Input-output impact risk propagation in critical infrastructure interdependency

Author

Owusu, A, Mohamed, S, Anissimov, Y

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Input-output impact risk propagation in critical infrastructure interdependency

A. Owusu, S. Mohamed & Y. Anissimov
Griffith University, Gold Coast, QLD 4222, Australia

Abstract

An attack on a critical infrastructure such as banking and finance resulting in loss or damage will not occur in isolation because infrastructures are interdependent. The recent global financial crisis has reaffirmed that the world economies are interdependent. Infrastructure sectors have direct and indirect interdependencies and are vulnerable to each others impacts and disruptions, deliberate or accidental which can be pernicious, resulting in derivative losses that reverberate perturbations globally. Owing to the complexity of interdependency, there is the need for managers to better understand how impact risk propagates. Propagated risks due to dependency, interdependency and multi-dependency have been broken down in detail to comb out the complexity of interconnectedness and the ripple effect in a network system. Using input-output methodology and risk vulnerability coefficient factors, the paper presents an analysis of impact risk transfers and their rippled effect in critical infrastructure system. The analysis explicitly provides details of the impact risk transfer and exhibits the rudiments of the transfer. An analysis is carried out to illustrate cascading of an impact among two interdependent and seven multi-interdependent infrastructures of varying, impact values, strength of interdependent relationship, vulnerability to risk impact, resilience to external impact and source of attack with results shown in tables and graphs. The results have been obtained by trivial mathematical solution of the matrix equations. Using iteration which may be tedious, the rudiments of transfer have been exhibited by manual computation in dependent and interdependent relationships. The iterative process reveals impact risk that is attributed to network interdependency and distinguishes it from that emanating from external sources. The application of the method has been demonstrated by showing the rippled effect of an impact in a real economy using seven out of 109 infrastructure sectors. Hence, the rippled effect of risk in any number of interdependent infrastructures can also be shown. The solution of equations involving a higher (greater than three) number of infrastructures is not a task for unaided human computation.

Keywords: Critical infrastructure, vulnerability, impact risk, interdependency.

1 Introduction

Input-output methodology brings into minds Wassily Leontief's economic input –output model. The model mats interdependency which Leontif used to show transactions among sectors of an economy and describe a set of linear equations which express the balances between the total input and the aggregate output of each commodity that is used in the course of one or several periods of time (Leontief, 1951a). Others have extended its application in infrastructure systems management(Ping

Chen et al., 2009) and to assess system inoperability(Santos, 2006, Kenneth and Haimes, 2005). This paper diverges from Leontif's basic tool and uses a generic cascading method in order to assess the impact due to interdependencies among critical infrastructure elements using vulnerability coefficients as the vehicle for transporting flow-on consequences. Although Leontif's model application has been varied here, the risk vulnerability coefficients factors that have been determined are still based on input-output commodity transactions among selected industries for a defined economic period for which they are assumed constant and at equilibrium.

2 Structure of impact risk propagation

Impact risk propagation structure for critical infrastructure network is represented in a compact form reformulated from Leontif's as:

$$x_i = \sum_{i,j=1}^{n} v_{ij} x_j + r_i \quad (1)$$

where:

x_i = *aggregated impact risk in infratsructure i($m)*

r_i = *external impact risk to infrastructure i(Sm)*

v_{ij} = *risk vulnerability coefficient factor*$(0 \le v_{ij} < 1)$

Assume critical infrastructure elements such as banking and finance, road transport, water supply, telecommunication services, electricity supply in a network is defined by a set A = [a_1, b_2, c_3, d_4, e_5], where a_1, b_2, c_3, d_4, e_5 are the critical infrastructures respectively. For simplicity, a subset of two elements with a binary (Rinaldi et al., 2001) interdependent relationship is defined as R = [(a_1, a_1), (a_1, b_2), (b_2, b_2), (b_2, a_1)]. A digraph of this relationship is as shown below in Fig. 1. Risk passes onto b_2 from a_1 and vise versa as goods/services are transacted. Dependent relationship is a special case of interdependent relationship shown in Fig. 1, for v_{12}= 0, where vulnerability to risk from infrastructure 2 to 1 is nil; or there no reversible derivative loss in the specified opposite direction. This format permits interdependent and dependent situations to be investigated concurrently, by varying the risk vulnerability coefficients for strength and dependency$\left(0 \le v_{ij} < 1\right)$. Vulnerability coefficients with subscripts $i = j$ refers to the infrastructure resilience to external (emanating from outside the network) impact and internal impact within the network.

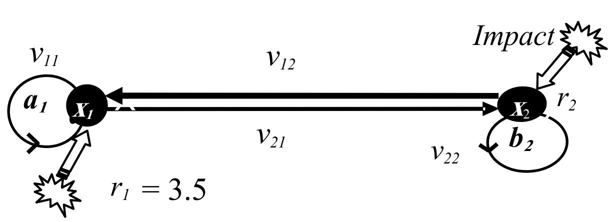


Figure 1. Interdependent infrastructures, impacts and risk vulnerability coefficient factors.

The matrix table of vulnerability coefficients is shown in Table 1 and the equations representing the risk impact propagation structure shown in Eq.2.

Table 1. Risk vulnerability coefficient matrix table.

			Input	
			(a_1) x_1	(b_2) x_2
Output	*Electricity Supply*	(a_1) x_1	$\rightarrow v_{11}$	v_{12}
	Telecommunication	(b_2) x_2	$\rightarrow v_{21}$	v_{22}

The impact risk equation which requires solution for two infrastructures is:

$$\begin{pmatrix} x_1 \\ x_2 \end{pmatrix} = \begin{pmatrix} v_{11} & v_{12} \\ v_{21} & v_{22} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} + \begin{pmatrix} r_1 \\ r_2 \end{pmatrix} \quad (2)$$

2.1 Impact risk transfer to dependent infrastructures

In order to evaluate impact risk transfer across two elements and discuss impact propagation to dependent infrastructures, two infrastructures (a_1, b_2) have been chosen as shown in Fig.3 with external impacts r_1 and r_2. Infrastructure a_1's aggregated impact risk is x_1 and that of infrastructure b_2 is x_2. Again, dependency is established with one arrow shown dotted to signify disconnection of flow from 2 to 1 and to curtail transitive flow of impact risk from 1 to 2 to 1. Quantitatively, the dependent relationship is created by assigning risk vulnerability coefficient of zero to v_{12}.

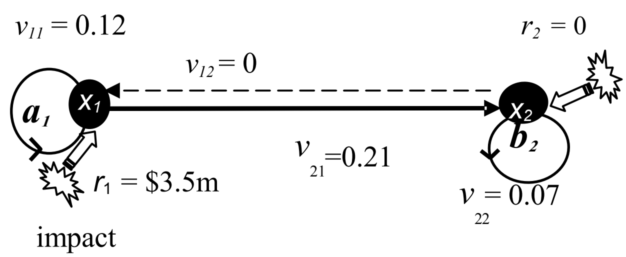


Figure 2. Dependent infrastructure, impact and risk vulnerability coefficient factors.

Table 2. Impact risk scenario 6.

r_1	=$3.5m	x_1	= $3.98m
r_2	= 0	x_2	= 0.90

$$x_1 = \frac{r_1}{(1-v_{11})} = \frac{3.5}{(1-0.12)} = \frac{3.5}{0.88} = \$3.98m$$

$$v_{21}x_1 = 0.21 \times 3.98 = \$0.84m$$

$$x_2 = \frac{r_2}{(1-v_{22})} + \frac{0.84}{(1-v_{22})} = \frac{0}{0.93} + \frac{0.84}{0.93} = 0 + 0.90 = \$0.90m$$

Figure 3. Rudiments of impact risk transfer in dependent relation (scenario 6, Table 4).

2.1.1 Rudiments of impact transfer in dependent infrastructures

It is seen from Fig. 2 that the transfer of impact risk from a_1 to b_2 is $v_{21}x_1$. The resultant of impact risk to b_2 is x_2. However, the risk associated with this impact is taken as x_2 minus $v_{21}x_1$ minus r_2. $v_{12}x_2$, is the proportion of b_2 impact that would have been transferred back to a_1 if v_{12} was not equal to zero. In the scenario created in Fig. 2 and 3, $v_{12} = 0$, and an external impact on infrastructure a_1 is \$3.5m. That is, r_1 = \$3.5 and r_2 =0. The impact risk transfer to infrastructure b_2 is \$0.84m. There is no reverse impact risk transfer to infrastructure a_1. The impact risk to infrastructure b_2 (e_2) is increased by \$0.06 with aggregated impact of \$0.90. Impact risk to a_1 (e_1) *is* \$0.48.

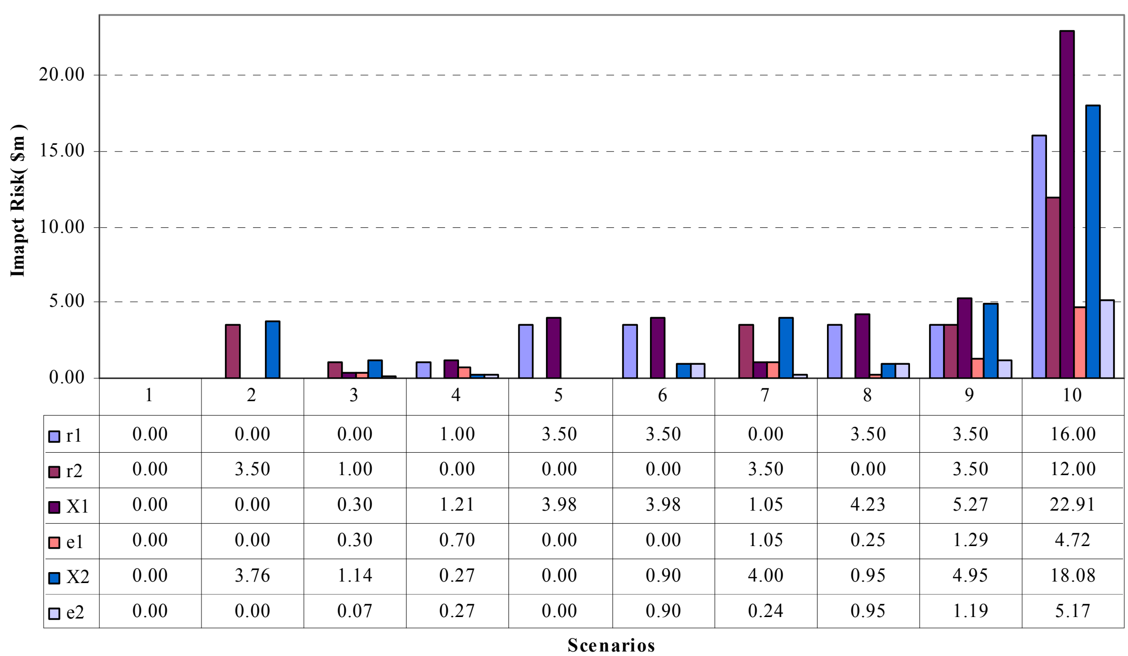
Further impact risks analysis has been conducted by assigning different values of external impacts r_1 and r_2 and varying vulnerability coefficient values to create different scenarios in Table 4, assuming risk vulnerability coefficient factors of $v_{11} = 0.12$, $v_{12} = 0.23$, $v_{21} = 0.21$ and $v_{22} = 0.07$.

Table 3. Vulnerability coefficient matrix table for two interdependent infrastructures.

	Source of Impact Risk	*Risk Vulnerability Coefficients*	
		(a_1) x_1	*(b_2) x_2*
Electricity Supply	*(a_1) x_1*	0.12	0.23
Telecommunication	*(b_2) x_2*	0.21	0.07

Table 4. Analysis of impact risk of two interdependent infrastructures.

Scenarios	*Impacts($m)*		*Risk vulnerability factors*		*Rippled Impacts($m)*			
	r_1	r_2	v_{12}	v_{21}	x_1	e_1	x_2	e_2
1	0.00	0.00	0.23	0.21	0.00	0.00	0.00	0.00
2	0.00	3.50	0.00	0.21	0.00	0.00	3.76	0.26
3	0.00	1.00	0.23	0.21	0.30	0.30	1.14	0.14
4	1.00	0.00	0.23	0.21	1.21	0.21	0.27	0.27
5	3.50	0.00	0.23	0.00	3.98	0.48	0.00	0.00
6	3.50	0.00	0.00	0.21	3.98	0.48	0.90	0.90
7	0.00	3.50	0.23	0.21	0.00	1.05	4.00	0.50
8	3.50	0.00	0.23	0.21	4.23	0.73	0.95	1.45
9	3.50	3.50	0.23	0.21	5.27	1.77	4.95	1.45
10	16.00	12.00	0.23	0.21	22.91	6.91	18.08	6.08



	1	2	3	4	5	6	7	8	9	10
r1	0.00	0.00	0.00	1.00	3.50	3.50	0.00	3.50	3.50	16.00
r2	0.00	3.50	1.00	0.00	0.00	0.00	3.50	0.00	3.50	12.00
X1	0.00	0.00	0.30	1.21	3.98	3.98	1.05	4.23	5.27	22.91
e1	0.00	0.00	0.30	0.70	0.00	0.00	1.05	0.25	1.29	4.72
X2	0.00	3.76	1.14	0.27	0.00	0.90	4.00	0.95	4.95	18.08
e2	0.00	0.00	0.07	0.27	0.00	0.90	0.24	0.95	1.19	5.17

Figure 4. Impact risk analysis of Table 4

2.2 Impact risk transfer among two interdependent infrastructures

With reference to Fig. 1 above and for the case where $v_{12} = 0.23$, a full interdependent relationship is achieved. Solution of the matrix Eq.2 for scenario 9 (Table 4) by iteration reveals the rudiments of the impact transfer which is shown below in Fig. 5. From Fig 5 below, impacts from network that is due to interdependency can be distinguished from impact from external sources.

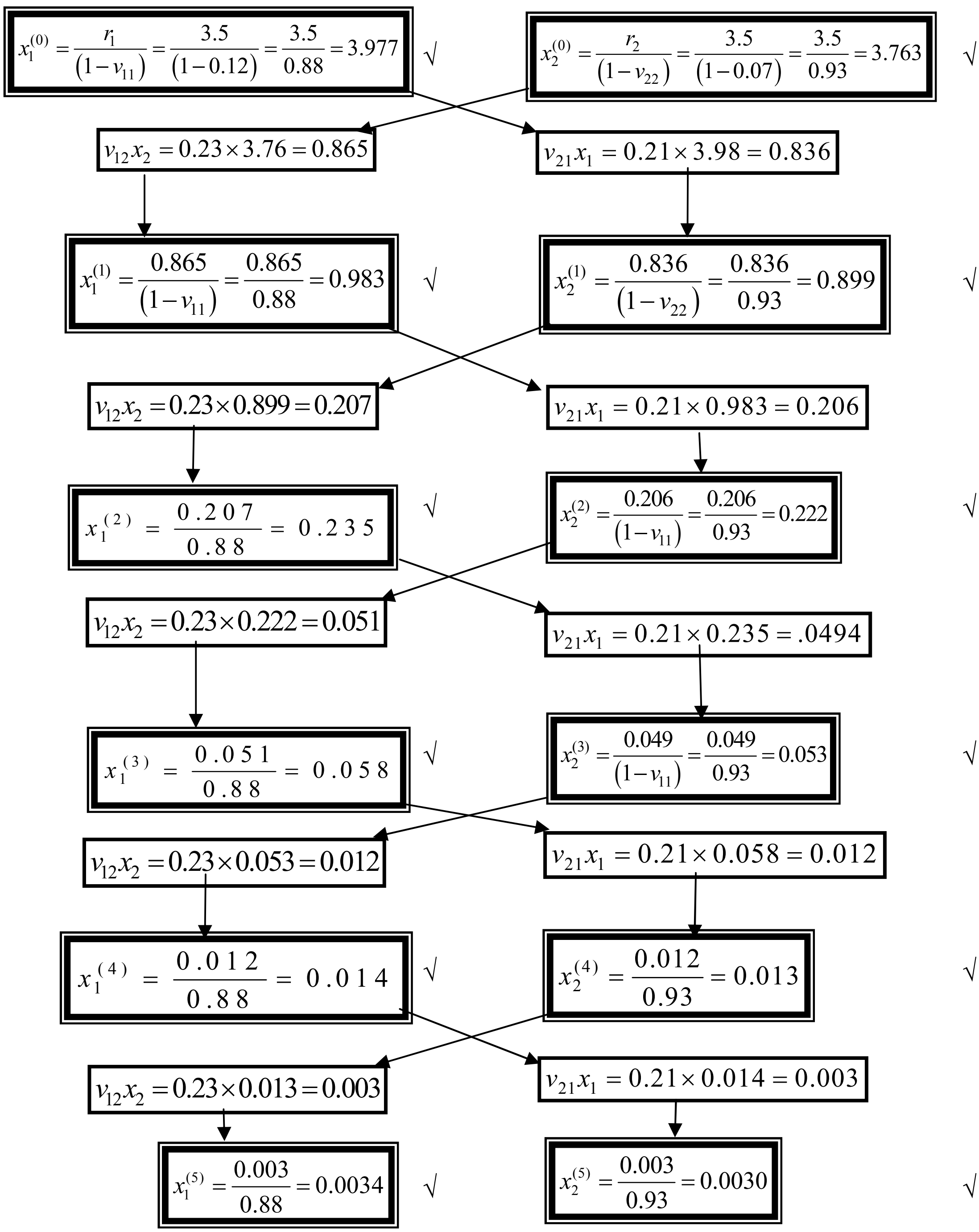


Figure 5. Rudiments of impact risk transfer in interdependent relationship, Table 4 in scenario 9.

2.3 Discussion

It can be seen from Table 4 that varying v_{12} or v_{21}, the strength of interdependency can be varied, although it is assumed constant and in equilibrium within a specified economic period. Similarly, varying v_{11} or v_{22}, the resilience of the infrastructures to external impact and impact due to network interdependency can also be varied. In scenario 9, the external impact value on each infrastructure is the same i.e., $r_1 = r_2 =$ \$3.5m. The rippled aggregated impact values are $X_1 =$ \$5.27m and $X_2 =$ \$4.95m respectively. The aggregated impact values are the sum of impacts of $r_1 =$ \$3.5m, when $r_2 = 0$ (scenario 8); and when $r_2 =$ \$3.5m, $r_1 = 0$ (scenario 7). This shows that impact effects are cumulative. Conversely, if there is no external impact on an infrastructure, impact due to interdependency can be worked out from anticipated the ripple. The aggregated impact risk is the sum of the following values identified in Fig. 5 with a tick (√):

$$x_1 = x_1^{(0)} + x_1^{(1)} + x_1^{(2)} + x_1^{(3)} + x_1^{(4)} + x_1^{(5)} + \cdots$$

$$x_1 = \$3.977 + 0.983 + 0.235 + 0.058 + 0.014 + 0.003 + \cdots = \$5.270m$$

$$e_1 = x_1 - \frac{r_1}{(1 - v_{11})} = \$5.270 - \$3.977 = \$1.293m$$

The impact due to interdependency is distinguished as e_1. Similarly,

$$x_2 = x_2^{(0)} + x_2^{(1)} + x_2^{(2)} + x_2^{(3)} + x_2^{(4)} + x_2^{(5)} + \cdots$$

$$x_2 = \$3.763m + 0.899 + 0.222 + 0.053 + 0.013 + 0.003 + \ldots = \$4.953m$$

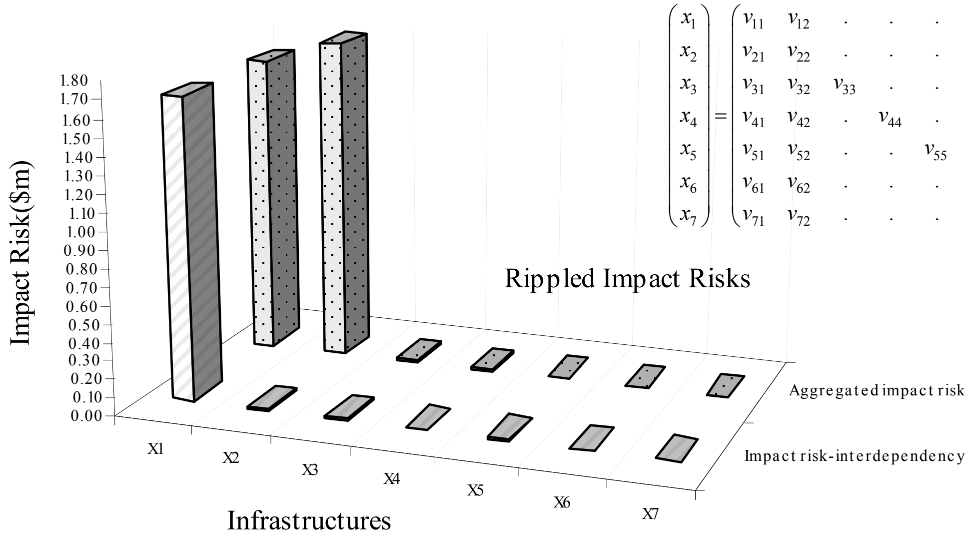
$$e_2 = x_2 - \frac{r_2}{(1 - v_{22})} = \$4.953m - \$3.763m = \$1.190m$$

3 Impact risk propagation in multi-interdependent infrastructures.

In order to obtain rippled impact risk on three or more infrastructures such as has been shown in Fig 6, one requires a solution of matrix equations with similar dimensions, involving *n x n*- risk vulnerability coefficient matrix with at least one external impact. A real life example is illustrated below with seven infrastructures. Their risk vulnerability coefficients are derived using data set from Australian National Accounts: Input-Output Tables - Electronic Publication 2004-05(Australian Bureau of Statistics, 2008). The interest here is to estimate the ripple impact risk on a subset of seven infrastructures due to interdependency after an attack on the Petroleum & coal sector with a loss of \$3.5m. The table and graph below shows results of the analysis using Matlab software for solution. The relevant vulnerability matrix extracted is shown below in Table 5.

Table 5 Indirect allocation of imports, recording intra-industry flows, subset of 7 of 109 industries (2004-05)*

Use / Supply	Oil and gas (x_1)	Petroleum & coal(x_2)	Electricity supply(x_3)	Water supply s/w/d(x_4)	Road transport(x_5)	Communication(x_6)	Banking (x_7)
Oil & gas (x_1)	0.01807036	0.45710732	0.03278607	0.00000000	0.00014925	0.00272210	0.00000711
Petroleum & coal (x_2)	0.00514174	0.02346229	0.01324657	0.00411838	0.12744161	0.01839544	0.00001070
Electricity supply (x_3)	0.00358537	0.00167922	0.16996914	0.01047018	0.00304076	0.01293909	0.00015885
Water supply, s/w/d. (x_4)	0.00011013	0.00143172	0.00653084	0.03596916	0.02017621	0.02060573	0.00005507
Road transport (x_5)	0.00122198	0.00196337	0.00492308	0.00140366	0.04721172	0.01464029	0.00012601
Communication (x_6)	0.00063216	0.00138985	0.00709946	0.00237620	0.02363424	0.02742048	0.00638212
Banking (x_7)	0.00271942	0.00052061	0.01810804	0.01077969	0.00616464	0.01188828	0.02293747



$$\begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \\ x_7 \end{pmatrix} = \begin{pmatrix} v_{11} & v_{12} & . & . & . & v_{16} & v_{17} \\ v_{21} & v_{22} & . & . & . & v_{26} & v_{27} \\ v_{31} & v_{32} & v_{33} & . & . & v_{36} & v_{37} \\ v_{41} & v_{42} & . & v_{44} & . & v_{46} & v_{47} \\ v_{51} & v_{52} & . & . & v_{55} & v_{56} & v_{57} \\ v_{61} & v_{62} & . & . & . & v_{66} & v_{67} \\ v_{71} & v_{72} & . & . & . & v_{76} & v_{77} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \\ x_7 \end{pmatrix} + \begin{pmatrix} 0 \\ 3.5 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

	X1	X2	X3	X4	X5	X6	X7
Impact risk-interdependency	1.673095577	0.010297544	0.014371568	0.005940859	0.009701484	0.006586702	0.006219117
Aggregated impact risk	1.673095577	3.594388536	0.014371568	0.005940859	0.009701484	0.006586702	0.006219117

Figure 6. Rippled impact risks ($m) on seven infrastructures due to interdependency.

4 Conclusion

This paper has exhibited impact risk propagation in a network of critical infrastructures and elucidated risk transfer due to network interdependency and or resilience of the infrastructures. The iteration has provided a better understanding of impact transfer in case of an attack. In the event of an attack, an economic loss due to relationships between critical infrastructure sectors and their interdependencies can be estimated by input-output methodology. This could be extremely helpful to infrastructure managers and decision makers in identifying potential points of failures in economic system, and offer options for investment in improved security. The results of data analysis reveal how total supply chain risk in interdependent sectors can be estimated. Such estimate, however, is as accurate and liable as the vulnerability coefficients used; which is expected to change from time to time.

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