Presented at the DLSU Research Congress 2016
De La Salle University, Manila, Philippines
March 7-9, 2016

Supply-Driven Input-Output Analysis-based Approach in Risk Analysis of Manufacturing Systems

Jesah Grace Masbad[1], Vianca Mae Noel[1], Rauvel Shay Omega[1] and Lanndon Ocampo[2,*]
[1] *Department of Industrial Engineering, University of San Carlos, 6000 Cebu City, Philippines*
[2] *Department of Mechanical and Manufacturing Engineering, University of San Carlos, 6000 Cebu City, Philippines*
**Corresponding Author: laocampo@usc.edu.ph*

Abstract: This paper proposes a supply-driven inoperability input-output model (SIIM) in analysing risks of manufacturing systems. The approach, derived from the Ghosh price model which is a variation of the Leontief input-output model, was previously debated for its implausibility in analysing sectors in an economic system although there were previous arguments that support its theoretical claims and application. The resemblance of economic systems and manufacturing systems in terms of system components, input-output concept, and component-wise interdependencies makes the approach appealing and highly plausible. This paper provides interesting insights in manufacturing risk analysis especially that the adoption of SIIM in micro-level systems particularly in manufacturing systems was not yet explored in current literature. The proposed approach is able to analyse the impact of supply perturbations in a manufacturing system brought about by natural or man-made disasters, sudden economic shifts and government policies. In this paper, entries of the transactions matrix represent the total value of the work in-process inventories produced by a process and supplied to the same or another process. Case studies were carried out in two manufacturing firms and scenarios were presented to elucidate the proposed approach. Results show that supply perturbation of upstream processes does not impact downstream processes as long as these processes remain independent of the perturbed upstream process as described in firm's system structure and topology. It also shows that the magnitude of impact of non-perturbed process depends on its nature of interdependence of the perturbed process. The proposed approach is highly significant for manufacturing and risk practitioners in formulating mitigation policies to achieve a resilient manufacturing system.

Key Words: risk analysis; supply inoperability; Ghosh price model; manufacturing system

1. INTRODUCTION

1.1 Rationale

While globalization forges borderless transactions among economies, this also undeniably brings tensions among them. Thus, countries felt the need to ensure that technological breakthroughs and advancements in general would lead nations forward and not hinder their growth. The Association of Southeast Asian Nations (ASEAN) was established to fulfill the goal of preserving peace, and promoting economic, social, and cultural cooperation across the region. ASEAN intends its economic community to be a single market and production base, allowing the free flow of goods, services, investments, skilled labor and the freer movement of capital across the region. With the ASEAN integration, manufacturing firms need to be very competitive since there would be free flow of goods and tough competition among industries of the same nature. Befitting approaches that would aid firms in carrying out appropriate decision-making strategies are essential in order to sustain a competitive advantage. Hayes and Wheelwright (1984) pointed out the need for manufacturing firms to shift from being reactive to being competitive which requires effective decision-making structure in carrying out the process. In the pursuit of effective decision-making, various areas must be considered such as supplier selection, production planning, production control, process prioritization, inventory management, quality management, and risk management, among others (Bates et al., 1995).

An essential input to manufacturing decision-making is the analysis of risks brought about by disruptions of internal and external components which firms are highly susceptible to. Understanding how to mitigate these risks from a systems approach advances current knowledge on manufacturing resilience research. Various risk analysis approaches have been proposed in literature such as strengths, weaknesses, opportunities and threats (SWOT) analysis, failure mode evaluation analysis (FMEA), analytic hierarchy process (AHP), and system dynamics (SD). See the works of Yang and Lee (1997), Tukundane et al. (2015) and Lolli et al. (2014) for the application of these methods. Generally, these tools are qualitative which may potentially lead to less reliable decisions. SD, although a quantitative one, is a simulation tool which propagates different results due to certain parameters and condition thus it does not provide a general description of a system.

The widespread economic practice of input-output models (IOM) has also encouraged researchers to work on its extensions. For instance, Ghosh (1958) has introduced a supply-driven perspective of Leontief's IOM wherein changes in supply or value-added inputs, rather than exogenous final demands, indicate changes in production output of sectors. Haimes and Jiang (2001) developed the inoperability input-output model (IIM) to quantify the impact of man-made or natural disasters of the affected economics sector and its cascading effect due to the interdependencies of other sectors within the system. Leung et al. (2007) extended this concept by introducing supply-side IIM (SIIM), derived from Ghosh price model, to understand the risks of increase in output prices due to disruptions in supply. While IIM works for risk analysis in economic systems, it also works for other analogous interdependent systems such as manufacturing systems. The final demand of manufacturing systems is found in their end-of-the-line process rather than on each process. Thus, SIIM is more suitable in the manufacturing context. In this perspective, analysing risks brought about by reductions in supply of value-added inputs is more plausible in manufacturing systems. Two case studies with different supply disruption scenarios were presented to elucidate the approach. The main contribution of this paper is in presenting a new methodological framework that holistically addresses risk analysis in manufacturing systems.

1.2 Preliminaries

Supply-side inoperability input-output model (SIIM)

SIIM was developed by Leung et al (2007) which analyzes and quantifies the cascading effects of perturbing the supply or value-added inputs of a sector. It is represented as shown in Eq. 1.

$$p = \left(I - \overset{-(s)*}{A}\right)^{-1} z^{*} \qquad \text{(Eq. 1)}$$

where p is the vector of the cost change in output due to value-added perturbation, $\overset{-(s)*}{A}$ is the interdependency matrix which is derived from the economic input-output data, and z^* is the value-added or supply perturbation vector whose elements represent the difference between the planned supply or nominal production and the perturbed value-added divided by nominal production, which is equivalent to the increase of value-added as a proportion of total planned input.

The interdependency matrix $\bar{A}^{(s)*}$ is computed using Eq. 2.

$$\bar{A}^{(s)*} = diag(x)^{-1} \bar{A}^{(s)} diag(x) \qquad \text{(Eq. 2)}$$

2. METHODOLOGY

The proposed methodology in assessing risks in manufacturing systems is as follows:

1. Construct the matrix $O = (o_{ij})_{nxn}$ where o_{ij} is the output of process i that becomes the input of process j which is expressed in aggregated monetary value of all products.
2. Form the matrix $A = (a_{ij})_{nxn}$ where $a_{ij} = \frac{o_{ij}}{x_i}$ is the ratio of output produced by process i to be consumed by process j.
3. Establish the interdependency matrix $A^{(s)} = A^T$ to form the input-output Ghosh model where z is the vector of value-added input of all the processes.
4. Compute for the supply interdependency matrix.
5. Compute for the $(I - A^{(s)*})^{-1}$.
6. Determine the inoperability vector *p*, an initial perturbation expressed in percentage as represented by z^* is also assumed.

3. CASE STUDY

3.1 Case Firm X

A case study was conducted in, Firm X an internationally recognized manufacturing firm which produces a wide variety of furniture products with premium quality. Firm X distributes furniture pieces with intricate designs all over the world. With rough competition in the industry, the firm has engaged into innovation in the products which made the manufacturing processes more complex and vulnerable to risk factors such as disruption caused by natural disasters, labour issues, supply shortage, etc. as the country faces these challenges more often. The case firm has 13 different processes, i.e. milling, assembly, fiber / stone casting, metal framing, powder coating, weaving, retouching, sanding, finishing, upholstery, final fitting, final quality check and final packing process. The products do not go through the same set of processes due to the high customization and intricate designs of the pieces. SIIM is used in two case scenarios to see how a certain perturbation affects the process system.

Scenario 1: The impact of local logging ban policy

High quality wood is the primary raw material needed by a furniture firm to produce premium pieces. The growing demand for logs not only by furniture firm also increased the number of forest trees being cut in order to respond to this need. Currently, Indonesia is in a two-year moratorium on logging due to the alarming speed of deforestation and to preserve the virgin forests which serves as home of endangered species including orangutans, tigers and elephants. The implementation of this log ban policy will definitely hurt the direct stakeholders which are the furniture businesses. An initial perturbation of 40% in its milling process caused by an implementation of a log ban policy which in turn, results to an increase of value-added as a proportion of total planned input.

Table 1 shows the resulting final perturbation values, for all processes in ICI given that there is an initial 40% value-added increase in the milling process as represented by z^*. Predictably, the milling process obtains the largest value of *p* since it is the only process being perturbed. However, due to the inherent interdependencies present within the system, the other processes yield a final perturbation. This is due to the direct and indirect interdependencies of processes caused by the complexity of the process flow.

Table 1. Value-added perturbation caused by log ban

Processes	z^*	*p*
Milling	0.40	0.4620
Assembly	0	0.4198
Fiber/Stone	0	0.0000

Metal Framing	0	0.0000
Powdercoat	0	0.0000
Weaving	0	0.0551
OD Retouching	0	0.0527
Sanding	0	0.4056
Finishing	0	0.2830
Upholstery	0	0.1769
Final Fitting	0	0.1999
Final QC	0	0.1964
Packing	0	0.0930

Scenario 2: Metal shortage caused by inclement weather

The furniture manufacturing firm in this case study utilizes metals specifically steel and aluminum as inputs in its metal framing process. In producing steel, iron ore is needed which can be obtained through either underground or open pit mining. When a bad weather strikes, the mining industry is one of the industries that will be directly affected. Previous occurrences like the work stoppages in the production of iron ore in Brazil due to the heavy rains have made an impact to the industry. This occurrence led to a supply shortage of metal which in turn increased the price of steel in the market (Reuters, 2012).

In the context of the manufacturing firm, the possibility of heavy rains or storms can trigger the iron ore mining operations to stop which will eventually affect the steel production. In this scenario, an eight percent increase in the price of steel is assumed to be caused by the supply disruption brought about by heavy rains.

Table 2. Value-added perturbation caused by metal shortage

Processes	z^*	p
Milling	0	0.0001
Assembly	0	0.0005
Fiber/Stone	0	0.0000
Metal Framing	0.08	0.0800
Powdercoat	0	0.0347
Weaving	0	0.0091
OD Retouching	0	0.0087
Sanding	0	0.0004
Finishing	0	0.0038
Upholstery	0	0.0033
Final Fitting	0	0.0032
Final QC	0	0.0031
Packing	0	0.0014

As mentioned, not all products go through the metal framing process. Thus having an eight percent value-added perturbation in metal framing causes a minimal effect to the other processes. The largest p value is the metal framing since it is the initially perturbed process. Total value-added cost-price of the other processes is expected to increase by a factor of $\boldsymbol{p}$. Final perturbation for the fiber/stone casting process has a zero value for the reason that it does not have inputs from the other process and has no interrelationship.

3.2 Case Firm Y

A case study was conducted in Firm Y which a mosquito coil is manufacturing firm situated in Cebu, Philippines. It is one of the top coil manufacturing firms in the country and has been in the business for 50 years. The mosquito coils manufactured by Firm Y come in different varieties such as size and scent. Although these coils vary greatly in terms of composition and characteristics, the processes that they undergo do not differ. All of Firm Y's products go through the same set of processes which are vertical mixing, weighing, blending, kneading, stamping, air drying, tunnel drying, coil harvesting, spraying, and packing.

Scenario 1: Coffee skin shortage brought about by tropical typhoons

Coffee is known to be a natural insect repellent thus one of the primary raw materials in manufacturing mosquito coils is coffee skin. Due to its climatic and soil conditions, the Philippines is blessed to be one of the few countries that are capable of cultivating and growing four varieties of commercially-viable coffee However, the country has been consistently ranked in the top five most disaster-hit countries over the last decade which makes agriculture and cultivation of various crops at great risk. The recent typhoon Haiyan, with local name Yolanda even destroyed at least 116 coffee bean hectares in ten towns of Antique (Mondragon, 2013).

Given a scenario of such disaster, SIIM is used to analyze and quantify its impact to Firm Y which acquires coffee skin for its mosquito coil production. The coffee skin shortage brought by the typhoon constitutes to a 20% price increase of coffee skin which directly perturbs the blending process

Table 3. Value-added perturbation caused by coffee skin shortage

Processes	z^*	p
Vertical Mixing	0	0.0000
Weighing	0	0.1981
Blending	0.2	0.3769
Kneading	0	0.1182
Stamping	0	0.0841
Air Drying	0	0.0828
Tunnel Drying	0	0.0251
Coil Harvesting	0	0.0247
Spraying	0	0.0232
Packing	0	0.0218

Table 3 shows the cost-price changes of the processes which are caused by having a 20% supply or value-added perturbation in the blending process. These values are expressed as the final perturbation values and these were obtained. As expected, the blending process has the largest p value for it is the one directly affected by the initial value-added perturbation. All other processes were affected thus having final perturbation values except for vertical mixing. The vertical mixing process is the first process in the system and it does not require inputs from other processes, e.g. blending process. Thus, it has a zero value which implies a value-added change in the blending process does not result to a cost-price change in the inputs of vertical mixing. This implies that the processes having direct interaction with the initially perturbed process (blending) i.e. those directly after it, have generally larger p values than the other processes. Compared to others, the final perturbation value for the last process (packing) is generally smaller.

Scenario 2: Coal price increase due to mine collapse

The drying process in manufacturing mosquito coils plays a very important role since the coils need to harden to stay firm and be an effective repellent. In Firm Y, the tunnel drying process uses a steam boiler which primarily consumes up to 3,240 kilograms of coal for 912 pairs of coil. Thus, coal is considered one of the high volume materials used in the firm's mosquito coil production.

At an open-pit mine of the largest coal producer in the Philippines, the western wall of the mine collapsed due to heavy rains and 13 miners were greatly injured. This led to a four-month suspension of work as mandated by the Department of Energy. The suspension of the mining operation is believed to have a large impact on the market since it supplies coal to more than 94% of the country's coal needs (Abadilla & Olchondra, 2015). This resulted to a disrupted coal supply which in turn caused a coal price increase. Considering the possibility of this occurrence, a value-added perturbation of 36% in the tunnel drying process is assumed.

Table 5. Value-added perturbation caused by coal price increase

Processes	z^*	p
Vertical Mixing	0	0.0000
Weighing	0	0.0000
Blending	0	0.0000
Kneading	0	0.0000
Stamping	0	0.0000
Air Drying	0	0.0000
Tunnel Drying	0.36	0.3600
Coil Harvesting	0	0.3545
Spraying	0	0.3333
Packing	0	0.3128

Unlike the previous scenario, results in Table 5 shows that having a disaster-driven coal price increase scenario, the tunnel drying process which is the one initially perturbed, has the same percentage of final perturbation mainly because of the interrelationships it has with the other processes. The firm generally has a linear process flow thus the affected processes will be those succeeding the perturbed process. The proceeding processes namely coil harvesting, spraying, and packing cannot further contribute to the effect of the initial perturbation to tunnel drying because no inputs from these processes are being used in tunnel drying. Coil harvesting, which is directly after tunnel drying, has a final perturbation value more or less similar with tunnel drying because it directly receives the outputs of the tunnel drying process. Thus, the cost-price change of tunnel drying's total inputs more or less directly reflects to that of coil harvesting values. Still having the concept of linear process flow or straightforward interrelationship of processes, processes preceding tunnel drying, i.e. vertical mixing down to air drying, have no p values since these processes do not receive inputs from tunnel drying.

4. CONCLUSION AND FUTURE WORK

In the light of the results, the supply-driven inoperability input-output model (SIIM) effectively quantifies the impact of supply or value-added perturbations caused by manmade or natural disasters to the affected process and its cascading effect due to interdependencies in the system. The application of SIIM yields relevant results in the context of manufacturing decision-making as a whole. When a process is disrupted through supply or value-added perturbations, it will inflict cascading effects to interdependent processes. Therefore, when certain processes are perturbed, the value of the change in input of the other processes will depend on its interrelationship with the perturbed processes.

Generally, the supply-driven approach adopted in the study undeniably addresses an interdependent system which is an inherent characteristic of most manufacturing systems. Moreover, it looks into the production processes as a system rather than isolating an element or a process. It can be inferred that SIIM effectively quantifies the actual impact on each process after a supply perturbation has occurred. This approach is most relevant for a production process system compared to the highly regarded demand-driven approach because each process in a manufacturing system does not have any final exogenous demand unlike economic sectors where final demand is naturally present. Thus, analyzing the changes in final demand is not essential for manufacturing systems. Using this approach, the interrelationship of processes in the system in the context of a manufacturing firm are concretely defined. With this, the management are able to plan out ahead mitigating policies in order to have a resilient manufacturing system. This paper paves interesting research questions in manufacturing system risk analysis which give room for future work.

5. REFERENCES

Bates, K., Amundson, S., Schroeder, R., & Morris, W. (1995). The Crucial Interrelationship between Manufacturing Strategy and Organizational Culture. Management Science, 41(10), 1565–1580.

Hayes, R., & Wheelwright, S. (1984). Restoring our Competitive Edge: Competing Through Manufacturing.

IBON International. (2014). ASEAN Community 2015: Integration for Whom?

Jiang P.,& Haimes, Y. (2004). Risk management for Leontief-based interdependent systems. Risk Analysis, 24(5), 1215–1229.

Leung M., Haimes Y.Y., Santos J. R. (2007). Supply- and output-side extensions to the inoperability input-output model for interdependent infrastructures. Journal of Infrastructure Systems, 13(4), 299–310.

Lolli, F., Ishizaka, A., Gamberini, R., Rimini, B., Messori, M. (2014). FlowSort-GDSS – A novel group multi-criteria decision support system for sorting problems with application to FMEA. Expert Systems with Applications, 42(17-18), 6342–6349.

Miller, R., & Blair, P. (2009). Input-Output Analysis: Foundations and Extensions. New York, NY: Cambridge University Press.

Mondragon, A. (2015). Antique's agriculture still reeling from Yolanda.

Olchondra, R., & Abadilla, D. D. (2015). 5 dead, 4 missing in coal mine collapse. Inquirer News.

Reuters. (2012). BHP iron ore, coal mines hit by bad weather, strikes. Interactive Investor.

Santos, J., &Haimes, Y. (2003). Modeling the Demand Reduction (IO) Inoperability Due to Terrorism of Interconnected Infrastructures. Risk Analysis, 24(6), 1437–1451.

Santos, J., Anderson, C., & Haimes, Y. (2007). A Risk-based Input–Output Methodology for Measuring the Effects of the August 2003 Northeast Blackout. Economic

Tan, C., Tan, P., Lee, S., & Pham, M. (2013). An Inoperability Input-Output Model (IIM) for Disruption Propagation Analysis.

Yang, J., & Lee, H. (1997). An AHP decision model for facility location selection. Facilities, 15(9), 241–254.