R7 - Internal Report on Risk Assessment & Management Model Development V0.0

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1 Problem Definition

1.1 R7 - Model Development for Risks posed by COVID-19 on U.S. Trade Supply Chain Infrastructure

Important to the mission of the of the Center of Excellence for Cross-Border Threat Screening and Supply Chain Defense (CBTS) is the provision of research and development support to the Department of Homeland Security (DHS), particularly for supply chain defense through early detection of and mitigation of bio-threats that may enter the country, and to assess and manage risks these may cause to society, the economy and the environment. This is the case of COVID-19, a novel coronavirus first detected in China and declared a "pandemic" by the World Health Organization (WHO) in March of 2020. Since its detection, COVID-19 has generated a growing and significant amount of evidence, some of which is of critical relevance for the DHS' Office of Countering Weapons of Mass Destruction (CWMD).

1.2 R13 - U.S. - Mexico Risk Taskforce to Support the Health Supply Chain Systems for Infrastructure and Workforce Threatened by the COVID-19 Pandemic

There are significant concerns in the U.S. and in Mexico to open the regional economies under the current to long-term effects of the COVID-19 pandemic. On April 22 of 2020, the National Association of Manufacturers (NAM) sent a letter signed by 327 CEO's to Mexico's President Andres Manuel Lopez Obrador "asking that his government refer to the guidance issued by the U.S. Department of Homeland Security to determine whether a particular factory be designated as essential and critical". On April 29 of 2020, 11 Senators sent a letter to Secretary of State Pompeo "to urge the State Department to coordinate with the Mexican government to clarify Mexico's definition of essential businesses to avoid disruptions in the U.S. supply chain". These two communications from the U.S. to Mexico are a reflection of recent changes on the nominal GDP growth in both the U.S. and Mexico.

The recent signing of the U.S.-Mexico-Canada trade agreement (USMCA) late in 2018 envisioned a basis to renew trade efforts between the regional economies by strengthening provisions on intellectual property, shipment value (de Minimis), financial services, currency, labor, and the environment. On April 24, 2020 the Trump administration notified Congress that the USMCA would take effect on July 1, 2020. It is worth noticing that no major public health provision was included that could anticipate the social, economic and environmental impacts currently posed by the COVID-19 pandemic. This has revealed significant stress and a number of vulnerabilities across all supply chain systems, threatening with the potential of collapse or a partial breakdown that could lead to an increase of social, economic and environmental risks. It is therefore hypothesized that from all supply chains, the ones that are of critical relevance to mitigate these potential risks are the ones supporting the regional health infrastructure and the health of the workforce.

In addition, since Dr. Medina-Cetina joined TAMU, he has developed a record of successful bi-national research, teaching, and service collaborations between U.S. & Mexico. This includes the Yucatan Initiative Project (`https://yucatan-initiative.tamu.edu/`), a multi-year sponsored project by the Government of Yucatan in Mexico, aimed at creating a set of multidisciplinary research, teaching and service projects, thought to support the regional economies of the States of Texas and Yucatan; and the Network to Network for the Gulf of Mexico project (`http://n2ngom.net/`) sponsored by the National Science Foundation (NSF) and co-sponsored by a group of industrial and government partners, aimed at integrating a binational coordinating organization tasked with the development and sponsorship of the decadal research agenda for the Gulf of Mexico, across more than 250 networks representing all economic sectors.

2 Objectives

- To formulate a comprehensive risk assessment model, identifying qualitatively the relevant variables and processes needed to assess the social, economic and environmental impacts posed by COVID-19 and other converging threats on the U.S. trade supply chain infrastructure, but also on the health of community, health of the workforce, and on the heatlhcare systems.
- To generate risk-mitigating strategies based on the associate risk assessment model, to address causes and effects posed by COVID19 on the vulnerable systems identified.

3 Hypothesis

- A Risk framework will be used to populate a Bayesian network model depicting qualitatively and using simple cause-effect graphical relations, highly complex interactions between processes changing in space and time. The identification of these processes and cause-effect relationships is needed for the assessment of the social, environmental, and economic states of risk posed by COVID-19.
- The formulated model will allow the identification and characterization of strategic evidence, to reveal the true impact of a complex spread of an infectious disease such as the COVID19 pandemic.
- By setting criteria to identify and characterize strategic components of risk assessment and management (threats, vulnerable systems, impacts, states of risk, mitigating actions), sources of evidence will be identified, alongside gaps or missing evidence that needs to be collected to produce a quantitative Risk Assessment.
- The resulting effort will improve the decision-making process for supply chains impacted by COVID-19, and other converging threats.

4 Methodology

4.1 Risk Assessment Framework

The framework is generally defined as:

$$Risk = [Hazard] * [Vulnerability] * [Consequence] \tag{1}$$

where:

- *Hazard* is the likelihood of occurrence of converging *Threats* (e.g., processes describing potential viral entries and transmission to humans, climate patterns exacerbating or reducing its life-cycle, processes describing geopolitical events or government-mandated changes due to the virus).
- *Vulnerability* is the likelihood of reaching an *Impact* in the vulnerable *System*, conditioned on a given *Threat* intensity (e.g. processes describing how trade dependent supply chain systems may react to converging threats associated to the virus, as these apply across land points of entry, air and seaports and across multiple countries).
- *Consequence* represents the value of the elements exposed to converging threats, and its characterized by the social, environmental, or economic *Impacts* on the vulnerable *Systems* (e.g. processes describing population mobility patterns as they may be exposed to the virus, type of port and/or associated personnel most likely to be affected, financial markets and economic sectors affected by the spread of the virus).

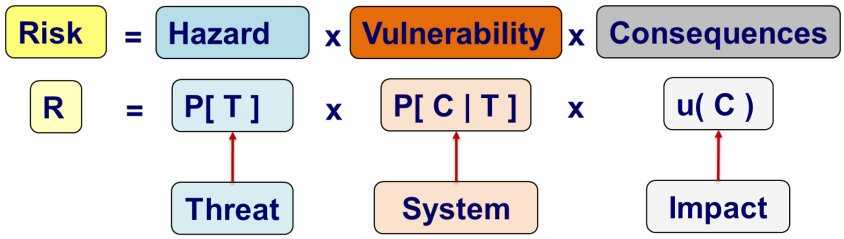

Figure 1: Risk assessment framework

4.2 Risk Assessment & Management Framework

The Risk Assessment Framework is expanded into the following form to represent Risk Assessment & Management:

$$R = [H * V * C] + [Cost(AC + PC) - AC - PC] \tag{2}$$

Where:
AC = Active Countermeasures
PC=Passive Countermeasures

In order to reduce the state of risk, mitigation actions such as active countermeasures (AC) and passive countermeasures (PC) can be applied. An AC has an impact on hazard reduction, and a PC has an impact on the vulnerability and/or consequence reduction. The implementation of either one of these generates costs. Therefore, the trade-off between the savings induced by the hazard or vulnerability and/or consequences reduction, and the costs associated with their implementation is what defines the risk measure.

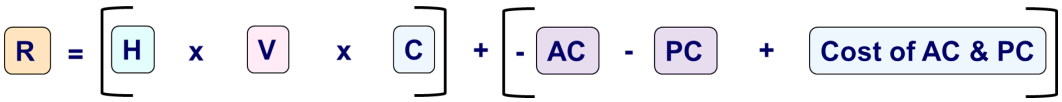

Figure 2: Risk assessment & management framework

4.3 Bayesian Networks

A Bayesian Network (BN) is a graphical representation of the joint probability distribution of a set of random variables, and is a combination of a graphical and a probabilistic model. Nodes and arcs compose a BN, where the nodes represent the random variables in the model, while the arcs illustrate the conditional probability relationships between variables [1]. A node is referred to as a parent node if it has one or more arcs directed to another node, called the child node.

Bayes theorem represents a probabilistic inference between a hypothesis (A) and the evidence (B) to assess the posterior conditional probability $P(A|B)$. This relationship is

interpreted as a causal dependency between 'parent' and 'child' nodes, represented with a Conditional Probability Table (CPT), which transmits the message through the network arcs [2]. When the probability is propagated from parent to child node (i.e. cause to effect) a prognostic analysis is performed. In contrast, a diagnostic analysis happens when the probability is propagated from child to parent nodes (i.e. effect to cause).

Figure 3 shows an example of a BN with three independent parent variables $(V1, V2, V3)$ and one child node $(V4)$, for a total of m=4 nodes, with each variable discretized in $n = 3$ states. Equation 3 describes the message propagation in prognosis $(\pi(Z))$, which produces a list with all the possible combinations of three discrete states of four variables $(m^n = 81)$. The diagnosis message $(\lambda(Z))$ is propagated from the child node to the parent nodes and is computed through Equation 4. In this case, the child node is instantiated with a prescribed distribution in order to infer the marginal probabilities of the parent nodes.

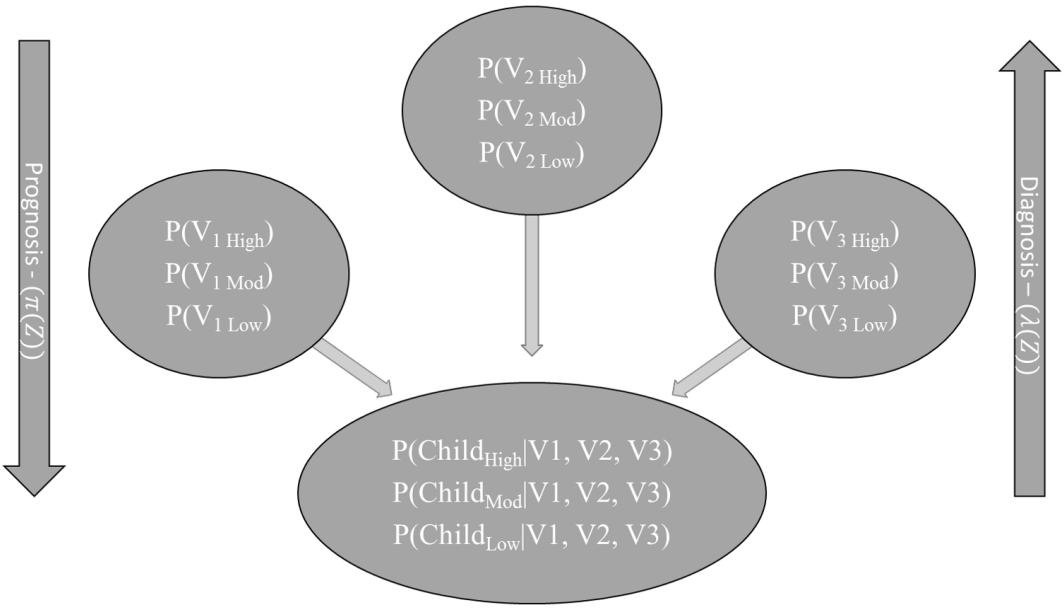

Figure 3: Example of a Bayesian Network

$$P(Child_i) = \sum_{j=1}^{27} \pi(Z_i) = \sum_{j=1}^{27} P(V_{1i}) * P(V_{2i}) * P(V_{3i}) * P(Child_i|V_{1i}, V_{2i}, V_{3i}) \quad (3)$$

$$P(Parent_k) = \sum_{j=1}^{27} \frac{\pi(Z) * \lambda(Z)}{\sum_{l=1}^{81} [\pi(Z) * \lambda(Z)]} \quad (4)$$

V: Parent Node
i:{low, moderate, high}
j:{1, 2, ... , 27} list of combinations where the Child node is low, moderate or high
k:{1,2,3} parent node index
l: {1,2,...,81} list of combinations for three classes of four nodes

4.4 Risk Assessment & Management Framework in Bayesian Networks

To illustrate the definition of Risk, the Figure 4 shows a synthetic case of social Risk Assessment with one *Threat*, one *Vulnerability*, and one *Consequence*.

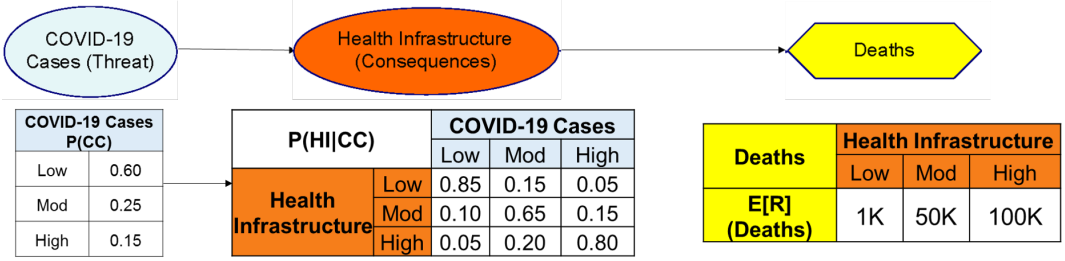

Figure 4: BN Synthetic Case 1

In this case, the hazard is the total number of COVID-19 cases, and $P(CC)$ is the marginal distribution, depicting the probability of the threat intensity to be in one of the three possible states (i.e. low, moderate, high). $P(HI|CC)$ is an assessment of the vulnerability, given the intensity of the threat. In the synthetic case, it represents a reduction in the capacity of health infrastructure, given the number of COVID-19 cases. The utility function $U(C)$ is evaluating the impact of the Consequences (C) as a number of deaths. The implementation of $U(C)$ translates the probability of the node *HI* to a number of deaths through the following expression:

$$U(C) = c_1 P(HI_{High}) * c_2 P(HI_{Mod}) * c_3 P(HI_{Low}) \tag{5}$$

This way, the equation for Risk presented previously:

$$Risk = [Hazard] * [Vulnerability] * [Consequences] \tag{6}$$

becomes:

$$Risk = P(CC) * P(HI|CC) * U(C) \tag{7}$$

Thus, it is illustrated how the Bayesian Network conforms to the definition of Risk, as shown by [3]. In Figure 4, the first table (from left to right) corresponds to the marginal probability distribution for the threat, while the second one is a conditional probability table that shows the probability of the variable *HI* to be in a Low, Mod, or High state, given the state of the variable *CC*.

This framework can be expanded to include multiple *Threats*, multiple *Vulnerabilities*, and multiple *Consequences*, as presented in Figure 5. This synthetic case includes two different threats in COVID-19 cases and Geopolitics, two vulnerable systems in Health Infrastructure and Economy, and two set of consequences: social (deaths), and economic (unemployment). The Bayesian Network shown in Figure 5 can be formulated as the expression of Risk in Equations 6, and 7.

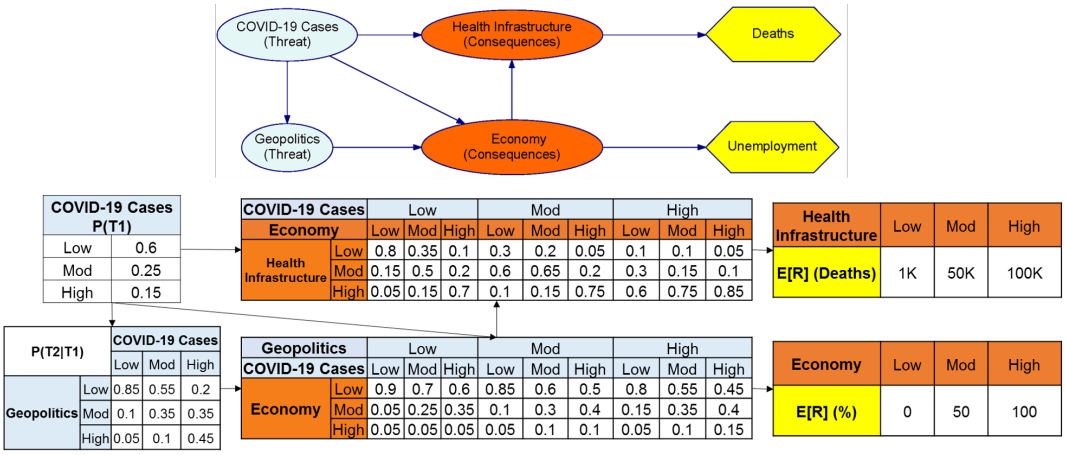

Figure 5: BN Synthetic Case 2

5 Model Development

5.1 Risk Assessment Model

Steps followed for model development:

- Identify Threats, Vulnerable Systems, and Impact Metrics
- Identify variables and processes defining the Threats, Vulnerable Systems, and Impact Metrics
- Identify dependencies between variables/processes within Threats, Vulnerable Systems, and Impact Metrics
- Identify dependencies between Threats, Vulnerable Systems, and Impact Metrics

Figure 6 shows the Risk Assessment Model developed following the previous steps and performing an extensive literature review. Figure 7 presents the minimum conceptual model that corresponds to the smallest group of variables representing all the cause-effect relationships between variables and processes. As such, the minimum conceptual model includes the main groups of variables that represent the threats, the vulnerable systems, and the states of risk. Figures 6, and 7 present the model for one location, this is, where all the entities of the supply chain are located in the same geographic region.

In order to extend the model to multiple geographies, Figure 8 and 9 show the minimum conceptual and complete model for different locations, respectively. High resolution images of the 4 models can be found in the appendix.

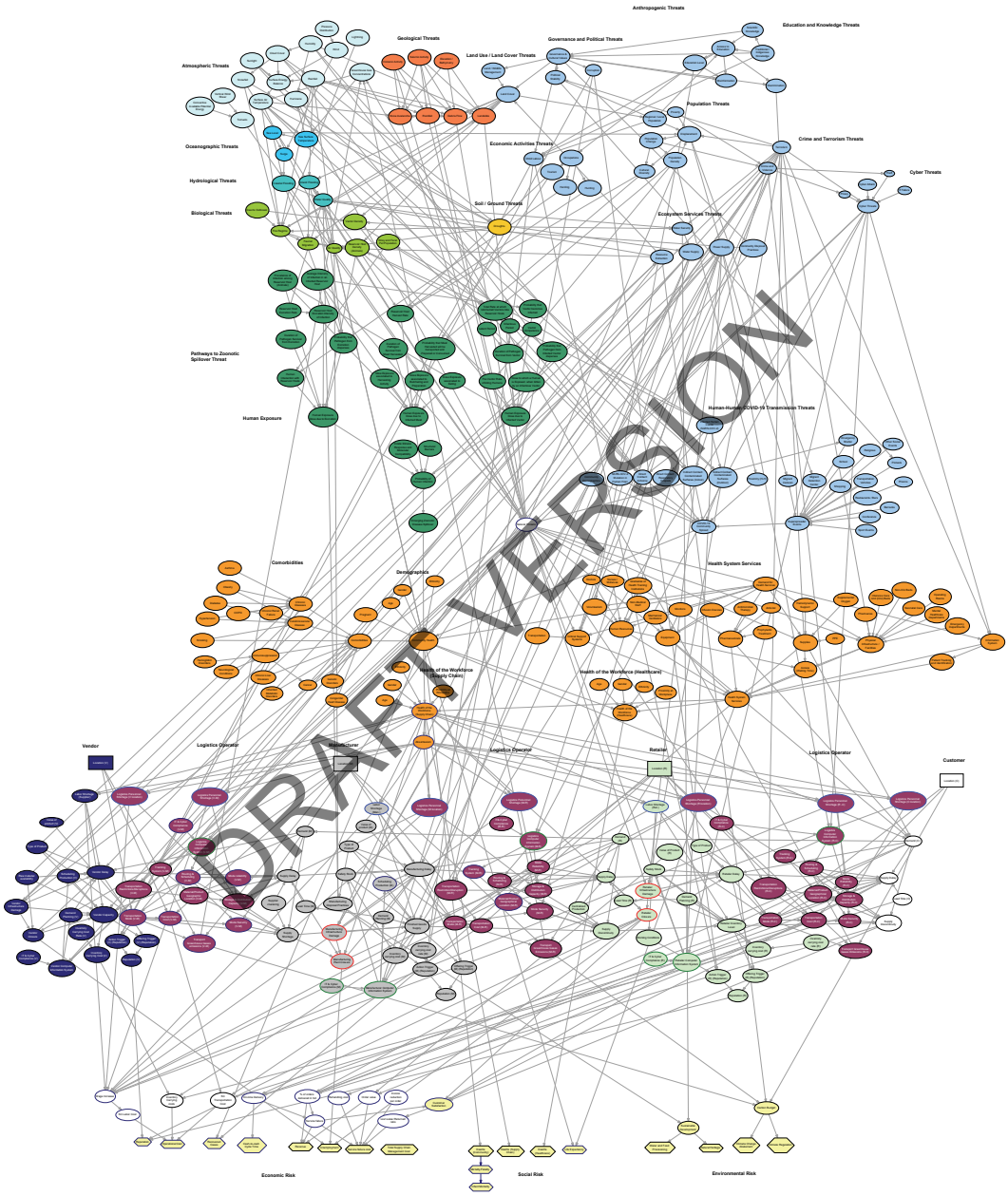

Figure 6: Complete Risk Assessment model - One location, see the appendix A.1 for a higher resolution version

Figure 7: Minimum Conceptual Risk Assessment model - One location, see the appendix A.1 for a higher resolution version

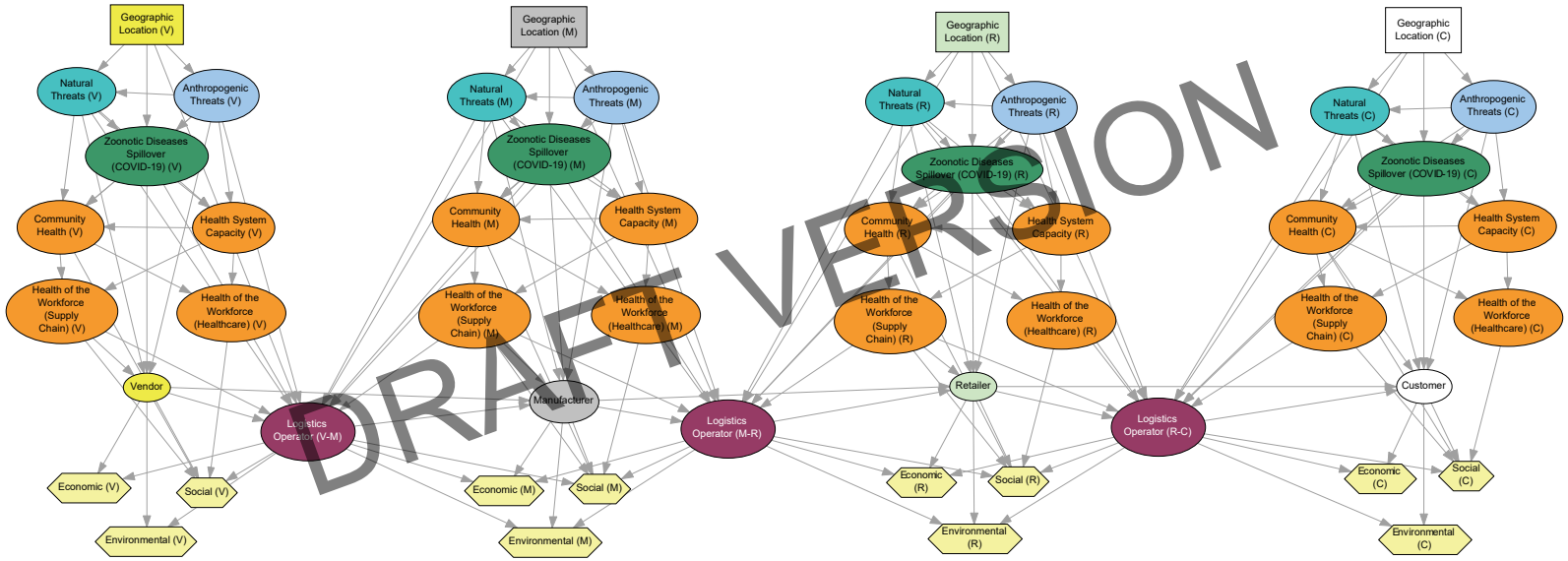

Figure 8: Minimum Conceptual Risk Assessment model - Multiple locations, see the appendix A.1 for a higher resolution version

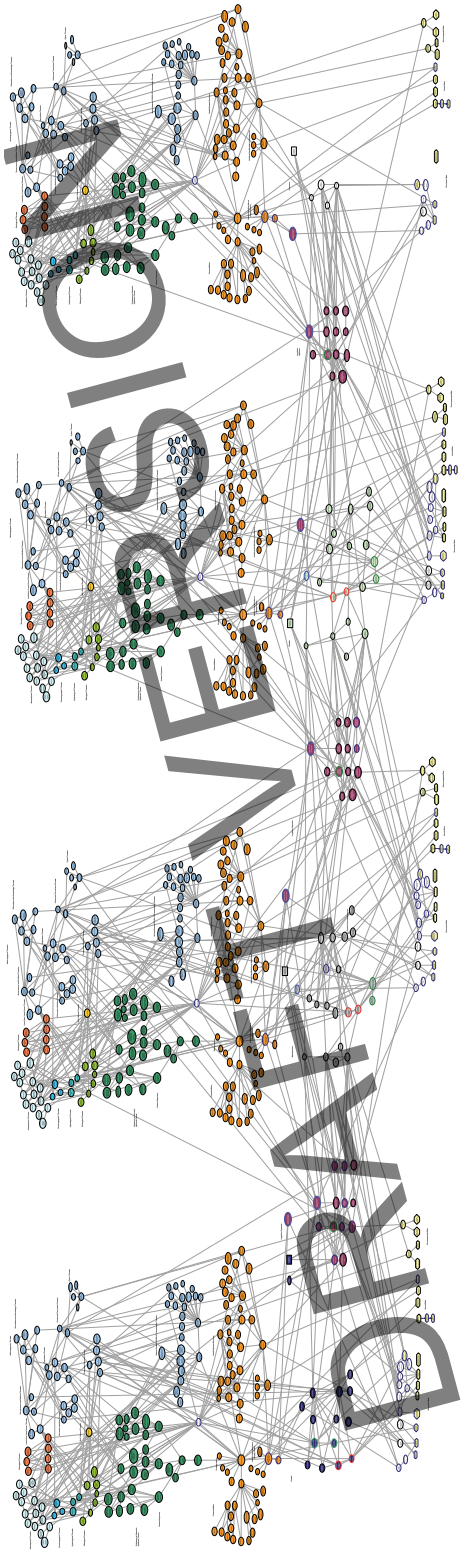

Figure 9: Complete Risk Assessment model - Multiple locations, see the appendix A.1 for a higher resolution version

Section 5.2 describes the structure of the Risk Assessment model by risk components, (Threats, Vulnerable Systems, Impacts, States of Risk), groups, and subgroups with the complete list of variables in each one. Definitions for the variables can be found in section 5.3.

5.2 Threats, Vulnerable Systems, Consequences & States of Risk - Variable grouping

5.2.1 Threats

5.2.1.1 Natural

Table 1: Natural Threats group

Subgroup	Variables	References
Geological	Volcanic Activity Seismic Activity Elevation/Bathymetry Snow Avalanche Rockfall Debris Flow Landslide	[4], [5], [6], [7], [8]
Atmospheric	Pressure Distribution Humidity Wind Lightning Cloud Cover Sunlight Snowfall Surface Air Temperature Surface Energy Balance Rainfall Greenhouse Gas Concentrations Hurricane Vertical Wind Shear Convective Available Potential Energy Tornado	[4], [9], [10], [11], [12]
Oceanographic	Sea Level Sea Surface Temperature Surge	[4], [13], [14]

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Table 1 Natural Threats group (continued)

Subgroup	Variables	References
Hydrological	Coastal Flooding Inland Flooding Water Quality	[4], [15], [16], [17]
Biological	Insect Outbreak Vector Density Stray and Feral Pet Population Reservoir Host Density (Animals) Air Quality Fauna Migration Fire Regime	[4], [18], [19], [20]
Soil/Ground	Drought	[4], [21]

5.2.1.2 Anthropogenic

Table 2: Anthropogenic Threats group

Subgroup	Variables	References
Land use/ Land cover	Land Cover Land/Wildlife Management	[4], [22]
Governance and politics	Governance & Cultural Values Political Stability Corruption	[4], [23], [24], [25], [26], [27], [28]
Economic Activities	Child Labour Tourism Herding Hunting Occupations	[4], [29], [30], [31]
Population	Poverty Regional/Local Population Population Change Population Density Displacement Cultural Diversity	[4], [32]

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Table 2 Anthropogenic Threats group (continued)

Subgroup	Variables	References
Education & Knowledge	Scientific Knowledge Traditional Indigenous Knowledge Access to Education Education Level Misinformation Discrimination	[4], [33], [34]
Crime & Terrorism	Terrorism Crime & Violence	[25], [26], [35], [36], [37], [38], [39]
Cyber Threats	Piracy Cyber Attack Theft IT Failure	[25], [26], [35], [36], [40], [41], [42], [43].
Ecosystem Services	Water Security Water Supply Power Supply Resource Extraction Community Disposal Practices	[4], [44], [45], [46]

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Table 2 Anthropogenic Threats group (continued)

Subgroup	Variables	References
Human-Human COVID-19 Transmission	Infected Human Cases (SARS-CoV-2) COVID-19 Community Spread Superspreader Events Community Demographics SARS-CoV-2 Mutation in Human Host Direct Contact: Airborne Direct Contact: Respiratory Droplets Indirect Contact: Contaminated Surfaces (Indoor) Indirect Contact: Contaminated Surfaces (Outdoor) Proximity (H-H) Migrant Caravan Migrant Detention Center Emergency Shelter School Religious Other Social Events Shopping Protests Transportation Vehicles Prison Restaurants/Bars Barracks Conference Sport Events	[47], [48], [49], [50], [51], [52], [53], [54], [55], [56]

5.2.1.3 Zoonotic Diseases Spillover

Table 3: Zoonotic Diseases Spillover Threats group

Subgroup	Variables	References
Human Infection	Emerging Zoonotic Disease Spillover Probability of Human Infection Structural Barriers Innate Immune Response & Molecular Compatibility	[19]
Human exposure due to excretion	Human Exposure dose due to Excretion Human Interaction with Reservoir Host Probability that Pathogen from Excretion Disperses Duration of Pathogen Survival from Excretion Reservoir Host Excretion Rate Reservoir Excretion Intensity of Infection Prevalence of Infection Among Reservoir Host (Animals) Average Intensity of Infection on an Infected Reservoir Host	[19], [57], [58], [59], [60], [61]
Human exposure due to infected meat	Human Exposure Dose due to Infected Meat Dose Exposure Associated to Harvesting Activity Dose Exposure Associated to Butchering and Preparation Dose Exposure Associated to Eating Duration of Pathogen Survival from Meat Harvested Probability that the Meat Harvested will be Transported and Prepared or Consumed Reservoir Host Harvest Rate	[19], [57], [58], [59], [60], [61], [62], [63]
Human exposure due to infected vector	Human Exposure Dose due to Infected Vector Per-vector Rate of Biting Humans Dose to which a Human is Exposed when Bitten by Infectious Vector Duration of Pathogen Survival from Vector Probability that Pathogen from Infected Vector Disperses Latent Period Infectious Period Vector Competence Total Rate at which Uninfected Vectors Bite Reservoir Host Probability that Vector becomes Infected	[19], [57], [58], [59], [60], [61]

5.2.2 Vulnerable Systems

5.2.2.1 Community Health

Table 4: Community Health group

Subgroup	Variables	References
Comorbidities	Chronic Diseases Cerebrovascular Diseases Immunosuppression Cancer Chronic Liver Diseases Congenital Heart Disease Genetic Disorders Inherited Metabolic Disorders Smoking Chronic Renal Failure COPD Asthma Obesity Diabetes Hypertension Hemoglobin Disorders Neurological Conditions	[64]
Demographics	Ethnicity Gender Age Pregnant	[64]
Health of the Workforce (Supply Chain)	Ethnicity Gender Age Proximity at Workplace Absenteeism	[65]
Health of the workforce (Healthcare)	Ethnicity Gender Age Proximity at Workplace	[65]

5.2.2.2 Health System Services

Table 5: Health System Services group

Subgroup	Variables	References
Critical support systems	Transportation Demand for Health Services	[66], [67], [68], [69], [70], [71], [72], [73]
Human resources	Doctors Nurses/Midwives Graduates of Health Training Institutions Non-medical Staff Volunteerism Access (Waiting Time) Demand for Health Services	[66], [67], [68], [69], [70], [71], [73]
Equipment	Infusion Devices Mechanical Ventilators Monitors Demand for Health Services	[66], [67], [68], [69], [70], [71], [72]
Pharmaceuticals	Antimicrobial Therapy Antiviral Prophylactic Treatment Demand for Health Services	[66], [67], [68], [69], [70], [71]
Supplies	Hemodynamic Support PPE Supplemental Oxygen Demand for Health Services	[66], [67], [68], [69], [70], [71]
Physical infrastructure/facilities	Emergency Departments Intensity Care Unit (ICU) Beds Mental Healthcare Departments Neonatal Care Non-ICU Beds Operating Rooms Pharmacies Access (Waiting Time) Demand for Health Services	[66], [67], [68], [69], [70], [71], [72], [73]
Information System	Patient Tracking & Identification	

5.2.2.3 Supply Chain

Table 6: Supply Chain group

Subgroup	Variables	References
Vendor/Supplier	Geographical Location (V) Labor Shortage (Supplier) Value of Product (V) Type of Product Raw material availability Vendor Infrastructure Damage Vendor Closure IT & Cyber Compliance (V) Vendor Computer Information System Scheduling Production (V) Demand Planning (V) Inventory Carrying Cost Rate (V) Inventory Carrying Cost (V) Vendor Delay Vendor Capacity Action Trigger (V) (Reputation) Offering Trigger (V) (Reputation) Reputation (V)	[23], [24], [74], [75], [76], [77], [78], [79], [80], [81], [82], [83], [84], [85], [86]

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Table 6 Supply Chain group (continued)

Subgroup	Variables	References
Manufacturer	Geographic Location (M) Demand (M) Supply Delay Supplier Clustering Supply Shortage Lead Time Labor Shortage (M) Value of Product (M) Type of Product (M) Safety Stock Manufacturing Disposal Practices Manufacturing Infrastructure Damage Manufacturing Plant Closure IT & Cyber Compliance (M) Manufacturer Computer Information System Scheduling Production (M) Demand Planning Inventory Carrying Cost (M) Inventory Carrying Cost Rate (M) Action Trigger (M) (Reputation) Offering Trigger (M) (Reputation) Reputation (M) Manufacturing Delay Finished Goods Supply	[40], [41], [85], [86], [87], [88], [89], [90], [91], [92], [93], [94].

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Table 6 Supply Chain group (continued)

Subgroup	Variables	References
Retailer	Geographic Location (R) Labor Shortage (R) Demand (R) Supply Delay Centralized Production Supply Discontinuity Lead Time (R) Type of Product (R) Value of Product (R) Safety Stock Retailer Infrastructure Damage Retailer Closure Working Conditions IT & Cyber Compliance (R) Retailer Computer Information System Demand Planning Inventory Carrying Cost Rate Inventory Carrying Cost Retailer Delay Action Trigger (R) (Reputation) Offering Trigger (R) (Reputation) Reputation Retailer Inventory Level	[36], [85], [86], [91], [94], [95], [96], [97], [98], [99].
Customer	Geographic Location Demand (C) Lead Time (C) Supply Delay Supply Discontinuity	[77], [85], [89], [91], [93], [100], [101].

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Table 6 Supply Chain group (continued)

Subgroup	Variables	References
Logistics Operator	Logistics Personnel Shortage Transportation Restrictions/Disruptions Transportation Mode IT & Cyber Compliance Logistics Computer Information System Tracking System Transportation Cost Routing and Scheduling Material/Product Geographical Location Transport Greenhouse Gases Emissions Mode Reliability Storage & Distribution Capacity Mode Security	[25], [85], [86], [92], [102], [103], [104], [105], [106].

5.2.3 Impacts

5.2.3.1 Environmental

Table 7: Environmental Consequences

Subgroup	Variables	References
Climate-related metrics	Carbon Budget	[107]
Sustainable Development Goals	Sustainable Development	[108].

5.2.3.2 Economic

Table 8: Economic Consequences

Subgroup	Variables	References
Supply Chain Performance Metrics	Wage Increase SC Labor Cost Inventory Carrying Cost SC Transportation Cost On-time Delivery Invoice Reduction per order Lost Sales/Returned Ratio Order Value Rehandling Cost Service Failure Customer Satisfaction % of Orders delivered in full	[23], [24], [35], [41], [76], [85], [94], [96], [103], [109], [24], [35], [36], [41], [96], [98], [102], [103]

5.2.4 States of Risk

5.2.4.1 Social

Table 9: Social States of Risk

Subgroup	Variables	References
Death-related indexes	Deaths (Community) Deaths (Supply Chain) Deaths (Healthcare) Mortality/Fatality Infant mortality	[4], [110], [111], [112]
Health indexes	Recovered cases Life expectancy	[4], [110], [113]

5.2.4.2 Environmental

Table 10: Environmental States of Risk

Subgroup	Variables	References
Climate-related metrics	Climate change abatement Climate regulation	[4], [25], [41], [103]
Sustainable Development Goals	Water and food provisioning Natural heritage	[4], [114], [115]

5.2.4.3 Economic

Table 11: Economic States of Risk

Subgroup	Variables	References
Supply Chain Performance Metrics	Operational Cost Cash-to-cash Cycle Time Service Failure Cost Total Supply Chain Management Cost	[23], [24], [35], [41], [76], [85], [94], [96], [103], [109].
Business metrics	Unemployment Revenue Reputation	[24], [35], [36], [41], [96], [98], [102], [103]

5.3 Variable Definitions for Risk Assessment Model

5.3.1 Threats

5.3.1.1 Natural

Geological

Volcanic Activity: the likelihood of volcanic activity events such as emission of gases, non-explosive lava emissions to extremely violent explosive bursts [116].

Seismic Activity: measures earthquake likelihood, mechanisms, and magnitude for a given geographical location [117].

Elevation/Bathymetry: Elevation is the distance above sea level for a given location. Bathymetry is the ocean's depth below sea level for a given location [118].

Snow Avalanche: the likelihood of rapid flow of snow mass and ice on slopes, which can contain soils, rocks, and vegetation [119]. Snow avalanches are classified according to their destructive potential, mass, path length, and impact pressure [120].

Rockfall: the likelihood of a mass of rock from a bedrock on a steep slope is detached with a small or no shear displacement [121]. Rockfalls are characterized by slope height, geologic character, volume, climate, presence of water on slope, and rockfall history [122].

Debris Flow: the likelihood of a gravity-driven movement of sediments containing water as a mixture that flows fast or extremely fast [123]. Debris flow size can be classified based on total volume, peak discharge, and area inundated by debris [124].

Earth slide: the likelihood of a downslope movement of a soil mass that occurs on a surface of rupture or on a relatively thin zone of intense shear strain. [125]. Slides are characterized by material, mechanism, mass, and velocity among other parameters [126, 127].

Atmospheric

Pressure Distribution: distribution of atmospheric pressure that varies in terms of geographical location and season.

Humidity: amount of water vapor contained in the air that can be measured as vapor pressure, mixing ratio, or specific humidity [128].

Wind: it refers to wind velocity. Wind speeds can be classified by using the Beaufort Wind Scale [129].

Lightning: only cloud to ground lightning discharge is considered in this variable. The intensity of the discharge can be characterized by electric current, current duration, and voltage [130].

Cloud Cover: "total area of the sky nearest to the earth that is covered with clouds" [131]. Cloud cover can be measured in terms of "Okta" or one-eighth of the sky [131].

Sunlight: amount of sunlight reaching Earth's surface that is measured in units of watts per square meter [132].

Snowfall: accumulation of snow that is often measured by visibility, and by measuring liquid equivalent snowfall rate [133].

Surface Air Temperature: temperature measured at a standard height of 1.5 or 2 meters above the surface [134].

Surface Energy Balance: "sum of all fluxes of energy passing each second through a horizontal surface of unit area" [135]. Measured in Joules per second per square meter, or watts per square meter.

Rainfall: the intensity of rainfall is characterized by the average rainfall for a specific duration and frequency [136].

Greenhouse Gas Concentration: includes carbon dioxide, methane, nitrous oxide, and halogenated gases (chlorine, fluorine, or bromine). Concentrations of these gases are measured in parts per million (ppm), parts per billion (ppb), or parts per trillion (ppt) by volume [137].

Hurricane: "a rotating low-pressure weather system that has organized thunderstorms but no fronts (a boundary separating two air masses of different densities)" [138]. Hurricanes are classified based on their wind speed as suggested in the Saffir-Simpson Hurricane Wind Scale [139].

Vertical Wind Shear: change of winds' direction and velocity at increasing heights in the atmosphere [140].

Convective Available Potential Energy: "it describes the instabilily of the atmosphere and provides an approximation of updraft strength within a thunderstorm" [141]. CAPE is expressed in joules per kilogram and can range from zero to over 5000.

Tornado: "a violently rotating column of air touching the ground, usually attached to the base of a thunderstorm" [142]. Tornadoes are classified as "weak", "strong", or "violent" based on their estimated wind speeds and resultant damage according to the National Weather Service [142].

Oceanographic

Sea Level: refers to "Relative Sea Level", which is the height of the ocean with respect to land along a coastline for a given region or location [143].

Sea Surface Temperature: water temperature measurements taken at depths that range from 1 millimeter to 20 meters [144].

Surge: also known as "storm surge", which is the result of increased sea level due to a tropical or extratropical cyclone impacting a coast. Storm surge height depends on storm's forward speed, central pressure, angle of approach (relative to the coast), and the local topography and bathymetry [145].

Hydrological

Coastal Flooding: inundation of land areas along a coast as a consequence of sea level rise [146].

Inland Flooding: inundation of land as a consequence of moderate or intense rainfall over short or long periods respectively. [146].

Water Quality: "measure of the suitability of water for a particular use based on selected physical, chemical, and biological characteristics" [147].

Biological

Insect Outbreak: the likelihood of "an explosive increase in the abundance of a particular specie of insects that occurs over a relatively short period of time" [148].

Vector Density: degree of concentration of vector population per area at a given time [19].

Stray and Feral Pet Population: domestic and non-domestic dogs and cats population for a specific location or region at a given time [52].

Reservoir Host Density (Animals): degree of concentration of infected animals from a pathogen per area at a given time [19].

Air Quality: the degree at which ambient air for a given location and time is pollution-free. The U.S. Environmental Protection Agency issued a national air quality index since 1976 that provides a daily air quality report by state [149].

Fauna Migration: the likelihood of movement of individual or group of animals as a consequence of a natural or anthropogenic threat [4].

Fire Regime: "the spatial and temporal pattern of fires and their effects in a given area and over a given time period" [150].

Soil/Ground

Drought: drought indices are employed to quantify meteorological, agricultural and hydrological droughts such as Rainfall Anomaly Index (RAI), Palmer Drought Severity Index (PDSI), Standardized Precipitation Index (SPI), Reconnaissance Drought Index (RDI), Standardized Precipitation Evapotranspiration Index (SPEI), Crop Moisture Index (CMI), Soil Moisture Drought Index (SMDI), and Standardized Runoff Index (SRI) [151].

5.3.1.2 Anthropogenic

Land use/Land cover

Land Cover: it measures how much area of a region is covered by forests, wetlands, impervious surfaces, agriculture, and other land and water types [152].

Land/Wildlife Management: this variable represents the availability of governmental programs to preserve and improve habitats for a given location and time [152].

Governance and politics

Governance and Cultural Values: it represents the likelihood of how governance and cultural values can influence other anthropogenic processes such as corruption and political stability [4].

Political Stability: probability that a political system can cope a threat or a combination of threats in a given location and time [153].

Corruption: the likelihood of presence of corruption in a supply chain system [28].

Economic Activities

Child Labour: the likelihood of presence of child labour practices in a supply chain system [29].

Tourism: the likelihood of how tourism has an effect on the eating habits of a given region. Exotic eating habits can enable the emerge of parasites in food [52].

Herding: the likelihood of herding practices in a given time and location [52].

Hunting: the likelihood of hunting practices in a given time and location [52].

Occupations: the likelihood of diversity in terms of jobs and economic occupations for a given region. [52].

Population

Poverty: it is defined by a set of money income thresholds that vary by country, family size, and composition to determine the degree of poverty [154, 155].

Regional/Local Population: the degree of overpopulation for a given location and time [32].

Population Change: the degree of difference in size of population between two periods of time (e.g. monthly, yearly, etc.) [32].

Population Density: human population per unit area for a given location and time. [32].

Cultural Diversity: the likelihood of how cultural diversity has an effect on the eating habits of a given region. Exotic eating habits can enable the emerge of parasites in food [52].

Education & Knowledge

Scientific Knowledge: this variable aims to represent the degree of production of knowledge for a specific country or region at a given time. This can be measured by using qualitative and quantitative indexes such as the h-index, g-index, impact factor, etc. [156].

Traditional Indigenous Knowledge: "a network of knowledges, beliefs, and traditions intended to preserve, communicate, and contextualize Indigenous relationships with culture and landscape over time" [157].

Access to Education: the degree at which a population have access to formal education at a given location and time. This might be measured using proxies such as number of school institutions, teachers, students, etc. [158].

Education Level: this variable measures the distribution of the highest levels of education achieved in a community. The International Standard Classification of Education (ISCED)

suggest 8 levels of education based on the complexity of educational content [159].

Misinformation: the degree of "information that is false or inaccurate, and not supported by scientific evidence" [33] that is produced in a given region and time.

Discrimination: the degree of racial discrimination activities or events for a given location and time [34].

Crime & Terrorism

Terrorism: the likelihood of terrorism activities defined as "the use of force or violence against persons or property in violation of the criminal laws of the United States for purposes of intimidation, coercion, or ransom" [37].

Crime & Violence: this variable can be characterized by country or regional level indicators such as rates of violent crime, incarceration, homicide, etc. [38].

Cyber Threats

Piracy: the likelihood of misuse of data outside the principal purpose of releasing data by the owner [42].

Cyber Attack: likelihood of an attack to IT infrastructure with the intention of corrupting or damaging data/information [43].

Information Theft: the likelihood of loss of control over sensitive information [42].

IT Failure: likelihood of a failure in the normal operation of IT networks, leading to unavailability of critical services [42].

Ecosystem Services

Water Security: the degree of how reliable is the access to "affordable and safe drinking water in adequate supply for basic needs" [44].

Water Supply: the degree of how reliable is the access to affordable and clean water to satisfy the needs of both health-care system and supply chain system [44].

Power Supply: it refers to the degree of supply of electric power for both health-care and supply chain systems [73].

Resource Extraction: refers to activities involved in the withdrawal of raw materials from the environment, for further processing to add value. Extraction practices my or may not be sustainable, given their impact on the natural environment [45, 46]

Community Disposal Practices: it captures if garbage disposal practices are enforced or not in a community [52].

Human-Human COVID-19 Transmission

Infected Human Cases (SARS-CoV-2: number of infected human cases by SARS-CoV-2 for a given location and time [55].

COVID-19 Community Spread: the degree and likelihood of COVID-19 spread in a community for a given time [55].

Superspreader Events: refers to events where a large number of secondary cases relative to the standard reproductive rate, R_0, are initiated, thus acting as a catalyst for outbreaks. They can be classified as 'societal' or isolated' [160].

The following variables of the model are included as parent nodes for *Superspreader Events*. In the context of the model, they refer to the likelihood of a given event, situation, or activities in a mentioned location, to become a *superspreader event* [160]:

- *Migrant Caravan*
- *Migrant Detention Center*
- *Emergency Shelter*
- *School*
- *Religious*
- *Other Social Events*
- *Shopping*
- *Protests*
- *Transportation Vehicles*
- *Prison*

- *Restaurants/Bars*
- *Barracks*
- *Conference*
- *Sport Events*

Community Demographics: involves demographic characteristics such as income inequality, unemployment, health insurance, gender, and race. These characteristics are related to the rates of COVID-19 spread [161].

SARS-CoV-2 Mutation in Human Host: the likelihood of a new SARS-CoV-2 mutation in human hosts, and its infectivity intensity [162].

Direct Contact: Airborne: the likelihood of having a direct contact with SARS-CoV-2 via airborne for a given location and time [54].

Direct Contact: Respiratory Droplets: the likelihood of having a direct contact with SARS-CoV-2 via respiratory droplets for a given location and time [54].

Indirect Contact: Contaminated Surfaces (Indoor): the likelihood of having an indirect contact with SARS-CoV-2 via contaminated surfaces in an indoor location at a given time [53].

Indirect Contact: Contaminated Surfaces (Outdoor): the likelihood of having an indirect contact with SARS-CoV-2 via contaminated surfaces in an outdoor location at a given time [53].

Proximity (H-H): the likelihood and intensity of concentration of people for a given location and time. Mobility data from mobile devices, social media, and commercial air travel are useful to characterize this variable, and its effect on COVID-9 spread in a community [163].

5.3.1.3 Zoonotic Diseases Spillover

Human Infection

Emerging Zoonotic Disease Spillover: likelihood and intensity of a zoonotic disease spillover in a community at a given time [19].

Probability of Human Infection: probability of a human to be infected from a zoonotic disease [19].

Structural Barriers: physical barriers such as "skin, mucous membranes, mucus, stomach acid or the absence of functional receptors that enable the pathogen to enter its target cells or tissues" [19].

Innate Immune Response & Molecular Compatibility: protective mechanisms that include apoptosis or the induction of interferon-induced resistance in surrounding cells [19].

Human exposure due to excretion

Human Exposure dose due to Excretion: the likelihood and intensity of the exposure dose due to animal excretion for a given location and time [19].

Human Interaction with Reservoir Host: the likelihood of a human of being in contact with a pathogen reservoir host at a given location and time [52].

Probability that Pathogen from Excretion Disperses: the likelihood that excretions from infected animals disperse at a given location and time [19].

Duration of Pathogen Survival from Excretion: it measures how much time the pathogen from excretion survives [19].

Reservoir Host Excretion Rate: "rate at which pathogen is shed from a reservoir host" at a given location and time. [19].

Reservoir Excretion Intensity of Infection: the average intensity of infection from a reservoir host excretion [19].

Prevalence of Infection Among Reservoir Host (Animals): the likelihood of prevalence of infection among reservoir hosts at a given location and time [19].

Average Intensity of Infection on an Infected Reservoir Host: in average, the pathogen intensity of infection on infected animals at a given location and time [19].

Human exposure due to infected meat

Human Exposure Dose due to Infected Meat: the likelihood and intensity of the exposure dose due to infected meat for a given location and time [19].

Dose Exposure Associated to Harvesting Activity: the dose related to humans that are exposed to a pathogen infection due to harvesting of infected animals [19].

Dose Exposure Associated to Butchering and Preparation: the dose related to humans that are exposed to a pathogen infection due to butchering and preparation of infected meat [19].

Dose Exposure Associated to Eating: the dose related to humans that are exposed to a pathogen infection due to eating infected meat [19].

Duration of Pathogen Survival from Meat Harvested: it measures how much time the pathogen from infected meat survives [19].

Probability that the Meat Harvested will be Transported and Prepared or Consumed: the likelihood of infected meat will be transported, prepared or consumed at a given location and time [19].

Reservoir Host Harvest Rate: "rate at which reservoir hosts are harvested" at a given location and time [19].

Human exposure due to infected vector

Human Exposure Dose due to Infected Vector: the likelihood and intensity of the exposure dose due to infected vector for a given location and time [19].

Per-vector Rate of Biting Humans: total rate at which infected vectors bite humans at a given location and time [19].

Dose to which a Human is Exposed when Bitten by Infectious Vector: the dose related to humans that are exposed to a pathogen infection when bitten by infectious vector [19].

Duration of Pathogen Survival from Vector: it measures how much time the pathogen from an infected vector survives [19].

Probability that Pathogen from Infected Vector Disperses: the likelihood of pathogen dispersion from infected vectors at a given location and time [19].

Latent Period: "the period of time between the occurrence of infection and the onset of infectiousness (when the infected individual becomes infectious)" [164].

Infectious Period: the time interval during which a host is capable to transmit a pathogen directly or indirectly to another susceptible host [165].

Vector Competence: probability that an infected vector transmits a pathogen to humans [166].

Total Rate at which Uninfected Vectors Bite Reservoir Host: rate at which uninfected vectors bite reservoir hosts at a given location and time [19].

Probability that Vector becomes Infected: the likelihood of a vector to become infected by biting an infected animal [19].

5.3.2 Vulnerable Systems

5.3.2.1 Community Health

Comorbidities

Chronic Diseases: group of "conditions that last 1 year or more and require ongoing medical attention or limit activities of daily living or both" [167]. The model includes the following conditions: asthma, chronic renal failure, COPD, diabetes, hypertension, and obesity. The Chronic Diseases variable represents the likelihood and distribution of chronic conditions for a given population and time.

Cerebrovascular Diseases: "group of conditions that affect blood flow and the blood vessels in the brain" [168]. The model includes the following conditions: diabetes, hypertension, obesity, and smoking. The Cerebrovascular Diseases variable represents the likelihood and distribution of cerebrovascular conditions for a given population and time.

Immunosuppression: "decreased capacity to neutralize external organisms, which may result in repeated, more severe, or prolonged infections, as well as an increased susceptibility to cancer development" [169]. This variable represents the likelihood and distribution of immunosuppression conditions for a given population and time.

Cancer: the likelihood and distribution of cancer disease for a given population and time [170].

Chronic Liver Diseases: "gradual destruction of liver tissue over time" such as cirrhosis and Fibrosis of the liver diseases [171]. This variable represents the likelihood and distribu-

tion of chronic liver diseases for a given population and time.

Congenital Heart Disease: the likelihood and distribution of congenital heart defects for a given population and time [170].

Genetic Disorders: "disease caused in whole or in part by a change in the DNA sequence away from the normal sequence" [172].This variable represents the likelihood and distribution of genetic disorders for a given population and time.

Inherited Metabolic Disorders: the likelihood and distribution of inherited metabolic disorders for a given population and time [170].

Smoking: the likelihood and distribution of current or former cigarette smokers for a given population and time [170].

Chronic Renal Failure: the likelihood and distribution of chronic renal failure diseases for a given population and time [170].

COPD: the likelihood and distribution of chronic obstructive pulmonary diseases (COPD) for a given population and time. It includes emphysema and chronic bronchitis. [170].

Asthma: the likelihood and distribution of asthmatic people for a given population and time [170].

Obesity: the likelihood and distribution of obese people for a given population and time [170].

Diabetes: the likelihood and distribution of diabetic people for a given population and time [170].

Hypertension: the likelihood and distribution of hypertension cases for a given population and time [170].

Hemoglobin Disorders: the likelihood and distribution of hemoglobin disorders for a given population and time. It includes sickle cell disease (SCD) and thalassemia. [170].

Neurological Conditions: the likelihood and distribution of neurological conditions such as dementia for a given population and time. [170].

Demographics

Ethnicity: the likelihood and distribution of race for a given population and time. [64].

Gender: the likelihood and distribution of sex for a given population and time. [64].

Age: the likelihood and distribution of age for a given population and time. [64].

Pregnant: the likelihood and distribution of pregnant people for a given population and time. [170].

Health of the Workforce (Supply Chain):

Ethnicity: the likelihood and distribution of workforce's race from a supply chain system for a given population and time. [64].

Gender: the likelihood and distribution of workforce's sex from a supply chain system for a given population and time. [64].

Age: the likelihood and distribution of workforce's age from a supply chain system for a given population and time. [64].

Proximity at Workplace: the likelihood and intensity of concentration of people for a given supply chain workplace and time. Mobility data from mobile devices and social media are useful to characterize this variable, and its effect on COVID-9 spread at the workplace [163].

Absenteeism: the likelihood and intensity of number of absent workers due to health related issues [65].

Health of the workforce (Healthcare):

Ethnicity: the likelihood and distribution of workforce's race from a healthcare system for a given population and time. [64].

Gender: the likelihood and distribution of workforce's sex from a healthcare system for a given population and time. [64].

Age: the likelihood and distribution of workforce's age from a healthcare system for a given population and time. [64].

Proximity at Workplace: the likelihood and intensity of concentration of people for a given healthcare workplace and time. Mobility data from mobile devices and social media are useful to characterize this variable, and its effect on COVID-9 spread at the workplace [163].

5.3.2.2 Health System Services

Critical support systems

Transportation: the availability of emergency medical transportation such as ambulances in a given location and time [73].

Demand for Health Services: the likelihood and intensity of demand for critical support systems to provide healthcare services [72].

Human resources

Doctors: the availability of medical doctors to provide healthcare services in a given location and time [72].

Nurses/Midwives: the availability of nurses and midwives to provide healthcare services in a given location and time [71].

Graduates of Health Training Institutions: the availability of graduates from health training institutions to provide healthcare services in a given location and time.

Non-medical Staff: the availability of non-medical staff such as pharmacists, social workers, general staff, etc. for a given location and time [72].

Volunteerism: the availability of medical volunteers to provide healthcare services for a given location and time [72]

Access (Waiting Time): the degree and likelihood of time to wait for accessing to health-care services provided by medical staff in a healthcare facility or system in a given location and time [173].

Demand for Health Services: the likelihood and intensity of demand for human resources to provide healthcare services [72].

Equipment

Infusion Devices: the availability of infusion devices to provide healthcare services in a healthcare facility or system in a given location and time [72].

Mechanical Ventilators: the availability of mechanical ventilators to provide healthcare services in a healthcare facility or system in a given location and time [72].

Monitors: the availability of monitors to provide healthcare services in a healthcare facility or system in a given location and time [72].

Demand for Health Services: the likelihood and intensity of demand for medical equipment to provide healthcare services [72].

Pharmaceuticals

Antimicrobial Therapy: the availability of antimicrobial therapy to provide healthcare services in a healthcare facility or system in a given location and time [72].

Antiviral: the availability of antiviral to provide healthcare services in a healthcare facility or system in a given location and time [65].

Prophylactic Treatment: the availability of prophylactic treatment to provide healthcare services in a healthcare facility or system in a given location and time [72].

Demand for Health Services: the likelihood and intensity of demand for pharmaceuticals to provide healthcare services [72].

Supplies

Hemodynamic Support: the availability of hemodynamic support to provide healthcare services in a healthcare facility or system in a given location and time [72].

PPE: the availability of proper personal protective equipment (PPE) for healthcare workers in a healthcare facility or system in a given location and time [72].

Supplemental Oxygen: the availability of supplemental oxygen to provide healthcare services in a healthcare facility or system in a given location and time [72].

Demand for Health Services: the likelihood and intensity of demand for medical supplies to provide healthcare services [72].

Physical infrastructure/facilities

Emergency Departments: the availability of emergency department facilities to provide healthcare services in a healthcare system at a given location and time [73].

Intensity Care Unit (ICU) Beds: the availability of ICU beds to provide healthcare services in a healthcare facility or system at a given location and time [73].

Mental Healthcare Departments: the availability of mental healthcare department facilities to provide healthcare services in a healthcare system at a given location and time [73].

Neonatal Care: the availability of neonatal care facilities to provide healthcare services in a healthcare system at a given location and time [73].

Non-ICU Beds: the availability of non-ICU beds to provide healthcare services in a healthcare facility or system at a given location and time [73].

Operating Rooms: the availability of operating room facilities to provide healthcare services in a healthcare system at a given location and time [73].

Pharmacies: the availability of pharmacy facilities to provide pharmaceuticals and medical supplies in a healthcare system at a given location and time [73].

Access (Waiting Time): the degree and likelihood of time to wait for accessing to healthcare facilities in a healthcare system at a given location and time [173].

Demand for Health Services: the likelihood and intensity of demand for physical infrastructure and facilities to provide healthcare services [72].

Information System

Patient Tracking & Identification: the availability of a patient level tracking and identification system to record, track, and identify all patients [71].

5.3.2.3 Supply Chain

Vendor/Supplier

Geographical Location (V): place where a particular point or object exists. It is often given in terms of latitude and longitude [78]. In this case refers to the place where the facilities of the Vendor/Supplier are located.

Labor Shortage (Supplier): likelihood of a disequilibrium in the market between supply and demand, where the quantity of workers demanded exceeds the supply available and willing to work at a particular wage and working conditions at a particular place and time. It is measured as the difference between the demanded and the available workers for a given set of conditions. [79]. This variable measures the *labor shortage* in the Vendor/Supplier.

Value of Product (V): worth in monetary terms of the technical, economic, service, and social benefits a customer company receives in exchange for the price it pays for a product. Typically measured in monetary terms per unit [74].

Type of Product: set of characteristics of offered goods and/or services. Products can be classified according to offering, purchase frequency, and features [80]. This variable refers to the type of product offered by the Vendor/Supplier.

Raw material availability: availability of prime materials from which a product is made. It is expressed as the ratio of available units of materials with respect to the required units. [25]. Shortage of raw materials is driven by institutional or structural inefficiency or by a physical limitation or constraint, among others. Its consequences can be of technological, geographical or operational in nature [81].

Vendor Infrastructure Damage: the likelihood of direct physical damage or loss of functionality of the physical systems or networks that provide circulation of people, goods, services and information in the supply chain. Measured as the degree of loss of functionality of the infrastructure [82]

Vendor Closure: the likelihood of closure of system or networks of facilities of entities in the supply chain, in this case for the Vendor/Supplier [83].

IT & Cyber Compliance (V): set of security and safety standards aimed to assess, prevent, and mitigate IT & Cyber Risks [36]. This variable refers to the application of said standards in the operation of the Vendor/Supplier.

Vendor Computer Information System: availability of the system comprised by hardware and software applications that supports the integration and coordination of Supply Chains for effective Supply Chain Management in activities such as inventory management, production control, and order tracking among others [84].

Scheduling Production (V): process of defining the independent demand items an organization must produce and when they are needed, providing a detailed arrangement of the time and quantities that have to be produced or provided for various products.[41]. This variables captures the existence and degree of implementation of the scheduling process for the Vendor/Supplier.

Demand Planning: the process of "identifying, aggregating, and prioritizing, all sources of demand for the integrated supply chain of a product or service at the appropriate level, horizon and interval" [85].

Inventory Carrying Cost (V): measure of the costs incurred to hold inventory as a result of the cost of opportunity cost, shrinkage costs, insurance and taxes, obsolescence, theft, use of storage facilities and other causes. [85, 86].

Inventory Carrying Cost Rate (V): ratio of inventory carrying cost and total cost of inventory, measured typically as a percentage [86].

Vendor Delay: the likelihood of a 4late or postponed shipping of goods from the Vendor/Supplier to the Manufacturer, measured in time units. [93]

Vendor Capacity: measured limit or ability of physical facilities, personnel and process of an entity in the Supply Chain to meet the customer's needs for goods or services. It includes the ability to produce, store, transport or transform materials or services [91], [85]

Reputation (V): set of perceptions of stakeholders or individuals about what an organization represents and the way the firm manages its assets [36].

Action Trigger (V) (Reputation): reputation trigger, or component, related with the company's actions, including quality of management, treatment of employees, working conditions, resource utilization, long term investment, corporate social responsibility, and firm's culture [36].

Offering Trigger (V) (Reputation): reputation trigger, or component, related with the products and services offered, availability of products and services, branding, inventiveness,

consumer experience, and image of brand users [36].

Manufacturer

Geographic Location (M): see *Geographic Location (V)* . In this case refers to the place where the facilities of the Manufacturer are located.

Demand (M): the known quantity that will be purchased for a specific product or service based on open production orders from the Manufacturer to the Vendor/Supplier [85], [91].

Supply Delay: likelihood of late or postponed delivery of goods/services from the Vendor/Supplier to the Manufacturer, measured in time units. [93]

Supplier Clustering: "geographically proximate group of interconnected companies and associated institutions in a particular field, linked by commonalities and complementaries" [90]

Supply Shortage: likelihood of a scenario where the quantity demanded by the Manufacturer is greater than the quantity supplied by the Vendor/Supplier, according to its capacity [93].

Lead Time: time interval between the placement of an order by the Manufacturer, and its delivery from the Vendor/Supplier [91], [86].

Labor Shortage (M): see *Labor Shortage (Supplier)*. This variable applies for a labor shortage on the Manufacturer.

Value of Product (M): see *Value of Product (V)*. This variables applies for the *Value of Product* of the Manufacturer.

Type of Product (M): see *Type of Product (V)*. This variable refers to the *Type of Product* offered by the Manufacturer.

Safety Stock (M): extra stock that is held as a contingency against future variability of supply and/or demand, such as demand rising or suppliers being unable to deliver goods [94].

Manufacturing Disposal Practices: activities and actions oriented to waste management including collection, transport, treatment and disposal of waste; control, monitoring and regulation of production. It also includes the prevention of waste production through reuse

and recycling [92].

Manufacturing Infrastructure Damage: see *Vendor Infrastructure Damage*. This variable applies for the physical damage on the infrastructure of the Manufacturer.

Manufacturing Plant Closure: see *Vendor Closure*. Applies for the Manufacturer.

IT & Cyber Compliance (M): see *IT & Cyber Compliance*. This variable refers to the application of the standards in the operation of the Manufacturer.

Manufacturer Computer Information System: see *Vendor Computer Information System*. Applies for the Computer Information System that supports the Manufacturer's Operations.

Scheduling Production (M): see *Scheduling Production (V)*. This variable captures the existence and degree of implementation of the scheduling process for the Manufacturer.

Demand Planning (M): see *Demand Planning* in previous section. This variable applies for the Manufacturer's *demand planning*.

Inventory Carrying Cost (M): see *Inventory Carrying Cost (V)*. This variable refers to the *Inventory Carrying Cost* of the Manufacturer.

Inventory Carrying Cost Rate (M): see *Inventory Carrying Cost Rate (V)*. This variable refers to the *Inventory Carrying Cost Rate* of the Manufacturer.

Reputation (M): see *Reputation (V)*. This variable refers to the *Reputation* of the Manufacturer.

Action Trigger (M) (Reputation): see *Action Trigger (V) (Reputation* . This variable refers to the *Action Trigger* reputation component of the Manufacturer.

Offering Trigger (M) (Reputation): see *Offering Trigger (V) (Reputation*. This variable refers to the *Offering Trigger* reputation component of the Manufacturer.

Manufacturing Delay: analogous to *Vendor Delay*. The likelihood of late or postponed shipping of finished goods from the Manufacturer to the Retailer, measured in time units [93].

Finished Goods Supply: inventory of items that have been through the manufacturing process, can be sold as a completed items or as repair parts, and are ready for distribution. [85, 94].

Retailer

Geographic Location (R): see *Geographic Location (V)* . In this case refers to the place where the facilities of the Retailer are located.

Labor Shortage (R): see *Labor Shortage (M)*. This variable applies for a *Labor Shortage* for the Retailer.

Demand (R): the known quantity that will be purchased for a specific product or service based on open production orders from the Retailer to the Manufacturer [85], [91].

Supply Delay: the likelihood of late or postponed delivery of goods/services from the Manufacturer to the Retailer, measured in time units. [93]

Centralized Production: the likelihood of concentration within a particular location and/or group of manufacturing activities and companies that supply finished goods to the Retailer [91].

Supply Discontinuity: analogous to *Supply Shortage*. The likelihood of a scenario where the quantity demanded by the Retailer is greater than the quantity supplied by the Manufacturer, according to its capacity [93].

Lead Time (R): time interval between the placement of an order by the Retailer, and its delivery from the Manufacturer [91], [86].

Type of Product (R): see *Type of Product (V)*. This variable refers to the type of product offered by the Retailer.

Value of Product (R): see *Value of Product (V)*. This variables applies for the Value of Products of the Retailer.

Safety Stock (R): see *Safety Stock (M)*. This variable applies for the Retailer's *Safety Stock*.

Retailer Infrastructure Damage: see *Vendor Infrastructure Damage*. This variable applies for the physical damage in the infrastructure of the Retailer.

Retailer Closure: see *Vendor Closure*. Applies for the Retailer's facilities.

Working Conditions: "refers to the working environment and aspects of an employee's terms and conditions of employment. This covers such matters as: the organisation of work and work activities; training, skills and employability; health, safety and well-being; and working time and work-life balance" [99].

IT & Cyber Compliance (R): see *IT & Cyber Compliance*. This variable refers to the application of the standards in the operation of the Retailer.

Retailer Computer Information System: see *Vendor Computer Information System*. Applies for the *Computer Information System* that supports the Retailer's Operations.

Demand Planning: see *Demand Planning (M)* in previous section. This variable applies for the Retailer's *Demand Planning*.

Inventory Carrying Cost: see *Inventory Carrying Cost (V)*. This variable refers to the *Inventory Carrying Cost* of the Retailer.

Inventory Carrying Cost Rate (R): see *Inventory Carrying Cost Rate (V)*. This variable refers to the *Inventory Carrying Cost Rate* of the Retailer.

Reputation: see *Reputation (V)*. This variable refers to the *Reputation* of the Retailer.

Action Trigger (R) (Reputation): see *Action Trigger (V) (Reputation)*. This variable refers to the *Action Trigger* reputation component of the Retailer.

Offering Trigger (R) (Reputation): see *Offering Trigger (V) (Reputation*. This variable refers to the *Offering Trigger* reputation component of the Retailer.

Retailer Delay: analogous to *Vendor Delay*. Late or postponed shipping of goods from the Retailer to the Customer, measured in time units. [93]

Retailer Inventory Level: stock of goods or products in a facility which are intended to be sold in a specific period [94], [85].

Customer

Geographic Location (C): see *Geographic Location (V)* . In this case refers to the place where the Customer, or the Customer's facilities are located.

Demand (C): the known quantity that will be purchased for a specific product or service based on open production orders from the Customer to the Retailer [85], [91].

Lead Time (C): time interval between the placement of an order by the Customer, and its delivery from the Retailer [91], [86].

Supply Delay: the likelihood of a late or postponed delivery of goods/services from the Retailer to the Customer, measured in time units. [93]

Supply Discontinuity: analogous to *Supply Shortage*. The likelihood of a scenario where the quantity demanded by the Customer is greater than the quantity supplied by the Retailer, according to its capacity [93].

Logistics Operator

Logistics Personnel Shortage: see *Labor Shortage (M)*. This variable applies for a labor shortage on the Logistics Operator.

Transportation Restrictions/Disruptions: the likelihood that set of constraints of varying nature, such as regulatory, economic, or environmental reduce the transportation capacity of the Logistics Operator. [106].

Transportation Mode: method of transportation used to move goods from one point to another [86], [85].

IT & Cyber Compliance: see *IT & Cyber Compliance*. This variable refers to the application of the standards in the operation of the Logistics Operator.

Logistics Computer Information System: see *Vendor Computer Information System*. Applies for the Computer Information System that supports the Logistics operations.

Tracking System: set of technologies used to monitor and record the location of shipments as they move throughout the supply chain [85]. This variable refers to the application of tracking technologies by the Logistics Operator.

Transportation Cost: total expenditures for the movement of freight from one point to another [41].

Routing and Scheduling: process of determining how shipments will move across the supply chain, including detailed information about carriers involved, routes, and estimated time enroute [85].

Material/Product Geographical Location: see *Geographical Location (V)* This variables refer to the place where the materials or products are located while being transported.

Transport Greenhouse Gases Emissions: emission of gases contributing to the greenhouse effect, such as carbon dioxide, nitrous oxide, methane, ozone, and chloro-fluorocarbons, resulting from transportation activities [92].

Mode Reliability: refers to the consistency of a transportation mode to meet customer requirements in terms of pickup and delivery times of goods or materials [41].

Storage & Distribution Capacity: measured limit or ability of physical facilities, personnel and process of a Logistics Operator for an effective flow and storage of goods or services, meeting the customer's requirements [91], [85].

Mode Security: the likelihood for a shipment to be the target of piracy or theft, in relation with the transportation mode [41].

5.3.3 Consequences

5.3.3.1 Environmental

Climate-related metrics

Carbon Budget: the magnitude and likelihood of greenhouse gas emissions from a supply chain system at a given location and time [107].

Sustainable Development Goals

Sustainable Development: the degree and likelihood of achieving sustainable goals including water security and waste control in a given location and time [108].

5.3.3.2 Economic

Supply Chain performance metrics

Wage Increase: likelihood of wage increase as a consequence of labor shortage in the entities of the Supply Chain [24].

SC Labor Cost: expenses originated from salaries attributed to the usage of direct labor in the entities of the Supply Chain [86].

Inventory Carrying Cost: see *Inventory Carrying Cost (V)*. This variable refers to the total *Inventory Carrying Cost* in the Supply Chain.

SC Transportation Cost: see *Transportation Cost*. This variable refers to the total *Transportation Cost* in the Supply Chain.

On-time delivery: the likelihood that a scheduled shipment is delivered on the expected date, or within an allowable tolerance [86].

Invoice reduction per order: deduction in an invoice, requested by a customer, to get a compensation for inconveniences or added costs after a service failure [41].

Lost sales/returned ratio: ratio of the customers experiencing service failure that request the orders to be corrected to the customers that refuse the orders [41].

Order Value: total revenue by orders delivered in full [41].

Rehandling Cost: costs associated with correcting orders, such as reshipping correct items and returning incorrect and refused items, after a service failure [41].

Service Failure: likelihood of an entity of the supply chain of failing to fulfill customer's orders in a satisfactorily manner [41].

Customer Satisfaction: measure of satisfaction of customers with the quality of the goods and services offered, and delivered [85].

% or Orders delivered in full: percentage of orders that are received by the customer in the quantities committed with respect to the total number of orders [86].

5.3.4 States of Risk

5.3.4.1 Social

Death-related indexes

Deaths (Community): total number of deaths at the community level conditioned by *Community Health*.

Deaths (Deaths (Supply Chain): total number of deaths in the Supply Chain Workforce conditioned by the *Health of the Workforce (Supply Chain)* variable.

Deaths (Healthcare): total number of deaths in the Healthcare Workforce conditioned by the *Health of the Workforce (Healthcare)* variable.

Mortality/Fatality: ratio of total number of deaths to total population in a time interval. It is a measure of the frequency of occurrence of death in a defined population [112]

Infant Mortality: ratio of number of deaths among children under 1 year of age to the total number of births reported during a specified time interval [112].

Health indexes

Recovered Cases: total number of SARS-CoV-19 recovered cases at the community level.

Life Expectancy: refers to the average number of years a person may expect to live [111].

5.3.4.2 Environmental

Climate-related metrics

Climate Change Abatement: the degree of reduction of greenhouse gas emissions from supply chain systems at a given location and time [107].

Climate Regulation: the degree of ecosystem services to store greenhouse gas emissions due to supply chain systems activities [174].

Sustainable Development Goals

Water and Food Provisioning: the degree of securing provision of food and water to a population at a given location and time [114].

Natural Heritage: the degree of conservation of habitats of threatened animal and plant species, and sites with natural value such as research significance or natural beauty [115].

5.3.4.3 Economic

Supply Chain Performance Metrics

Operational Cost: daily expenses originated by the execution of a company's activities, including salaries, transportation and warehousing, and inventory carrying costs. [41], [94].

Cash-to-cash Cycle Time: average elapsed time between payment to a vendor for materials or services and the receipt of payment from a customer for shipments [86].

Service Failure Cost: cost associated with the inability of an entity of the supply chain to correctly fulfill customer's orders. These costs originate from lost sales of refused orders, invoice deduction of rectified orders, and rehandling costs associated with correcting the orders. [41].

Total Supply Chain Management Cost: in the context of the model, this variable represents the total implementation cost of active and passive countermeasures that mitigate the vulnerability of the entities in the Supply Chain System. In Supply Chain Management literature, *Total Supply Chain Management Cost* refers to the total costs to "manage order processing, acquire materials,manage inventory, and manage supply-chain finance, planning, and IT costs, as represented as a percent of revenue" [85].

Business metrics

Unemployment: refers to the percentage of workers in the labor force who do not have currently a job [96].

Revenue: amount of income originated from sales made to customers that comes into a business [94, 85].

Reputation: see *Reputation (V)*. This variable represents the economic state of Risk derived from the Reputation of the entities in the Supply Chain.

5.4 Risk Assessment & Management Model

The Risk Assessment model is expanded to the Risk Assessment & Management model through the inclusion of mitigating strategies. In order to do this, the following steps were followed:

- Identify strategies oriented to reduce the threat intensity (Active countermeasures)
- Identify strategies oriented to reduce the vulnerability of the systems (Passive countermeasures)
- Identify strategies oriented to reduce the overall impacts (Passive countermeasures)

The same 4 models described in 5.1 are presented from Figure 10 to 13, including complete and minimum conceptual models for one, and different locations. High resolution versions of the model can be found in the appendix.

Section 5.5 lists the variables of mitigating strategies, grouping them by Active, or Passive countermeasures. Definitions for the variables can be found in section 5.6.

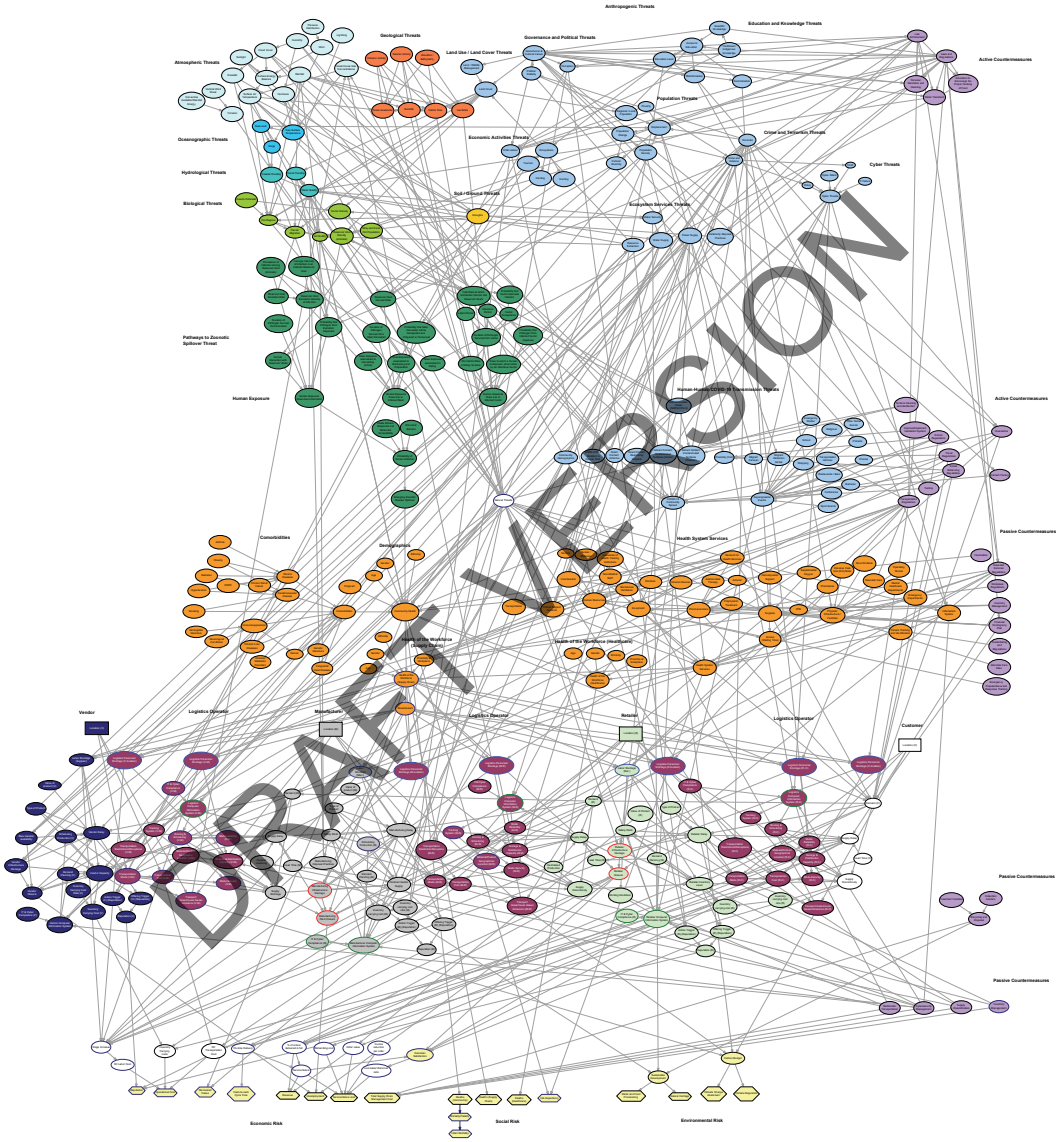

Figure 10: Complete Risk Assessment & Management model - One location, see the appendix A.2 for a higher resolution version

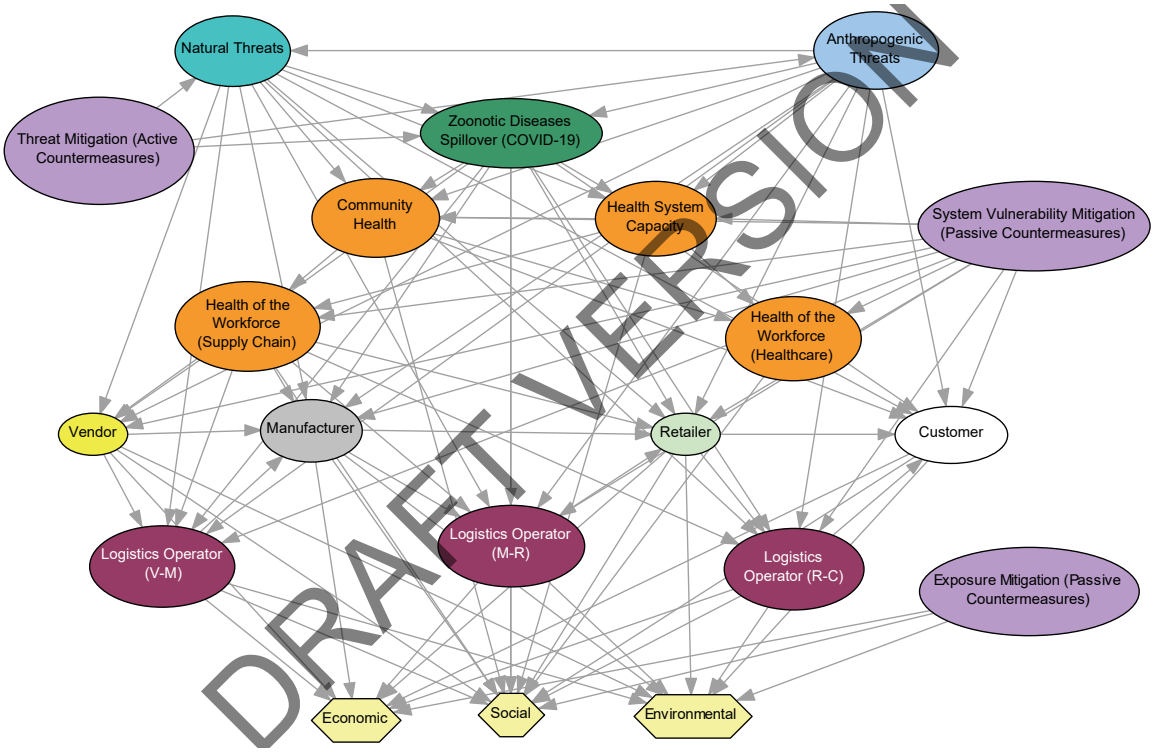

Figure 11: Minimum Conceptual Risk Assessment & Management model - One location, see the appendix A.2 for a higher resolution version

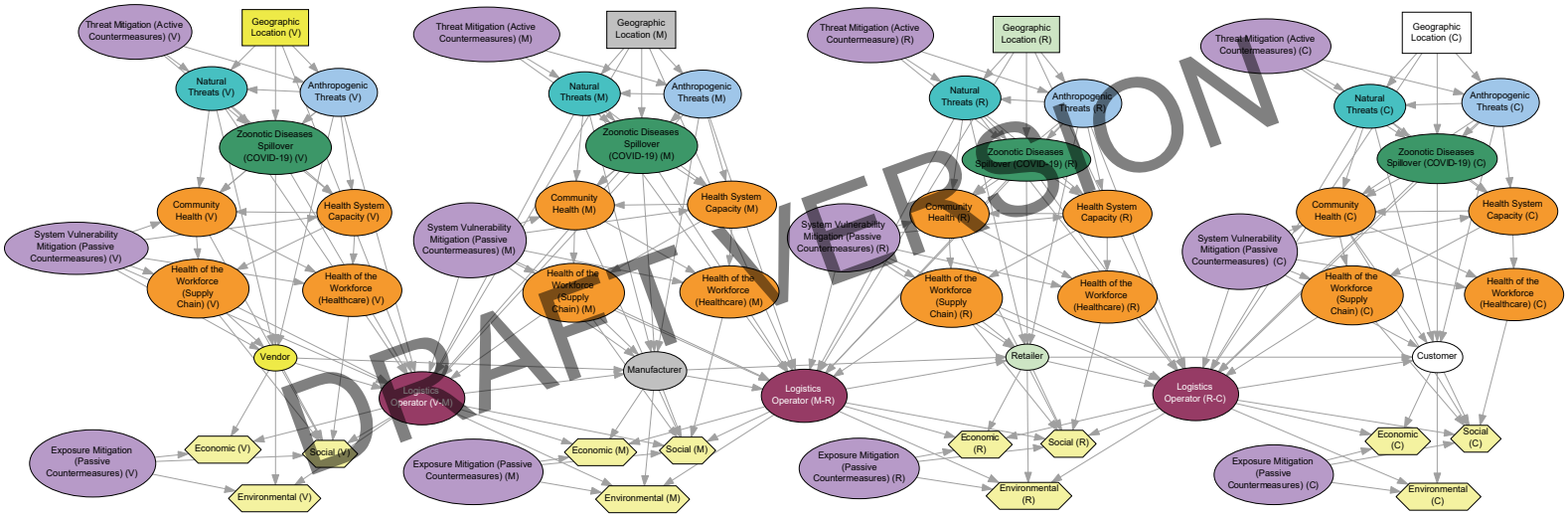

Figure 12: Minimum Conceptual Risk Assessment & Management model - Multiple locations, see the appendix A.2 for a higher resolution version

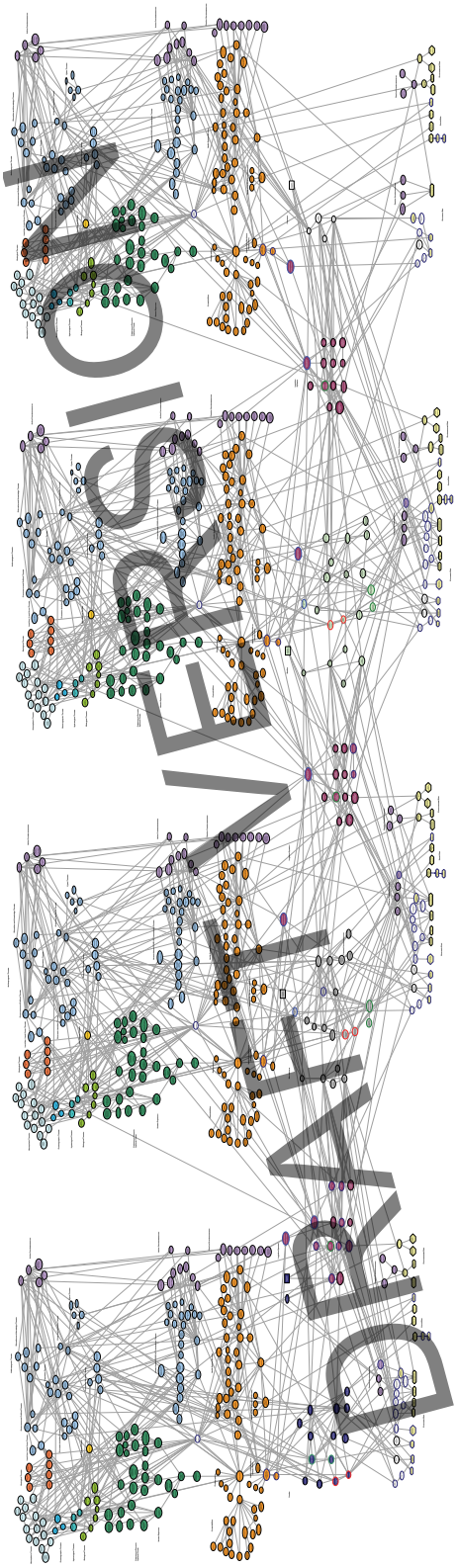

Figure 13: Complete Risk Assessment & Management model - Multiple locations, see the appendix A.2 for a higher resolution version

5.5 Mitigating Strategies - Variable grouping

5.5.1 Active Countermeasures

Table 12: Active Countermeasures group

Subgroup	Variables	References
Laws & Regulations	Law Enforcement Laws and Regulations School Regulations Travel Regulations Social Distancing Regulations Transportation Regulations	[24], [25], [28], [41], [75], [96], [97], [102], [175], [176], [177], [178]
COVID-19 Active Countermeasures	Personal sanitation and cleaning Surface cleaning and disinfection Improve/implement ventilation system Testing Quarantine Contact Tracing	[47], [65], [75], [175], [179], [180], [181], [182], [151], [183], [184], [185], [186], [187]
Food & Water Treatment	Education to encourage the proper cooking of food Water treatment	[52]

5.5.2 Passive Countermeasures

Table 13: Passive Countermeasures group

Subgroup	Variables	References
COVID-19 Passive Countermeasures	Essential services regulations Workplace regulations Vaccination	[65], [75], [96], [97], [188], [189], [190], [191], [192]

Continued on next page

Table 13 Passive Countermeasures group (continued)

Subgroup	Variables	References
Healthcare Services Management	Credentialing and regulations Inventory Management (Healthcare) Financial contingency plan Alternate care sites Alternate care sites Emergency preparedness and response training Cybersecurity management	[40], [41], [189], [190]
Supply Chain Management	Multi-modal transportation Supply diversification Inventory management (Supply Chain) Cybersecurity measure	[35], [36], [40], [41], [96], [103], [109], [193], [94], [86]
Recycling & Disposal Management	Treatment facilities Collection centers Recycling and disposal	[25], [41], [92], [194],

5.6 Variable Definitions for Risk Assessment & Management Model

5.6.1 Active Countermeasures

Laws & Regulations

Law Enforcement: enforcement mechanisms to ensure an effective and efficient application of laws and regulations [28].

Laws and Regulations: set of policies and regulations to mitigate the effect of threats on vulnerable systems, or to reduce a state of vulnerability of a system [28].

School Regulations: set of policies and regulations aimed at mitigating the spread of SARS-CoV-19 in educational institutions, including reduction of activities or school closures [178].

Travel Regulations: set of policies applied to human travel within national borders and across countries, aimed at mitigating the spread of COVID-19 [24].

Social Distancing Regulations: this variable refers to the characteristics and validity of policies and regulations pertinent to the physical distancing in a society with the objective to

mitigate the spread of COVID-19.

Transportation Regulations: set of policies and restrictions that apply to different modes of transportation in order to mitigate the spread of COVID-19 [75].

COVID-19 Active Countermeasures

Personal sanitation and cleaning: cleaning and sanitation practices including washing your hands and using hand sanitizer [195].

Surface cleaning and disinfection: the use of bleach and isopropyl alcohol (IPA) to clean and sanitize contaminated surfaces by SARS-CoV-2 [47].

Improve/implement ventilation system: ventilation and filtration provided by heating, ventilating, and air-conditioning (HVAC) to reduce COVID-19 Airborne transmission [195].

Testing: COVID-19 testing mechanisms applied to a population in a given location and time. This variable is strongly conditioned on the availability of tests, and proper facilities for testing [185].

Quarantine: quarantine mechanisms such as self-isolation and mandatory state-managed quarantine [182].

Contact Tracing: set of methods to identify people who have been in close contact with a COVID-19 positive case [182].

Food & Water Treatment

Education to encourage the proper cooking of food: education mechanisms to inform about how to proper cook certain meats that could contain diseases [52].

Water treatment: water treatment mechanisms to ensure safe drinking water for a population [52].

5.6.2 Passive Countermeasures

COVID-19 Passive Countermeasures

Essential services regulations: regulations that define the set of industries and business activities that are typically instrumental to continue critical infrastructure viability, and in which their workers are allowed to access their workplaces during times of community restrictions [191].

Workplace regulations: regulations pertaining to social distancing, employee shifts, employee in-person interaction with public, feasibility of teleworking, workplace geographic isolation, policies regarding sick leaves, priority for operations continuity, among others to create a safe workplace for workers and clients, reducing the overall exposure to SARS-CoV-2 [192].

Vaccination: vaccines applied to a population in a given location and time. This variable is strongly conditioned on the availability of vaccines, and proper facilities for vaccination [65].

Healthcare Services Management

Credentialing and regulations: credentialing and verification processes to ensure that volunteers that intend help on providing healthcare services are trained and certified [71].

Inventory Management (Healthcare): process of ensuring availability of products through safe and efficient control, storage, and replenishment of stock [94, 86]. This variables refer to the management of products and materials required in Healthcare Services.

Financial contingency plan: contingency resources to acquire equipment, human resources (including payroll), pharmaceuticals, and supplies that are not used on a day-to-day basis [69].

Alternate care sites: availability of designated areas to provide immediate care such as waiting rooms, hallways, cafeterias, offices, schools, large restaurants, hotels, etc. [69].

Emergency preparedness and response training: initial and periodic disaster training exercises, e.g. "principles of healthcare delivery using PPE" [196].

Cybersecurity management: set of security and safety standards aimed to assess, prevent, and mitigate IT & Cyber Risks [36]. This variable refers to the application of said standards

in the operation of the entities of the Supply Chain and Healthcare Services systems.

Supply Chain Management

Multi-modal transportation: practice of using more than one transportation mode, such as motor, water, and air carriers during the movement of materials or goods [91, 85].

Cybersecurity management: see *Cybersecurity management* in the previous section. This is the same variable. It is included in this section, because it is also a parent node for variables on the Supply Chain System [103].

Supply Diversification: act of increasing the flexibility and choices of sources of supply for certain products, materials, and/or services, mitigating potential impacts on material availability of political or geographical causes [197].

Inventory management: see *Inventory Management (Healthcare)*. This variable refers to Inventory Management in the Supply Chain entities.

Recycling & Disposal Management

Treatment facilities: specialized facility whose function is to change the physical, chemical, or biological characteristics of hazardous waste in order to neutralize such waste, recover energy material resources, render the waste nonhazardous o less hazardous, or render the waste safer to transport, store or dispose [194]. This variable refers to the use of *Treatment facilities* by the entities of the Supply Chain when dealing with waste.

Collection centers: specialized facility in charge of holding hazardous materials temporarily, before being treated, disposed of, or stored somewhere else [194]. This variable refers to the use of *Collection Centers* by the entities of the Supply Chain when dealing with waste.

Recycling and disposal: recycling refers to the processing and use of waste within production and consumption processes [92]. Disposal is the discharge, deposit, dumping, spilling, or placing of solid or hazardous waste in a facility at which the waste will remain after closure [194]. This variable refers to the application of *Recycling*, and *Disposal* practices by the entities in the Supply Chain.

6 Case Studies

After the literature review and model formulation, the following case studies were used to perform a qualitative pre-validation of the Risk Assessment & Management Model. This pre-validation allowed for the further identification of variables and processes, and cause-effect relationships. The resulting model is referred to as V 1.0.

6.1 Shortage of Personal Protective Equipment

In July, 2020, Federal Emergency Management Agency (FEMA) Administrator Pete Gaynor, raised concerns over a potential shortage of Personal Protective Equipment (PPE) in the U.S., given the increase of Covid-19 cases in some areas of the country [198]. While the inventory levels of masks, gloves, and other PPEs improved with respect to the first months of the pandemic, a new surge of Covid-19 cases, and thus demand, put further strains on the supply of PPEs [199]. This implies that an increase in the number of Covid-19 cases is followed by an increase in demand, resulting in a shortage of PPE.

However, not only an increased demand causes a shortage of protective equipment. In July 2020, large parts of China, including the city of Wuhan, declared red alerts as heavy rain cause severe flooding. This caused a disruption for several supply chains, including PPEs. According to Michael Einhorn, president of Dealmed (a U.S. medical supplies distributor), the floods created another major roadblock in terms of PPE getting into the U.S., with delays of up to three weeks [200]. In this case, it is evident that natural threats, such as floods, create a supply disruption in terms of delay.

In order to mitigate the effects of the increased number of Covid-19 cases and disruptions in the supply chains, FEMA put in place a Supply Chain Stabilization Task Force to address the limited supply of critical protective and life-saving equipment [201]. Among the measures considered by the Task Force, the increase of availability of critical resources has a prominent role, through the inclusion of multi modal transportation for the improvement of the transportation capacity of critical supplies. Within the risk framework explained previously, this measure is categorized as a Passive Countermeasure, oriented to the reduction of the vulnerability of the systems; in this case, the Supply Chain.

This case study is represented in the Risk Assessment & Management Model by the following variables:

- Infected Human Cases (SARS-COV-2)
- COVID-19 Community Spread
- Health System Services
- Community Health
- Health of the Workforce (Supply Chain)

- Health of the Workforce (Healthcare)
- Demand (in Supply Chain System)
- Supply Delay (in Supply Chain System)
- Supply Discontinuity (in Supply Chain System)
- Inland Flooding
- Natural Threats
- Vendor Infrastructure Damage
- Vendor Closure
- Multi-modal Transportation (in Supply Chain System)
- Storage & Distribution Capacity (in Supply Chain System)

6.2 Medicines supply chain disruption

China and India are major producers of active pharmaceutical ingredients (API), that are shipped to manufacturing plants across the globe to fabricate finished products. The supply chain was disrupted by the national lockdowns, with India manufacturing capacity falling to 20-30% due to problems with transport and shipping, as well as labor shortage. In China, shut-down of manufacturing facilities hit the supply of medicines, causing a spill of the disruptions over the U.S. where, in January, the Food & Drug Administration announced the first Covid-19-related drug shortage due to an issue with the manufacturing of active pharmaceutical ingredients [202] [203].

In addition to this, generic drugmakers faced shipment issues around April 2020, because the cancellation of commercial flights cut the cargo capacity, preventing the shipment of the required supplies to the U.S. from India and China [204].

This case study shows, in first place, how national lockdowns derived in the closure of facilities, and coupled with labor shortage, resulted in a reduction of the capacity in the supply chain entities. This capacity reduction in a geographical region (i.e. India and China) translated into medicine shortage in a different location (i.e U.S.). Secondly, the disruptions on the supply chain are accentuated by the travel regulations imposed as a mean to control the outbreak.

The following variables in the Risk Assessment & Management model are represented by this case study:

- Travel Regulations
- COVID-19 Community Spread
- Transportation Restriction/Disruption (in Supply Chain System)

- Storage & Distribution Capacity (in Supply Chain System)
- Supply Delay (in Supply Chain System)
- Supply Discontinuity (in Supply Chain System)
- Essential Services Regulations
- Transportation Restriction
- Labor Shortage (in Supply Chain System)
- Vendor Closure

6.3 Covid-19 spread in Mink farms

On 23 and 25 April 2020 the first two Covid-19 mink outbreaks were reported at the Netherlands in farms farms holding 12,000 and 7500 animals, respectively. The virus was introduced by an infected farm worker in both cases [205]. Following the cases of the Netherlands, other outbreaks were reported in Spain, Italy, The U.S., Greece, and Denmark. According to [206] and [207], after the virus introduction by humans, it has since evolved, and spilled back from mink farms into the community.

During the passage through mink, the virus accumulated mutations in the spike protein gene. This is a concern because spike mutations, and their understanding, are crucial for the development of Covid-19 treatments and vaccines. After evidence review, the European Centre for Disease Prevention and Control and WHO concluded that the risk for the population was not increased, and that a surveillance at the human-animal interface is vital in order to track the possible mutations of the SARS-CoV-2 virus [207]. Despite this, Denmark, Spain, and other countries have ordered the culling of the mink farm population in an attempt to control the outbreaks, and the spillover into the communities . The reduction of mink population worldwide has had a disruptive effect on the fur industry and its supply chain that is reflected in a reduced availability of raw materials, in an industry that was facing scrutiny during the previous years [208].

The described situation in this case study reveals the potential for Human-to-mink transmission, the potential mutation of the virus in a new host, and finally the transmission from mink to human in return. The case study also shows how the policies and countermeasures, in this case the culling of mink populations, has an impact on supply chains by reducing the availability of raw materials.

This case study is represented by the following variables from the Risk Assessment & Management Model:

- Infected Human Cases (SARS-COV-2)
- Reservoir Host Density

- Human Exposure Dose Due to Excretion
- Emerging Zoonotic Diseases Spillover
- Community Health
- Laws and Regulations
- Raw Material Availability (in Vendor, within Supply Chain System)
- Vendor Delay (in Vendor, within Supply Chain System)
- Vendor Capacity (in Vendor, within Supply Chain System)
- Supply Delay (in Supply Chain System)
- Supply Discontinuity (in Supply Chain System)
- Unemployment
- Revenue
- Deaths Community
- Deaths (Supply Chain)
- Deaths (Healthcare

6.4 Migration caused by natural threats

Migration due to environmental threats such as hurricanes has been recognized in the literature in recent years. The Intergovernmental Panel on Climate Change (IPCC) uses the term "environmental refugees" to refer to vulnerable people who is moving because of extreme environmental events [209].

In the month of November 2020, two category 4 hurricanes (Eta and Iota) impacted Central American countries, and as a result, they suffered meaningful economic, social, and environmental losses such as rivers overflowing, crops destroyed, cattle washed away, schools flooded, and roads engulfed in landslides. It is very likely that due to the circumstances people from Central America will tend to migrate to Mexico and U.S. [210]. Additionally, the likelihood of getting infected of COVID-19 in a migration caravan is high due to close contact between people.

News has also reported concerns about COVID-19 spread in emergency shelters due to more people seeking refuge that can increases the likelihood of direct or indirect contact with a COVID-19 case. Many people has lost their homes because of the storms, and are looking for basic necessities such as shelter and clean drinking water [210].

This case study involves variables from the Risk Assessment and Management Model such as:

- Hurricane.
- Natural Threats.
- Displacement.
- Migrant Caravan.
- Emergency Shelter.
- Superspreader Events.
- COVID-19 Community Spread.

6.5 PPE and Customer Satisfaction in Mexico

On February 27th, 2020, the first COVID-19 case in Mexico was reported [211]. Less than 3 weeks after the first case, a protest organized by Mexican Social Security Institute (IMSS) staff took place to demand medical supplies and personal protective equipment (PPE) [212]. A more recent protest was reported by infobae Mexican News on January 1st, 2021 [213]. The demands are similar to the previous protest: medical supplies, PPE, tests, and vaccines.

From this case study, several variables were identified from the Risk Assessment and Management Model:

- Personal Protective Equipment (PPE).
- Demand.
- Supply Delay.
- Supply Discontinuity.
- Customer Satisfaction.

The disruption on the supply of PPE for the medical staff generated a dissatisfaction that resulted on a protest. One of the inferred causes of the lack of PPE for the medical staff is a global supply disruption where the demand surpassed the production capacity of supply chains. However, it has been reported that there is an absence of support from the Mexican Government to provide PPE that contributed to the shortage [212].

6.6 COVID-19 Spread, PPE, and Health Workers Deaths in Mexico

97,632 Mexican health-care workers were infected between Feb 28 and Aug 23, and the main reason attributed to this infection was that nearly half of the workers did not have PPE at work [212]. Additionally, a lack of proper training of the health-care workers to manage COVID-19 patients has facilitated the spread of the disease in the medical staff [**BBC2020**].

On September 3rd, 2020, Amnesty International reported that "more Mexican health-care workers had died of COVID-19 than any other country" [212]. 1,320 Mexican health-care workers were reported as confirmed COVID-19 deaths by Amnesty International. Diseases such as obesity, diabetes, and hypertension, which are common between Mexican medical doctors, further compromised the health of the staff, and contributed to the number of deaths [212].

This case study is represented by several variables from the Risk Assessment and Management Model:

- COVID-19 Community Spread.
- Community Health.
- Obesity.
- Diabetes.
- Hypertension.
- Chronic Diseases.
- Cerebrovascular Diseases.
- Comorbidties.
- Doctors.
- Nurses/Midwives.
- Graduates of Health Training Institutions.
- Human Resources.
- PPE.
- Supplies.
- Health System Services.
- Health of the Workforce (Healthcare).
- Deaths (Healthcare).
- Financial Contingency Plan.
- Emergency Preparedness and Response Training.

The last two variables are passive countermeasures that were identified when recreating this case study in the Model. It has been hypothesized that by implementing a Financial Contingency Plan to increase the supply of PPE for medical staff could reduce the number of infected health-care workers, and therefore reduce the number of COVID-19 deaths in the health-care sector. Furthermore, a proper Emergency Preparedness and Response Training to manage the COVID-19 disease on patients could help to avoid direct contact between infected patients and health-care workers, and consequently reducing the likelihood of infection between health-care workers.

7 Model Validation

After the pre-validation of the model through case studies, an expert knowledge elicitation will be carried out in order to validate the models presented in previous sections.Figure 14 shows the sequence of activities for the validation process.

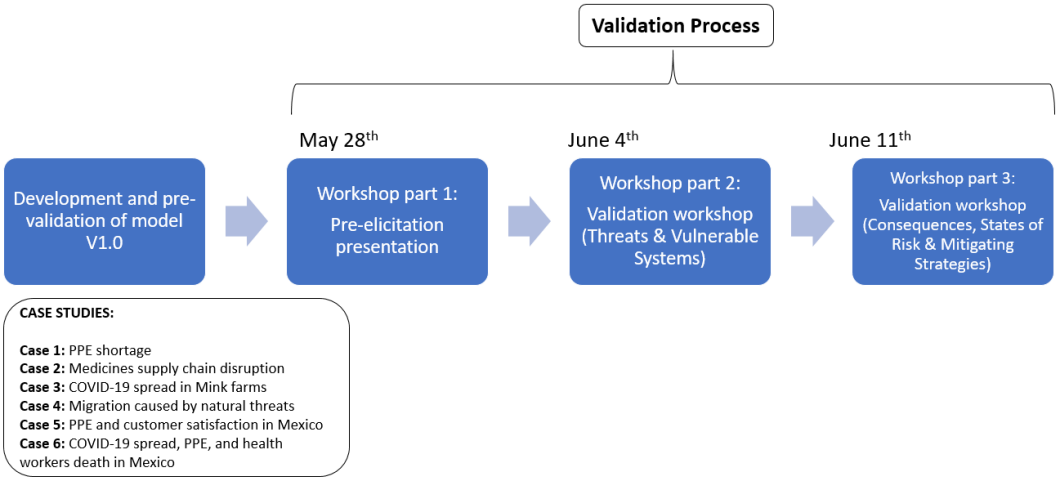

Figure 14: Model validation process

7.1 Workshop #1 - Pre-elicitation presentation

The first workshop consists of a Pre-elicitation presentation where the research team will introduce the project and its objectives, the risk assessment and management framework, and the Bayesian Networks. The team will also explain the expected outcomes of the process, and the workflow for Workshops #2, and #3.

7.2 Workshop #2

The Risk Assessment Management model has 5 components: Threats, Systems, Impacts, States of Risk, and Mitigating Strategies. During this workshop, the experts will be assigned

to different breakout rooms according to their expertise to discuss, first, the Threats component, and later, the Systems component. The discussion on the breakout rooms will be focused on:

- Identification of Variables and Processes
  - Have the main variables/processes been captured in the model?
  - Are there any variables/processes missing?
- Identification of Cause-effect relationships
  - Are the cause-effect relationships correct?
  - Are there any relationships missing?
- Prioritization of Variables and Processes

7.3 Workshop #3

During the last workshop, experts will be assigned once more to breakout rooms to provide feedback on the Impacts, and States of Risk components. The discussion on the breakout rooms will be focused on:

- Identification of Variables and Processes
- Identification of Cause-effect relationships
- Prioritization of Variables and Processes

Following that, there will be a plenary session to discuss potential Mitigating Strategies to be included in the model. Finally, the research team will share with the participants a series of surveys intended to gather additional feedback on:

- Sources of evidence for the variables in the model
- Comments or observations on the development of the workshops
- Additional feedback on the model

8 Conclusions

- A Risk definition where the Risk is expressed as the product of Hazard, Vulnerability, and Consequences serves as the Risk Assessment Framework for the model development.

- In order to fulfill the objectives of the R7 and R13 projects, a Version 1.0 of a Risk assessment Model was formulated. This model maps qualitatively the participating processes needed to simulate 'prognosis and diagnosis scenarios' of social, economic and environmental impacts posed by COVID19 on the U.S. trade supply chain infrastructure. The risk assessment model also address he public health impacts of the COVID-19 pandemic on the U.S. – Mexico health supply chain systems for health infrastructure and for the health of the workforce.

- The Risk Assessment Framework is expanded to Risk Assessment & Management, through the inclusion of Active and Passive Countermeasures. The Active Countermeasures have an impact on hazard reduction, while the Passive Countermeasures have an impact on the vulnerability and/or consequence reduction.

- The model formulation followed a sequence of activities, starting with the identification of the risk components (Threats, Vulnerable Systems, and Impacts), the identification of variables and processes defining the risk components, as well as the dependencies between variables within and across components. The final activity was the identification of mitigating strategies (Active and Passive Countermeasures). The listed activities were performed based on a literature review.

- After the literature review, 6 different case studies were analyzed to perform a qualitative pre-validation of the Risk Assessment & Management Model. This pre-validation allowed for the further identification of variables and processes, and cause-effect relationships. The resulting model is referred to as V 1.0.

- After the pre-validation process, and the resulting Version 1.0 of the Risk Assessment & Management model, a formal validation process will take place based on structured expert knowledge elicitation. The validation process is oriented to assess the relevance of the identified variables/processes within the project objectives, and the improvement of the decision-making.

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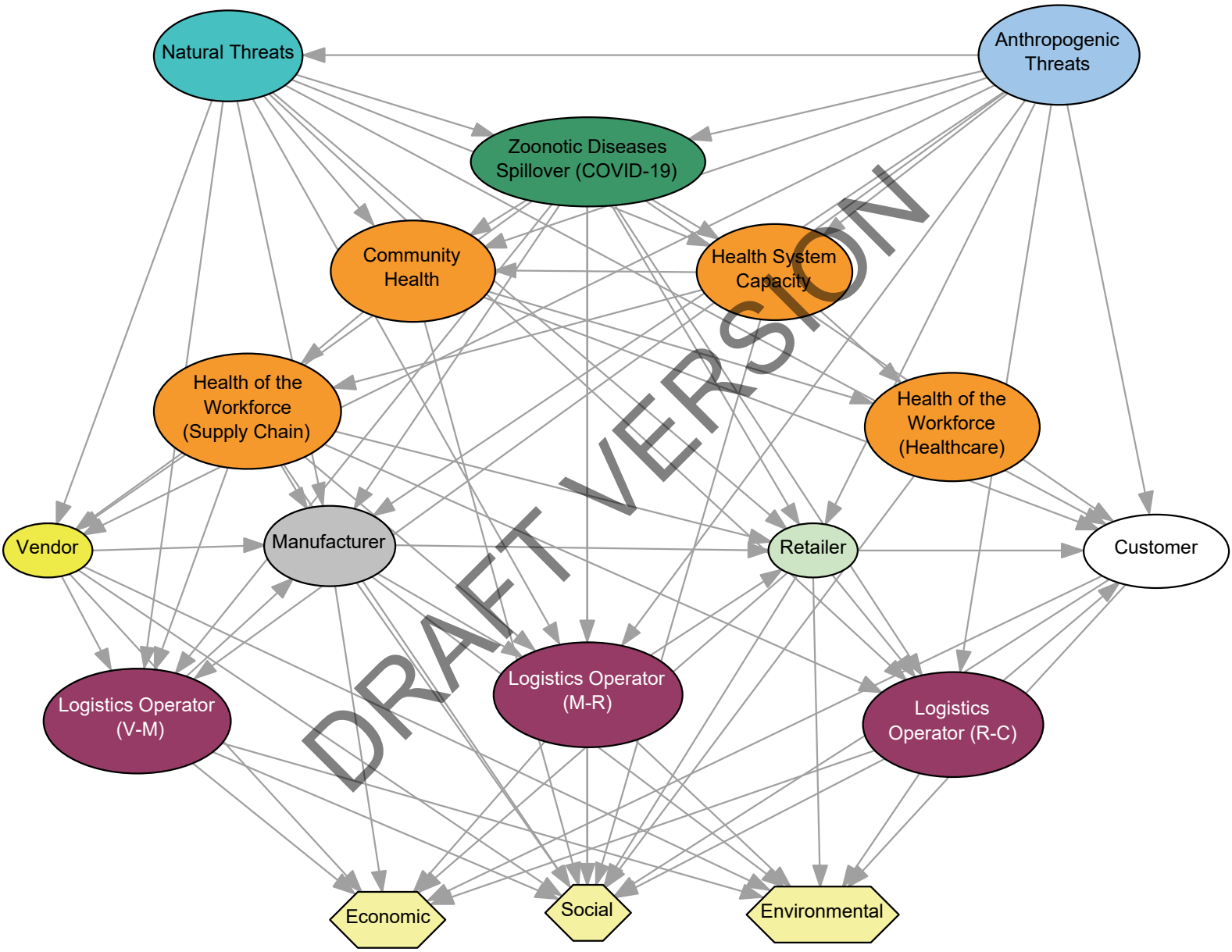
A Bayesian Network models

A.1 Risk Assessment models

- Minimum conceptual, one location
- Minimum conceptual, different locations
- Complete model, one location
- Complete model, different locations

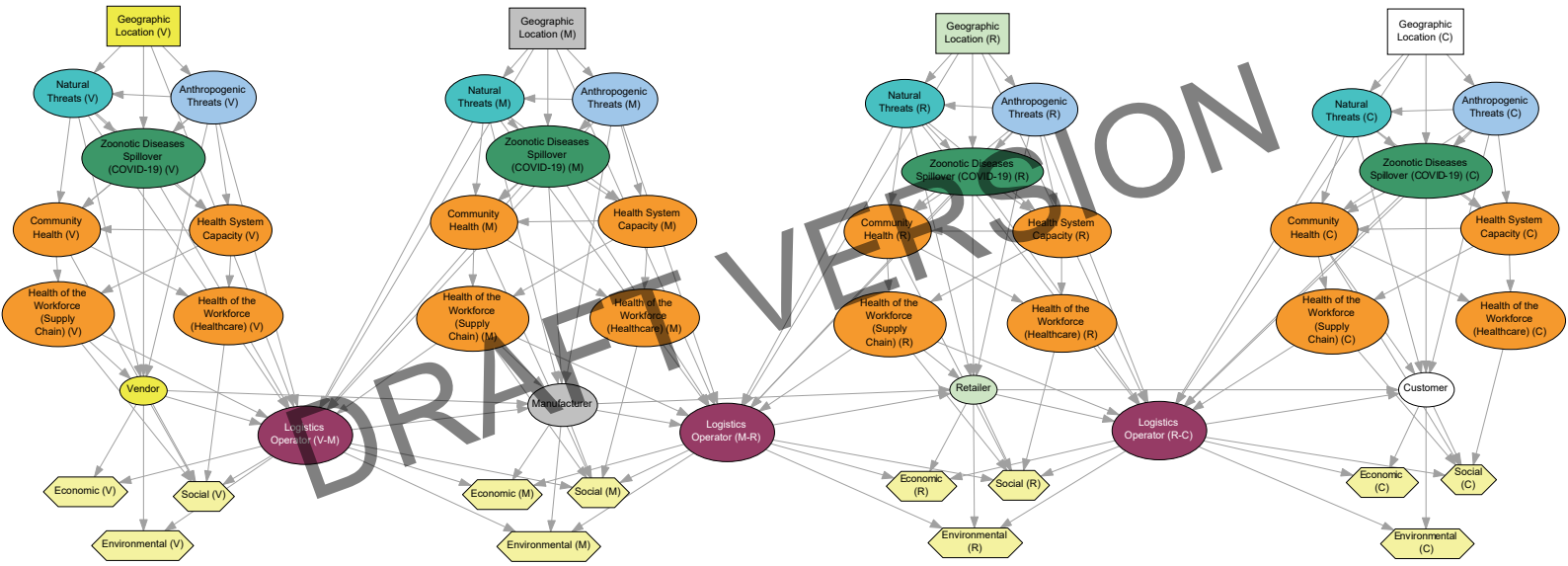
Risk Assessment
Minimum conceptual
One location


Natural Threats
Anthropogenic Threats
Zoonotic Diseases Spillover (COVID-19)
Community Health
Health System Capacity
Health of the Workforce (Supply Chain)
Health of the Workforce (Healthcare)
Vendor
Manufacturer
Retailer
Customer
Logistics Operator (V-M)
Logistics Operator (M-R)
Logistics Operator (R-C)
Economic
Social
Environmental
DRAFT VERSION

Risk Assessment

Minimum conceptual

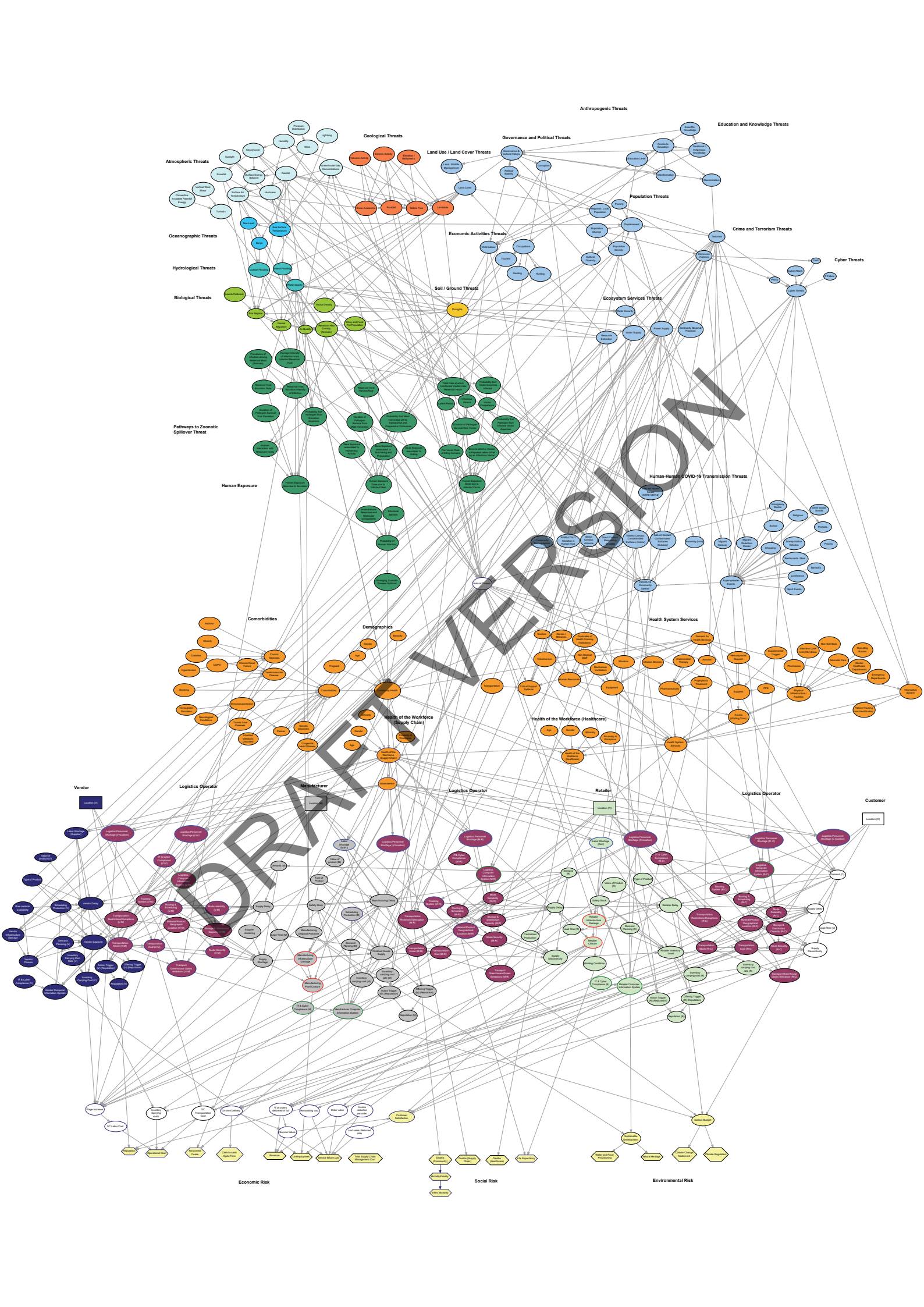
Different locations



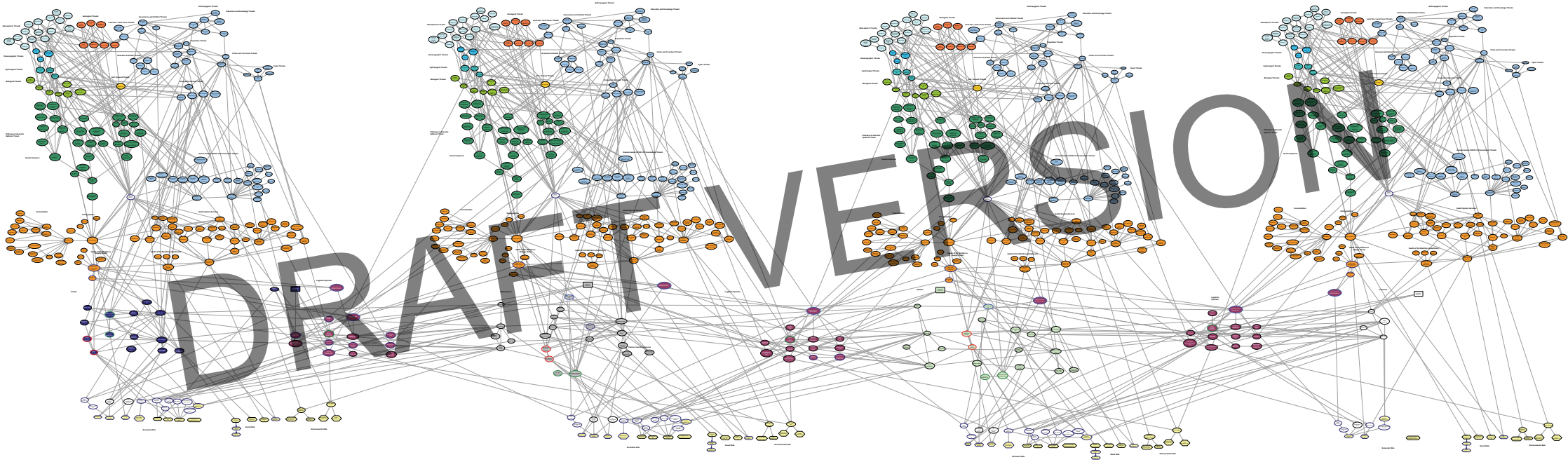
Risk Assessment

Complete model

One location


Anthropogenic Threats
Education and Knowledge Threats
Geological Threats
Governance and Political Threats
Atmospheric Threats
Land Use / Land Cover Threats
Population Threats
Oceanographic Threats
Economic Activities Threats
Crime and Terrorism Threats
Cyber Threats
Hydrological Threats
Soil / Ground Threats
Biological Threats
Ecosystem Services Threats
Pathways to Zoonotic Spillover Threat
Human Exposure
Human-Human COVID-19 Transmission Threats
Comorbidities
Demographics
Health System Services
Health of the Workforce (Supply Chain)
Health of the Workforce (Healthcare)
Vendor
Logistics Operator
Manufacturer
Logistics Operator
Retailer
Logistics Operator
Customer
Economic Risk
Social Risk
Environmental Risk
DRAFT VERSION

Risk Assessment
Complete model
Different locations


DRAFT VERSION

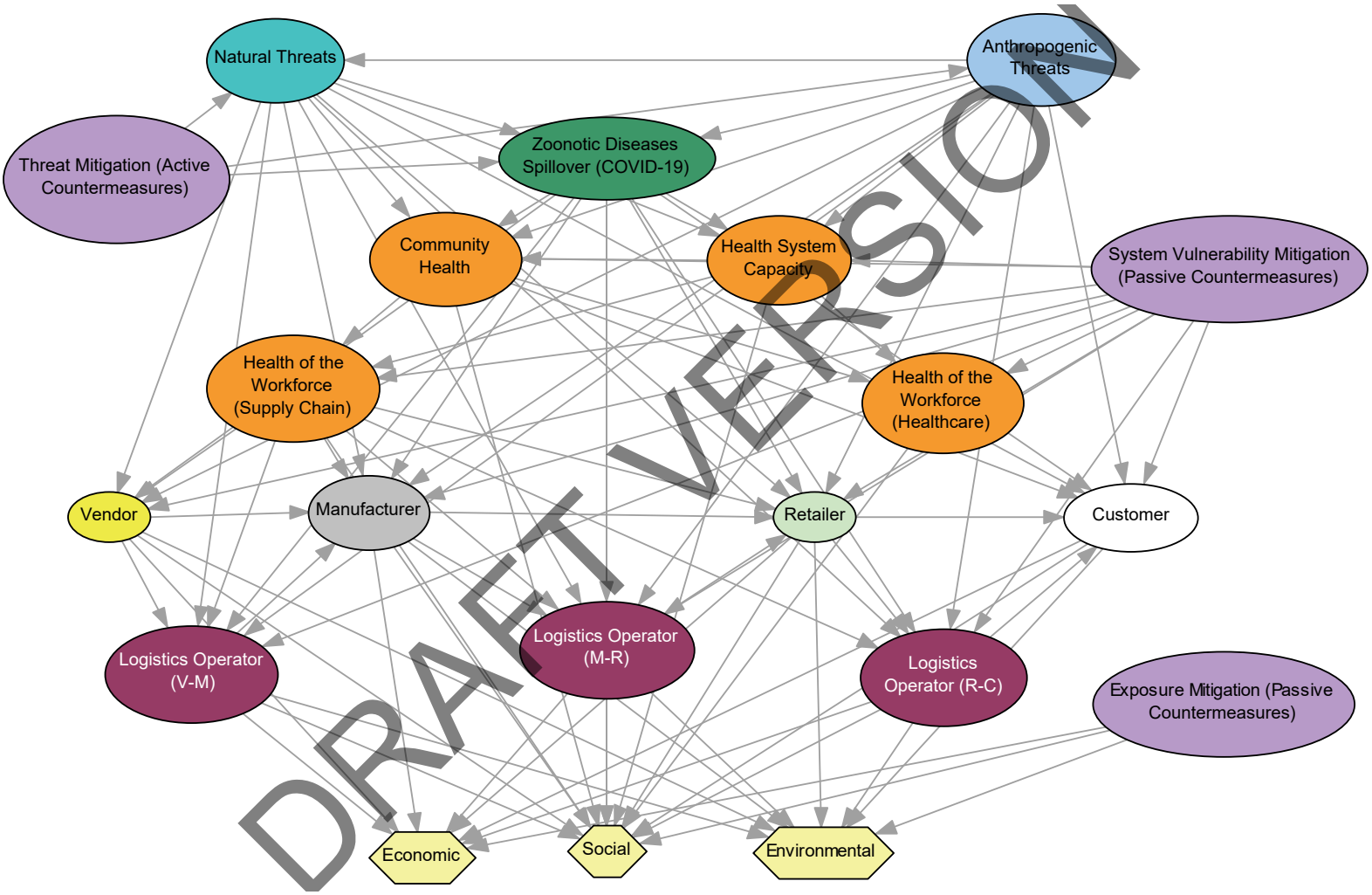
A.2 Risk Assessment & Management models

- Minimum conceptual, one location
- Minimum conceptual, different locations
- Complete model, one location
- Complete model, different locations

Risk Assessment & Management

Minimum conceptual

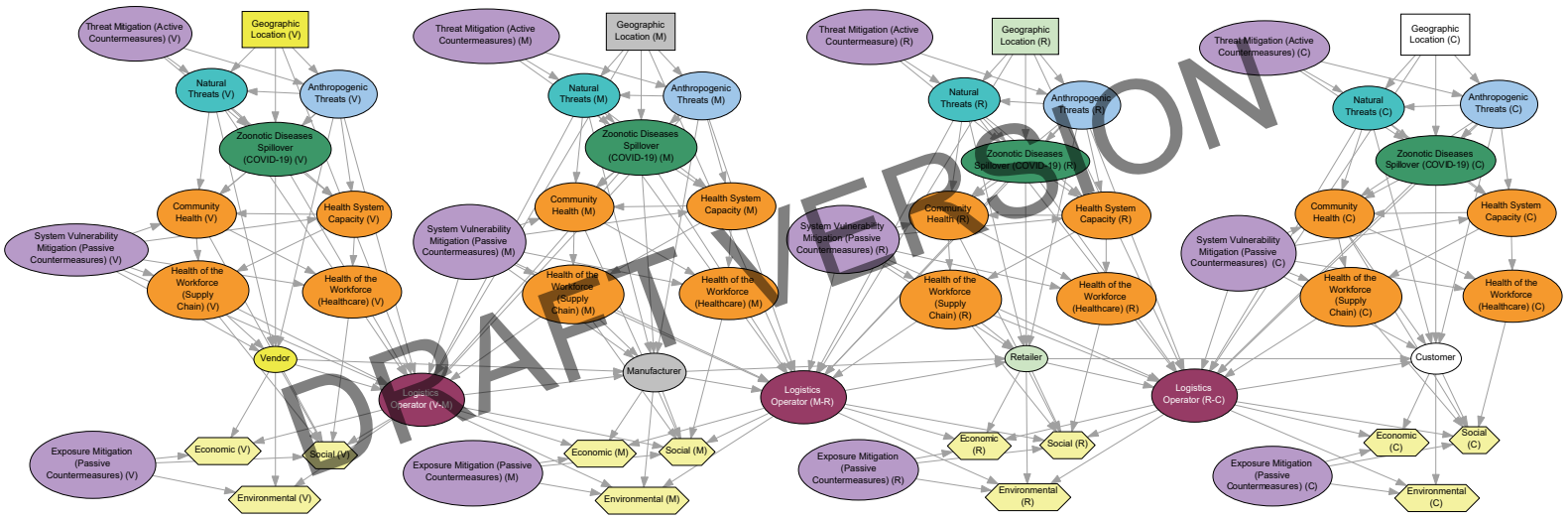
One location


Natural Threats
Anthropogenic Threats
Threat Mitigation (Active Countermeasures)
Zoonotic Diseases Spillover (COVID-19)
Community Health
Health System Capacity
System Vulnerability Mitigation (Passive Countermeasures)
Health of the Workforce (Supply Chain)
Health of the Workforce (Healthcare)
Vendor
Manufacturer
Retailer
Customer
Logistics Operator (V-M)
Logistics Operator (M-R)
Logistics Operator (R-C)
Exposure Mitigation (Passive Countermeasures)
Economic
Social
Environmental
DRAFT VERSION

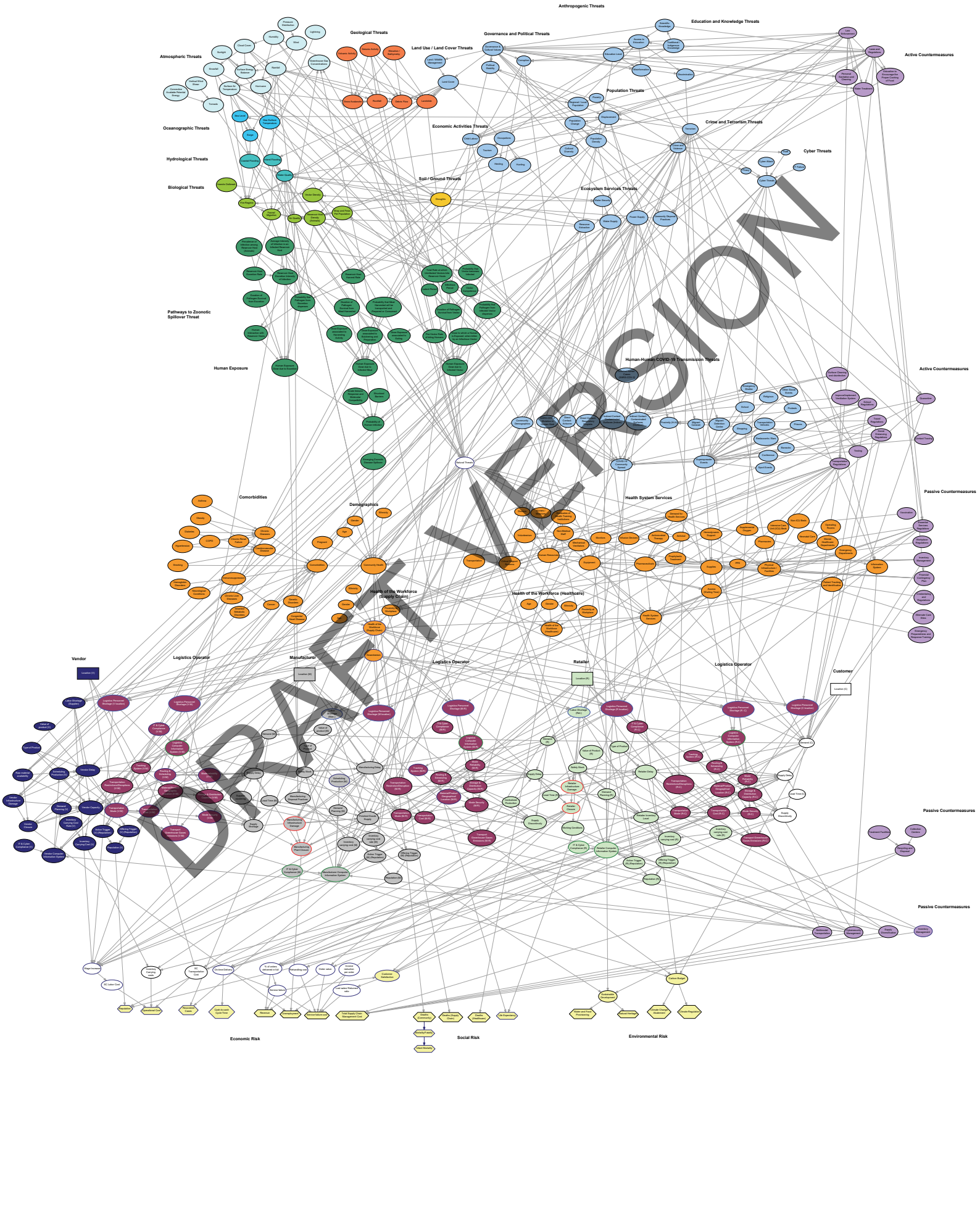
Risk Assessment & Management

Minimum conceptual

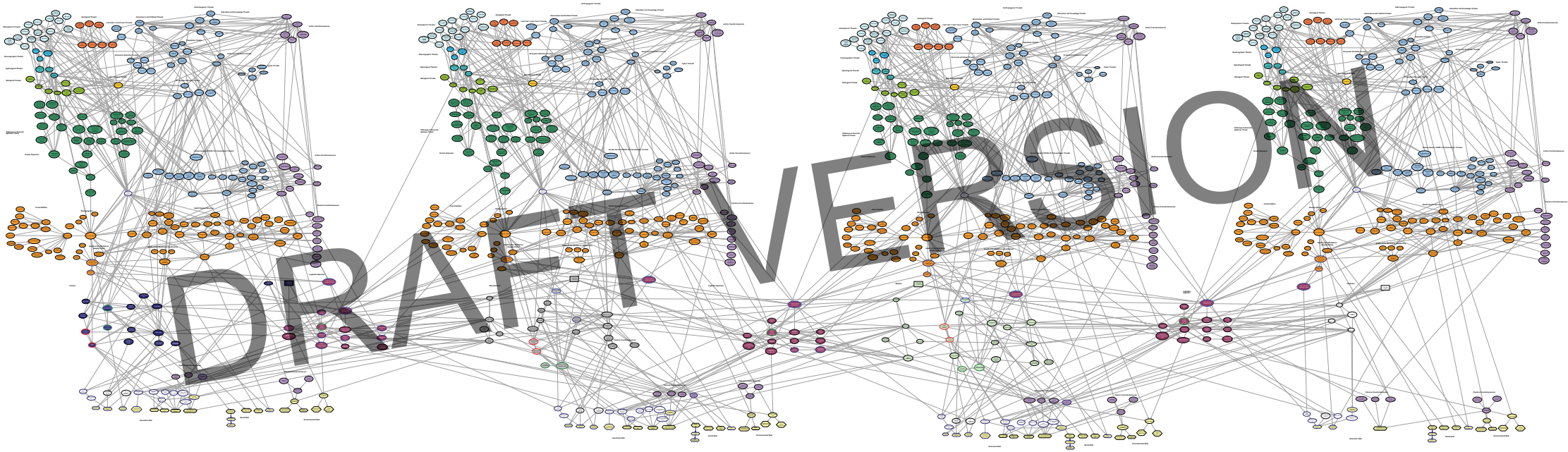
Different locations



Risk Assessment & Management
Complete model
One location


Anthropogenic Threats
Education and Knowledge Threats
Geological Threats
Governance and Political Threats
Land Use / Land Cover Threats
Active Countermeasures
Atmospheric Threats
Population Threats
Oceanographic Threats
Economic Activities Threats
Crime and Terrorism Threats
Hydrological Threats
Cyber Threats
Biological Threats
Soil / Ground Threats
Ecosystem Services Threats
Pathways to Zoonotic Spillover Threat
Human Exposure
Human-Human COVID-19 Transmission Threats
Active Countermeasures
Comorbidities
Demographics
Health System Services
Passive Countermeasures
Health of the Workforce (Supply Chain)
Health of the Workforce (Healthcare)
Vendor
Logistics Operator
Manufacturer
Logistics Operator
Retailer
Logistics Operator
Customer
Passive Countermeasures
Passive Countermeasures
Economic Risk
Social Risk
Environmental Risk
DRAFT
VERSION

Risk Assessment & Management
Complete model
Different locations


DRAFT VERSION