CEE 498
Final Project Report

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2 Infrastructure interdependency analysis

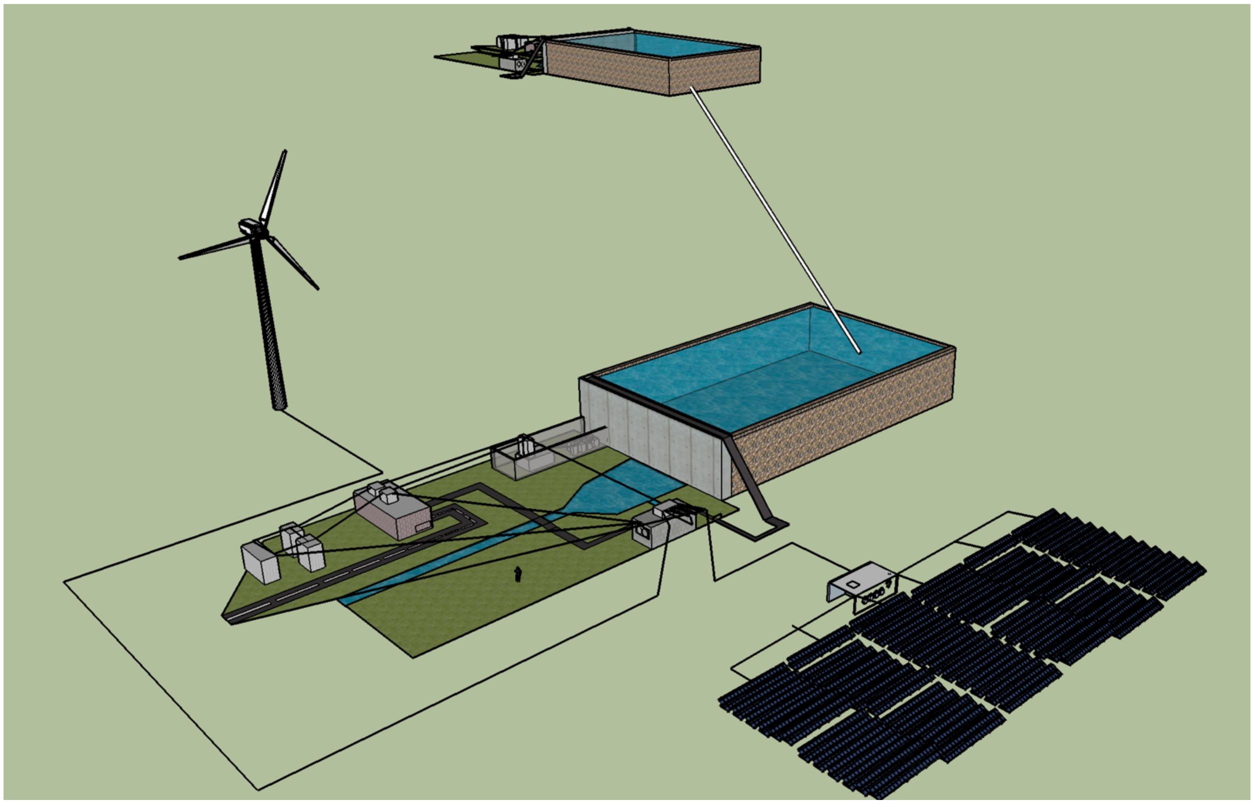

Fig. 1: **Abstract design of a smart-grid system** *(Wind, Solar, Hydroelectric Storage)*

In this part of the problem, a system of interdependent infrastructures is modeled and analyzed to understand the influence that critical infrastructures can have on one another. The eleven interdependent sectors are: air transportation, electricity, wireless telecommunications (TLC wireless), wired telecommunications (TLC wired), water management, rail transportation, finance, fuel & petroleum grid, natural gas, naval ports, satellite communication & navigation. The analysis aims to first explain the mathematical model in detail before it is applied to assess the impact of smart grid technologies on the overall system, and the damage propagation on critical infrastructure systems initiated by a snowstorm. Finally, the maximum initial impact that the system can weather is modeled through optimization.

The inoperability input-output model was used to design and the mutual dependencies between industry sectors. Infrastructure dependencies are given in the form of a matrix of coefficients where a_{ij} is the coefficient of failure propagation from the j_{th} to sector i for an outage period of 6-12 hours.

All tables and figures are included in the report. Parts of the code are embedded in the text; however the comprehensive code is attached in the appendix.

Question 2.1 Given (1) and (2), show (analytically) that (3) is an equivalent matrix model.

Proof 1: Matrix Equivalency

$$x_i = o_i + f_i = \sum_j x_{ij} + f_i \quad (1)$$

$$x_{ij} = a_{ij} x_j \quad (2)$$

$$x = \begin{bmatrix} x_1 \\ \dots \\ x_n \end{bmatrix}, f = \begin{bmatrix} f_1 \\ \dots \\ f_n \end{bmatrix}, A = \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \dots & a_{nn} \end{bmatrix}$$

$$x = \begin{bmatrix} a_{11}x_{11} + \cdots + a_{1n}x_{1n} + f_1 \\ \cdots \\ a_{n1}x_{n1} + \cdots a_{nn}x_{nn} + f_n \end{bmatrix} = Ax + f$$

Question 2.2 *Explain how to interpret the last row of table 2. Does this seem like a reasonable set of assumptions?*

The last row of table two means that there is an infrastructure degradation of infrastructure 11, i.e., satellite communication & navigation doesn't have any inoperability impact on the other infrastructures. The assumption seems reasonable as there is most likely an impact but looking at the other coefficients, it is probably a negligible number as electric utilities are probably not as interdependent with satellite communication as it is with other infrastructures.

Question 2.3 *Explain how we can interpret the indices defined in equations (4) and (5) for a given infrastructure i or j.*

The dependency index of the i^{th} row which is a row summation gives the sum of a coefficients representing the other infrastructures' impact on the i^{th} infrastructure. The influence index of the j^{th} column is a column summation that results in the total a coefficients representing the j^{th} infrastructure's inoperability impact on other infrastructures. Equation 4 shows the dependency index κ_i, representing the average degradation effect of infrastructure i caused by all the other critical infrastructure sectors. Equation 5 shows the influence index λ_j, representing the average degradation effect caused to all the other critical infrastructure sectors from infrastructure j.

Question 2.4 *Write a solution to equation (3) for x: Call S the matrix that multiplies vector f in the resulting equation (i.e., your solution should look something like x = Sf). You need to define S and show how to compute it in terms of other parameters given in the problem. Can you establish any relationship between s_{ij} (the ij^{th} element of S) and a_{ij}? Are there any requirements on any matrices you manipulate in order calculate your solution?*

Proof 2: Matrix S

$$x = Ax + f$$

$$(I - A)x = f$$

$$x = (I - A)^{-1}f = Sf$$

$$S = (I - A)^{-1}$$

This analytical solution requires matrix A to be a square matrix, matrix S to be invertible and that the equation to have one unique solution x. When matrix S is multiplied by the external degradation vector f, the resulting solution, x, is the vector representing the total damage on the infrastructure assets, both direct and indirect. While s_{ij} coefficients account for both direct damage from the external degradation and indirect damage coming from other infrastructures through dependency, the a_{ij} coefficients only include the former as stated previously.

Question 2.5 *Give a written explanation of what each element in the matrix S means (i.e., define s_{ij}).*

Each element in S gives the correlation between the degradation factor for a given infrastructure and its direct impact on the other infrastructures. As such, s_{ij} is the coefficient of propagation of direct and indirect inoperability from a failure in the j^{th} sector and impacting the i^{th} sector.

Question 2.6 *Explain from a modeling and data collection standpoint why it is easier to obtain the values for the elements in matrix A compared to matrix S.*

Matrix A isolates the dependency and the influence from the direct degradation and this helps the model to be more accurate. In fact, the direct degradation factor can be accurate as it is a direct model of how the output is affected by an incident, while the interdependency analysis is more complex and involves more uncertainty. It is better to have a model with a distinction between the two in the form of an addition in that case.

Question 2.7 *Define the overall dependency index, denoted $\bar{\kappa}_i$, and the overall influence index, denoted $\bar{\lambda}_j$, which are analogous to the indices defined in (4) and (5) but they operate on the elements of matrix S instead of matrix A. How can you interpret the overall indices $\bar{\kappa}_i$ and $\bar{\lambda}_j$? How do they differ from κ_i and λ_j?*

$\bar{\kappa}_i$ shows the overall degradation effects brought by f to all the critical infrastructure sectors.

$\bar{\lambda}_j$ shows how infrastructure j can be affected by all the degradation effects from vector f.

The difference between the two sets of indices is whether the degradation effects are from internal (mutual dependencies) or external sources.

Question 2.8 *Analyze the coefficients of matrix A given in Table 2 for the fuel & petroleum grid and naval port sectors. Which infrastructure assets have the greatest influence over each of these sectors? Which infrastructure assets do fuel & petroleum grid and naval port influence the most?*

In order to know which infrastructure assets have the greatest influence over the fuel and petroleum grid sector, we looked for the highest coefficient in the 8th row and found the 2nd value which corresponds to **electricity** to be the maximum. Air transportation is the most dependent on fuel and petroleum because it is the maximum value of the 8th column.

Embedded Code #1: highest indices

```
% find the highest values for row 8
hrow_fuel = find(A(8,:)==max(A(8,:)));
disp(hrow_fuel)
```

Similarly, we computed the maximum values for row and column 10 to find the sectors most correlated with naval ports. Electricity, water and rail are the sectors that influence naval ports the most. The fuel and petroleum grid sector is the most dependent on naval ports.

Question 2.9 *Calculate the indices κ_i and λ_j, compare and analyze them for the different sectors. You may wish to plot them to illustrate the comparison. Summarize what you find.*

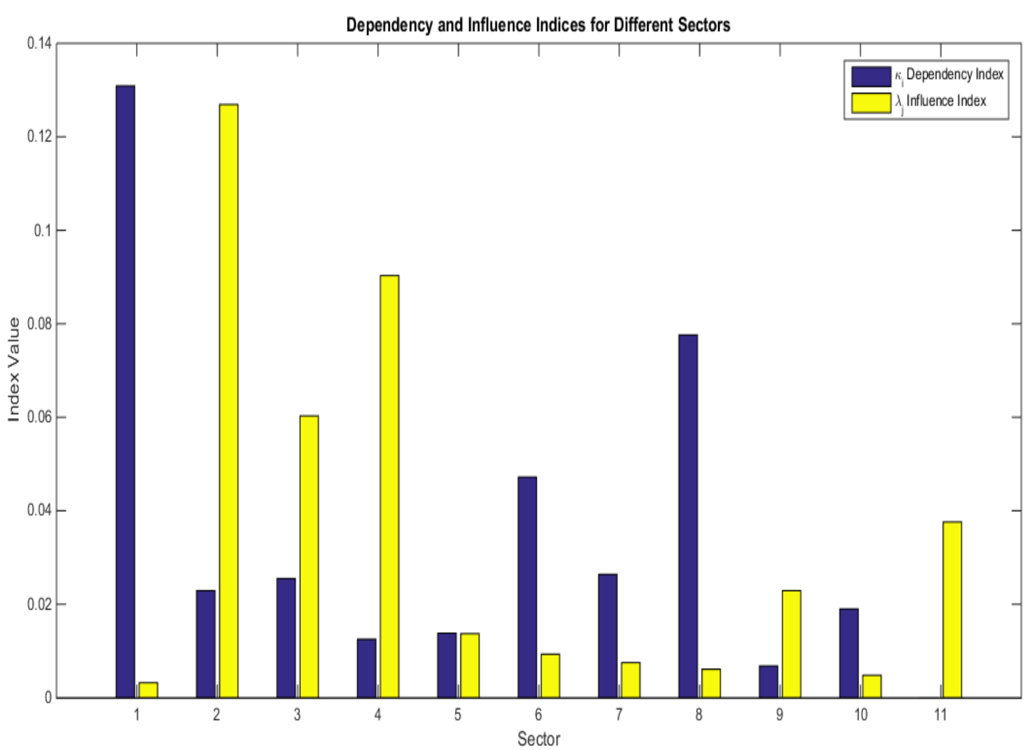

Fig. 2: <u>**Bar Chart Comparison of Influence and Dependency Indices for Each Infrastructure**</u>

Many observations can be drawn from this plot. First, there is no apparent correlation between dependency and influence for each sector. Sector 5, water management, is the only sector to have close dependency and influence indexes, thus the only sector to have as much impact as it is impacted in its interaction with other critical infrastructures. The sector with the highest dependency index is air transportation (0.13) and the sector with the highest influence index is electricity (0.125). The sector with the lowest dependency index is satellite communication and navigation (0) while the sector with the lowest influence index is air transportation (0.008). Here is a ranking of sectors' dependency indexes from highest to lowest: air transportation, fuel and petroleum grid, rail, finance, wireless telecom, electricity, naval ports, water management, wired telecom, natural gas, satellite communication and navigation. Here is a ranking of sectors' influence indexes from highest to lowest: electricity, wired telecom, wireless telecom, satellite communication and navigation, natural gas, water management, rail, finance, fuel and petroleum grid, naval ports, air transportation.

Question 2.10 *Compute matrix S and calculate the overall indices κ_i and λ_j. Compare them with κ_i and λ_j. Do you observe any interesting features? Explain.*

We computed matrix S on Matlab using the following code:

Embedded Code #2: matrix S

```
% create identity matrix
I = eye(n);
% calculate S
S = inv(I-A);
```

After calculating the row and column sums of matrix S, we used a bar plot to compare the overall indices to the indices obtained with matrix A.

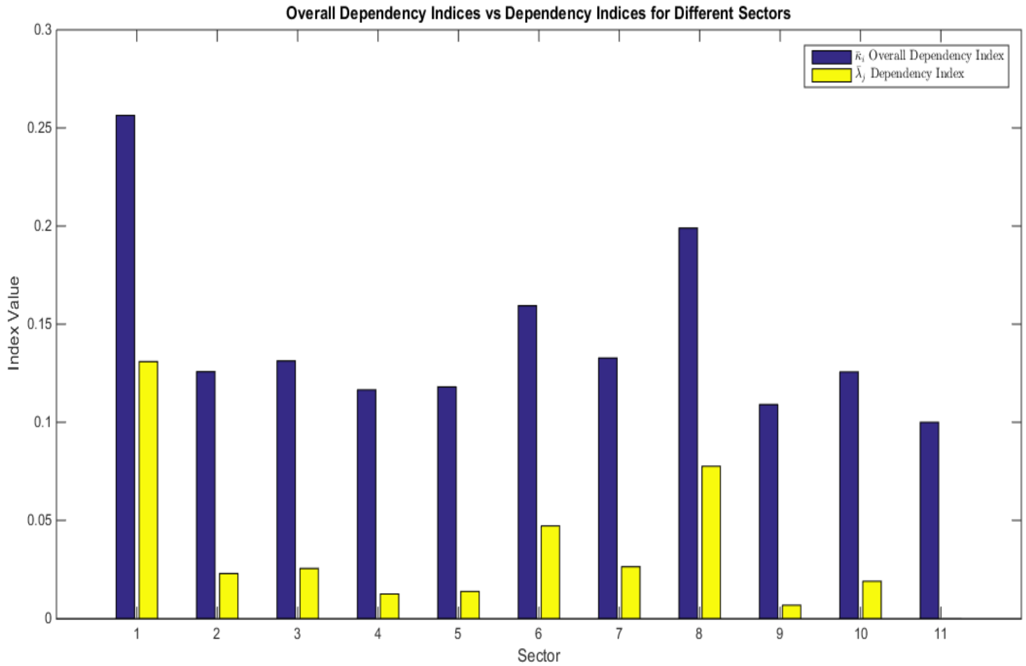

Fig. 3: <u>Bar Chart Comparison of Overall Dependency Indices and Dependency Indices</u>

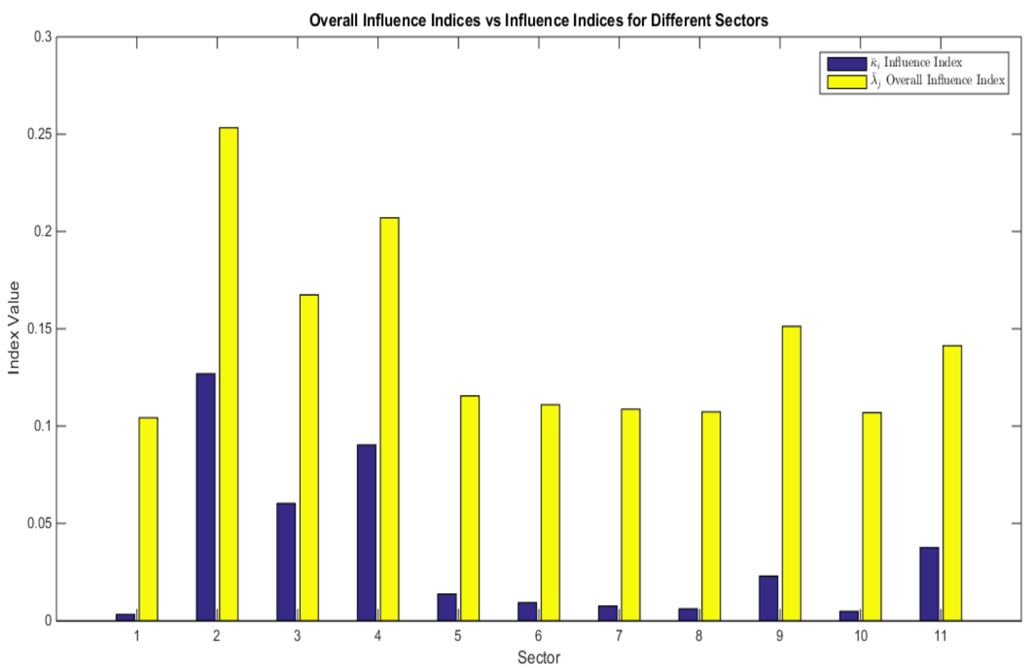

Fig 4: <u>Bar Chart Comparison of Overall Dependency Indices and Dependency Indices of Each Sector</u>

Overall indices are always higher than direct indices. There is also a correlation between the dependency/influence index and the corresponding overall index: they're proportional. Because of this, the same interpretations made in question 2.9 can be re-stated here in terms of relative dependency and influence.

Question 2.11 *With the incorporation of smart grid technologies into the electricity generation infrastructure, the electricity utilities can be more efficient. At the same time, the additional technology introduces new dependencies in various infrastructure assets. For example, we expect that the dependency between the electricity infrastructure and the communications infrastructure might change. Which coefficient(s) of matrix A will change, and in which direction (increase/decrease)? You must explain any changes you believe would be necessary to model the incorporation of new technology into the electricity grid.*

The generation, transmission and distribution components of a smart-grid are usually connected using inter control communications center. It is a communication hub connecting the various network elements in real time. However, these tailored centers depend on the existing low-level communication infrastructure between the generation, transmission and distribution sites: MPLS (Multiprotocol Label Switching), Satellite, POTS (Plain Old Telephone Service) or Leased Lines. This means that all three communications sectors: wireless telecommunications, wired telecommunications and satellite communication will affect the electricity sector more if a smart grid is installed. As a result, we assume that the coefficients $a_{2,3}$, $a_{2,4}$ and $a_{2,11}$ will increase. A smart grid will by definition impact power systems architecture to make them more efficient, thus changing the existing electricity grid. Natural gas is a possible solution to Renewable Energy intermittence for electricity generation. As such, the natural gas sector's influence $a_{2,9}$ on electricity could increase with the installation of a smart grid that uses natural gas for electricity generation. Coefficients in other sectors could increase their influence on electricity, for instance: naval ports for shipping of energy resource and equipment, finance for initial installation costs, fuel and petroleum grid because of the increased use of electric cars as a result of the smart grid. However, research doesn't show any other notable increase in dependency/influence between the eleven sectors as a result of a smart grid.

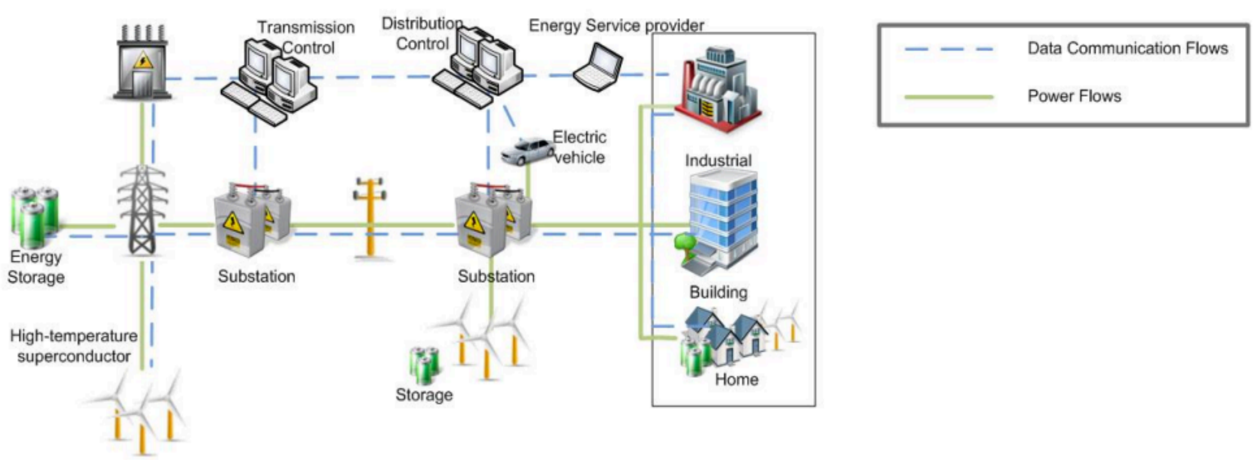

Fig. 5: **<u>Smart Grid Flow Chart from "Communication Network Interdependency in Smart Grids", 2015, by the European Union Agency for Network and Information Security</u>**

Question 2.12 *Assume that any coefficient(s) that you indicated in the previous question increase/decrease (as you specified) by 10%. Compute the new matrix S, and recalculate the overall indices κ_i and λ_j. Compare them to the previous ones and comment any interesting features that you observe. Which infrastructure assets are affected most by this change?*

We used the following code to compute the new S matrix, assuming a 10% increase in the coefficients that represent the influence of the wired telecom, wireless telecom, and satellite communication sectors on the electricity sector.

Embedded Code #3: matrix A with smart grid dependencies

```
A_sg = A; % smart grid
A_sg(2,3) = 1.1*A(2,3);
A_sg(2,4) = 1.1*A(2,4);
A_sg(2,11) = 1.1*A(2,11);

%calculate new S
S_sg = inv(I-A_sg)
```

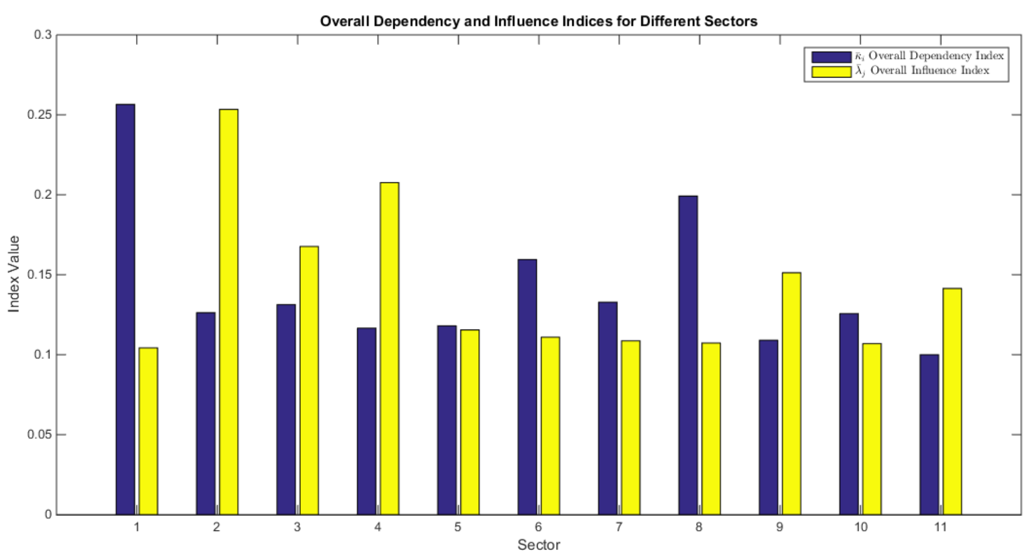

Fig. 6: **Bar Chart Comparison of the Dependency and Influence of Each Infrastructure Asset after Smart Grid Technology Implementation**

In order to compare the new overall indices to the old ones, we plotted the difference between the new indices and the old ones in a bar plot.

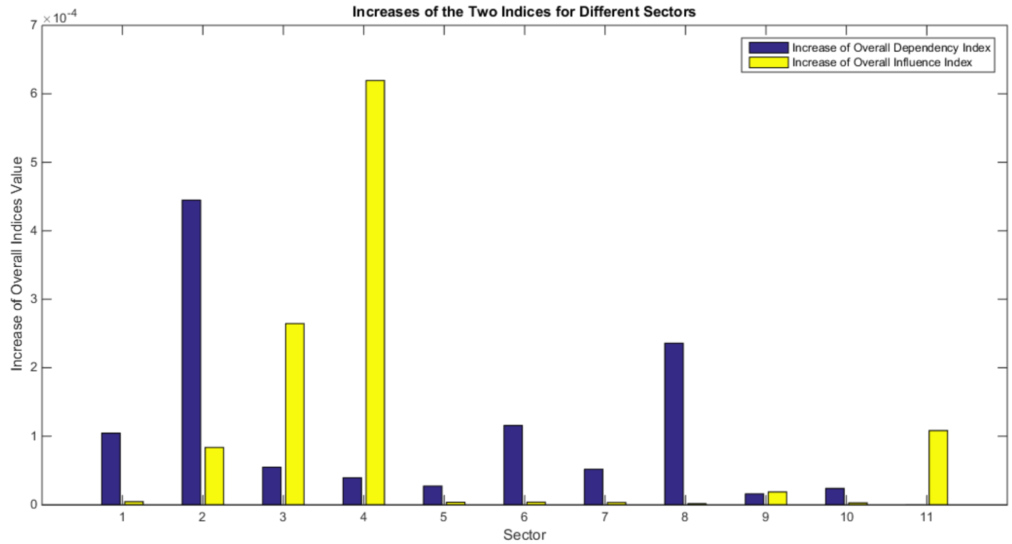

Fig.7: <u>Bar Chart Illustrating the Change in Indices Caused by the Smart Grid Integration</u>

The infrastructure assets impacted most by this change are: wired telecom, wireless telecom, electricity and fuel and petroleum grid, rail, air transportation. The influence of communications increases as expected while the dependency of electricity, fuel and petroleum grid, and transportation increases substantially.

Question 2.13 *Consider a sudden strike of a strong snow storm. Assume it creates an external reduction of 50% of the rail transportation (cancelled and delayed trains due to the heavy snow), 10% of the electricity sector (electricity outages), 35% of air transportation (cancelled flights) and 20% of the naval port operations (shipping delays and decreased efficiency in handeling inventory). What is the effect on other infrastructure assets? How much do critical infrastructure dependencies further degrade the already damaged infrastructure? Are other infrastructure assets degraded even without being directly affected by the storm?*

In order to answer the questions, we modeled the snowstorm's impact on infrastructure through an initial f vector with the following values: 0.35 for air transportation (1st row), 0.1 for electricity (2nd row), 0.5 for rail (6th row), 0.2 for naval ports (10th row). The other rows were assigned a value of 0. We then used the expression x = S * f to compute the new vector showing the impacts the snowstorm had on other sectors indirectly.

Embedded Code #4: matrix A with smart grid dependencies

```
% Create vector f_ss to indicate external shock from snowstorm
% 50% damage to 6 rail
% 10% damage to 2 elec
% 35% damage to 1 air
% 20% damage to 10 naval
f_ss = zeros(n,1);
f_ss(6) = 0.5;
f_ss(2) = 0.1;
```

```
f_ss(1) = 0.35;
f_ss(10) = 0.2;

% Calculate vector x that indicates infrastructure impacts from snowstorm
x_ss = S * f_ss;
```

The output given by Matlab is the following vector: **[0.39; 0.11; 0.02; 0.01; 0.01; 0.53; 0.02; 0.7; 0.01; 0.22; 0]**.

The table below shows that the already damaged infrastructure are all further damaged by critical infrastructure dependencies. air transportation, electricity and rail transportation are further degraded by 4%, 1% and 3% respectively. This corresponds to about a 10% increase on average from the original degradation value. Other infrastructure assets were damaged although they weren't directly affected by the snowstorm, because of critical infrastructure dependencies, except for satellite communication. The most affected sector is fuel and petroleum grid (70%) while natural gas, TLC wired and water management are least affected by the snowstorm. Satellite communication is not affected at all because it isn't dependent on the critical sectors modeled in matrix A.

Infrastructure System	Degradation (%)
Air Transportation	**39**
Electricity	**11**
Wireless telecommunications (TLC wireless)	2
Wired telecommunications (TLC wired)	1
Water management	1
Rail transportation	**53**
Finance	2
Fuel & Petroleum grid	70
Natural Gas	1
Naval Ports	22
Satellite Communication & Navigation	0

Table 1: Total Degradation of Each Sector after Propagation of the Snowstorm *(initially damaged sectors are bolded)*

Question 2.14 *In your opinion, is matrix A presented in Table 2 an appropriate influence matrix to analyze the effects of a heavy snow storm? What limitations does it have?*

Matrix A isn't appropriate to analyze the effects of a snowstorm on the infrastructure assets because it only takes into account direct damage and not overall damage. Moreover, the critical infrastructure assets list modeled in matrix A isn't exhaustive; there are other critical sectors that would be directly damaged by a snowstorm depending on its extent and context, such as ground transportation, food and agriculture, healthcare, etc. These are among the 16 critical sectors listed by the U.S. Department of Homeland Security as paramount to the nation's stability.

Question 2.15 *Simulate the propagation of the initial damage through the k^{th} tier of impacts using the recursive relation defined in lecture 12: $x(k) = Ax(k-1) + f$. Plot $x(k)$ as a function of k and explain what you observe. How does $x(k)$ compare to Sf (occasionally, always, only for some f, for all f)? Is $x(k)$ larger or smaller than Sf? Is it a coincidence, or is there something more fundamental about what you observe?*

Embedded Code #5: matrix S

```
      runs = 10000; % number of MC runs
% Initialize storage matrix for x values
xAll = NaN(m,runs);
% Use snowstorm external shock f_ss
for i = 1:runs
    % Generate matrix of random multipliers
    % Want random values between 0.9 and 1.1, inclusive
    mults = (1.1-0.9) .* rand(m) + 0.9;
    % Use element-wise matrix multiplication to sample a new matrix A
    A_samp = A .* mults;
    % Calculate x vector
    x_samp = (I-A_samp)\f_ss;
    % Put into the storage matrix
    xAll(:,i) = x_samp;
end
```

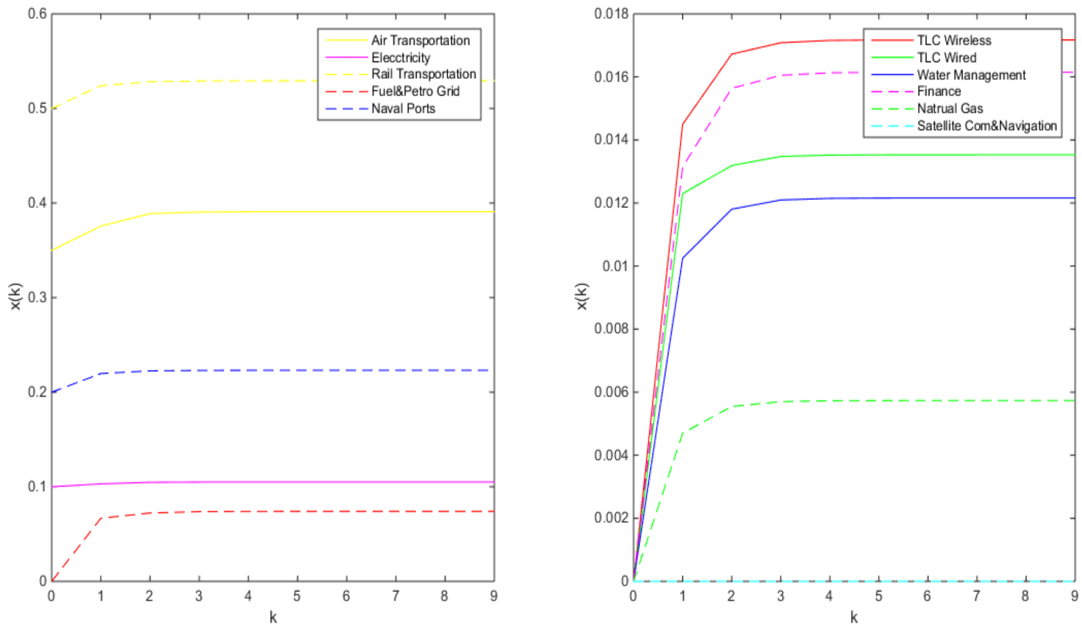

Fig. 8: **<u>Propagation of the Initial Snow Storm Damage through the kth Tier of Impacts</u>**

The above figures show the propagation of the initial damage in each sector in the form of a curve. In all cases except for satellite communication, x(k) approaches Sf as k increases. During the first tiers, x(k) values are smaller than Sf. Since the model simulates the propagation of the initial damage caused by interdependencies, this result makes sense as the total degradation is supposed to increase as sectors impact each other until the threshold value defined by the matrix S coefficients is attained. Thus, Sf is larger than x(k) but x(k) approaches Sf as k goes to infinity, and the difference is infinitesimally small after the third tier.

Question 2.16 *Assume that the values in Table 2 are the expected values of uniform distributions with ranges of 10% of the mean value. Perform a Monte Carlo analysis to quantify the uncertainty in x given the uncertainty in A. Plot the results and compare them to the deterministic analysis and comment any interesting features that you observe. Which infrastructure is the most robust to the uncertainty? Which one is the most sensitive to the uncertainty? Is the uncertainty on x uniform? Do you expect it to be uniform? You may also wish to look at the effect on S of uncertainty on A.*

Embedded Code #6: Monte Carlo Simulation Matrix A

```
runs = 10000; % number of MC runs
% Initialize storage matrix for f values
xAll_randf = NaN(m,runs);
% Use snowstorm external shock f_ss
for i = 1:runs
    % Generate vector of random multipliers
```

```
    % Want random values between 0.9 and 1.1, inclusive
    mults = (1.1-0.9) .* rand(m,1) + 0.9;
    % Use element-wise vector multiplication to sample a new vector f
    f_samp = f_ss .* mults;
    % Calculate x vector
    x_samp = (I-A)\f_samp;
    % Put into the storage matrix
    xAll_randf(:,i) = x_samp;
end
```

We used histogram plots to observe and analyze the results:

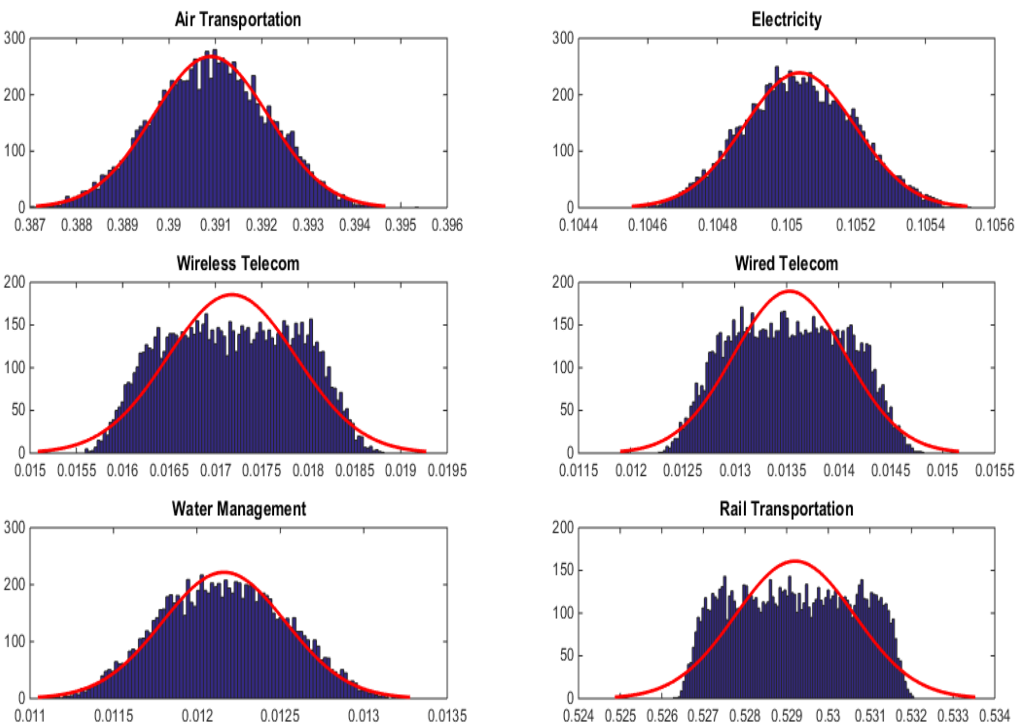

Fig. 9: <u>Uncertainty Distribution in Matrix A for sectors 1-6 based on a Monte Carlo Simulation with ranges of 10% of the mean value</u>

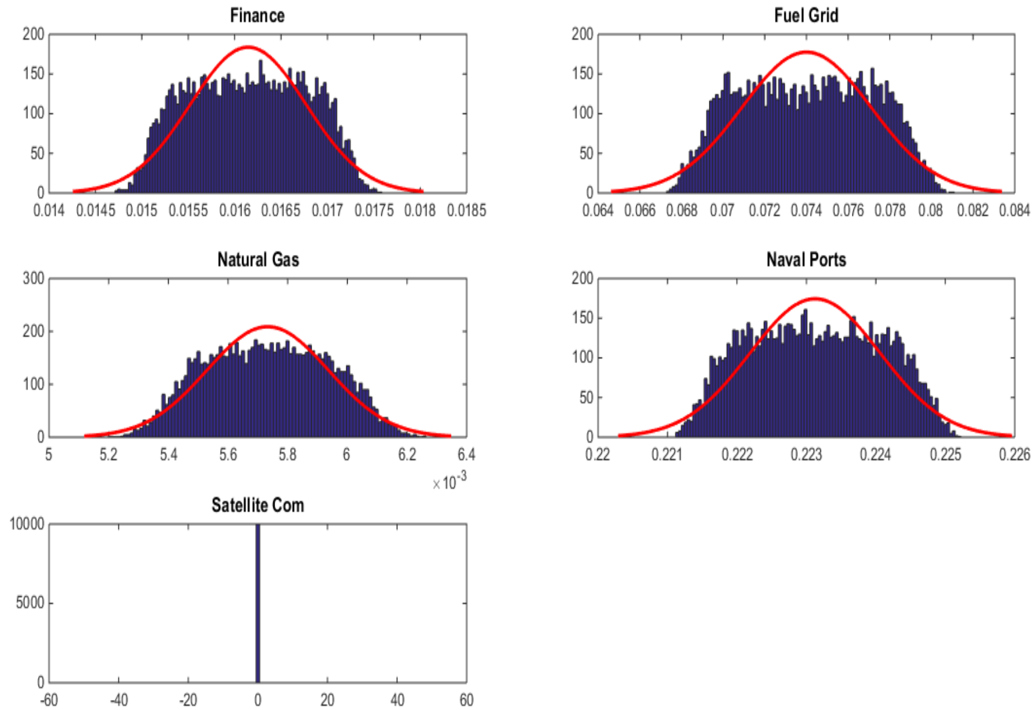

Fig. 10: Uncertainty in Matrix A Distribution for sectors 7-11 based on a Monte Carlo Simulation with ranges of 10% of the mean value

The uncertainty in x resulting from the uncertainty in A has a normal distribution for all the sectors, although we did not necessarily expect it to be based on the mathematical relation between A and x. Indeed, the distribution of A should be linear.

Apart from satellite communication which is biased by its non-dependency the most robust sectors to uncertainty are electricity and natural gas, followed by water management. The sectors that are most sensitive to uncertainty are TLC wired, rail transportation and naval ports.

Below are the box plot representations the uncertainty distribution for each sector, with the deterministic value for x represented in blue points. The red lines represent the median values of x resulting from the given uncertainty. Although uncertainty sensitivity changes from one sector to the other, all of the x values are on or very close to the median value of the Monte Carlo simulation runs.

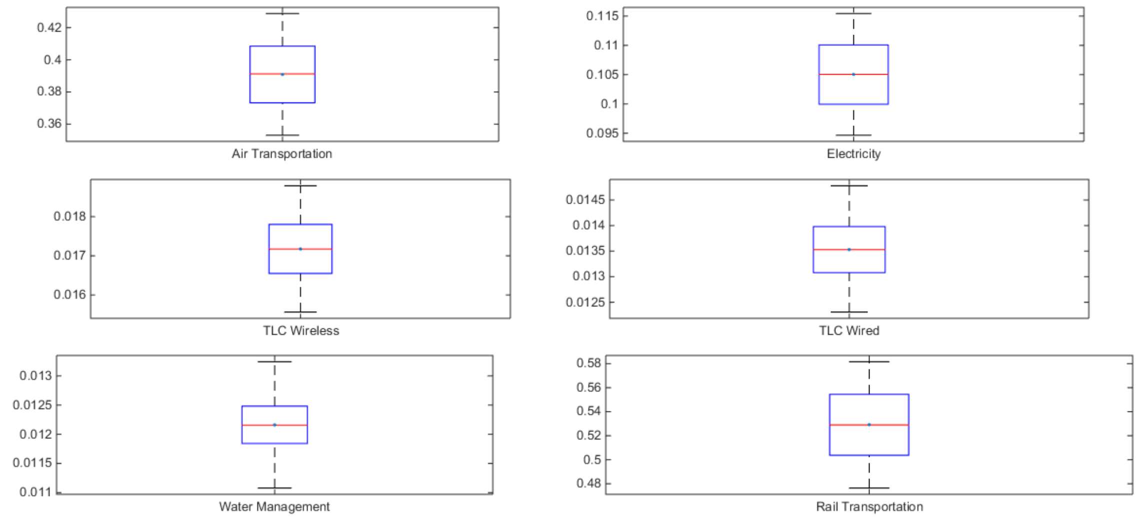

Fig. 11: **Box Plots Illustrating the Uncertainty Distributions for Sectors 1-6 based on a Monte Carlo Simulation with ranges of 10% of the mean value**

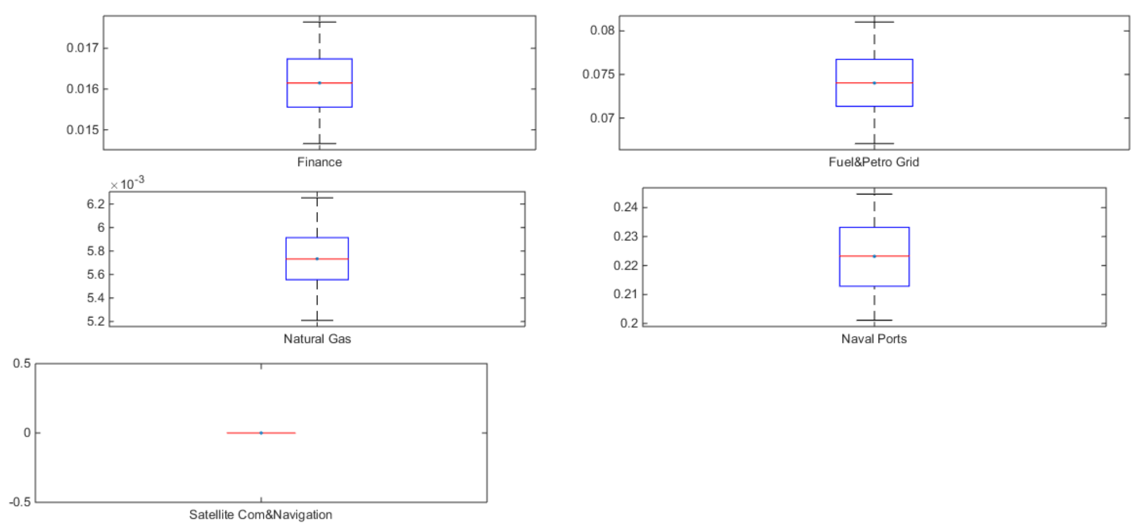

Fig. 12: **Box Plots Illustrating the Uncertainty Distributions in Matrix A for Sectors 7-11 based on a Monte Carlo Simulation with ranges of 10% of the mean value**

Question 2.17 Instead of uncertainty on A, assume the magnitude of the initial disruption caused by the snowstorm is uncertain. Assume the uncertainty on follows a uniform distribution with a range of 10% of the deterministic value used previously. What do you observe? What is worse, the 10% uncertainty on A, or the 10% uncertainty on f?

Embedded Code #7: Monte Carlo Simulation vector f

```
runs = 10000; % number of MC runs
% Initialize storage matrix for f values
xAll_randf = NaN(m,runs);
% Use snowstorm external shock f_ss
for i = 1:runs
    % Generate vector of random multipliers
    % Want random values between 0.9 and 1.1, inclusive
    mults = (1.1-0.9) .* rand(m,1) + 0.9;
    % Use element-wise vector multiplication to sample a new vector f
    f_samp = f_ss .* mults;
    % Calculate x vector
    x_samp = (I-A)\f_samp;
    % Put into the storage matrix
    xAll_randf(:,i) = x_samp;
end
```

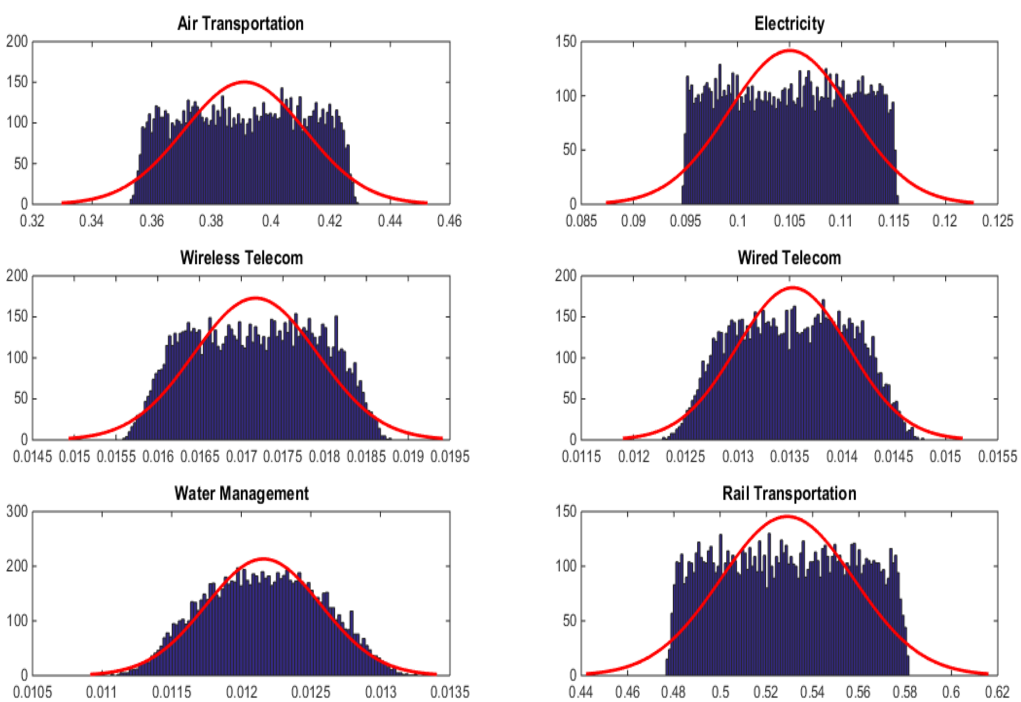

Fig. 13: <u>Uncertainty in vector f Distribution for sectors 7-11 based on a Monte Carlo Simulation with ranges of 10% of the mean value</u>

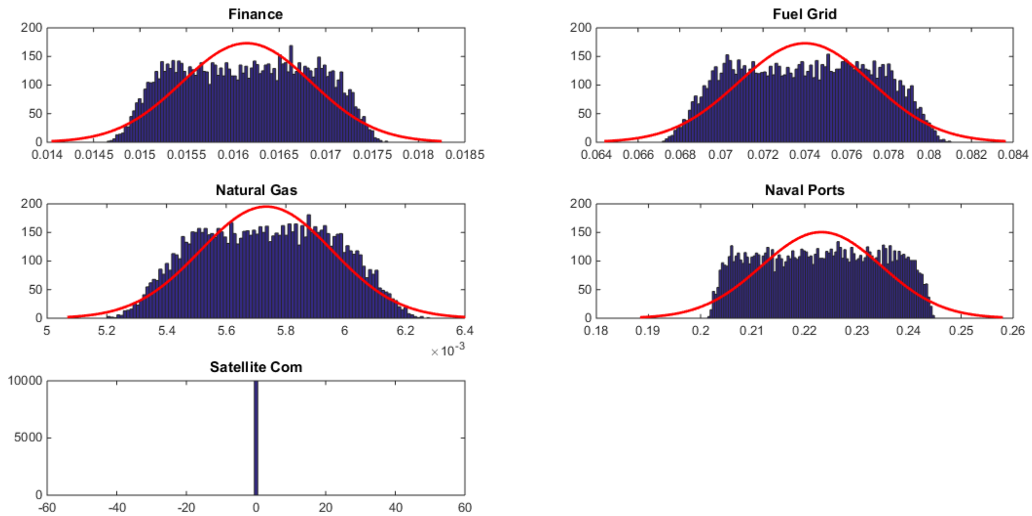

Fig. 14: Uncertainty Distributions in vector f for sectors 7-11 based on a Monte Carlo Simulation with ranges of 10% of the mean value

Again we observe normal distributions in uncertainty for all the sectors. Apart from satellite communication, the most robust sectors to uncertainty in this case are water management natural gas, and TLC wired while the most sensitive are rail transportation and naval ports. In order to compare uncertainties, we computed the difference between standard deviations for each sector in each scenario. The standard deviations caused by the uncertainty in vector fare higher than those caused by the uncertainty in Matrix A in all cases except for TLC wired, water management and natural gas. The sector that is most impacted by this difference is rail transportation. An interesting thing that was noticed is the sensitivity of the transportation sector that tends to be generally higher than that of the other sectors.

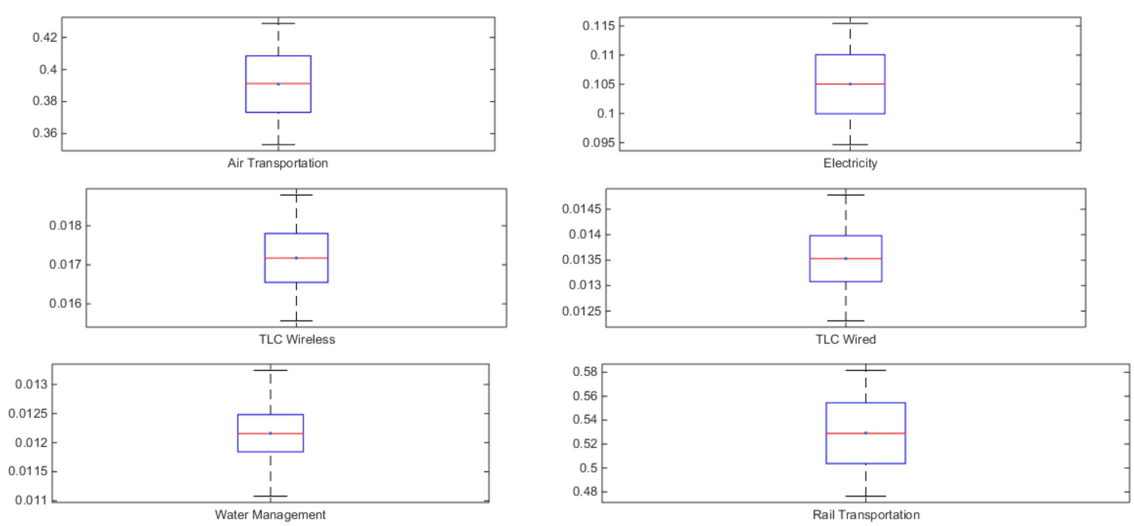

Fig. 15: Box Plots Illustrating the Uncertainty Distributions in vector f for Sectors 1-6 based on a Monte Carlo Simulation with ranges of 10% of the mean value

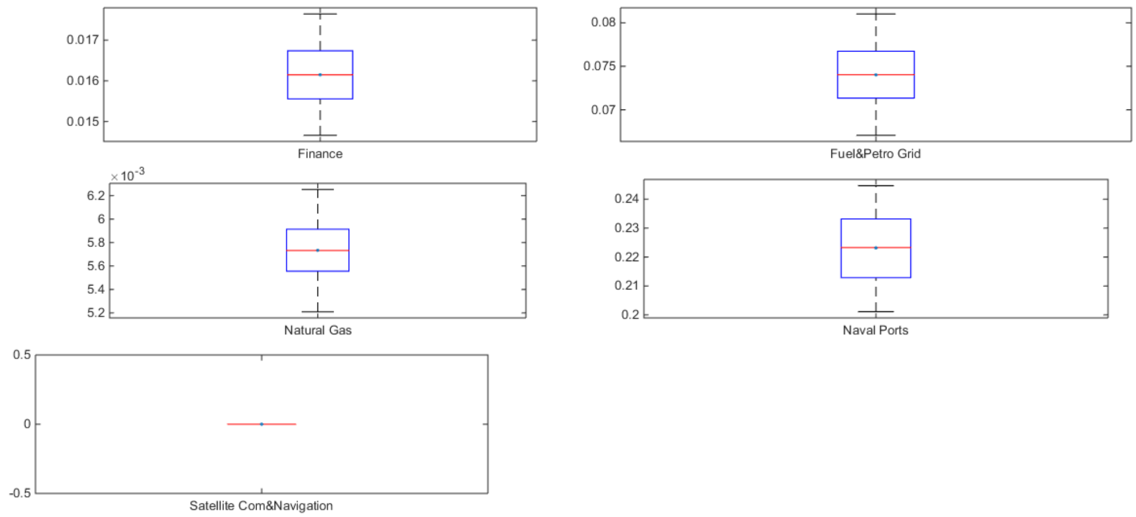

Fig. 16: <u>Box Plots Illustrating the Uncertainty Distributions in vector f for Sectors 7-11 based on a Monte Carlo Simulation with ranges of 10% of the mean value</u>

Question 2.18 We used the lower bounds of the uncertainty distributions (i.e -10%) to run the models defined by A and f

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Embedded Code #8: Uncertainty Comparison on lower and upper bound uncertainties

```
% Compare results from running lower and upper bounds for both A and f_ss

% lower bound for A (-10%)
A_lower = 0.9 .* A; % SC 11/06: dot multiply for correctness
x_lowerA = (I-A_lower)\f_ss;

% lower bound for f (-10%)
f_lower = 0.9 .* f_ss;
x_lowerf = (I-A)\f_lower;

% upper bound for A (+10%)
A_upper = 1.1 .* A;
x_upperA = (I-A_upper)\f_ss;

% upper bound for f (+10%)
f_upper = 1.1 .* f_ss;
x_upperf = (I-A)\f_upper;
```

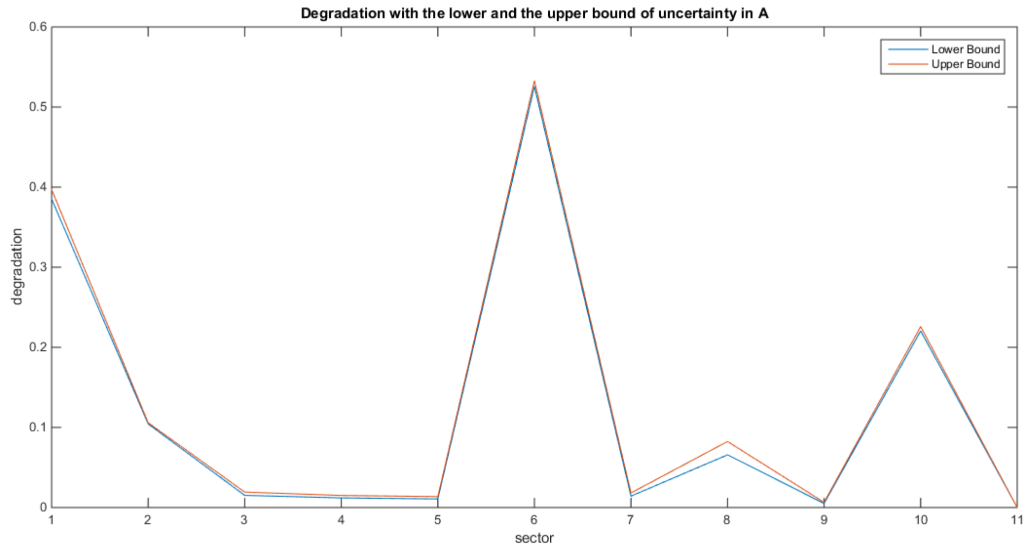

Fig. 17: <u>Total Degradation Values (x) Comparison Resulting from the Lower and Upper Bound Values of Matrix A</u>

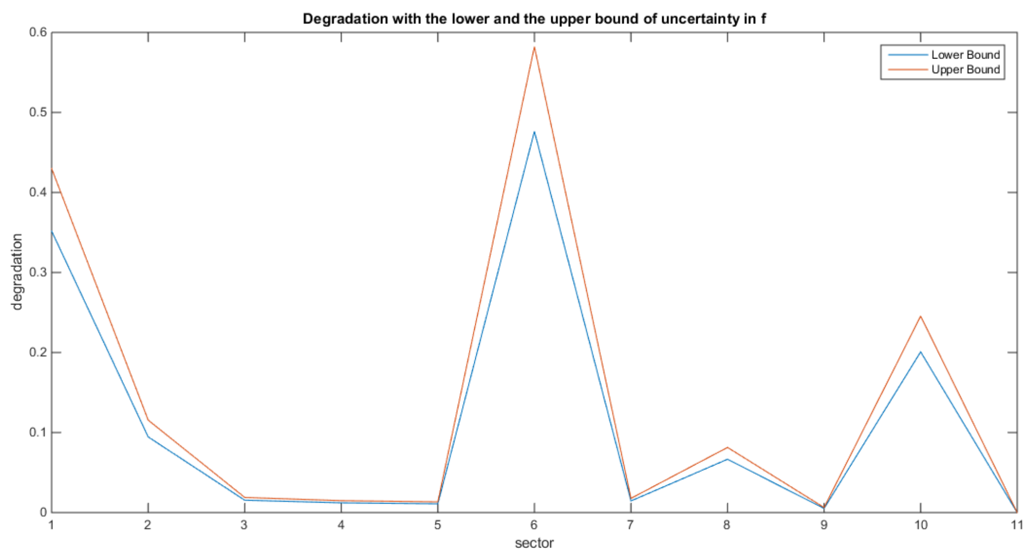

Fig. 18: <u>Total Degradation Values (x) Comparison Resulting from the Lower and Upper Bound Values of vector f</u>

In this problem we decided to use curves in order to illustrate the difference between the total degradation values when the lower bounds are used and the total degradation resulting from upper bound values for Matrix A and vector f. The obvious interpretation is that f has a higher impact on total degradation with a clearly higher range of values from the upper bound to the lower bound obtained x's. Moreover, the uncertainty in matrix A seems to have very little impact on overall degradation values. These results are in accordance with the ones we found previously.

Question 2.19 *If the total level of degradation to air fuel & petroleum grid, TLC wireless, and finance cannot be greater than 20%, 30%, and 35%, respectively, what is the maximum initial impact fmax that the system can absorb? Your solution might be an analytical solution or a solution to an optimization problem, you will need to decide.*

We used an optimization problem approach to solve this question. The linprog function in Matlab allows to minimize a function under given constraints. Here the constraints are twofold: the maximum values for f vector elements defined in the prompt, and the elements in f have to be within the interval [0,1]. Because of this, we used the upper and lower bound input option in the linprog function to write the following code:
m

Embedded Code #8: Linprog Optimization for optimized

```
% Maximize f subjected to these constraints
% degradation to fuel petroleum grid, TLC wireless and finance cannot
% be greater than 20%, 30% and 35%:
% S(8,:)*f<=0.2
% S(3,:)*f<=0.3
% S(7,:)*f<=0.35
% Each element in f should be positive: -fi<=0
% Optimization method using the linprog function
% Minimize f_opt = - f

f_opt=[-1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1]';

options=opt('linprog','Algorithm','dual-simplex')

A_opt=[S(8,:); S(3,:); S(7,:)];
b_opt=[0.2;0.3;0.35];
l_b= zeros(11,1); %lower bound is zero
u_b= ones(11,1); %upper bound is one

[x,v] = linprog(f_opt,A_opt,b_opt,[],[],l_b,u_b;)
[x, fval, exitflag, output, lambda] = ...
    linprog(f_opt, A_opt, b_opt, Aeq, beq, l_b, u_b,options)
```

The maximum initial impact that the system can absorb is defined by the vector f as follow: **[1; 0; 0; 0.76; 1; 1; 0.23; 0; 0; 1; 1]**. The following table interprets this results in terms of infrastructure assets. Eletricity, TLC wireless, Fuel & Petroleum Grid and natural gas can't sustain any initial damage. Air transportation, water management, rail transportation, naval ports and satellite communication can each sustain maximum initial damage without impacting the constraints. TLC wired can sustain a 76% initial impact while finance, which is one of the constrained sectors, can sustain a 23% initial impact.

Critical Infrastructure	Degradation
air transportation	100
electricity	0
wireless telecommunications (TLC wireless)	**0**
wired telecommunications (TLC wired)	76
water management	100
rail transportation	100
finance	**23**
fuel & petroleum grid	**0**
natural gas	0
naval ports	100
satellite communication & navigation	100

Table 2: <u>Maximum Initial Impact to Meet Constraints on Select Sectors</u> *(bolded)*

References

Mattioli, R., and Moulinos, K. (2015). *Communication Network Interdependency in Smart Grids*. European Union Agency for Network and Information Security.

Egozcue, E., Rodriguez, D.H., Ortiz, J.A., Villar, V.F., and Tarrafeta, L. (2012). *Smart Grid Security*. European Network and Information Security Agency