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THESIS

INTERDICTING AN ADVERSARY'S ECONOMY VIEWED AS A TRADE SANCTION INOPERABILITY INPUT-OUTPUT MODEL

by

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March 2017

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The United States has made use of economic sanctions to achieve political goals by limiting the relationship between trade, travel, and finance. However, economists are uncertain if the use of economic sanctions is effective and achieves the desired results. Applying the notion of demand-based inoperability, we present two nonlinear models to identify the optimal placement of sanctions and assess the sanctions' cascading effects to all sectors of an adversary's economy. For purposes of demonstration and validation, we pose a hypothetical scenario in which the U.S. considers trade sanctions on Canada. Specifically, our analysis proposes the Trade Sanction Inoperability Input-Output Model (TS-IIM). We devised this model to permit ranking of sectors by the order in which the greatest production loss occurs. Given the strong dependence of Canada on the United States, is it reasonable to expect that a sanction could result in economic repercussions? In response to this question, we also present the Inter-Country Inoperability Input-Output Model (IC-IIM), which extends the TS-IIM by considering the reduction in trade in value added (TiVA) the U.S. economy will experience. Our results from the TS-IIM and IC-IIM lead us to conclude that the proper design of a sanction considers not only the impact to an adversary's economy, but also sanction's associated repercussions at home.

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The United States has made use of economic sanctions to achieve political goals by limiting the relationship between trade, travel, and finance. However, economists are uncertain if the use of economic sanctions is effective and achieves the desired results. Applying the notion of demand-based inoperability, we present two nonlinear models to identify the optimal placement of sanctions and assess the sanctions' cascading effects to all sectors of an adversary's economy. For purposes of demonstration and validation, we pose a hypothetical scenario in which the U.S. considers trade sanctions on Canada. Specifically, our analysis proposes the Trade Sanction Inoperability Input-Output Model (TS-IIM). We devised this model to permit ranking of sectors by the order in which the greatest production loss occurs. Given the strong dependence of Canada on the United States, is it reasonable to expect that a sanction could result in economic repercussions? In response to this question, we also present the Inter-Country Inoperability Input-Output Model (IC-IIM), which extends the TS-IIM by considering the reduction in trade in value added (TiVA) the U.S. economy will experience. Our results from the TS-IIM and IC-IIM lead us to conclude that the proper design of a sanction considers not only the impact to an adversary's economy, but also sanction's associated repercussions at home.

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LIST OF ACRONYMS AND ABBREVIATIONS

BEA	Bureau of Economic Analysis
CVMA	Canadian Vehicle Manufacturer’s Association
DIIM	Dynamic Inoperability Input-Output Model
DOC	Department of Commerce
DOD	Department of Defense
GDP	Gross Domestic Product
I-O	Input-Output
IC-IIM	Inter-Country Inoperability Input-Output Model
ICIO	Inter-Country Input-Output
IIM	Inoperability Input-Output Model
ISIC	International Standard Industrial Classification
IT-IIM	International Trade Inoperability Input-Output Model
M	Million
NCR	National Capital Region
OECD	Organisation for Economic Co-operation and Development
ONS	Office for National Statistics
STAN	Structural Analysis
TiVA	Trade in Value Added
TS-IIM	Trade Sanction Inoperability Input-Output Model
UK	United Kingdom
U.S.	United States
USD	United States dollar

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EXECUTIVE SUMMARY

Over the past 20 years, the United States has made use of economic sanctions to impose higher costs on adversaries and achieve political goals by limiting the relationship between trade, travel and finance. However, economists are uncertain if the use of economic sanctions is effective in achieving the desired results (Cortright and Lopez 2000).

This thesis takes up the challenge of assessing and improving the design of an economic sanction. We define an economic *sanction* in this thesis as a restriction that eliminates the imports into the United States from a particular foreign country. Our analysis is based on the use of an extended version of the demand-based inoperability input-output model (IIM), as described by Santos (2003). This model measures impact on an economy in terms of *inoperability*, which is defined as normalized production loss as a direct result of a disruption to an industry within the economy. Moreover, it considers a *demand-side* perturbation, which is defined as a reduction in demand for commodities produced from a particular sector or set of sectors. The *design* of an economic sanction, in the context of this thesis, is the selection of the sector or set of sectors to sanction.

We propose two optimization models. The first, the Trade Sanction Inoperability Input-output Model (TS-IIM), selects the sector or set of sectors that, if sanctioned, maximizes production loss (i.e., inoperability) to an adversary. The second, which we named the Inter-Country Inoperability Input-Output Model (IC-IIM), has the same objective function of the TS-IIM, but it includes a maximum tolerance threshold on the repercussions to the United States.

Using data from the Organisation for Economic Co-operation and Development (OECD), we consider a hypothetical scenario in which the U.S. considers trade sanctions on Canada. Using the TS-IIM reveals that United States sanctions on the Canadian automotive industry would create a $193.3 billion production loss to the Canadian economy. This is not surprising, as the Canadian automotive industry is the largest contributor of GDP for Canada. In addition, the U.S. is the largest importer of

automobiles and automotive parts from Canada due to the Automotive Product Trade Agreement (Auto Pact) established between the U.S. and Canada in 1965, as expanded by the United States-Canada Free Trade Agreement of 1988 (CVMA 2011).

Given the interdependency between the U.S. and Canadian economies, we also consider repercussions on the United States for sanctioning sectors within Canada. We use the IC-IIM to identify sanctions while also limiting the repercussions to the United States. Results from the IC-IIM indicate that the sectors identified by the TS-IIM would cause large repercussions. Using parametric analysis on the threshold for possible repercussions, a sanction of the Canadian automotive sector is never part of an optimal solution provided from the IC-IIM.

The models and analysis used in this thesis can be adapted for use by the U.S. Department of State to combat the financing of terrorism and the hostile actions of our adversaries. Creating inoperability by means of sanctions can limit the production of commodities and cash flow from certain sectors critical to the sustainment of our adversary's military infrastructure. Sanctions have the ability to mitigate war; or, if necessary, sanctions may be the source of a competitive edge.

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I. INTRODUCTION

A. BACKGROUND

In response to the support of terrorism, abuse of human rights, and development of nuclear programs in direct violation of nuclear treaties, the United States (U.S.) has been involved with numerous economic sanctions on countries around the world. According to Masters 2015, an economic sanction is defined as “the withdrawal of customary trade and financial relations for foreign and security policy purposes (Masters 2015). In the 1990s, over 50 sanctions were implemented, and this decade was referred to by many as the “sanctions decade.” Of these sanctions, 12 were implemented by the United Nations Security Council; all of the remaining sanctions were implemented by the United States.

One of the most notable recent sanctions on the Central Bank of Iran was Executive Order 13599 signed by President Obama in February 2012. This sanction isolated the bank, effectively disrupting the export of Iranian oil to other countries by terminating the means of payment. The U.S. targeted the Central Bank of Iran because most of the revenue generated from Iranian oil sales is processed through this bank. As of 2016, the U.S. has sanctions imposed against 23 countries, including Crimea, Syria, and North Korea (U.S. Department of Treasury, Office of Foreign Assets Control 2016). However, the U.S. has also recently relaxed sanctions against Iran and Cuba as part of ongoing negotiations with these countries.

Because the United States has sharply increased the frequency of its use of sanctions as a diplomatic tool to influence nations, it is important to assess the extent to which sanctions work as intended.

Numerous economists, politicians, and humanitarians argue that economic sanctions are not effective political trade tools. For example, Cortright and Lopez (2000) studied the effectiveness of sanctions by reviewing their aftereffects once imposed as compared to the initial objectives. Their framework for evaluating the effectiveness of a sanction is based on the political, economic, and humanitarian impact on the nation sanctioned. The authors concluded that the sanctions imposed by the United Nations in the 1990s were often ineffective, due primarily to their poor implementation, enforcement, or design. Cortright and Lopez also recommended the creation of an expert entity whose purpose is to measure the impact sanctions may have on a foreign nation (2000).

B. MOTIVATION

This thesis takes up the challenge of assessing and improving the design of economic sanctions. We define an economic *sanction* in this thesis as a restriction that reduces or eliminates the imports into the United States from a particular foreign country. As a concrete example, in Table 1 is shown the trade volume between the United States and Iran for each month in the years 2004 and 2014 (U.S. Census Bureau 2004, 2014). Specifically, import volume, export volume, and the trade balance in millions of U.S. dollars (USD) between the U.S. and Iran are presented. The last row entitled "TOTAL" shows the aggregate trade activity over the course of each year in millions of USD. One observes that there is a two-way trade relationship between the United States and Iran in 2004 but not in 2014. When comparing the two periods, total U.S. exports to Iran increased by 119%. However, because of the steady increase in sanction activity between 2010 and 2014, there was no import activity from Iran to the United States in 2014.

Table 1. 2004 vs. 2014 U.S. Trade in Goods with Iran. Adapted from U.S. Census Bureau (2004, 2014).

	2004			2014		
Month	Exports	Imports	Balance	Exports	Imports	Balance
January	11.3	11.5	-0.3	14.4	0.0	14.4
February	6.2	15.1	-8.8	11.0	0.0	11.0
March	7.8	14.2	-6.4	18.8	0.0	18.8
April	4.4	10.6	-6.2	14.5	0.0	14.5
May	8.1	12.6	-4.5	11.7	0.0	11.7
June	7.4	10.5	-3.1	17.6	0.0	17.6
July	10.0	11.7	-1.7	18.7	0.0	18.7
August	7.1	11.8	-4.7	18.3	0.0	18.3
September	6.7	13.6	-6.9	11.4	0.0	11.4
October	6.1	15.4	-9.3	15.5	0.0	15.5
November	4.7	9.7	-5.1	16.6	0.0	16.6
December	5.5	14.9	-9.3	18.0	0.0	18.0
TOTAL	85.1	151.6	-66.5	186.6	0.0	186.6

Table 1 shows the effects economic sanctions has on Iranian imports to the U.S. within the period of a decade.

Assessing the differences in trade activity, specifically the restriction of imports from a particular country, is the topic of study for this thesis. We focus on disrupting exogenous demand of commodities from industries within a particular country's economy by means of sanctions. Sanctions can be implemented unilaterally, or multilaterally. A *unilateral sanction* is a sanction implemented by a single country, while a *multilateral sanction* is imposed by two or more countries. These countries may be cooperating or acting independently in imposing sanctions.

Sanctions are implemented by limiting trade for specific sectors within an economy. Building on previous work, we define a *sector* of an economy as a group of similar industries, products, or services that are aggregated together and treated as a single *commodity*. The Organisation for Economic Co-operation and Development (OECD) uses 34 standard sectors to characterize economic activity for all countries within its database.

In this thesis, we define the *design* of a sanction in terms of:

- Which sector(s) of an economy to target, and
- Whether that sanction is carried out unilaterally or multilaterally.

We primarily restrict attention to the potential effectiveness of unilateral sanctions imposed by the United States.

We measure the effectiveness of a design in terms of production loss in USD. We extend the inoperability input-output model (IIM) as described in Santos (2003) to quantify *inoperability*, which is a point estimate of the resulting normalized production loss for the sanctioned country experienced by foreign nations after an economic sanction has been implemented by the United States.

C. SCOPE OF THESIS

We present the trade sanction inoperability input-output model (TS-IIM) to identify the optimal design of an economic trade sanction based on the resulting estimated production loss experienced by an adversary's economy. Our model extends the IIM of Santos (2003) so that we maximize production loss. We populate this model with data from the OECD. We use this extended model to consider the following questions:

1. Which sector of an adversary's economy should be targeted to maximize the impact on its economy as a whole?
2. Which sector of an adversary's economy should be targeted to maximize the impact on a specific sector?
3. To what extent are trade sanctions effective tools for economic warfare?

The remainder of this thesis is organized as follows. Chapter II provides background information and a review of the relevant literature. Chapter III presents a model for targeting the sectors of an adversary's economy based on the estimated impact on that economy. Chapter IV extends this model to consider possible economic ramifications to the U.S. as well. Chapter V summarizes our findings and describes topics for future research.

II. LITERATURE REVIEW

This chapter reviews several families of models used to study sector interdependence and economic inoperability.

A. THE LEONTIEF INPUT-OUTPUT MODEL

Perhaps the most well-known macroeconomic model of sector interdependence is the input-output model created by Wassily Leontief for which he won the Nobel Prize for Economics in 1973 (Nobel Media AB 2014). In the Leontief model, the economy of a country is partitioned into n industrial sectors. The core of the model is an $n \times n$ technology matrix where each element $a_{i,j}$ is a coefficient that represents the amount of production from sector i that is consumed to produce one unit of commodity in sector j. The model has an inherent linear assumption; the amount of sector i consumed to produce each additional unit from sector j remains constant. In other words, this model does not account for economies of scale. Despite the linear assumption, this model is the standard used by numerous developed countries, including the U.S., for the purpose of planning and forecasting specific econometrics such as gross domestic product (GDP) (Horowitz and Planting 2006). Within the U.S. Department of Commerce (DOC), the Bureau of Economic Analysis (BEA) uses this model to analyze national and regional economies within the U.S. The analysis by the BEA answers questions regarding the U.S. economy's growth, development, and interindustry relationships, as well as its relative rank within the world. In addition, the Office for National Statistics (ONS)—the largest independent producer of national statistics in the United Kingdom (UK)—uses this model for the UK in the same way that the BEA does for the United States.

B. INOPERABILITY INPUT-OUTPUT MODELS

Santos (2003) describes the Inoperability Input-Output model (IIM), which is a derivative of the Leontief Input-Output model with three major differences. The first is the notion of a *demand-side* perturbation, which is defined as a reduction in demand for a particular sector or set of sectors. The second is the introduction of the term *inoperability*, which is defined as normalized production loss as a direct result of a disruption to an industry within the economy. Another interpretation of inoperability is the percentage of unrealized production resulting from an economic disturbance compared to the as-planned production. The third major difference is the creation of the *interdependency matrix*, which quantifies the inoperability relationship each industry has with all others within the economy. With these three additions, the production loss in USD from a disruption can be calculated (Santos 2003).

Jiang and Haimes (2004) use the IIM to study the cascading effects of a large-scale disruption to the economy—such as a terrorist attack, war, or a catastrophic natural disaster. The intent of their research is to develop a plan for post-perturbation response to minimize the total loss to the economy. Their model achieves this by redistributing inoperability as follows. When the as-planned production is not met due to the perturbation, that production loss is moved from sectors that benefit the economy most to other sectors where it has less effect, thereby allowing the most beneficial or critical sectors to thrive and close the gap between as-planned production and actual production (Jiang and Haimes 2004). For example, let us assume that electricity is the most important sector in the economy and steel is required to make electricity as well as automobiles. In response to a disruption that results in a shortfall of steel, it is more helpful to the economy as a whole to take steel originally intended to produce automobiles and redistribute it to make electricity. Reducing inoperability in the electricity sector at the expense of more inoperability in the vehicle sector will result in a healthier economy. Jiang and Haimes (2004) showed how optimal resource allocation within the economy after the disaster occurred could be beneficial to the public. Their study examines the ways in which the U.S. economy can recover after it has been attacked or experienced a natural disaster but does not study the effects of limiting trade between two countries (Jiang and Haimes 2004).

Santos and Haimes (2004) use data from the BEA to conduct an interdependency analysis on the U.S. economy in the event of an induced demand-side perturbation on the airline industry. Their research primarily focuses on the airline industry in a national twelve-sector economy. They use this model to estimate the monetary losses to the entire economy resulting from a 10% reduction in demand for airline travel due to a terrorist attack. In addition, they rank the sectors that they expect to experience the largest production loss in USD. Their ranking system reveals not only the production loss associated with each sector, but also the industries from which the general public would benefit most if the sectors were made more resilient (Santos and Haimes 2004).

Jung, Santos, and Haimes (2008) present an international trade IIM (IT-IIM), which uses data from the BEA to analyze the effects a potential perturbation at the Port of Los Angeles would have on all sectors of the U.S. economy. This study considers two types of direct perturbations: (1) a reduction in capacity of the port and (2) restrictions on imported goods, also known as an embargo. They limit the IT-IIM to a static analysis of the U.S. economy, and their results represent potential economic loss (Jung, Santos, and Haimes 2008).

Wei, Dong, and Sun (2009) use the IIM to study supply chain risk management and mitigation strategies. They use a method called the "ordered weighted averaging operator" to create the technology matrix for the IIM. They calculate inoperability and economic loss metrics to understand the vulnerabilities associated with each node within the supply chain system. They use a Monte Carlo simulation to verify their research findings (Wei, Dong, and Sun 2009).

Noting that economic disruptions are not bounded by state lines, Barker, Grant, Landers and Pant (2011) use a multi-regional IIM to analyze the cascading effects to multiple states within the continental U.S. that could result from a two-week shutdown of the port of Catoosa, located on the Arkansas River near Tulsa Oklahoma. They combine results from the multi-regional IIM with a simulation of port operations that include terminal closure, crane outage and departure stoppage. They estimate a mean loss of \$37.9 M to the multiregional economy and a loss of \$101.9 M when including cascading effects to surrounding 10 states (Barker, Grant, Landers and Pant 2011).

To gain a better understanding of economic effects that influenza has on the workforce, Santos, May, and Haimar (2012) conduct an IIM study to analyze the consequences when members of the workforce do not show for work within the national capital region (NCR). They measure consequences in terms of economic loss and inoperability. Of the 65 sectors they consider, they observe that the top 10 most vulnerable sectors account for more than half of the economic losses. These ten sectors also appear to contribute the most to the NCR GDP (Santos, May, and Haimar 2012).

C. DYNAMIC INOPERABILITY INPUT-OUTPUT MODELS

Lian and Haimes (2006) present an extension to the IIM known as the dynamic inoperability input-output model (DIIM). This model includes additional industry resilience coefficients that reflect conditional risk mitigation options for each industry and a stochastic recovery process. Collectively, these features make it possible to gain an understanding of not only how resiliency plays a part in measuring perturbation impact to the economy, but also the speed at which it will recover in the event of a terrorist attack (Lian and Haimes 2006).

Christie, Kapur, and Reed (2009) use the DIIM to assess the engineering resilience and interconnectedness of a networked infrastructure in the event of a natural disaster such as a hurricane. Using data from the aftermath of hurricane Katrina within an eleven-system interdependent infrastructure, they obtain results that give insight on how to better prepare for such a disaster with respect to needs like power, water and telecommunication services (Christie, Kapur, and Reed 2009).

Jonkerena and Giannopoulosa (2014) use an extension of the DIIM to measure economic losses and resilience that may result from the failure of critical infrastructure within a particular country's economy. They use data from the World Input-Output database as described by Dietzenbacher, Los, Stehrer, Timmer and de Vries (2015). The DIIM assumes that the recovery path for a disrupted economic sector is a concave-up, decreasing curve. However, their research offers alternative sector recovery paths that depend on the type of disaster experienced. Jonkeren and Giannopoulosa apply this model to Europe to consider the impact of a severe winter storm (2014).

Lian, Santos, and Haimes (2007) use the DIIM to show how a hypothetical cyber-attack in the Gulf Coast region that could create a five-week shortage in the supply of crude oil. They estimate the total loss to the entire economy to be approximately $8 billion. In their analysis, they found the Midwest, Gulf Coast, and East Coast of the U.S. would be significantly affected but that the West Coast and Rocky Mountain Region would suffer negligible economic impacts (Lian, Santos, and Haimes 2007).

D. MILITARY APPLICATIONS OF INPUT-OUTPUT MODELS

Snodgrass, Gallagher, and McIntyre (2004) use a Leontief Input-Output model to represent, at a macro level, the cascading effects and interactions that take place within a military force during combat. In their research, the technology matrix represents resource dependencies within the U.S. military force. They use this matrix to capture the cascading effects to the entire fighting force when one area of the fighting force is degraded or destroyed otherwise not captured in a combat simulation. The goal of their research is to develop a military strategy that could assess the damage to the entire military system vice singular assets within it (Snodgrass, Gallagher, and McIntyre 2004).

Gallagher and Shariff (2012) use the Leontief Input-Output model to analyze two Air Force budget allocation scenarios. Specifically, they use their model to assess the effects of budget reallocation among different entities within the Department of Defense (DOD). Their analysis is based on the premise that allocating a greater percentage of the DOD budget to one specific area will adversely affect other areas of the DOD. They use this model to gain an understanding of the interdependencies among the different budget areas within the DOD (Gallagher and Shariff 2012).

E. OUR CONTRIBUTION IN CONTEXT

In this thesis, we propose two optimization models. The first, named the Trade Sanction Inoperability Input-output Model (TS-IIM), selects the sector or set of sectors that, if sanctioned, maximizes production loss (i.e., inoperability) to an adversary. We use the TS-IIM to gain insight on the interdependencies of industries within an economy and to assess the potential consequences that a U.S. imposed sanction could have on an adversary’s entire economy. This information can be used to identify the sectors that, if targeted in a sanction, could cause the greatest economic disruption to an adversary’s economy. Similarly, this analysis can be used to identify the sectors within our own economy that if targeted may pose a significant threat to our national security.

The second optimization model, named the Inter-Country Input-Output Model (IC-IIM), has the same objective function of the TS-IIM, but it includes a maximum tolerance threshold on the repercussions to the United States. As we discover, the interconnectedness between countries suggests that careless U.S. sanctioning could result in potentially large repercussions for our own economy.

III. MODEL

A. TRADE SANCTION INOPERABILITY INPUT-OUTPUT MODEL

We follow the notation and mathematical development in Santos (2003). The basic Leontief input-output model is

$$x = Ax + c\,,$$

where A is the ($n \times n$) technology matrix, x is an ($n \times 1$) vector that represents total production in each of the interconnected industry sectors, and c is an ($n \times 1$) vector that represents the final demand for all sectors.

Consider a perturbation to final demand to an adversary's economy created by a U.S. sanction restricting all imports from that country, specifically

$$\delta c = \hat{c} - \tilde{c},$$

where $\hat{c}$ is the "as-planned" final demand vector, $\tilde{c}$ is the "degraded" final demand vector representing the amount of exports from our adversary's economy excluding exports to the U.S., and δc the reduction in final demand.

This reduction in final demand triggers a reduction in production, δx, which we describe as

$$\delta x = \hat{x} - \tilde{x},$$

where $\hat{x}$ is the as-planned production and $\tilde{x}$ is the degraded production.

Degraded production and degraded demand are linked through the basic Leontief equation:

$$\delta x = A\,\delta x + \delta c\,.$$

From this, Santos (2003) derives the basic inoperability model

$$q = A^{*}q + c^{*}$$

where

$$c^* = \left[\left(\mathrm{diag}\left(\hat{x} \right) \right)^{-1} \delta c \right]$$
$$A^* = \left[\left(\mathrm{diag}\left(\hat{x} \right) \right)^{-1} A \mathrm{diag}\left(\hat{x} \right) \right]$$
$$q = \left[\left(\mathrm{diag}\left(\hat{x} \right) \right)^{-1} \delta x \right].$$

The matrix, $diag\left(\hat{x} \right)$ denotes the square matrix whose diagonal entries are the elements of $\hat{x}$, and whose off-diagonal entries are zero.

We consider each of these terms in more detail.

The vector c^* is "the demand-based perturbation vector expressed in terms of the normalized degraded final demand" (Santos 2003, p.39). For sector *i*, we have

$$c_i^* = \frac{\hat{c}_i - \tilde{c}_i}{\hat{x}_i}.$$

That is, c_i^* is the difference between "as-planned" final demand and degraded final demand, normalized by "as-planned" production. In the equilibrium $\hat{x}_i \geq \hat{c}_i$, we have by construction $0 \leq c_i^* \leq 1$.

The vector q is the "demand-based inoperability vector expressed in terms of normalized production loss" (Santos 2003, p.39). For sector *i*, we have

$$q_i = \frac{\hat{x}_i - \tilde{x}_i}{\hat{x}_i}.$$

That is, q_i represents the ratio of production loss relative to the "as-planned" production. By construction, $0 \leq q_i \leq 1$ for all sectors *i*.

The matrix A^* is "the interdependency matrix for the demand-based model which indicates the degree of coupling of the industry sectors" (Santos 2003, p. 39). Equivalently,

$$a_{i,j}^* = a_{i,j} \left(\hat{x}_j \middle/ \hat{x}_i \right).$$

That is, $a^*_{i,j}$ indicates the amount of inoperability contributed to sector i from sector ***j*.**

Consider the economy of a foreign country represented using the terms defined above. Let c_i^{US} represent the demand for sector i by the U.S. from our adversary's country, which we assume in practice is equal to the amount of sector i that is exported to the United States. We assume that the U.S. demand for sector i cannot be replaced by demand from another foreign country. Thus, if the U.S. were to completely sanction sector i, then it could degrade final demand according to

$$\hat{c}_i - \tilde{c}_i = c_i^{US}.$$

That is, $\hat{c}_i$, is the "as-planned" final demand or exports for all sectors *i*, and $\tilde{c}_i$ is the "degraded" final demand for all sectors *i*. The variable $\tilde{c}_i$ represents the amount of exports to all countries from our adversary's economy excluding exports to the United States. The difference between these two values, c_i^{US}, is equal to the amount of sector i that is exported to the United States.

In practice, this means that

$$0 \le c_i^* \le \frac{c_i^{US}}{\hat{x}_i} \le 1.$$

Based on these definitions, we introduce the following mathematical program.

Index Use

$i \in N$ sector (alias *j*)

Data [units]

$\hat{x}_i$ adversary's as-planned production for sector $i \in N$ [millions USD]

$\hat{c}_i$ adversary's as-planned final demand for sector $i \in N$ [millions USD]

c_i^{US} adversary's as-planned exports to U.S. for sector $i \in N$ [millions USD]

$a_{i,j}^*$ amount of inoperability contributed to adversary's economy to sector $i \in N$ from sector $j \in N$

c_i^* adversary's normalized demand-based perturbation for sector $i \in N$

s maximum number of sectors that can be targeted in a trade sanction

Variables

q_i adversary's demand-based inoperability for sector $i \in N$

y_i binary attack variable for sector $i \in N$

Formulation

$$\max_{y_i} \sum_{i \in N} q_i \hat{x}_i \qquad (1.1)$$

$$s.t. \quad q_i = \sum_{j \in N} a_{i,j} q_i + c_i^* \qquad \forall i \in N \qquad (1.2)$$

$$c_i^* = \frac{c_i^{US}}{\hat{x}_i}(y_i) \qquad \forall i \in N \qquad (1.3)$$

$$\sum_{i \in N} y_i \le s \qquad (1.4)$$

$$0 \le q_i \le 1 \qquad \forall i \in N \qquad (1.5)$$

$$y_i \in \{0,1\} \qquad (1.6)$$

Discussion

The objective function (1.1) sums the production loss in millions of USD for the adversary's entire economy. Constraints (1.2) calculate inoperability for all industries within the economy. Constraints (1.3) calculate the normalized demand-based perturbation vector based on the sectors of the economy to attack. The assumption is that a sector, if targeted, suffers the largest possible decrease in final demand. Constraint (1.4) restricts the number of sanctions or attacks to a specified scalar value. Constraints (1.5) stipulate that no value in the demand-based inoperability vector may be less than 0 or greater than 1. Constraints (1.6) is a binary constraint where a value of 1 indicates that the corresponding sector was sanctioned and the value of 0 indicates that the corresponding sector was not sanctioned.

B. CASE STUDY: CANADIAN 34-SECTOR TRADE SANCTION MODEL

In this section, we demonstrate how our model can be used to interdict an adversary's economy. To do so, we consider the unilateral trade relationship between Canada and the United States. We consider exports from Canada imported into the U.S. as potential targets for the sanction. The effect will be a restriction on Canadian goods imported into the U.S. from a particular industry. The United States and Canada are strong allies; however, conducting an analysis on a country with which there exists a strong bilateral trade relationship is helpful to understanding the effects of a sanction, and in showing the associated risk that comes with a higher degree of interdependency between two economies.

Throughout our analysis, we use data from the OECD, which standardizes a national economy into 34 sectors, defined by the inter-country input-output (ICIO) industry list in Figure 1. These sectors are, in turn, a consolidation of 95 industries defined by the International Standard Industrial Classification (ISIC) of industrial activities.

Figure 1. Industry Breakdown for the 2015 OECD I-O Database.
Source: Data Sources for Input-Output Database 2015 ed. (2015)

ICIO 34 industry list	ISIC Rev.3	ICIO 34 industry list	ISIC Rev.3
1 Agriculture, hunting, forestry and fishing	01, 02, 05	18 Manufacturing n.e.c; recycling	36, 37
2 Mining and quarrying	10,11,12,13,14	19 Electricity, gas and water supply	40, 41
3 Food products, beverages and tobacco	15, 16	20 Construction	45
4 Textiles, textile products, leather and footwear	17, 18, 19	21 Wholesale and retail trade; repairs	50, 51, 52
5 Wood and products of wood and cork	20	22 Hotels and restaurants	55
6 Pulp, paper, paper products, printing and publishing	21, 22	23 Transport and storage	60,61,62,63
7 Coke, refined petroleum products and nuclear fuel	23	24 Post and telecommunications	64
8 Chemicals and chemical products	24	25 Finance and insurance	65, 66, 67
9 Rubber and plastics products	25	26 Real estate activities	70
10 Other non-metallic mineral products	26	27 Renting of machinery and equipment	71
11 Basic metals	27	28 Computer and related activities	72
12 Fabricated metal products except machinery and equipment	28	29 Research and development; Other business activities	73, 74
13 Machinery and equipment n.e.c	29	30 Public admin. and defence; Compulsory social security	75
14 Computer, electronic and optical products	30, 32, 33	31 Education	80
15 Electrical machinery and apparatus n.e.c	31	32 Health and social work	85
16 Motor vehicles, trailers and semi-trailers	34	33 Other community, social and personal services	90,91,92,93
17 Other transport equipment	35	34 Private households with employed persons	95

Figure 1 illustrates the standardized 34 sectors that compose an economy according ICIO. Within an economy, there are 95 industries according to ISIC and each sector is made up of one or more industries as depicted.

Export data for the economy of Canada, of which sectors 19 through 34 total less than 1% of all exports, are shown in Table 2. For purposes of this analysis, we assume that only the first 18 sectors are subject to the possibility of a trade sanction.

Table 2. Canadian Industry Sectors for 34-Industry Analysis

Sector	Industry Description	Subject to Sanction	Exports
1	TTL_C01T05: Agriculture, hunting, forestry and fishing	YES	$4,578,424,000
2	TTL_C10T14: Mining and quarrying	YES	$53,345,194,000
3	TTL_C15T16: Food products, beverages and tobacco	YES	$10,976,995,000
4	TTL_C17T19: Textiles, textile products, leather and footwear	YES	$3,206,385,000
5	TTL_C20: Wood and products of wood and cork	YES	$14,403,424,000
6	TTL_C21T22: Pulp, paper, paper products, printing and publishing	YES	$14,849,182,000
7	TTL_C23: Coke, refined petroleum products and nuclear fuel	YES	$12,238,648,000
8	TTL_C24: Chemicals and chemical products	YES	$18,039,237,000
9	TTL_C25: Rubber and plastics products	YES	$8,574,877,000
10	TTL_C26: Other non-metallic mineral products	YES	$2,114,611,000
11	TTL_C27: Basic metals	YES	$16,432,853,000
12	TTL_C28: Fabricated metal products	YES	$5,369,976,000
13	TTL_C29: Machinery and equipment, nec	YES	$13,100,999,000
14	TTL_C30T33X: Computer, Electronic and optical equipment	YES	$10,422,383,000
15	TTL_C31: Electrical machinery and apparatus, nec	YES	$4,122,905,000
16	TTL_C34: Motor vehicles, trailers and semi-trailers	YES	$66,000,396,000
17	TTL_C35: Other transport equipment	YES	$8,755,102,000
18	TTL_C36T37: Manufacturing nec; recycling	YES	$6,227,086,000
19	TTL_C40T41: Electricity, gas and water supply	NO	<1%
20	TTL_C45: Construction	NO	
21	TTL_C50T52: Wholesale and retail trade; repairs	NO	
22	TTL_C55: Hotels and restaurants	NO	
23	TTL_C60T63: Transport and storage	NO	
24	TTL_C64: Post and telecommunications	NO	
25	TTL_C65T67: Financial intermediation	NO	
26	TTL_C70: Real estate activities	NO	
27	TTL_C71: Renting of machinery and equipment	NO	
28	TTL_C72: Computer and related activities	NO	
29	TTL_C73T74: R&D and other business activities	NO	
30	TTL_C75: Public administration and defence; compulsory social security	NO	
31	TTL_C80: Education	NO	
32	TTL_C85: Health and social work	NO	
33	TTL_C90T93: Other community, social and personal services	NO	
34	TTL_C95: Private households with employed persons	NO	

Table 2 shows the 34 Canadian Industry sectors, a description of what comprises them, the amount of exports to the U.S. in USD for year 2005 and indicates which sectors are subject to a sanction. Source: OECD

We follow the notation and mathematical development of the National 12-Industry Sector Case Study in Santos (2003). Accordingly, we must first generate the Leontief Technical coefficient matrix A for year 2005. We achieve this by collecting data from the OECD database of Input-Output tables, specifically the table titled, “LEONTFT: Leontief Inverse Matrix (total)” for Canada in year 2005. We denote this table Q^{-1} and we derive A according to

$$\left(Q^{-1}\right)^{-1} = Q$$
$$Q = I - A$$
$$A = -Q + I.$$

At this point in his analysis, Santos (2003) generates the “as-planned” final demand vector $\hat{c}$ and subsequently calculates the “as-planned” production vector $\hat{x}$. However, given the availability of data from the OECD database, we first generate the “as-planned” production vector $\hat{x}$ and then calculate the “as-planned” final demand vector $\hat{c}$.

Within the OECD Structural Analysis (STAN) Database the “as-planned” production vector $\hat{x}$ for year 2005 is titled, “PROD Production (gross output), current prices.” This vector is in Canadian dollars and must be converted to USD.

Following Santos (2003) and according to the basic Leontief input-output model, we are given

$$\hat{x} = A\hat{x} + \hat{c}.$$

Manipulating this equation to calculate $\hat{c}$, we arrive equivalently at

$$\hat{c} = \hat{x} - A\hat{x}.$$

When inspecting the OECD production data for Canada in 2005, we observe that $\hat{x}$ has two missing production values for sectors 28 and 29. As can be seen in Figure 1, sector 28 is composed of industry 72 and sector 29 is composed of industries 73 and 74. However, the only data available is the sum of industries 71 through 74 (C71T74) and the value of industry 71 (C71), as shown in Figure 2.

Figure 2. Data for Industries C71T74 and C71. Source: OECD Structural Analysis (STAN) Database (2015)

Country	Canada						
Variable	PROD Production (gross output), current prices						
Unit	National currency						
Time	2000	2001	2002	2003	2004	2005	2006
Industry							
C71T74 Renting of mach. and equip. - other business activities	1.18949E+11	1.2544E+11	1.29948E+11	1.36216E+11	1.44969E+11	1.53542E+11	1.65294E+11
C71 Renting of machinery and equipment	13234000000	14547000000	14520000000	15274000000	15635000000	15986000000	16616000000

Figure 2 shows raw 2005 production data collected from the OECD STAN Database for industries C71T74 and C71.

We find the sum of sectors 28 and 29 for year 2005 according to

$$\hat{x}_{28} + \hat{x}_{29} = \text{C71T74 - C71}.$$

We assume that "as-planned" final demand for these sectors is nonnegative and use the following system of equations to find feasible production values for $\hat{x}_{28}$ and $\hat{x}_{29}$.

$$\begin{aligned}&\hat{c} = \hat{x} - A\hat{x}\\&\hat{x}_{28} + \hat{x}_{29} = \text{C71T74 - C71}\\&\hat{c}_{28}, \hat{c}_{29} \geq 0\\&\hat{x}_{28}, \hat{x}_{29} \geq 0.\end{aligned}$$

Although there are multiple solutions to these equations, we use the values $\hat{x}_{28} =$ \$34,500,000,000 and $\hat{x}_{29} =$ \$103,500,000,000. These production values meet all constraints with the system of equations.

Santos (2003) calculates the demand-based interdependency matrix A^* using

$$a^*_{i,j} = a_{i,j}\left(\hat{x}_j / \hat{x}_i\right).$$

However, we calculate c^* according to

$$c^*_i = \frac{c^{US}_i}{\hat{x}_i}\left(y_i\right),$$

where the "as-planned" exports to the U.S. for year 2005, c_i^{US}, is generated from the OECD STAN Bilateral Trade Database in goods and is titled, "Bilateral Trade by Industry and End-use." To account for sectors that are not subject to sanction we assume $c_i^{US} = 0$, $\forall i \in \{19, 20, 21 \ldots 34\}$.

At this point, we have all necessary input data to perform our analysis.

C. RESULTS: CANADIAN 34 SECTOR TRADE SANCTION MODEL

The purpose of the Trade Sanction Inoperability Input-Output Model (TS-IIM) is to calculate the economic impact of trade sanctions imposed on an adversary's country. The two metrics that Santos (2003) emphasizes are inoperability and production loss. Results from the Canadian 34-sector analysis appear in Table 3, and include additional metrics.

Table 3 lists, in descending rank order, the sectors that if attacked will create the largest impact (i.e., product loss) on the Canadian economy as a whole. The corresponding sector number ("Sector") and description ("Sector Description") are shown for each.

Continuing from left to right, the remaining columns in Table 3 are headed as follows:

- c_i^* is the percent reduction in demand for each sector by means of U.S. trade sanction.
- q_i is the inoperability or the normalized percentage of production not realized for each sector.
- δx_i represents the production loss in USD for each sector.
- $\sum_i \delta x_i$ is the production loss in USD to the entire Canadian economy.
- $\sum_i q_i \big/ 34$ is the average inoperability among 34 sectors.
- $\delta x_i \big/ \sum_i \delta x_i$ represents the percentage of production loss to the entire Canadian economy that can be attributed to the sector that was attacked.
- $\sum_i \delta x_i \big/ \sum_i \hat{x}_i$, the final column, represents the percentage of total production loss to the entire Canadian economy in USD for each sector attacked.

Table 3. Results from 2005 Canadian 34 Sector Trade Sanction Analysis

Rank Order	Sector	Sector Description	c_i^*	q_i	δx_i	$\sum_i \delta x_i$	$\sum_i q_i / 34$	$\delta x_i / \sum_i \delta x_i$	$\sum_i \delta x_i / \sum_i \hat{x}_i$
1	16	TTL C34: Motor vehicles, trailers and semi-trailers	0.56	1.00	$108,610,003,280	$193,347,458,112	0.0732	56.17%	7.83%
2	2	TTL C10T14: Mining and quarrying	0.34	0.38	$59,661,264,970	$79,692,385,317	0.0203	74.86%	3.23%
3	8	TTL C24: Chemicals and chemical products	0.34	0.45	$23,813,596,764	$44,787,817,624	0.0210	53.17%	1.81%
4	11	TTL C27: Basic metals	0.33	0.45	$22,149,842,559	$39,764,217,689	0.0194	55.70%	1.61%
5	5	TTL C20: Wood and products of wood and cork	0.40	0.46	$16,298,914,598	$32,795,156,106	0.0204	49.70%	1.33%
6	6	TTL C21T22: Pulp, paper, paper products, printing and publishing	0.22	0.28	$19,073,774,279	$30,406,669,981	0.0130	62.73%	1.23%
7	7	TTL C23: Coke, refined petroleum products and nuclear fuel	0.21	0.21	$12,577,658,550	$30,305,340,178	0.0112	41.50%	1.23%
8	13	TTL C29: Machinery and equipment, nec	0.39	0.45	$15,129,033,645	$29,734,027,330	0.0209	50.88%	1.20%
9	3	TTL C15T16: Food products, beverages and tobacco	0.13	0.15	$12,827,716,357	$26,145,006,691	0.0099	49.06%	1.06%
10	14	TTL C30T33X: Computer, Electronic and optical equipment	0.49	0.64	$13,662,701,875	$24,674,991,753	0.0250	55.37%	1.00%
11	17	TTL C35: Other transport equipment	0.40	0.58	$12,647,620,349	$21,437,742,757	0.0212	59.00%	0.87%
12	9	TTL C25: Rubber and plastics products	0.30	0.33	$9,227,425,140	$19,959,741,193	0.0141	46.23%	0.81%
13	18	TTL C36T37: Manufacturing nec; recycling	0.27	0.28	$6,509,172,996	$13,213,253,783	0.0119	49.26%	0.54%
14	12	TTL C28: Fabricated metal products	0.15	0.16	$5,963,358,348	$12,252,674,239	0.0079	48.67%	0.50%
15	15	TTL C31: Electrical machinery and apparatus, nec	0.48	0.53	$4,505,922,875	$9,682,230,102	0.0181	46.54%	0.39%
16	1	TTL C01T05: Agriculture, hunting, forestry and fishing	0.08	0.09	$5,339,358,069	$9,513,049,387	0.0044	56.13%	0.39%
17	4	TTL C17T19: Textiles, textile products, leather and footwear	0.26	0.32	$3,963,412,499	$6,608,359,485	0.0102	59.98%	0.27%
18	10	TTL C26: Other non-metallic mineral products	0.15	0.17	$2,413,828,457	$4,231,970,994	0.0058	57.04%	0.17%

Table 3 shows the results from the 2005 Canadian 34 Sector Trade Sanction Analysis. The results are in descending order and identify the sectors of the Canadian economy that if sanctioned by the U.S. will produce the largest economic impact.

Recall that the premise of this research is to identify the optimal design of an economic sanction by answering the first two of the original thesis research questions below.

1. Which sector of an adversary's economy should be targeted to maximize the impact on its economy as a whole?
2. Which sector of an adversary's economy should be targeted to maximize the impact on a specific sector?
3. To what extent are sanctions effective tools for economic warfare?

Regarding question 1, for year 2005, the sector within the Canadian economy that should be targeted to maximize the impact on the entire economy is sector 16, "TTL_C34: Motor vehicles, trailers and semi-trailers." According to the results, a demand based perturbation $c_{16}^{*} = .56$ results in $q_{16} = 1$ rendering sector 16 inoperable. The "as-planned" production $\hat{x}$ in 2005 was \$108.6 billion USD. Since $q_{16} = 1$, δx_{16} is equal to \$108.6 billion USD, this would be the largest production loss value when compared to all other sectors. The total production loss to the entire economy, $\sum_i \delta x_i$, with a demand based perturbation $c_{16}^{*} = .56$ results in the greatest production loss of \$193.3 billion USD. The average inoperability, $\sum_i q_i / 34$, is greatest when sector 16 is sanctioned and results in a value of .0732, which is 3.6x greater than the industry with a rank order of 2. The column header, $\delta x_i / \sum_i \delta x_i$, can be interpreted as an interconnectedness ratio. A smaller percentage means that particular industry is more interconnected with the entire economy. In contrast, a larger percentage means that a demand-based perturbation will be more contained, reflecting a smaller degree of interconnectedness. Within Table 3, the interconnectedness ratio ($\delta x_i / \sum_i \delta x_i$) results range from 41.50% to 74.86%. For sector 16, the interconnectedness ratio $\delta x_{16} / \sum_i \delta x_i$ has a value of 56.17%, meaning that 56.17% of the production loss is a result of the industry that was sanctioned. The complement, 43.83%, is the ratio of production loss to all other sectors of the economy capturing the cascading effects. With respect to this metric, sector 16 ranks as the 12th most interconnected sector. The ratio of production loss in USD to the entire economy is $\sum_i \delta x_i \Big/ \sum_i \hat{x}_i$ and sector 16 has a value of 7.83%. The second largest production loss ratio to the entire economy is 3.23% and is attributed from sector 2, "TTL_C10T14: Mining and quarrying." Regarding question 2, we found that the best way to maximize the impact on a specific sector was to sanction that sector directly. Indirect sanctions in every case proved to be suboptimal. Regarding question 3, the results that were found using the TS-IIM suggest that trade sanctions can be effective tools to conduct economic warfare.

The results presented in Table 3 are not surprising and can be understood with historical knowledge of the Canadian automotive industry. Dykes and Anastakis (2006) document the history of the automotive history in Canada and note that in 1904 the production of the Ford Model "C" began in Ontario to avoid a 35% import tax into Canada. Demand for the production of vehicles in Canada grew as a result of World War I, and in 1965 the Automotive Products Trade Agreement ("Auto Pact") was formed. The Auto Pact was formed to establish duty-free trade for automobiles and automotive parts between Canada and the United States. Prior to this agreement tariffs on Canadian exports into the U.S. ranged between 17.5% and 25%. With the Auto Pact in place, the Canadian Automotive industry grew rapidly between the mid-1960s and 1970s. However, with that growth the Canadian and U.S. automotive industries because more interdependent making our economies more interdependent.

The Canadian Vehicle Manufacturers' Association (CVMA) acts as an advocate for the Canadian automotive industry. They use industry research and government relations to reach their objectives. According to the CVMA (2011), "In 1964, prior to the signing of the Auto Pact, Canada produced 671,000 vehicles. By 2007, this number had reached 2.56 million, maintaining Ontario as the largest auto assembly jurisdiction in North America" (Canadian Vehicle Manufacturer's Association 2011). The CVMA (2011) also states, "The automotive sector is one of the most important industries in Canada. One in seven Canadians is either directly or indirectly employed in the automotive industry. It is one of Canada’s most strategic business sectors and is the single biggest contributor to Canada’s manufacturing Gross Domestic Product (GDP)” (CVMA 2011). This statement supports the results in Table 3 from the TS-IIM.

Given the strong bilateral trade relationship between the U.S. and Canada, in the event that the U.S. decided to sanction the Canadian economy would there be any repercussions? Can those repercussions be quantified? Will a sanction on particular sectors within the Canadian economy result in effects that are counterproductive to the health of the U.S. economy? In the next chapter, we propose two methods that address these questions.

IV. CALCULATING TRADE SANCTION REPERCUSSIONS

We are interested in measuring the negative repercussions to the U.S. of imposing a sanction on sectors in another country.

A. INTER-COUNTRY INOPERABILITY INPUT-OUTPUT MODEL

The OECD database has an Inter-Country Input-Output (ICIO) table that shows the sector interdependencies for countries and regions around the world. Table 4 displays the countries and regions included in the ICIO table. There are a total of 62 countries and regions included in the ICIO table. Mexico and China have multiple regions represented in the ICIO table.

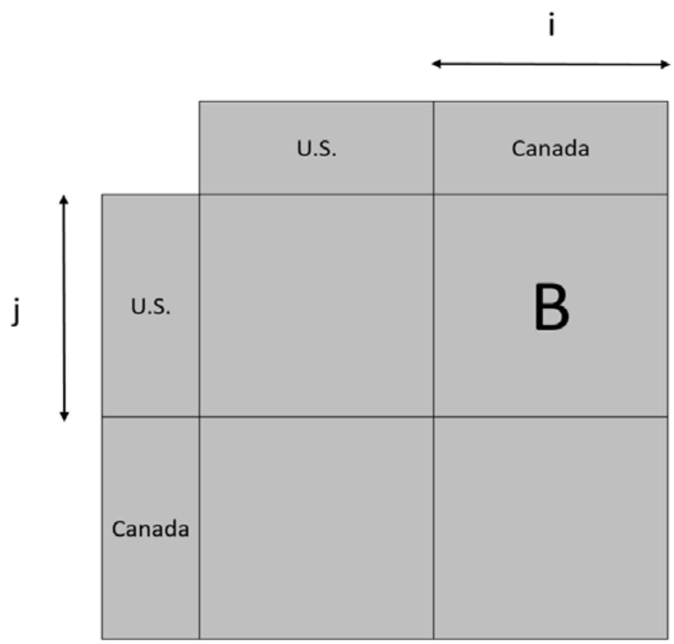
Table 4. ICIO Table Countries and Regions. Adapted from Data Sources for Input-Output Database 2015 ed. (2015)

Country Code	Description	Country Code	Description	Country Code	Description
AUS	Australia	CYP	Cyprus	MEX.GMF	Mexico Global Manufacturing
ARG	Argentina	GRC	Greece	ROU	Romania
AUT	Austria	HKG	Hong Kong SAR	MEX.NGM	Mexico Non-Global Manufacturing
BGR	Bulgaria	HUN	Hungary	RUS	Russian Federation
BEL	Belgium	HRV	Croatia	NLD	Netherlands
BRA	Brazil	ISL	Iceland	SAU	Saudi Arabia
CAN	Canada	IDN	Indonesia	NZL	New Zealand
BRN	Brunei Darussalam	IRL	Ireland	SGP	Singapore
CHL	Chile	IND	India	NOR	Norway
CHN	China	ISR	Israel	THA	Thailand
CZE	Czech Republic	KHM	Cambodia	POL	Poland
CHN.DOM	China Domestic sales only	ITA	Italy	TUN	Tunisia
DNK	Denmark	LTU	Lithuania	PRT	Portugal
CHN.PRO	China Processing	JPN	Japan	TWN	Chinese Taipei
EST	Estonia	LVA	Latvia	SVK	Slovak Republic
CHN.NPR	China Non processing goods exporters	KOR	Korea	VNM	Viet Nam
FIN	Finland	MLT	Malta	SVN	Slovenia
COL	Colombia	LUX	Luxembourg	ZAF	South Africa
FRA	France	MYS	Malaysia	ESP	Spain
CRI	Costa Rica	MEX	Mexico	RoW	Rest of the world
DEU	Germany	PHL	Philippines		

The values within the ICIO table represent the *Trade in Value Added* (TiVA) from row j to column i. The ICIO table quantifies for the entire year the TiVA from each sector within a particular country to all other sectors for countries found within Table 4.

Consider a subset of the ICIO table including only the U.S. and Canada as countries. Furthermore, let B denote the subset of this matrix associated with only the TiVA from U.S. to Canada (see Figure 3).

Figure 3. The Matrix B Represents the *Trade in Value Added* (TiVA) from a Sector *j* in the U.S. to a Sector *i* in Canada.



Within Figure 3, there are four quadrants or matrices. As stated previously the matrix that we will use for the analysis is labeled *B.* In order to understand what matrix *B* depicts it may be easier to interpret the rows *j* as export sectors and the columns *i* as import sectors. When a sanction is issued from the U.S. to Canada, the buying capacity of Canada is reduced as well. When this occurs, fewer commodities are exported from the U.S. to Canada, and the U.S. economy is negatively impacted.

Table 5 shows actual values for the matrix B for the year 2005. The elements within Table 5 express the aggregate amount of TiVA contributed from U.S. sector row to Canadian sector column. Let $b_{j,i}$ represent the amount of TiVA contributed from U.S. row j to Canadian column i. In the case of Table 5, this shows how the U.S. affects Canada.

Let B represent the ICIO table and v represent the as planned value added. In a manner analogous to A^*, we define the matrix B^*, called the Inter-Country interdependency matrix, as,

$$B^* = \left[\left(\text{diag}(v) \right)^{-1} B \, \text{diag}(v) \right].$$

The matrix, $diag(v)$, denotes the square matrix whose diagonal entries are the elements of v, and whose off-diagonal entries are zero.

From B^* we can calculate the negative repercussions to the U.S. resulting from a sanction on Canada affecting the buying capacity of the Canadian economy. Specifically for a sanction on sector i the total repercussion to the U.S. is given by

$$\sum_j b^*_{j,i} = \theta_i ,$$

where $b^*_{j,i}$ is the amount of inoperability contributed from Canadian sector column i to U.S. row sector *j*. For a given vector $y = \{y_1, y_2, \text{y}_3 ...\}$ of binary sanctions the total repercussion is

$$\sum_i y_i \sum_j b^*_{j,i} \ .$$

Table 5. U.S. and Canada ICIO Table (Matrix B)

	CAN_C01T05AGR	CAN_C10T14MIN	CAN_C15T16FOD	CAN_C17T19TEX	CAN_C20WOD	CAN_C21T22PAP	CAN_C23PET	CAN_C24CHM	CAN_C25RBP	CAN_C26NMM	CAN_C27MET	CAN_C28FBM	CAN_C29MEQ	CAN_C30.32.33CEQ	CAN_C31ELQ	CAN_C34MTR	CAN_C35TRQ	CAN_C36T37OTM
USA_C01T05AGR	354.6	0.0	945.5	4.3	461.5	58.9	0.0	6.5	16.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0
USA_C10T14MIN	13.0	435.9	22.2	2.3	7.6	26.5	1229.5	111.7	25.2	44.9	335.5	5.9	3.6	1.2	1.6	9.1	2.1	14.7
USA_C15T16FOD	199.7	1.5	693.2	1.9	0.8	6.3	3.0	50.3	15.7	0.5	1.0	2.5	1.4	0.8	0.2	6.8	0.3	1.5
USA_C17T19TEX	21.0	3.7	4.1	243.9	0.7	9.7	4.6	36.5	32.9	0.8	1.3	3.5	1.7	0.6	1.9	16.9	1.3	58.8
USA_C20WOD	4.1	0.4	2.9	0.2	250.9	145.0	0.7	2.8	8.1	1.7	2.4	8.3	2.3	1.2	0.5	6.5	0.6	119.6
USA_C21T22PAP	29.7	29.5	355.4	24.9	41.2	2665.2	32.0	192.6	68.1	62.6	10.9	29.9	23.6	14.9	10.8	20.8	6.6	95.0
USA_C23PET	104.6	78.6	17.8	11.4	22.2	35.9	100.3	278.8	261.2	9.4	29.0	22.5	15.4	3.1	6.2	21.5	6.7	19.6
USA_C24CHM	945.8	146.5	128.2	39.9	39.8	503.6	455.8	3559.9	1019.0	49.8	97.2	205.4	115.3	28.6	16.1	127.1	16.1	138.0
USA_C25RBP	30.1	7.2	275.1	27.1	45.9	78.4	26.5	205.6	438.4	30.5	3.4	54.4	65.1	38.9	38.7	530.3	12.8	191.6
USA_C26NMM	10.5	24.4	30.5	0.7	8.2	2.9	2.9	18.0	17.5	240.0	45.0	22.3	5.7	0.8	6.7	136.9	5.5	7.4
USA_C27MET	5.4	106.1	1.7	0.4	2.1	6.2	0.9	28.1	6.9	13.7	1527.8	1109.9	618.5	51.2	171.6	828.8	173.2	121.3
USA_C28FBM	65.9	35.8	156.7	0.6	16.7	8.6	4.0	38.2	33.6	8.4	57.9	452.0	212.3	49.1	81.9	263.2	65.8	48.5
USA_C29MEQ	181.5	767.2	5.0	0.5	1.1	10.8	1.2	22.6	11.5	1.7	215.5	518.2	1543.0	123.2	33.9	835.5	167.2	62.0
USA_C30.32.33CEQ	6.3	13.1	3.4	2.1	5.9	45.7	1.5	17.7	13.6	1.9	5.1	46.8	148.5	1288.0	57.7	399.8	97.1	119.2
USA_C31ELQ	3.4	32.0	1.0	0.1	8.0	1.1	0.3	2.8	2.2	0.5	7.2	9.6	164.5	242.8	214.0	287.1	6.3	4.4
USA_C34MTR	7.0	106.3	2.4	0.4	0.5	1.5	0.5	3.7	106.3	0.5	5.3	9.3	103.1	70.7	3.8	19834.4	15.6	3.4
USA_C35TRQ	32.5	29.6	2.6	0.6	0.7	2.3	0.9	6.2	3.1	0.4	3.3	8.3	45.8	15.2	5.4	40.0	2014.3	2.7
USA_C36T37OTM	10.1	3.9	6.1	11.6	2.5	45.6	1.6	82.8	43.3	30.5	18.6	6.9	10.3	11.0	1.5	19.9	3.3	290.0

Table 5 shows a subset of matrix *B* for sectors 1–18 in year 2005. The elements within this matrix represent the aggregate amount of trade in value added contributed from U.S. sector row to Canadian sector column in millions of USD.

Using the ICIO matrix in this manner preserves the notion of inoperability in our analysis, as the matrix *B** quantifies the inoperability contributed from Canadian column sector *i* to U.S. row sector *j*. That is, a reduction in Canadian buying power creates a demand-side perturbation for the U.S. economy.

We now assume that there is a limit on the total repercussion that the U.S. is willing to accept when imposing a sanction. We denote this as v.

This leads to the following formulation for the Inter-Country Inoperability Input-Output Model (IC-IIM).

$$\max_{y_i} \sum_{i \in N} q_i \hat{x}_i \tag{1.1}$$

$$s.t. \quad q_i = \sum_{j \in N} a_{i,j} q_i + c_i^* \qquad \forall i \in N \tag{1.2}$$

$$c_i^* = \frac{c_i^{US}}{\hat{x}_i}\left(y_i\right) \qquad \forall i \in N \tag{1.3}$$

$$\sum_{i \in N} y_i \leq s \tag{1.4}$$

$$0 \leq q_i \leq 1 \qquad \forall i \in N \tag{1.5}$$

$$y_i \in \{0,1\} \tag{1.6}$$

$$\sum_i y_i \sum_j b_{j,i}^* \leq v \tag{1.7}$$

Discussion

The objective function (1.1) and constraints (1.2)-(1.6) are as above. Constraint (1.7) puts a limit on the acceptable repercussion to the U.S., measured in loss of Trade In Value Added (TiVA) to the U.S. economy. The TS-IIM did not consider the negative consequences to the U.S.; however, the IC-IIM does by means of constraint (1.7). With this addition, we hope to identify sanctions that maximize production loss within our adversary's country while staying below a tolerable threshold for loss of TiVA.

We note that our focus on demand-side inoperability ignores any direct supply-side repercussions to the U.S. economy; in essence, we assume that any commodities previously imported from Canada can be replaced or substituted with commodities obtained elsewhere. However, in situations where Canada exports a rare commodity—one without replacement or a suitable substitution—to the United States exclusively, the matrix in the lower left corner of Figure 3 could be used for analysis. In what follows, we focus exclusively on demand-side inoperability as described above.

B. RESULTS: INTER-COUNTRY INOPERABILITY INPUT-OUTPUT MODEL

The first step in using the IC-IIM is to calculate the repercussion to the U.S. when sanctioning each sector *i* in Canada, measured as the total trade in value lost, θ_i. Table 6 lists these repercussions, ordered from low-to-high in value for θ_i. In addition, Table 6 displays the lost value to Canada. We observe that a sanction on sector 16, "TTL_C34: Motor vehicles, trailers and semi-trailers" not only has the largest impact on Canada ($193B), but also the largest repercussion to the U.S. ($25B).

Table 6. Repercussions in Lost Value to U.S. when Sanctioning Sectors in Canada (Year 2005 Data)

Rank Order	Sector	Sector Description	Lost Value to U.S. (all sectors) when sanction imposed on Canada sector *i* θ_i	Lost Value to Canada (all sectors) when sanction imposed on Canada sector *i* c_i^*	$\sum_i \delta x_i$	Relative Cost (Lost Value US)/Lost Value Canada) $\theta_i / \sum_i \delta x_i$
1	4	C17T19: Textiles, textile products, leather and footwear	$297,411,012	0.26	$6,608,359,485	$0.05
2	10	C26: Other non-metallic mineral products	$353,608,439	0.15	$4,231,970,994	$0.08
3	15	C31: Electrical machinery and apparatus, nec	$445,732,999	0.48	$9,682,230,102	$0.05
4	5	C20: Wood and products of wood and cork	$457,561,468	0.40	$32,795,156,106	$0.01
5	9	C25: Rubber and plastics products	$1,261,377,846	0.30	$19,959,741,193	$0.06
6	7	C23: Coke, refined petroleum products and nuclear fuel	$1,621,924,533	0.21	$30,305,340,178	$0.05
7	18	C36T37: Manufacturing nec; recycling	$1,778,967,698	0.27	$13,213,253,783	$0.13
8	11	C27: Basic metals	$1,952,290,395	0.33	$39,764,217,689	$0.05
9	1	C01T05: Agriculture, hunting, forestry and fishing	$2,168,650,121	0.08	$9,513,049,387	$0.23
10	17	C35: Other transport equipment	$2,551,981,513	0.40	$21,437,742,757	$0.12
11	14	C30T33X: Computer, Electronic and optical equipment	$3,320,544,666	0.49	$24,674,991,753	$0.13
12	2	C10T14: Mining and quarrying	$3,617,116,268	0.34	$79,692,385,317	$0.05
13	3	C15T16: Food products, beverages and tobacco	$4,020,040,695	0.13	$26,145,006,691	$0.15
14	13	C29: Machinery and equipment, nec	$4,040,085,172	0.39	$29,734,027,330	$0.14
15	12	C28: Fabricated metal products	$4,089,313,995	0.15	$12,252,674,239	$0.33
16	6	C21T22: Pulp, paper, paper products, printing and publishing	$5,746,568,151	0.22	$30,406,669,981	$0.19
17	8	C24: Chemicals and chemical products	$5,859,378,015	0.34	$44,787,817,624	$0.13
18	16	C34: Motor vehicles, trailers and semi-trailers	$25,519,324,890	0.56	$193,347,458,112	$0.13

Table 6 shows the repercussion to the U.S. when sanctioning each sector *i* of Canada, for sectors 1–18 in year 2005. Rows are rank ordered (from low to high) in terms of the total trade in value lost, θ_i , to the United States.

Table 6 also shows the "relative cost" of sanctioning each Canadian sector. More specifically,

$\frac{\theta_i}{\sum_i \delta x_i}$ is the amount of TiVA in USD lost by the U.S. for every $1 USD in production lost by the Canadian economy. This metric assesses how expensive a sanction is to the United States. Using this metric, the most expensive sanction to the U.S. is sector 12, "TTL_C28: Fabricated metal products" at a cost $0.33 USD TiVA for every $1 USD Canadian production. The second most expensive sanction is sector 1, "TTL_C01T05: Agriculture, hunting, forestry and fishing" at a cost of $0.23 USD TiVA for every $1 USD Canadian production. The third most expensive sanction is sector 6, "TTL_C21T22: Pulp, paper, paper products, printing and publishing" at a cost of $0.19 USD TiVA for every $1 USD Canadian production.

The results in Table 6 show clearly that the interconnected nature of the U.S. and Canadian economies means that a sanction on Canada can have potentially serious economic repercussions to the U.S. We now turn to the IC-IIM to consider how to target individual sectors in the Canadian economy optimally while limiting repercussions to our own economy.

Table 7 shows the optimal solution y_i^* for all $v \in \{1, 2, 3, ...30\}$ in billions of USD, with the additional restriction $\sum_i y_i \leq 18$.

Table 7. IC-IIM Results for U.S. and Canada (Year 2005)

Rank Order	Sector i	Sectors to attack given budget (v): y_i^*																														Row Sum	Rel. Freq.
1	4	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	28	93.33%
2	10	0	1	0	0	0	0	0	0	1	0	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	21	70.00%
3	15	1	1	1	0	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	27	90.00%
4	5	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	30	100.00%
5	9		0	0	1	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	22	73.33%
6	7		0	0	0	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	24	80.00%
7	18		0	0	0	0	0	0	0	0	0	0	1	0	1	1	0	0	1	0	0	1	0	0	1	1	0	0	1	1	0	9	30.00%
8	11		0	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	26	86.67%
9	1			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.00%
10	17			0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	17	56.67%
11	14				0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	1	1	0	1	0	1	1	1	0	1	10	33.33%
12	2				0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	26	86.67%
13	3					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	2	6.67%
14	13					0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	1	0	1	1	1	1	1	1	9	30.00%
15	12					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.00%
16	6						0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.00%
17	8						0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1	1	1	1	1	1	1	1	11	36.67%
18	16																										0	0	0	0	0	0	0.00%
Attack Budget (v)		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**		
Canadian Production Loss		**42.4**	**53.3**	**82.2**	**99.1**	**128.7**	**149.4**	**168.5**	**189.1**	**203.0**	**218.8**	**223.0**	**236.2**	**244.4**	**253.4**	**257.6**	**269.1**	**274.2**	**282.3**	**289.2**	**298.8**	**305.7**	**313.9**	**318.9**	**327.1**	**332.2**	**343.6**	**343.6**	**356.8**	**358.3**	**369.8**		
U.S. Lost TiVA		**.9**	**1.5**	**2.8**	**3.9**	**4.8**	**5.9**	**6.7**	**7.9**	**8.7**	**9.6**	**10.0**	**11.7**	**12.5**	**13.9**	**14.3**	**15.8**	**16.5**	**17.6**	**18.4**	**19.9**	**20.9**	**21.7**	**22.4**	**23.5**	**24.2**	**25.7**	**25.7**	**27.5**	**28.2**	**29.7**		

Table 7 provides the optimal solutions for y_i given different budget for repercussion (v). Black cells indicate attacks that are infeasible because the repercussion of sanctioning that sector alone exceeds the given budget. The two rightmost columns provide information about how often sectors are sanctioned given different values of v . The unit for the bottom three rows are billions of USD.

Consider, as an example, the case where we have a maximum $v = \$5 billion$ in allowable repercussions. In this case, there are four sectors sanctioned, namely sectors 2, 4, 5, and 15. The sum of all production loss, $\sum\sum_i \delta x_i$, to the Canadian economy given these four sanctions is \$128.7 billion. The total trade in value lost, $\sum_i \theta_i y_i$ experienced by the U.S. for the four sectors sanctioned is \$4.8 billion.

Of the 18 sectors that are subject to a sanction, sector 5, "TTL_C20: Wood and products of wood and cork," was sanctioned for every value of v. The second most sanctioned sector is sector 4, "C17T19: Textiles, textile products, leather and footwear" for a total of 28 times. The third most sanctioned sector is sector 15, "C31: Electrical machinery and apparatus, nec" for a total of 27 times. This raises the question as to why these sectors are sanctioned more frequently than others. What we found were that these sectors have the lowest "relative cost" values for $\frac{\theta_i}{\sum_i \delta x_i}$ making these the cheapest sectors for the U.S. to sanction. Sectors 5, 4 and 15 had values of $\frac{\theta_i}{\sum_i \delta x_i}$ equal to \$0.01, \$0.05 and \$0.05, respectively.

Sectors 1, 6, 12, and 16 were not sanctioned for any value of v .These sectors are, "TTL_C01T05: Agriculture, hunting, forestry and fishing," "TTL_C21T22: Pulp, paper, paper products, printing and publishing," "TTL_C28: Fabricated metal products" and "TTL_C34: Motor vehicles, trailers and semi-trailers," respectively. When assessing why these sectors were not sanctioned you must observe two factors. These two factors are $\frac{\theta_i}{\sum_i \delta x_i}$ and θ_i. As stated previously the three most expensive sectors to sanction are sectors 6, 1, and 12 at a cost of \$0.33, \$0.23, and \$0.19, respectively. In regard to sector 16, we have concluded that it is relatively inexpensive when observing TiVA loss, but the aggregate loss given a complete sanction of sector 16 results in a \$25.5 billion value for θ_i due to the size of this sector, which is the largest for value for θ_i.

V. CONCLUSION

A. SUMMARY

The primary goal of this research is to identify the optimal design of an economic trade sanction based on the resulting estimated production loss experienced by an adversary's economy. Expanding upon the mathematical development in Santos (2003) and using data from the OECD database, we develop the TS-IIM. For purposes of demonstration and validation, we pose a hypothetical scenario in which the U.S. and Canada are adversaries instead of allied nations. Specifically, our analysis using the TS-IIM identifies sector 16, "TTL_C34: Motor vehicles, trailers and semi-trailers" as the sector to sanction within Canada to create the largest estimated production loss, which we approximate to be $193.3 billion. Further investigation helps us to gain an understanding as to why exports of sector 16 from Canada to the U.S. would be so detrimental to the health of the Canadian economy if sanctioned. A long history of bilateral trade between the two nations specifically with the automotive industry dating back to 1965 has allowed tariff- free trade between the two nations. For greater than half a century, the bilateral trade relationship between the U.S. and Canada has resulted in higher economic interdependency between the two nations, thus making sector 16 of considerable importance to the economy of Canada.

Given the strong dependence by Canada on the U.S., is it reasonable to expect that a sanction of sector 16 by the U.S. could result in economic repercussions? In response to this question, we present the IC-IIM, which extends the TS-IIM but also considers the trade in value loss (TiVA) the U.S. economy will experience. This allows us to prevent a scenario that leads to mutual economic destruction of the U.S. and Canadian economies. In particular, a sanction on sector 16 as indicated in Table 3 without gaining an understanding of the repercussions to the U.S. the effects could be detrimental to the economic health of the United States.

B. FUTURE WORK

There are four enhancements to the IC-IIM that could be beneficial to this field of study. The first would be to consider partial sanctions. Currently, if a sector is sanctioned then the entire sector is sanctioned. However, if we consider partial sanctions along with the tradeoff cost of a sanction, the optimal sectors to target would likely change.

The second enhancement would address how employment within each sector is impacted given a reduction in demand. Given a reduction in demand there will be a reduction in production thus a reduction in the size of each sectors workforce. This would give us another layer to the narrative of how each economy is impacted.

The third enhancement to the IC-IIM would be to include as many countries as possible in the model instead of just the U.S. and Canada. This would allow us to observe not only the repercussions from U.S.-issued sanctions, but also the indirect repercussions issued by allied countries, creating a multilateral IC-IIM.

The final improvement would be to create a user-friendly graphical interface to allow policy makers and politicians the ability to conduct this type of analysis independently. The purpose of this tool would be to gain a rough understanding of the impact to all countries impacted directly or indirectly.

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