LIDAR-Based Framework for Integrating Local-specific Vulnerability Conditions in Deriving Perturbations to the Dynamic Inoperability Input-Output Model

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ABSTRACT

The prevalent adverse impacts of disastrous events intensified by the alarming threats of climate change have underscored the urgency to develop new strategies to enhance preparedness and resilience within an economy. Consequently, more reliable models to estimate the associated direct and indirect economic losses resulting from these disruptive events have been formulated. However, recent techniques and technologies that may be potentially capable of increasing the precision of these risk estimates have not yet been fully integrated into existing disaster loss estimation models. Further, though the prioritization of key sectors in resilience enhancement planning requires a holistic approach from the regional and national levels, the degree of vulnerability varies based on local-specific conditions. Hence, this research explores the relative novelty of the use of flood hazard maps in economic input-output analysis. It proposes a framework to integrate the spatial dimension in evaluating the associated macroeconomic losses from local-specific vulnerability conditions. The research will demonstrate the framework through an adaptation of the Light Detection and Ranging or LIDAR-based 3D flood hazard map data developed by the Philippine government agencies in collaboration with various research institutions to derive perturbations to the Inoperability Input-output Model. The research will investigate the impact on regional economic losses and recovery behavior from having a heterogeneous sector distribution across identified local areas of high vulnerability. The resulting methodology will have flexibility and scalability over flood hazard maps of different return periods and other hazard maps for other regions and disasters.

1. Introduction

Flooding, as an aftermath of torrential rains, exacerbates the direct and indirect impacts of disasters to an economy. Amidst the clamor for understanding the repercussions of unmitigated consequences of climate change, the inlands and coastal communities are becoming more and more susceptible to the risk of flooding. Sound flood management practices have been shared and continue to be developed both in the national and international levels.[23,36] While methods that provide accurate and extensive information systems for receiving and providing information have been the focus of recent hydrological and flood management studies.[13]

Risk assessment and management techniques have provided decision makers a quantitative approach for analyzing the impacts of disastrous events such as tropical storms accompanied by flooding. In disaster risk analysis, the integration of concepts from various fields of knowledge such as infrastructure renewal,[(2)(4)(8-10)] econometric models,[(14)] input-output modeling,[(7)(22)(27)] statistical analysis[(3)(6)(18)(20)(33-34)] and multi-criteria decision-making[(19)(34)] strengthen the reliability of information that is significant to the formulation of disaster preparedness plans. Still, the increasing degree of accuracy of recently developed models for obtaining spatial information has not been fully integrated to existing economic risk assessment techniques. However, acquired spatial information through flood hazard maps has already found its use in flood risk management, land-use planning, emergency planning and management, public awareness and flood insurance.[15, 17]

The vulnerability to disaster consequences varies between the different sectors across an economic region. This variability is a function of the sectors' interdependency on various material and service inputs and outputs. The density of the sources of these inputs and outputs, which is often heterogenous in distribution across the region, influences the levels of dysfunctionality depending on whether the sources are situated on the high-risk flood areas of the region that can prohibit their accessibility.

Consequently, this research aims to explore the novelty of using recently generated high-accuracy spatial information for the further understanding of the economic impacts of intraregional variability in dysfunctionality levels experienced by various manufacturing, service and infrastructure systems in times of natural calamities. Moreover, the flexibility of flood hazard maps in reflecting changes in surface structure as a result of natural causes or the implementation of mitigating strategies over time makes it possible to analyze corresponding changes in economic losses resulting from these strategies.

The remainder of this paper is organized as follows: Section 2 provides the literary work on the use of I-O models for the estimation of economic risks and the Inoperability Input-output model (IIO) to which a proposed LIDAR-based Initial Perturbation (LIP) Framework will be integrated into an Inoperability Input-output (IIO) Model; Section 3 discusses the components of the proposed LIP-IIO framework. Section 4 presents the results and findings of the LIP-IIO framework as demonstrated on the case of Tropical

Storm Sendong that struck Iligan City in Northern Mindanao, Philippines in December, 2011; The paper culminates with a synthesis of the findings of the research and the identified areas for future research endeavors.

2. Methodological Background

a. Leontief's Economic Input-output Model

A depiction of the American economic structure, the I/O model of Wassily Leontief was awarded a Nobel Prize in 1973.(24-25) The I/O model considers an economic system as a set of interrelated sectors assuming producer and consumer roles in the production process.(24) The total value of the goods or service produced by a sector (i.e. producer role) is distributed to intermediate consumers (i.e. producers as consumers) and to end-users (i.e. final demand). Hence, the original economic input-output model is a representation of the inter-industry flow of goods and services through economic transactions between these producers and consumers.(32)

In mathematical form, the total production output (supply) from all sectors, **x**, as reflected in Eq. (1), is the sum of the intermediate consumption among interdependent sectors (i.e. **Ax** as intermediate demands) and the demand of the final consumers (i.e. **c** as final demands),

$$\mathbf{x} = \mathbf{A}\mathbf{x} + \mathbf{c}, \tag{1}$$

where **x** = total output vector
c = final consumption vector
A= interdependency or technical coefficients matrix.

Initially, Leontief's input-output model was utilized for the analysis of the impact of introducing new products, changes in household consumption patterns, increases in government spending and net exports on final demand. The standard input-output analysis would be concerned in finding the value of output, x_i, from each sector i that will satisfy specific forecasted final demand levels, c_i.(27)

b. Quantifying Direct and Indirect Economic Risks from Disasters

The industry-by-industry total requirement of the Philippines is one of the data sets for the input-output (I-O) accounts that are prepared by the National Statistics Coordination Board (NSCB), National Statistics Office.30 The accounts are a reflection of the flow of goods and services over the production process of different industries and service sectors on a national level. The abundant collection of economic transaction information has contributed to the recent growth of I–O model applications. Today, extensions of the I/O model are applied to the analysis of infrastructure interdependencies and risks of terrorism,(33) regional electric power blackouts,(1) inventory management,(7) sequential decisions with multiple objectives,[34] multiregional disaster preparedness policies,[11] geospatial analysis,[16] and agent-based simulation.[35]

The *Inoperability Input-output Model (IIM)* was formulated to investigate the losses resulting from the propagation of direct and indirect disruption among interdependent sectors. The IIM introduced the now widely used risk analysis metrics, namely, economic loss and inoperability.[21][32] With the interdependency matrix **A** assumed invariant to changes in output and consumption levels even when a system is in a disrupted state, the IIM defines economic loss as

$$\mathbf{x} - \tilde{\mathbf{x}} = \mathbf{A}(\mathbf{x} - \tilde{\mathbf{x}}) + (\mathbf{c} - \tilde{\mathbf{c}}). \qquad (2)$$

where $\tilde{\mathbf{x}}$ = reduced output vector (system in disrupted state)
$\tilde{\mathbf{c}}$ = reduced consumption vector (system in disrupted state)
$\mathbf{x} - \tilde{\mathbf{x}}$ = economic loss vector
$\mathbf{c} - \tilde{\mathbf{c}}$ = change in final consumption vector

Eq. (2) relates how the economic loss, $\mathbf{x} - \tilde{\mathbf{x}}$, is a function of propagated intermediate disruptions resulting to the reduced flow of goods and services to satisfy intermediate demands (i.e. $\mathbf{A}(\mathbf{x} - \tilde{\mathbf{x}})$) and final demands (i.e. $\mathbf{c} - \tilde{\mathbf{c}}$). Economic loss quantifies the unfulfilled proportion of the required production output, **x**, in terms of its associated monetary value (in thousands of dollars). Intuitively, the total economic impact is the sum of economic losses of all the *n* sectors of a region. Hence, the sectors experiencing the highest economic losses are critical to the region's economic recovery following a disastrous event.

Inoperability is the normalized economic loss, $x_j - \tilde{x}_j$, from (2) with respect to its required total output, x_j as shown in Eq. (3).

$$q_j = (x_j - \tilde{x}_j) / x_j. \qquad (3)$$

The reduced production output variable, $\tilde{x}_j$, has a range $[0, x_j]$. Hence, a completely disrupted sector has an inoperability of 1 while a totally unaffected sector has an inoperability of zero. For the derivations of the inoperability equation in (4) that relates **q** with **A*** and **c***, the reader is referred to the work in (33).

$$\mathbf{q} = (\mathbf{I} - \mathbf{A}^*)^{-1}\mathbf{c}^*, \qquad (4)$$

where $\mathbf{q}$ = inoperability vector
$\mathbf{c}^*$ = final consumption perturbation vector
$\mathbf{A}^*$ = interdependency matrix.

3. Methodology

a. Disaster Risk Exposure Assessment for Mitigation – Light Detection and Ranging (DREAM-LIDAR) Project Database

The Department of Science and Technology (DOST) of the Philippine Government, heeding the President's call for a more accurate and holistic system for disaster response, prevention and mitigation, formed Project NOAH – Nationwide Operational Assessment of Hazards. Acknowledging the significance of managing and formulating risk reduction activities, different government agencies, namely, PAGASA, PHIVOLCS and the DOST-Advanced Science and Technology Institute (ASTI) along with researchers from University of the Philippines have worked together on various NOAH components.[31]

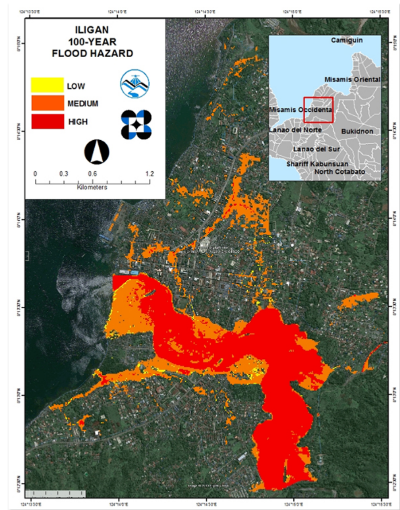

Figure 1. Iligan Flood Hazard Map,100-year return period

Disaster Risk Exposure Assessment for Mitigation – Light Detection and Ranging (DREAM-LIDAR), being one of the components of Project NOAH, is responsible for generating flood inundation and hazard maps utilizing the Light Detection and Ranging Technology for the country's river basins, watersheds and other flood-prone areas. Figure 1 shows a flood hazard map for Iligan city, one of the devastated cities of region ten from the onslaught of Tropical storm Sendong (i.e. International name Washi) in December of 2011. The DREAM-LIDAR component is almost complete in its preparation of flood hazard maps and the map shown in Figure 1 has been one of the first sets of maps developed for the Northern Mindanao region. These hazard maps are made available on the DOST website (http://noah.dost.gov.ph) in 5, 10, 25, 50 and 100 year return periods. Area vulnerability is categorized in color codes of yellow, orange and red in the order of increasing risk.[12]

b. Integrated Map Data Layers

Similar to the merging of data to generate flood hazard maps, additional information is required in order to identify the risks involved in the different areas of a region. Specifically, risks can be mitigated by providing timely and accurate information to the population within the area at risk by facilitating the reduction of the exposure to the high-risk area. In investigating the level of exposure, existing locations of industries, structures, and people who may be the subjects for exposure along with their densities enable the analysis of the impacts of specific disastrous events. Figure 2 and figure 3 which show population density and land use of a region, respectively, provide useful information in identifying the areas of highest exposure levels.

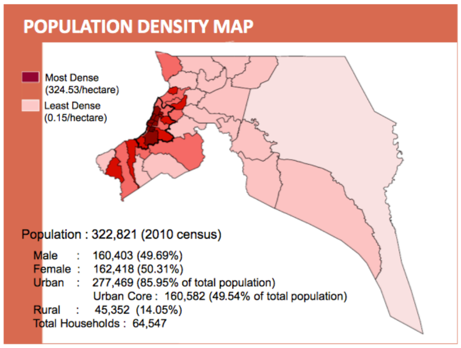

Figure 2. Population Density Map of Iligan[5]

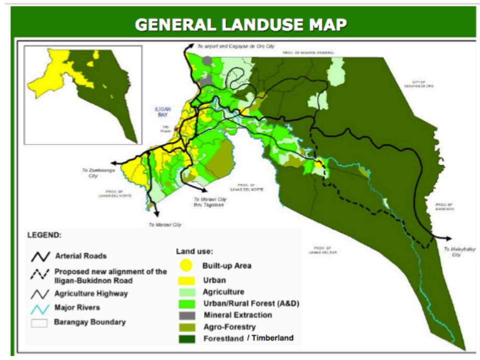

Figure 3. Existing General Land Use Map of Iligan[5]

One of the assumptions of the proposed LIDAR-based Initial Perturbation framework is that the map of interest is reflective of the underlying behavior of exposure of a specific sector to represent the level of dysfunctionality once the sector is exposed to a low, medium, or high-risk area based on the flood hazard map color code and coordinates. For example, the population density map is representative only of the impact of the disaster on the housing sector if the population density leads to the same density of housing across the region. In the case of the labor force density, proximity may well be another underlying assumption that has to be verified in assessing the sufficiency of using the same population density map to represent the impact on the labor sector. This may also be the case for other sectors that provide services (i.e density of those for whom the service must be provided for) where population density and service demand may or may not have perfect correlation. Hence, the novelty of the use of maps and its integration to hazard maps resulting in a map overlay exposes the application of other existing types of maps and may even arise to the demand for new sector-specific output density maps.

c. LIDAR-based Initial Perturbation (LIP-IIOA) Framework

With the spatial dimension integrating exposure data of each sector, the variability of exposure to the low, medium, and high-risk areas identifiable from the LIDAR flood hazard map can be obtained resulting into a local-specific distribution of vulnerability conditions for the sectors. Consequently, a distribution of initial inoperability may be used to evaluate the associated macroeconomic losses from specific disasters instead of implementing a single regional initial inoperability multiplier. In the latter, the only factor to express initial inoperability diversity is the difference in the total input required by a sector that is disrupted by the regional multiplier.

Consider sector i and assume that its expected output, x_i, is linearly distributed across the areas where the product (or service) is made. Further, assume that proportions pR_i, pO_i and pY_i of the output, x_i, are made in regions defined by the flood hazard maps as high-risk, medium-risk, and low-risk, respectively. For a general model, initial inoperability levels associated by providing the product or service in a risk area such as $qR_{o,i}$, $qO_{o,i}$, and $qY_{o,i}$ may be obtained from previous disaster data and/or through expert elicitation. However, for the purpose of demonstration of the framework, let

$$qR_{o,i} = 1, \text{ completely dysfunctional in high-risk area} \qquad (5)$$
$$qY_{o,I} = 0, \text{ completely functional in low-risk area}$$

while $qO_{o,i}$ will be sector specific.

Combining exposure variability across risk areas, the LIDAR-based effective inoperability is

$$q_{o,i}^{eff} = \mathrm{pR}_i * \mathrm{qR}_{0,i} + \mathrm{pO}_i * \mathrm{qO}_{0,i} + \mathrm{pY}_i * \mathrm{qY}_{0,i} \,. \qquad (6)$$

Since $q_{o,i}^{eff}$ is defined as the effective initial sector inoperability, it can directly be representative of the initial inoperability vector as an input to the IIM. This effective sector initial inoperability, $q_{o,i}^{eff}$, may be formulated as a cross product of the initial sector inoperability vector and the column under the technical coefficient matrix of the region of interest, A_R, corresponding to the input requirement of sector i. The complexity of correlated initial inoperability values, however, leaves the use of the cross product representation for only the sectors whose exposure distribution cannot easily be attributed to any existing maps.

The value assigned to $qR_{o,i} = 1$ and $qY_{o,I} = 0$ may further be investigated but the framework proposes that the same level of dysfunctionality be associated per sector with each color code of the flood hazard map in order to investigate different scenarios whose hazard maps may vary per region of interest or land development or both. The hazard maps, by themselves, are capable of reflecting the impacts of mitigation strategies on topography and land use.[15]

d. The Case of Tropical Storm "Sendong" (International name - Washi)

The persistence in addressing the significant impacts on the economy and public safety from evolving threats from natural disasters has resulted to the publication of economic loss estimates among aggregated sectors (Table 1) by the region X's Office of Civil Defense's Regional Disaster Risk Reduction and Management Council.[29] The classic IIOA model was applied to compare these economic losses from the losses computed from having a homogenous initial inoperability multiplier. Then, the LIP-IIOA was employed to obtain $qO_{o,I}$ values based on the reported economic losses of the same set of sectorial groups.

To represent the diversity in the agricultural sector and its proportions of affected areas within the medium and high risks ranges, the map overlay was made between the flood hazard map and the existing land use map. On the contrary, a population density map has been utilized for overlay with the flood hazard map with some sectors such housing and health.

4. Results and Discussion

The economic losses resulting from the use of a homogenous initial inoperability factor representing the dysfunctionality or inability of the region to produce its expected total economic output are summarized in Table 1. The Inoperability Input-output model assumes a regional initial inoperability of 41.36% to match the total regional economic losses published in a post disaster needs assessment commissioned by the Office of Civil Defense Regional Disaster Risk Reduction and Management Council of the region (2012).[29] However, individually, the computed economic losses using a homogenous initial sector inoperability multiplier yield disproportionate values from their sector assessed economic losses (see Table 1). Hence, for the case presented, a heterogenous distribution of initial inoperability reflecting sector vulnerability is a more suitable model.

Sector Aggregation	Region's Economic Loss Assessment	Economic Losses at Homogenous Qo	Economic Losses LIDAR-based Qo
SOCIAL SECTOR			
Housing	162,329,785.00	32,713,372.76	162,551,447.37
Health	27,858,988.00	11,063,981.61	27,850,254.04
Education		8,108,151.91	34,690,381.87
INFRASTRUCTURE			
Transport	92,300,000.00	67,633,382.42	92,280,201.37
Flood Control			
Water Supply & Dist'nSystems	55,000,000.00	7,113,615.26	48,110,216.09
Power	216,002,000.00	72,213,261.16	215,541,794.18
Telecommunications	2,750,000.00	35,026,631.33	10,054,193.30
PRODUCTIVE SECTOR			
Agriculture	639,900,000.00	231,815,124.83	639,589,997.88
Trade, Industry & Services	22,750,000.00	876,366,427.27	226,515,489.68
HUMAN RECOVERY NEEDS			
Governance, DRRM	32,552,000.00	16,088,363.23	6,626,297.88
Environment			
Social Protection, Gender, Livelihood	136,170,871.00	-	32,469,945.37

Table 1. Sector Economic Loss Estimates of Homogenous Vulnerability Distribution

Sector vulnerability is a function of the existence and intensity of an initiating event such as a tropical storm as well as the degree of exposure to the initiating event. Analyzing the degree of exposure of a sector in the case presented, the compounded impact of various spatial information derived from the flood hazard maps, population density and land use maps show consistency between high flood risk areas and urban or densely populated communities. The United Nations Office for the Coordination of Humanitarian Affairs (OCHA) through MapAction published a map of full and partial damages to housing in Iligan brought about by Sendong.[28] An overlay of Project NOAH's Flood Hazard Map supports the criticality of the damage as shown in Figure 4.

The proportion of fully damaged houses over partially damaged ones can be observed to be greater in medium to high flood risk areas. For a 100-year return period flood, the corresponding LIDAR factor, LO, is 0.79 for the housing sector for Iligan. A similar map in (26) highlighting the inaccessible areas in Iligan and Cagayan De Oro three weeks after Sendong struck the region can be utilized to compare the impact of heterogeneity in identified medium to high risk areas on the transportation sector.

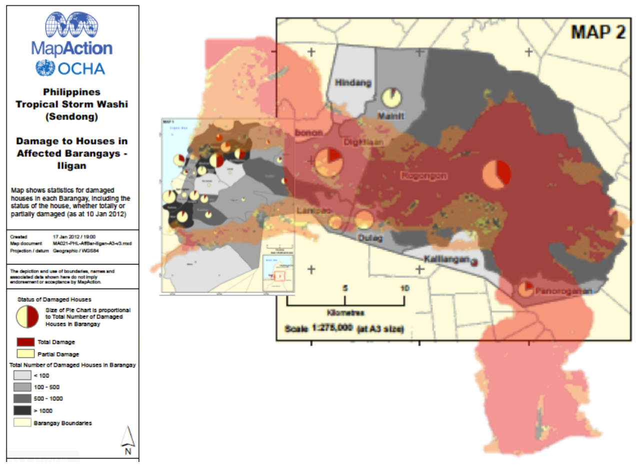

Figure 4. Damaged Houses – Hazard Map Overlay

However, it can be observed that for two out of the nine aggregated sectors, namely, communication and trade, industry and services, large variances were exhibited from the assessed economic loss values. This may have been brought about by the same assumption of proportionality to urban communities utilized in overlaying spatial information from the flood hazard map with the available population density and land use maps. The differences suggest that either initial inoperability belonging to these groups are not accurately reflected by these maps or that a joint inoperability function is required. The first may be true for the communication sector. Hence, further analysis on existing maps and development of new maps may be required for certain sectors. While the second hypothesis (i.e. joint function) can be explained by the complexity of the set of input required by each manufacturing sector holding a double level map insufficient to reflect inoperability dependency over n sectors. This is beyond the scope of this research. On the other hand, the deviation from the assessed losses for the water supply and distribution systems sector may be due to the increased demand for water resulting from displacement and increased sanitary needs of the region during the time of the disaster and initial recovery stage.

5. Conclusion and Areas for Future Research

The proposed LIP-IIO Framework has demonstrated the difference in individual sector economic losses when inoperability is modeled as a function of sector exposure to multi-level risk areas. As a result, more accurate economic loss values can be obtained whenever heterogeneity in sector inoperability can be described using existing maps and databases. However, it is suggested that the complexity of highly variable and highly dependent outputs be tested for joint impact functions and derive appropriate density maps among highly dependent sectors. Lastly, the framework can be integrated with other economic models (e.g., computable general equilibrium) to model other resilience options.

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