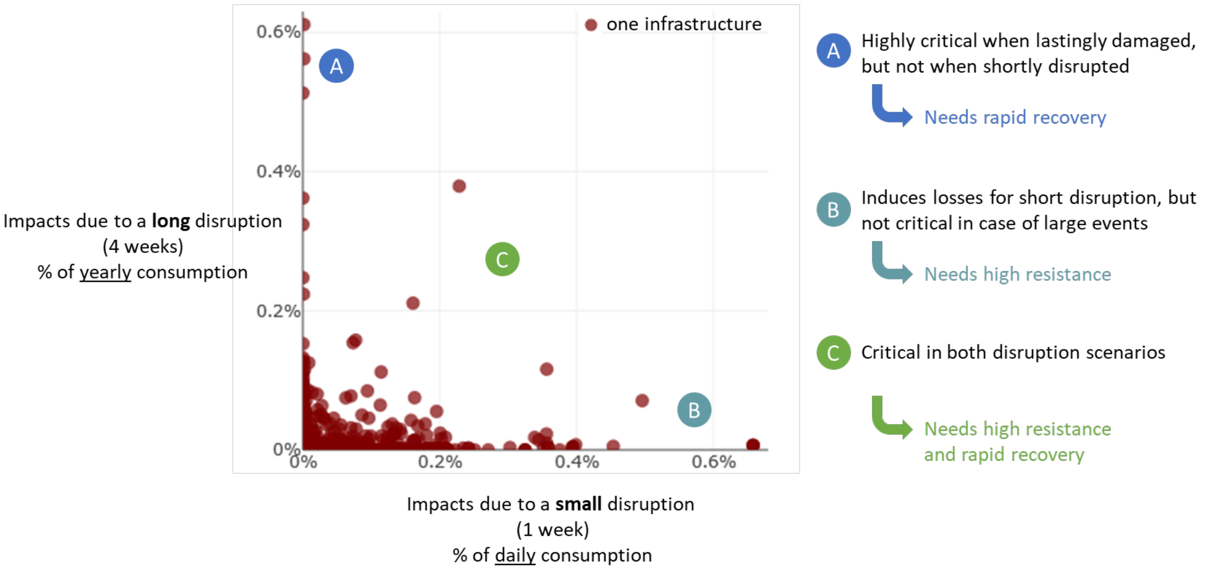


Figure 7-6. Combining criticality scores to short and long disruptions help design intervention strategies. Each red bubble represents a transportation infrastructure, whose coordinates are the loss it generates when disrupted for one week and four weeks.

Chapter 8. Next challenges for assessing resilience

We conclude by identifying new questions that could be tackled by the present model. We also discuss potential solutions to enhance the accuracy and robustness of the results.

8.1 Model extension

- *Cost benefit analysis of resilience policies.* In Chapter 7 we characterize the potential of various policies in mitigating the indirect loss of transportation disruptions. Assessing the costs of these solutions would enable the comparison of their cost effectiveness.
- *Quality of transportation services.* The model assumes well-functioning transportation services. In developing countries, the reliability of transportation services is a crucial impediment to the functioning of supply chains. Data characterizing service quality, such as average delays or merchandise loss per trip, could be plugged into the model. This extension would allow us to evaluate the role of service quality in amplifying or damping disruptions.
- *Workforce's ability to move and income.* When a disaster hits, the ability of people to reach their workplace is a crucial impediment to economic recovery. We could capture this phenomenon by modeling of workers and by refining the modeling of urban transportation. In turn, we could evaluate how the propagation of disruption along supply chains affect workers income.

8.2 Data gap and uncertainties

- *Uncertainties on cost estimates and bottleneck identification.* Detailed data on supply chains would unleash the full potential of the model. In their absence, we have integrated a variety of data to reproduce plausible supply-chain patterns. We have been able to reproduce the nonlinear behavior of disaster-induced impacts, and to highlight to role of bottlenecks. But the accuracy of absolute cost estimates and the robustness of fine-grained bottleneck identification are limited by the availability of data. In practice, any new datasets that help spatially pinpoint production, consumption, and supply chain could be integrated in the model, thereby improving the generation of supply-chain patterns.
- *The challenges of integrating heterogeneous datasets*. The main drawback of integrating heterogeneous datasets is the limited congruence between categories. For instance, information was lost when disaggregating GTAP sectoral data, which uses GSC code, with a survey and business registry encoded in ISIC Rev. 4.
- *Aggregation effects.* There is a trade-off between the computational intensity of the simulations and the degree of disaggregation. When choosing the OD nodes and when determining the number of firms per sector in the model, thresholds are applied to simplify the model. Simple robustness checks between aggregation levels are carried out to ensure that outputs are satisfactorily consistent. But an in-depth assessment of the importance of these thresholds are lacking. It would help modelers adjust these parameters according to the model output. For instance, we expect that a small-scale assessment of bottlenecks

requires a lower level of aggregation than country-wide criticality maps. Better understanding these parameters could help us bring the full potential of this model.

Improve data integration

- Firm registry: 2% of firms (c. 5000) have activity name but no activity code. We could get those guys

Appendix A.

Corrections applied to the road network dataset provided by Pant et al. (2018)

- In Mpanda, Katevi, we added an edge that was missing between nodes 5123 and 5105.
- In Bukoba, Kagera, we added several edges that were missing in the city, which was artificially interrupting roads.
- In Kagera, at the frontier with Burundi, a node was missing at the frontier. We also corrected inconsistent associations between nodes and edges.
- We found that road 5657 of the dataset was in fact a railway. We removed it.
- In Dodoma, we added an edge between node 2748 called Ntyuka junction and node 2738 called Chimwaga junction that was missing.
- In Tabora, we added an edge between the road 3254 and node 4541.
- In Tabora, we found that two edges were representing the same road. We removed edge 5506.
- In Tabora, we found that road 3260 was not connected to the right node. We connected it to nodes 4539 and 4535.
- In Tabora, we found that edges 5592 and 5515 did not have a consistent representation. We corrected them.
- In West Tabora, we found that edge 3272 was not correctly wired and did not have a consistent representation. We corrected it.
- In East Kigoma, we found that edge 1987 was not correctly wired and did not have a consistent representation. We corrected it.
- In South West Mbeya, we corrected inconsistencies in edges 1632 and 1633.
- Mwanza, Tanzania’s second largest city, was only represented by one node. We added two nodes and their associated edges.

Building sector classification from a diverse data source

The business registry uses the ISIC Rev. 4 classification to code sectors. This classification built and maintained by the United Nations. The one used by GTAP, abbreviated GSC, is a GTAP-specific one. To identify groups of firms from the registry to GTAP data, we needed to map ISIC Rev. 4 code into GSC.

GTAP provides a concordance table between GSC and ISIC Rev. 3, and the UN and concordance table between ISIC Rev. 3 and ISIC Rev. 4. Merging these tables to get a concordance table between ISIC Rev. 4 and GSC was however ineffective in mapping the activity of the Tanzanian firms. Only 13% of the companies could be unambiguously mapped into a GSC code, and 73% codes could not be mapped at all.

We built a specific concordance table. We classified the 396 valid ISIC Rev. 4 code of the business registry into the GSC codes, by analyzing and matching sectoral definitions. The resulting concordance table is presented in Appendix B, Table 8-10.

In some cases, it was not possible to give a one-to-one correspondence between an ISIC Rev. 4 code and a GSC code. For instance, even at the finer level, ISIC Rev. 4 does not differentiate between the extraction of oil and the extraction of gas, so we grouped together GSC sector 16 and 17. In total, we performed five groupings, reducing the number of sectors from 57 to 48; see Table 8-1. The number of firms registered in the business census per GSC sectors is shown on Figure 8-1 of Appendix B.

Table 8-1: Groupings of GTAP sectors.

New sector id and name	Grouped sector id and name
2– Vegetables & grains except rice	2– Wheat
	3– Cereal grains nec
	4 – Vegetables, fruit, nuts
	5 – Oil seeds
9 – Animal products	9 – Cattle, sheep, goats, horses
	10 – Animal products nec
	11 – Raw milk
	12 – Wool, silk-worm cocoons
16 – Oil & Gas	16 – Oil
	17 – Gas
19 – Meat products	19 – Meat: cattle, sheep, goats, horse
	20 – Meat products nec
23 – Food products nec	23 – Processed rice
	25 – Food products nec

On top of this technical adjustment, we had to group all agricultural sectors, which corresponds to GSC sectors 1 to 12. The business registry did obviously not contain data on farmers. The business registry contains less than two hundred firms from the agricultural sectors, whereas macroeconomic data shows that it is the largest sector of the United Republic of Tanzania both in terms of employment and GDP. To capture this sector, we used land use data to evaluate the spatial distribution of agricultural production. Since, from these data, it is not possible to distinguish the 12 GSC agricultural sectors, we grouped all of them into sector 1; see Table 8-2.

Table 8-2. Grouping of agricultural sectors.

New sector id and name	Grouped sector id and name
1 – Agriculture, except forestry and fishing	1 – Paddy rice
	2 – Wheat
	3 – Cereal grains nec
	4 – Vegetables, fruit, nuts
	5 – Oil seeds
	6 – Sugar cane, sugar beet
	7 – Plant-based fibers
	8 – Crops nec
	9 – Cattle, sheep, goats, horses
	10 – Animal products nec
	11 – Raw milk
	12 – Wool, silk-worm cocoons

Finally, we leave out of the scope sector #57 called “Dwellings”. This item corresponds to imputed rents from owners and does not correspond to a productive sector.

Averaged equivalence between monetary flows and tonnages

The transportation cost per road segment are given in USD per ton per km. The model simulates supply-chain flows in monetary terms. We use UN CommTrade data, which contains trade flows per ISIC Rev. 4 sector in monetary terms and in tonnages, to evaluate the average monetary value of one tone of product per sector. We use 2017 data for the United Republic of Tanzania[40]; see Table 8-3.

Table 8-3. Coefficients linking tonnages and monetary flows per GSC sector. They are based on 2017 UN CommTrade data for the United Republic of Tanzania

GSC id	Sector name	USD/kg
1	Agriculture, except forestry and fishing	1.05
13	Forestry	0.54
14	Fishing	0.26
15	Coal	0.13
16	Oil & Gas	2.34
18	Minerals nec	3.27
19	Meat: cattle, sheep, goats, horse	0.23
21	Meat products nec	1.25
22	Vegetable oils and fats	0.71
23	Food products nec	0.86
24	Sugar	0.29
26	Beverages and tobacco products	0.31
27	Textiles	0.34
28	Wearing apparel	0.18
29	Leather products	1.00
30	Wood products	0.06
31	Paper products, publishing	1.17
32	Petroleum, coal products	0.87
33	Chemical, rubber, plastic prods	0.34
34	Mineral products nec	0.65
35	Ferrous metals	1.47
36	Metals nec	0.38
37	Metal products	0.53
38	Motor vehicles and parts	0.34
39	Transport equipment nec	0.05
40	Electronic equipment	0.13
41	Machinery and equipment nec	0.12
42	Manufactures nec	0.14
43	Electricity	-
44	Gas manufacture, distribution	-
45	Water	-
46	Construction	0.44
47	Trade	0.18
48	Transport nec	-
49	Sea transport	-
50	Air transport	-
51	Communication	-
52	Financial services nec	-
53	Insurance	-
54	Business services nec	-
55	Recreation and other services	-
56	PubAdmin/Defence/Health/Educat	-

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[40] The monetary value for coal (GSC sector 15) in 2017 reported in the UN CommTrade data and consulted in December 2018 was several orders of magnitude higher than the other products. We used the 2010 value instead. In the absence of a GSC–ISIC Rev. 4 correspondence for GSC sector 32 (petroleum and coal products), we averages values from sector 33, 34, 15 and 16.

Appendix B.

Table 8-4: List of the 57 GTAP sectors with their description.

Id	Sector name	Description
1	Paddy rice	Paddy Rice: rice, husked and unhusked
2	Wheat	Wheat: wheat and meslin
3	Cereal grains nec	Other Grains: maize (corn), barley, rye, oats, other cereals
4	Vegetables, fruit, nuts	Veg & Fruit: vegetables, fruitvegetables, fruit and nuts, potatoes, cassava, truffles,
5	Oil seeds	Oil Seeds: oil seeds and oleaginous fruit; soy beans, copra
6	Sugar cane, sugar beet	Cane & Beet: sugar cane and sugar beet
7	Plant-based fibers	Plant Fibres: cotton, flax, hemp, sisal and other raw vegetable materials used in textiles
8	Crops nec	Other Crops: live plants; cut flowers and flower buds; flower seeds and fruit seeds; vegetable seeds, beverage and spice crops, unmanufactured tobacco, cereal straw and husks, unprepared, whether or not chopped, ground, pressed or in the form of pellets; swedes, mangolds, fodder roots, hay, lucerne (alfalfa), clover, sainfoin, forage kale, lupines, vetches and similar forage products, whether or not in the form of pellets, plants and parts of plants used primarily in perfumery, in pharmacy, or for insecticidal, fungicidal or similar purposes, sugar beet seed and seeds of forage plants, other raw vegetable materials
9	Cattle, sheep, goats, horses	Cattle: cattle, sheep, goats, horses, asses, mules, and hinnies; and semen thereof
10	Animal products nec	Other Animal Products: swine, poultry and other live animals; eggs, in shell (fresh or cooked), natural honey, snails (fresh or preserved) except sea snails; frogs' legs, edible products of animal origin n.e.c., hides, skins and furskins, raw, insect waxes and spermaceti, whether or not refined or coloured
11	Raw milk	Raw milk
12	Wool, silk-worm cocoons	Wool: wool, silk, and other raw animal materials used in textile
13	Forestry	Forestry: forestry, logging and related service activities
14	Fishing	Fishing: hunting, trapping and game propagation including related service activities, fishing, fish farms; service activities incidental to fishing
15	Coal	Coal: mining and agglomeration of hard coal, lignite and peat
16	Oil	Oil: extraction of crude petroleum and natural gas (part), service activities incidental to oil and gas extraction excluding surveying (part)
17	Gas	Gas: extraction of crude petroleum and natural gas (part), service activities incidental to oil and gas extraction excluding surveying (part)
18	Minerals nec	Other Mining: mining of metal ores, uranium, gems. other mining and quarrying
19	Meat: cattle, sheep, goats, horses	Cattle Meat: fresh or chilled meat and edible offal of cattle, sheep, goats, horses, asses, mules, and hinnies. raw fats or grease from any animal or bird.
20	Meat products nec	Other Meat: pig meat and offal. preserves and preparations of meat, meat offal or blood, flours, meals and pellets of meat or inedible meat offal; greaves
21	Vegetable oils and fats	Vegetable Oils: crude and refined oils of soya-bean, maize (corn), olive, sesame, ground-nut, olive, sunflower-seed, safflower, cotton-seed, rape, colza and canola, mustard, coconut palm, palm kernel, castor, tung jojoba, babassu and linseed, perhaps partly or wholly hydrogenated, inter-esterified, re-esterified or elaidinised. Also margarine and similar preparations, animal or vegetable waxes, fats and oils and their fractions, cotton linters, oil-cake and other solid residues resulting from the extraction of vegetable fats or oils; flours and meals of oil seeds or oleaginous fruits, except those of mustard; degras and other residues resulting from the treatment of fatty substances or animal or vegetable waxes.
22	Dairy products	Milk: dairy products
23	Processed rice	Processed Rice: rice, semi- or wholly milled
24	Sugar	Sugar
25	Food products nec	Other Food: prepared and preserved fish or vegetables, fruit juices and vegetable juices, prepared and preserved fruit and nuts, all cereal flours, groats, meal and pellets of wheat, cereal groats, meal and pellets n.e.c., other cereal grain products (including corn flakes), other vegetable flours and meals, mixes and doughs for the preparation of bakers' wares, starches and starch products; sugars and sugar syrups n.e.c., preparations used in animal feeding, bakery products, cocoa, chocolate and sugar confectionery, macaroni, noodles, couscous and similar farinaceous products, food products n.e.c.
26	Beverages and tobacco products	Beverages and Tobacco products
27	Textiles	Textiles: textiles and man-made fibres

28	Wearing apparel	Wearing Apparel: Clothing, dressing and dyeing of fur
29	Leather products	Leather: tanning and dressing of leather; luggage, handbags, saddlery, harness and footwear
30	Wood products	Lumber: wood and products of wood and cork, except furniture; articles of straw and plaiting materials
31	Paper products, publishing	Paper & Paper Products: includes publishing, printing and reproduction of recorded media
32	Petroleum, coal products	Petroleum & Coke: coke oven products, refined petroleum products, processing of nuclear fuel
33	Chemical, rubber, plastic prods	Chemical Rubber Products: basic chemicals, other chemical products, rubber and plastics products
34	Mineral products nec	Non-Metallic Minerals: cement, plaster, lime, gravel, concrete
35	Ferrous metals	Iron & Steel: basic production and casting
36	Metals nec	Non-Ferrous Metals: production and casting of copper, aluminium, zinc, lead, gold, and silver
37	Metal products	Fabricated Metal Products: Sheet metal products, but not machinery and equipment
38	Motor vehicles and parts	Motor vehicles and parts: cars, lorries, trailers and semi-trailers
39	Transport equipment nec	Other Transport Equipment: Manufacture of other transport equipment
40	Electronic equipment	Electronic Equipment: office, accounting and computing machinery, radio, television and communication equipment and apparatus
41	Machinery and equipment nec	Other Machinery & Equipment: electrical machinery and apparatus n.e.c., medical, precision and optical instruments, watches and clocks
42	Manufactures nec	Other Manufacturing: includes recycling
43	Electricity	Electricity: production, collection and distribution
44	Gas manufacture, distribution	Gas Distribution: distribution of gaseous fuels through mains; steam and hot water supply
45	Water	Water: collection, purification and distribution
46	Construction	Construction: building houses factories offices and roads
47	Trade	Trade: all retail sales; wholesale trade and commission trade; hotels and restaurants; repairs of motor vehicles and personal and household goods; retail sale of automotive fuel
48	Transport nec	Other Transport: road, rail; pipelines, auxiliary transport activities; travel agencies
49	Sea transport	Water transport
50	Air transport	Air transport
51	Communication	Communications: post and telecommunications
52	Financial services nec	Other Financial Intermediation: includes auxiliary activities but not insurance and pension funding (see next)
53	Insurance	Insurance: includes pension funding, except compulsory social security
54	Business services nec	Other Business Services: real estate, renting and business activities
55	Recreation and other services	Recreation & Other Services: recreational, cultural and sporting activities, other service activities; private households with employed persons (servants)
56	PubAdmin/Defence/Health/Educat	Other Services (Government): public administration and defense; compulsory social security, education, health and social work, sewage and refuse disposal, sanitation and similar activities, activities of membership organizations n.e.c., extra-territorial organizations and bodies
57	Dwellings	Dwellings: ownership of dwellings (imputed rents of houses occupied by owners)

Table 8-5: Technical coefficients derived from GTAP data. Column and row headers correspond to the sectors described in

Table 8-4. Row header "0" corresponds to imports. Values are percentage—e.g., 5 means 5%—and are rounded to the unit. Only the values that exceeds 0.005% are shown. A green color gradient is applied to ease the identification of high coefficients.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57
1	18																						73		15																																
2		1																							1																																
3			4						7	8	5	20										7			17	6																					1										
4				2																					12	2																					2										
5					7																4				7																																
6						17																		22		3																															
7							3																				36	2	1																												
8								1																																																	
9																			37							1																					1										
10																																																									
11																																																									
12																																																									
13													2	4																37	1		1					3	4	2	3	21															
14																																																									
15																																1																									
16																7																																									
17																																																									
18																		1														6	3	5		1										3											1
19																																																									
20																																																									
21																									1																																
22																																																									
23																																																									
24																										1																															
25									1	1	1	2													1	5																					1										
26																									4	8																					1										
27							1							1													1	1																													
28																												1																													
29																													1																												
30																														1									1			2				1											
31																															2			1						1	1	2		1											1		
32																																										1															
33																																	8			1		2	1	1	1	1															
34																																		3				2	1	2	2	1				8											
35																																			14			2	2		2	1				2											
36																																				9		1	1	1	1	1				1											
37																																															1										
38																																						1																			
39																																							1																		
40																																							1	1																	
41																																																									
42																																																									
43						2	4		1	1					17			1					1				1	1	1	1	6		8	1	7	1		2	2	7	4	11			2			1			1	1	1		1	2	
44																																	2	2								1	28														
45																										1			1		1																									2	
46																		1					4	1	3	1	1	2	2	1	2		2	3	3	2		1	2	2	1	1	1	5	2	10	1	1							1	1	34
47	8	49	12	9	10	6	29	10	7	5	2	3	5	6	8			11	10	4	17	9	10	15	6	17	18	28	32	19	18	42	23	17	18	27	8	31	20	30	20	16	3	10	6	5	2	6	2	2	7	5	12	2	12	4	
48	1		1			1	1			1								1				1				1						1		1										1	1	1	1	1			2	1	1		1		
49																																																									
50																																																			1				1		
51																										1		1	1		1	1	1	1	1	1			1	1	1	1	1	2	2	1	4	1		1	7	2	3		3	1	
52																																																				1	1				
53																																																					2				
54																		1						1				1							1	1							2	4	3	2	4	3	2	2	9	10	10	32	9	24	43
55													2		1			1																																							
56																																																									
57																																																									
0	3	9	3	1	2	2	23	8	1	1	1	5	1	22	2	92	96	3	2	1	12	2	1	2	6	9	7	8	6	2	9	5	20	10	19	13	6	15	18	14	14	14	20	3	6	13	4	47	76	77	9	28	23	3	12	5	1

Table 8-6: Export table derived from GTAP data. Column headers correspond to buying countries described in Table 3-5. Row headers corresponds to Tanzanian exporting sectors described in Table 3-2. "Tot." stands for total. Units are millions of USD, rounded to the unit. Only the values that exceeds 0.5 million USD are shown. A green color gradient is applied to ease the identification of high values. A red color gradient is applied to the "total" row and column.

	c_0	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8	c_9	c_{10}	c_{11}	c_{12}	c_{13}	Tot.
1			6						1	2	2	6			19
2									2			1	1		6
3			97			2			11	8	8	18	2	1	147
4			10						4	28	364	62	26	2	497
5		3				2			10	4	232	12	4		267
6															1
7			2						5		100	6	5		118
8			24						13	27	120	135	8	3	329
9									1	6	7	14	2		30
10										5	8	11	1		27
11															2
12															
13									3	21	36	51	6	3	119
14											15	5			22
15															2
16															
17															
18			2			1			8	3	219	226	8		468
19										7	7	16	5		37
20												2			4
21		2	28			2	2		217		12	17	2		283
22								1				2			5
23							10		1	3	3	7			27
24												2			4
25		12	93	2		2	1		46	32	49	124	36	4	401
26		29	7		8	3		4	100	12	33	227	4	4	430
27		2	76	1	5	1	8	21	17	4	10	13	3		162
28									8	24	10	26	3	1	74
29										10	18	6	1		38
30											30	1			33
31			25	2			3	1			2	2			39
32															
33		4	7	8	3	9	6	10	22	2	18	6	2		97
34		3	3	12		7	4	7	29	4	4	12	1		87
35			1	5	1	3	1	7	5	5	9	2			40
36			1						21	28	643	144	867	21	1725
37			2						7	4	3	8	3		30
38			2		2			1	14	3	3	7	1		35
39							3					4	4		14
40			9					1	3	2	2	6	2		26
41			7		6		2	3	19	6	4	8	3		60
42		3							11	11	9	7	2		43
43															
44															
45										4	3	8	1		17
46										4	4	9	2		20
47									7	51	52	124	17	7	257
48									5	48	43	101	11	5	214
49										2	3	5	2		12
50									1	11	9	18	4	1	45
51									1	9	8	30	3		51
52										2	3	5	3		13
53									1	15	8	9	3		37
54									12	49	67	170	19	4	323
55									2	19	19	46	6	3	95
56									6	39	15	35	14	2	111
57															
Tot.		63	406	33	28	36	48	59	620	519	2214	1755	1090	72	

Table 8-7: Import table derived from GTAP data. Column headers correspond to buying Tanzanian sector described in Table 3-5. Row headers corresponds to exporting countries described in Table 3-5. “Tot.” stands for total. Units are millions of USD, rounded to the unit. Only the values that exceeds 0.5 million USD are shown. A green color gradient is applied to ease the identification of high values. A red color gradient is applied to the “total” row and column.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
c_{0}																													
c_{1}																													
c_{2}			2	3				1		2								10	5	7	29	11			22	4	7	4	6
c_{3}			1		16																1								
c_{4}																								3					
c_{5}								10										2											
c_{6}			1					4																		3			
c_{7}			15																		13				2				
c_{8}		42		3														1		6	4			19	38		70	3	5
c_{9}				2				1		2								8			441	8	186	163	53	2	720	509	416
c_{10}		154		3				1		2								3		1	6	11			48	32	27	5	2
c_{11}				5				2						1				11			2	4		55	61	6	8	8	
c_{12}		43																				1					4		
c_{13}				6									9					3			3	5		29	21	19	11	7	3
Tot.		239	20	22	16			21		7			11	2				39	7	16	501	41	187	269	246	68	847	536	431

	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	Tot.
c_{0}																													
c_{1}																													1
c_{2}	3	23	2	277	21	14	16	31	30	33	7	69	7																647
c_{3}	5			1																									27
c_{4}								2			2	5																	16
c_{5}	3																												16
c_{6}	14			6		2			4		4	5																	46
c_{7}				4			14		3			8																	60
c_{8}	1	11	3	33	1	7		22	19	17	33	162	5				9	29	42	3	14	10	16	23	50	44	89		838
c_{9}	40	81	1485	1199	423	430	190	436	543	248	358	1185	361				38	36	65	7	20	8	9	10	52	22	26		9790
c_{10}	2	50	69	448	25	36	33	31	189	34	117	377	33	4		2	59	90	121	7	36	25	24	45	148	57	65		2424
c_{11}	2	25	129	325	73	31	22	26	89	1	64	127	10				4	6	25	3	7	4	5	3	15	5	6		1172
c_{12}				7		2		4			1	13						6	5		4		1	1	3	5	7		116
c_{13}	27	41	3	169	8	100	3	38	60	7	44	118	11				2	2	11		3	2		1	4	4	7		786
Tot.	98	233	1692	2471	552	624	279	591	939	341	631	2069	427	6		4	112	170	270	20	84	50	57	84	272	136	202		

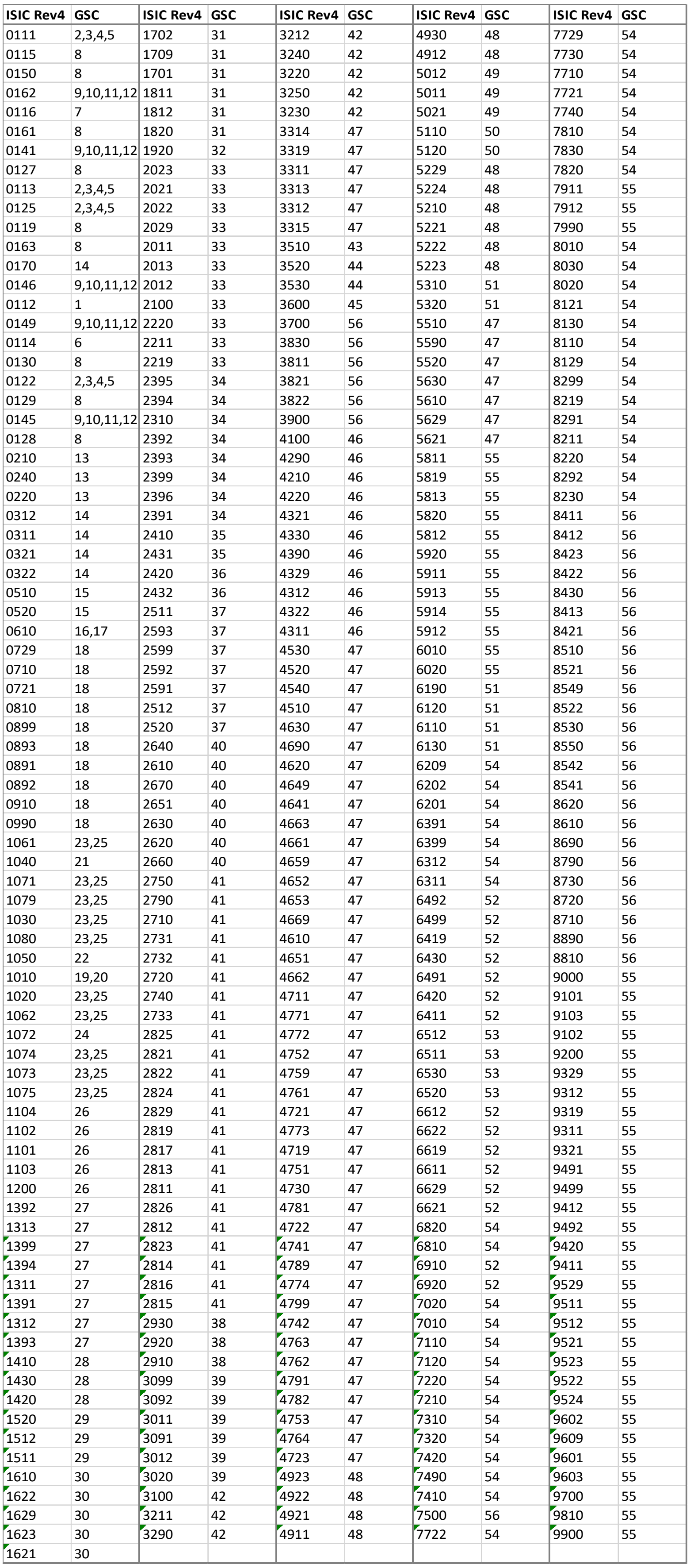
Table 8-8: Transit matrix. Column headers correspond to buying countries while row headers indicate supplying countries, as described in Table 3-5. “Tot.” stands for total. Units are millions of USD, rounded to the unit. Only the values that exceeds 0.5 million USD are shown. A green color gradient is applied to ease the identification of high values. A red color gradient is applied to the “total” row and column.

	c_0	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8	c_9	c_{10}	c_{11}	c_{12}	c_{13}	Tot.
c_0			15						4	34	21	21	3		98
c_1			7						21	167	104	104	13		416
c_2	34	59		72	2	28		54							250
c_3			18			1	1		2	19	12	12	1		66
c_4			2												3
c_5			9						2	14	9	9	1		44
c_6					2										2
c_7	14		29						33	262	164	164	20		685
c_8	23	35				17	17	37							129
c_9	188	277				134	138	294							1029
c_{10}	117	173				84	86	184							643
c_{11}	117	173				84	86	184							643
c_{12}	14	21				10	10	22							77
c_{13}															
Tot.	507	737	79	72	4	357	340	774	62	496	310	310	37		

Table 8-9: Household consumption per sector from GTAP data. Units are millions of USD, rounded to the unit. Only the values that exceeds 0.5 million USD are shown. A green color gradient is applied to ease the identification of high values.

Sector Id	Sector Name	Final Consumption	Sector Id	Sector Name	Final Consumption
1	Paddy rice	501	30	Wood products	9
2	Wheat	112	31	Paper products, publishing	27
3	Cereal grains nec	1568	32	Petroleum, coal products	2
4	Vegetables, fruit, nuts	3134	33	Chemical,rubber,plastic prods	54
5	Oil seeds	892	34	Mineral products nec	135
6	Sugar cane, sugar beet	49	35	Ferrous metals	25
7	Plant-based fibers	0	36	Metals nec	86
8	Crops nec	0	37	Metal products	122
9	Cattle,sheep,goats,horses	1180	38	Motor vehicles and parts	114
10	Animal products nec	776	39	Transport equipment nec	17
11	Raw milk	87	40	Electronic equipment	64
12	Wool, silk-worm cocoons	0	41	Machinery and equipment nec	55
13	Forestry	842	42	Manufactures nec	33
14	Fishing	96	43	Electricity	300
15	Coal	1	44	Gas manufacture, distribution	0
16	Oil	0	45	Water	153
17	Gas	0	46	Construction	147
18	Minerals nec	67	47	Trade	2145
19	Meat: cattle,sheep,goats,horse	1227	48	Transport nec	152
20	Meat products nec	128	49	Sea transport	7
21	Vegetable oils and fats	124	50	Air transport	16
22	Dairy products	144	51	Communication	37
23	Processed rice	644	52	Financial services nec	8
24	Sugar	102	53	Insurance	5
25	Food products nec	3125	54	Business services nec	144
26	Beverages and tobacco products	1342	55	Recreation and other services	265
27	Textiles	118	56	PubAdmin/Defence/Health/Educat	213
28	Wearing apparel	276	57	Dwellings	1443
29	Leather products	57			

Table 8-10: Concordance table between the ISIC Rev. 4 code present in the business registry and the GSC code of the GTAP database, prepared by the authors.



ISIC Rev4	GSC	ISIC Rev4	GSC	ISIC Rev4	GSC	ISIC Rev4	GSC	ISIC Rev4	GSC
0111	2,3,4,5	1702	31	3212	42	4930	48	7729	54
0115	8	1709	31	3240	42	4912	48	7730	54
0150	8	1701	31	3220	42	5012	49	7710	54
0162	9,10,11,12	1811	31	3250	42	5011	49	7721	54
0116	7	1812	31	3230	42	5021	49	7740	54
0161	8	1820	31	3314	47	5110	50	7810	54
0141	9,10,11,12	1920	32	3319	47	5120	50	7830	54
0127	8	2023	33	3311	47	5229	48	7820	54
0113	2,3,4,5	2021	33	3313	47	5224	48	7911	55
0125	2,3,4,5	2022	33	3312	47	5210	48	7912	55
0119	8	2029	33	3315	47	5221	48	7990	55
0163	8	2011	33	3510	43	5222	48	8010	54
0170	14	2013	33	3520	44	5223	48	8030	54
0146	9,10,11,12	2012	33	3530	44	5310	51	8020	54
0112	1	2100	33	3600	45	5320	51	8121	54
0149	9,10,11,12	2220	33	3700	56	5510	47	8130	54
0114	6	2211	33	3830	56	5590	47	8110	54
0130	8	2219	33	3811	56	5520	47	8129	54
0122	2,3,4,5	2395	34	3821	56	5630	47	8299	54
0129	8	2394	34	3822	56	5610	47	8219	54
0145	9,10,11,12	2310	34	3900	56	5629	47	8291	54
0128	8	2392	34	4100	46	5621	47	8211	54
0210	13	2393	34	4290	46	5811	55	8220	54
0240	13	2399	34	4210	46	5819	55	8292	54
0220	13	2396	34	4220	46	5813	55	8230	54
0312	14	2391	34	4321	46	5820	55	8411	56
0311	14	2410	35	4330	46	5812	55	8412	56
0321	14	2431	35	4390	46	5920	55	8423	56
0322	14	2420	36	4329	46	5911	55	8422	56
0510	15	2432	36	4312	46	5913	55	8430	56
0520	15	2511	37	4322	46	5914	55	8413	56
0610	16,17	2593	37	4311	46	5912	55	8421	56
0729	18	2599	37	4530	47	6010	55	8510	56
0710	18	2592	37	4520	47	6020	55	8521	56
0721	18	2591	37	4540	47	6190	51	8549	56
0810	18	2512	37	4510	47	6120	51	8522	56
0899	18	2520	37	4630	47	6110	51	8530	56
0893	18	2640	40	4690	47	6130	51	8550	56
0891	18	2610	40	4620	47	6209	54	8542	56
0892	18	2670	40	4649	47	6202	54	8541	56
0910	18	2651	40	4641	47	6201	54	8620	56
0990	18	2630	40	4663	47	6391	54	8610	56
1061	23,25	2620	40	4661	47	6399	54	8690	56
1040	21	2660	40	4659	47	6312	54	8790	56
1071	23,25	2750	41	4652	47	6311	54	8730	56
1079	23,25	2790	41	4653	47	6492	52	8720	56
1030	23,25	2710	41	4669	47	6499	52	8710	56
1080	23,25	2731	41	4610	47	6419	52	8890	56
1050	22	2732	41	4651	47	6430	52	8810	56
1010	19,20	2720	41	4662	47	6491	52	9000	55
1020	23,25	2740	41	4711	47	6420	52	9101	55
1062	23,25	2733	41	4771	47	6411	52	9103	55
1072	24	2825	41	4772	47	6512	53	9102	55
1074	23,25	2821	41	4752	47	6511	53	9200	55
1073	23,25	2822	41	4759	47	6530	53	9329	55
1075	23,25	2824	41	4761	47	6520	53	9312	55
1104	26	2829	41	4721	47	6612	52	9319	55
1102	26	2819	41	4773	47	6622	52	9311	55
1101	26	2817	41	4719	47	6619	52	9321	55
1103	26	2813	41	4751	47	6611	52	9491	55
1200	26	2811	41	4730	47	6629	52	9499	55
1392	27	2826	41	4781	47	6621	52	9412	55
1313	27	2812	41	4722	47	6820	54	9492	55
1399	27	2823	41	4741	47	6810	54	9420	55
1394	27	2814	41	4789	47	6910	52	9411	55
1311	27	2816	41	4774	47	6920	52	9529	55
1391	27	2815	41	4799	47	7020	54	9511	55
1312	27	2930	38	4742	47	7010	54	9512	55
1393	27	2920	38	4763	47	7110	54	9521	55
1410	28	2910	38	4762	47	7120	54	9523	55
1430	28	3099	39	4791	47	7220	54	9522	55
1420	28	3092	39	4782	47	7210	54	9524	55
1520	29	3011	39	4753	47	7310	54	9602	55
1512	29	3091	39	4764	47	7320	54	9609	55
1511	29	3012	39	4723	47	7420	54	9601	55
1610	30	3020	39	4923	48	7490	54	9603	55
1622	30	3100	42	4922	48	7410	54	9700	55
1629	30	3211	42	4921	48	7500	56	9810	55
1623	30	3290	42	4911	48	7722	54	9900	55
1621	30								

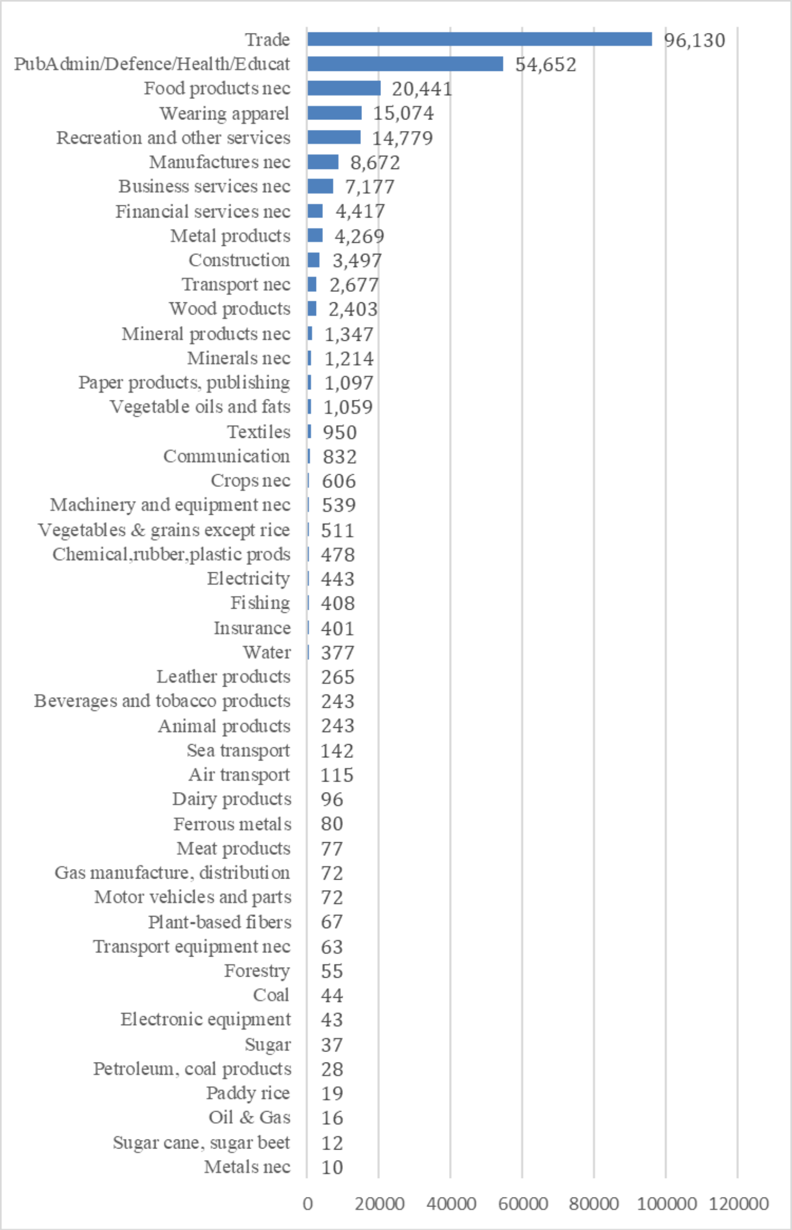


Figure 8-1: Number of firms listed the business registry per GSC sector.