Post-symposium Update
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Introduction to Functional Dependency Network Analysis (FDNA)

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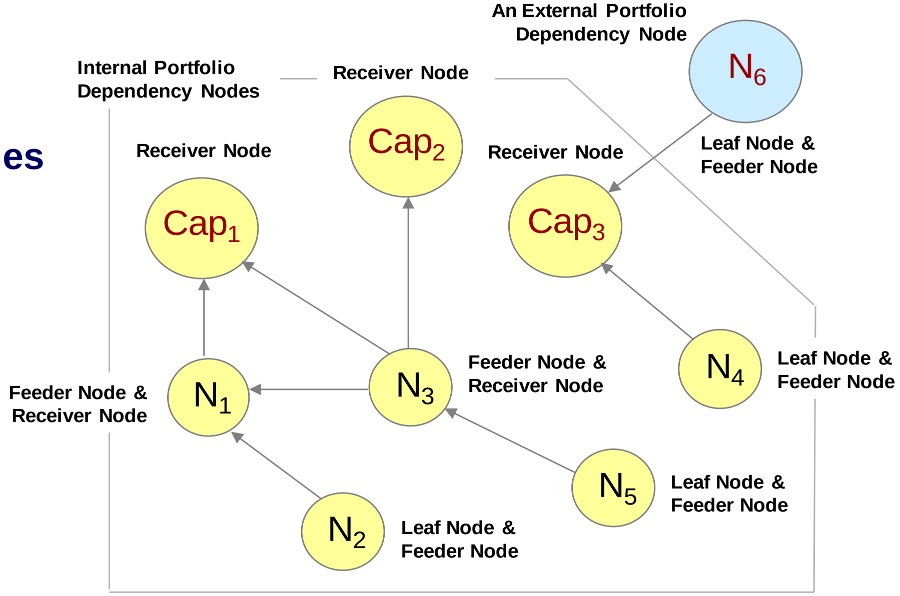
Functional Dependency Network Analysis (FDNA)

Critical considerations in engineering capabilities for a system are identifying, representing, and measuring **dependencies** between suppliers of technologies that enable capabilities and the providers of these capabilities that deliver services to consumers

The importance of this problem is many-fold; primary is enabling the study of consequence effects of failure in one capability as it ripples across to other dependent capabilities



Providing mechanisms to assess consequence effects early in design enables engineers to **minimize dependency risks** that, if realized, can have cascading negative (and potentially catastrophic) effects on the operability of a system's capability to deliver services to consumers

Functional Dependency Network Analysis (FDNA)

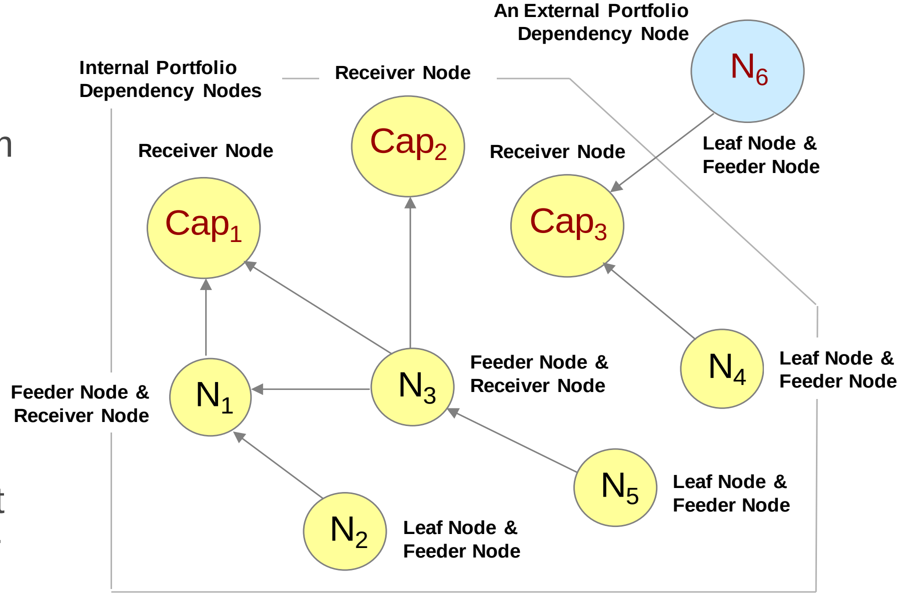
FDNA is an analytic approach that addresses the following question:

What is the consequence on the operability of capability if, due to the realization of risks, one or more contributing programs or supplier-provider chains degrade, fail, or are eliminated?

The FDNA is a methodology that enables management to study and anticipate the ripple effects of losses in supplier-program contributions on dependent capabilities before risks that threaten these suppliers are realized

An FDNA analysis identifies whether the level of operability loss, if such risks occu is acceptable

This enables management to better target risk resolution resources to those supplier programs that face high risk and are most critical to the operational capabilities of a portfolio



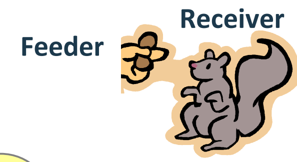
Functional Dependency Network Analysis (FDNA)

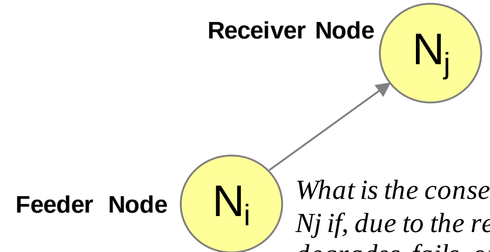
Dependence: A condition that exists between two nodes when the operability of one node relies, to some degree, on the operability of another node

What is meant by operability?

Operability: A measure of the value of a node's output; operability is a vNM utility measure expressed as "utils"; for example, a node that produces 60 widgets per hour might have this level of performance valued at 50 utils; or equivalently, its operability level is 50

Operability Range: Defined to range from 0 to 100 utils; a node is **wholly inoperable** if its operability level is 0 utils; a node is **wholly operable** if its operability level is 100 utils In FDNA, as a node's operability level increases so does the utility of its output





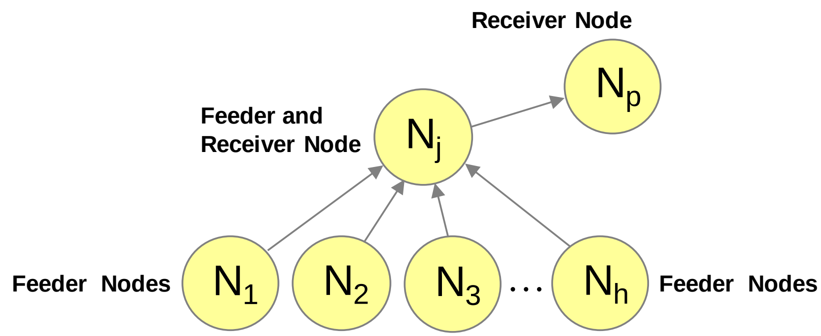
Suppose the operability of node Nj has a dependency on the operability of node Ni

What is the consequence on the operability of node Nj if, due to the realization of risks, node Ni degrades, fails, or is eliminated?

Receiver/Feeder Node: An FDNA graph can be viewed as a topology of receiver-feeder node relationships

A receiver node is one whose operability level relies on the operability level of at least one feeder node

In FDNA, a node may be a feeder and a receiver node as shown below



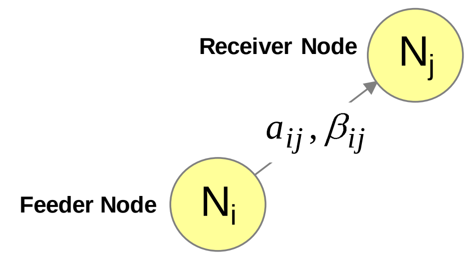
Functional Dependency Network Analysis (FDNA)

Strength of Dependency (SOD): The operability level (utils) a receiver node relies on receiving from a feeder node for the receiver node to continually increase its baseline operability level and ensure the receiver node is wholly operable when its feeder node is wholly operable

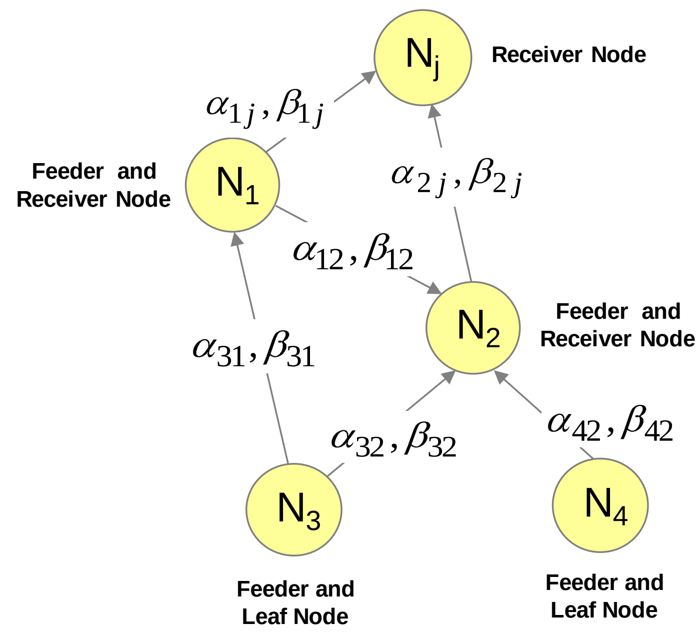
SOD Parameter Range $0 \le \alpha_{ij} \le 1$

$$SODP_j = \alpha_{ij} P_i + 100(1 - \alpha_{ij}),\ 0 \le P_i, P_j \le 100,\ 0 \le \alpha_{ij} \le 1$$

Baseline Operability Level (BOL) of Pj



From simple to increasingly intricate topologies



Criticality of Dependency (COD): Criticality of dependency (COD) enables the operability level of a receiver node to be constrained by the operability levels of its feeder nodes. This allows a receiver node's operability level to be limited by the performance of one feeder node, if appropriate, even when the receiver's other feeder nodes are wholly operable

COD Parameter Range $0 \le \beta_{ij} \le 100$

$$CODP_j = P_i + \beta_{ij},\ 0 \le P_i, P_j \le 100,\ 0 \le \beta_{ij} \le 100$$

Functional Dependency Network Analysis (FDNA)

More generally, the operability level of node N_j that is dependent on the operability levels of h feeder nodes $N_1, N_2, N_3, \ldots, N_h$ is

$$0 \leq P_j = Min(SODP_j, CODP_j) \leq 100$$

where

$$SODP_j = Average(SODP_{j1}, SODP_{j2}, SODP_{j3}, \ldots, SODP_{jh})$$

$$SODP_{ji} = \alpha_{ij} P_i + 100(1 - \alpha_{ij})$$

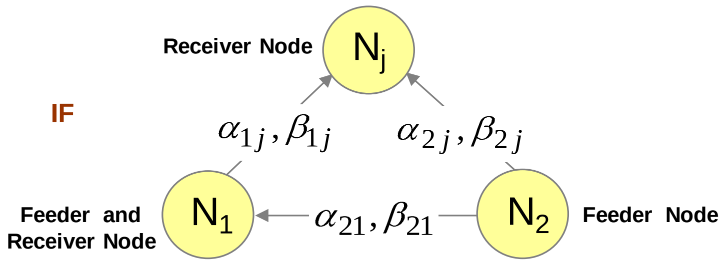
$$CODP_j = Min(CODP_{j1}, CODP_{j2}, CODP_{j3}, \ldots, CODP_{jh})$$

$$CODP_{ji} = P_i + \beta_{ij}$$

and $0 \leq \alpha_{ij} \leq 1, 0 \leq \beta_{ij} \leq 100, 0 \leq P_i, P_j \leq 100, i = 1,2,3, \ldots, h$

Example 1

IF



THEN

THESE ARE THE FDNA OPERABILITY EQUATIONS FOR THIS GRAPH

$$P_j = Min\left(\frac{\alpha_{1j}P_1}{2} + \frac{\alpha_{2j}P_2}{2} + 100\left(1 - \left(\frac{\alpha_{1j}+\alpha_{2j}}{2}\right)\right), P_1 + \beta_{1j}, P_2 + \beta_{2j}\right)$$

$$P_1 = Min(\alpha_{21}P_2 + 100(1 - \alpha_{21}), P_2 + \beta_{21})$$

α_{1j} is the strength of dependency fraction between N_1 and N_j, $0 \leq \alpha_{1j} \leq 1$

α_{2j} is the strength of dependency fraction between N_2 and N_j, $0 \leq \alpha_{2j} \leq 1$

α_{21} is the strength of dependency fraction between N_1 and N_2, $0 \leq \alpha_{21} \leq 1$

β_{1j} is the criticality of dependency constraint between N_1 and N_j, $0 \leq \beta_{1j} \leq 100$

β_{2j} is the criticality of dependency constraint between N_2 and N_j, $0 \leq \beta_{2j} \leq 100$

β_{21} is the criticality of dependency constraint between N_1 and N_2, $0 \leq \beta_{21} \leq 100$

$0 \leq P_1, P_2, P_j \leq 100$

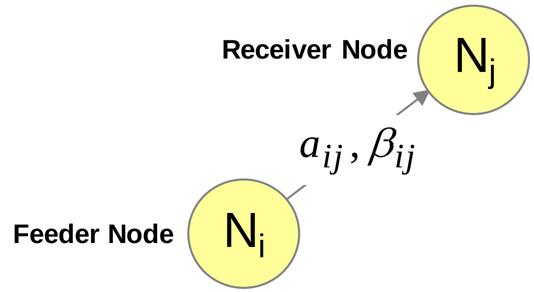
Functional Dependency Network Analysis (FDNA)

Determining Strength of Dependency (SOD)

A receiver node's baseline operability level can be used to determine α_{ij}. With this, we can ask the following: *What is the receiver node's baseline operability level (utils) prior to receiving its feeder node's contribution?* If the answer is 0 utils, then $\alpha_{ij} = 1$. If the answer is 50 utils, then $\alpha_{ij} = 0.50$. If the answer is 70 utils, then $\alpha_{ij} = 0.30$ and so forth. Thus, α_{ij} can be solved from the expression

$$100(1 - \alpha_{ij}) = x$$

where x is the receiver node's baseline operability level prior to receiving its feeder node's contribution. The greater the value of α_{ij} the greater the strength of dependency that receiver node N_j has on feeder node N_i and the less N_j's operability level is independent of N_i's level. The smaller the value of α_{ij} the lesser the strength of dependency that receiver node N_j has on feeder node N_i and the more N_j's operability level is independent of N_i's level. Next, we present a way to assess criticality of dependency.

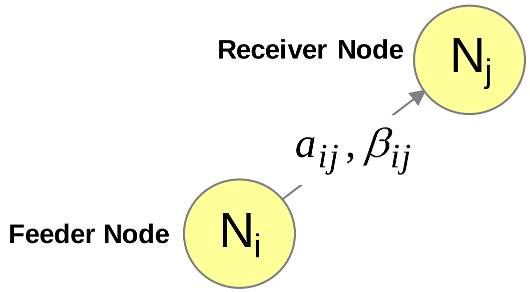


Functional Dependency Network Analysis (FDNA)

Determining Criticality of Dependency (COD)

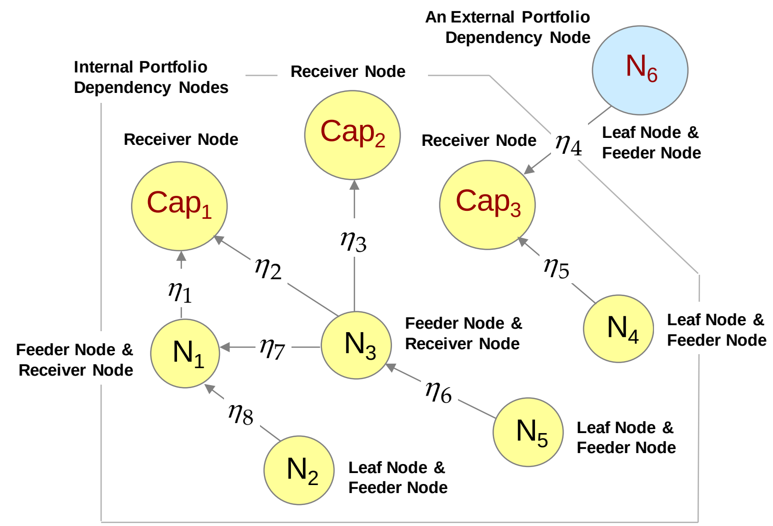
Criticality of dependency (COD) enables the operability level of a receiver node to be constrained by the operability levels of its feeder nodes. This allows a receiver node's operability level to be limited by the performance of one feeder node, if appropriate, even when the receiver's other feeder nodes are wholly operable. In general, the criticality of dependency constraint is the operability level β_{ij} (utils) such that the operability level of receiver node N_j with h feeder nodes can never be more than $P_i + \beta_{ij}$ for all i, where $i = 1,2,3, \ldots, h$, $0 \leq \beta_{ij} \leq 100$, and P_i is the operability level of feeder node N_i.

We can also characterize this constraint in terms of degradation in a receiver node's operability level, where degradation is measured from an operability level that has meaning with respect to the receiver node's performance goals or requirements. For example, in a single feeder-receiver node pair (below) the criticality of dependency constraint can be viewed as the operability level β_{ij} that receiver node N_j degrades to from a reference point operability level (such as its baseline operability level) when its feeder node's performance level has zero operational utility (no value or worth) to N_j.



Functional Dependency Network Analysis (FDNA)

Example 2



IF

THEN

$$\eta_1 \triangleq \alpha_{1Cap_1}, \beta_{1Cap_1} \quad \eta_2 \triangleq \alpha_{3Cap_1}, \beta_{3Cap_1} \quad \eta_3 \triangleq \alpha_{3Cap_2}, \beta_{3Cap_2} \quad \eta_4 \triangleq \alpha_{6Cap_3}, \beta_{6Cap_3}$$

$$\eta_5 \triangleq \alpha_{4Cap_3}, \beta_{4Cap_3} \quad \eta_6 \triangleq \alpha_{53}, \beta_{53} \quad \eta_7 \triangleq \alpha_{31}, \beta_{31} \quad \eta_8 \triangleq \alpha_{21}, \beta_{21}$$

THESE ARE THE FDNA OPERABILITY EQUATIONS FOR THIS GRAPH

$$P_1 = Min\left(\frac{\alpha_{21}P_2}{2} + \frac{\alpha_{31}P_3}{2} + 100\left(1 - \left(\frac{\alpha_{21}+\alpha_{31}}{2}\right)\right), P_2 + \beta_{21}, P_3 + \beta_{31}\right)$$

$$P_3 = Min(\alpha_{53}P_5 + 100(1 - \alpha_{53}), P_5 + \beta_{53})$$

$$P_{Cap_1} = Min\left(\frac{\alpha_{1Cap_1}P_1}{2} + \frac{\alpha_{3Cap_1}P_3}{2} + 100\left(1 - \left(\frac{\alpha_{1Cap_1}+\alpha_{3Cap_1}}{2}\right)\right), P_1 + \beta_{1Cap_1}, P_3 + \beta_{3Cap_1}\right)$$

$$P_{Cap_2} = Min\left(\alpha_{3Cap_2}P_3 + 100\left(1 - \alpha_{3Cap_2}\right), P_3 + \beta_{3Cap_2}\right)$$

$$P_{Cap_3} = Min\left(\frac{\alpha_{4Cap_3}P_4}{2} + \frac{\alpha_{6Cap_3}P_6}{2} + 100\left(1 - \left(\frac{\alpha_{4Cap_3}+\alpha_{6Cap_3}}{2}\right)\right), P_4 + \beta_{4Cap_3}, P_6 + \beta_{6Cap_3}\right)$$

Functional Dependency Network Analysis (FDNA)

Example 2

Operability Analysis Results for Three Time Periods t1, t2, and t3

FUNCTIONAL DEPENDENCY NETWORK ANALYSIS (FDNA)
A CAPABILITY PORTFOLIO

INPUT: αij Strength of Dependency (SOD)

α1Cap1	0.90	α4Cap3	0.85
α3Cap1	0.45	α53	0.30
α3Cap2	0.65	α31	0.15
α6Cap3	0.90	α21	0.28

INPUT: βij Criticality of Dependency (COD)

β1Cap1	10.00	β4Cap3	15.00
β3Cap1	55.00	β53	70.00
β3Cap2	35.00	β31	85.00
β6Cap3	10.00	β21	72.00

INPUT: IF these feeder nodes are functioning at these operability levels ...

Time t1: If operability levels of feeder nodes P2, P5, P4, and P6 are:		Time t2: If operability levels of feeder nodes P2, P5, P4, and P6 are:		Time t3: If operability levels of feeder nodes P2, P5, P4, and P6 are:	
P2	100	P2	75	P2	50
P5	100	P5	75	P5	50
P4	100	P4	75	P4	50
P6	100	P6	100	P6	100

OUTPUT: Then these receiver nodes are functioning at these operability levels...

P3	100.00	P3	92.50	P3	85.00
P1	100.00	P1	95.94	P1	91.88
PCap1	100.00	PCap1	96.48	PCap1	92.97
PCap2	100.00	PCap2	95.13	PCap2	90.25
PCap3	100.00	PCap3	89.38	PCap3	65.00

COD portion of receiver node operability level

P3	170.00	P3	145.00	P3	120.00
P1	172.00	P1	147.00	P1	122.00
PCap1	110.00	PCap1	105.94	PCap1	101.88
PCap2	135.00	PCap2	127.50	PCap2	120.00
PCap3	110.00	PCap3	90.00	PCap3	65.00

SOD portion of receiver node operability level

P3	100.00	P3	92.50	P3	85.00
P1	100.00	P1	95.94	P1	91.88
PCap1	100.00	PCap1	96.48	PCap1	92.97
PCap2	100.00	PCap2	95.13	PCap2	90.25
PCap3	100.00	PCap3	89.38	PCap3	78.75

Functional Dependency Network Analysis (FDNA)

A New Alternative to Matrix-Based Dependency Analysis Approaches

In general, the rows and columns of a matrix can always be considered a representation of in-flows and out-flows of a process or entities; from this, the matrix equation

$$AX = B$$

can be interpreted as an interdependency matrix **A** that when multiplied by the vector **X** produces the vector **B**; often, we want to find **X** for a given **B**

When dependency analyses are modeled by matrix equations, there are certain mathematical restrictions from linear algebra that affect solutions to these equations

For this research, it was initially thought Leontief's original input-output model [Leontief, 1966]

$$(I - A)X = B$$

could be leveraged onto the supplier-provider dependency problem identified in this research

However, matrix algebra restrictions (eg, the Hawkins-Simon condition) occurred too often when its original formulation was applied in this research context

Thus, it became necessary to think anew about dependencies and what mutual relationships between entities really mean, whether these entities are economic sectors, critical infrastructure systems-of-systems, or receiver-feeder nodes in an FDNA graph of a supplier-provider network

Functional Dependency Network Analysis (FDNA)
A New Alternative to Matrix-Based Dependency Analysis Approaches

A Composition of Functions Strategy

FDNA equations are constructed from mathematical graphs in ways that enable solutions to be derived by a composition of functions; that is, FDNA equations are algebraically formulated by composing functional dependency relationships across a mathematical graph

This strategy avoids matrix algebra and linear system solution issues that can occur with matrix-based solutions to dependency problems

As a result, FDNA can solve dependency problems that are otherwise intractable in a matrix-based approach; in fact, FDNA can solve dependency problems when the dependency matrix involves Hilbert or Markov forms

Such forms are show-stoppers in finding solutions to the matrix equations

$$AX = B \quad \text{or} \quad (I - A)X = B$$

If **A** is a Hilbert matrix, then the inverse of **A** quickly becomes "numerically singular" (computationally non-invertible)

If **A** is a Markov matrix, then the matrix (I – **A)** is singular (non-invertible)

The Hilbert Matrix

$$\begin{pmatrix} 1 & \frac{1}{2} & \frac{1}{3} & \cdots \\ \frac{1}{2} & \frac{1}{3} & \frac{1}{4} & \cdots \\ \frac{1}{3} & \frac{1}{4} & \frac{1}{5} & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

A 3x3 Markov Matrix

$$\begin{pmatrix} 1/5 & 1/2 & 3/10 \\ 3/10 & 3/10 & 3/5 \\ 1/2 & 1/5 & 1/10 \end{pmatrix}$$

Functional Dependency Network Analysis (FDNA)

Summary

This paper presented a brief introduction to Functional Dependency Network Analysis (FDNA)

FDNA was developed to model and measure dependency relationships between suppliers of technologies and providers of services these technologies enable the enterprise to deliver

The importance of the dependency problem in enterprise engineering is many-fold

Primary is enabling the study of ripple effects of failure in one capability on the operability of other dependent capabilities across an enterprise

Providing mechanisms to anticipate these effects early in design enables engineers to minimize dependency risks that, if realized, may have cascading negative effects on the ability of an enterprise to deliver services to users

Functional Dependency Network Analysis (FDNA)

Summary

The motivation for FDNA came from the need to address dependency problems that could not be fully expressed or solved in matrix-based protocols, such as those that characterize input-output (I/O) models in economic science

FDNA equations are constructed from mathematical graphs in ways that enable solutions to be derived by a composition of functions; that is, FDNA equations are algebraically formulated by a composition of functional dependency relationships across a mathematical graph

This strategy avoids matrix algebra and linear system solution issues (such as stability) that sometimes arise in matrix-based input-output approaches

The FDNA structure is visualized by graph theory to represent and model a range of complex dependency relationships between entities

FDNA has the potential to be a generalized modeling approach for a variety of dependency problems, including those in the domains of input-output economics, critical infrastructure risk analysis, and non-stationary, temporal, dependency analysis problems

Functional Dependency Network Analysis (FDNA)

Summary

Additional research areas include the following:

Analytical Scalability: Research how to approach risk analysis in engineering enterprise systems that consist of dozens of capability portfolios with hundreds of supplier programs. Explore representing large-scale enterprises by domain capability portfolio clusters and investigate a concept for portfolio cluster risk management

Non-stationary Considerations: Extend the FDNA calculus to address non-stationary, temporal, dependency analysis problems. Explore how FDNA can expand and integrate into time-varying modeling and simulation environments, such as those in systems dynamics methods and tools

Optimal Adaptive Strategies: Research how to optimally adapt an engineering system's supplier-provider network to reconfigure its nodes to maintain operability if risks that threaten these nodes are realized. Consider this problem in stationary and non-stationary perspectives

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FDNA is a methodology that enables management to study and anticipate the ripple effects of losses in supplier-program contributions on dependent capabilities before risks that threaten these suppliers are realized

FDNA identifies whether the level of operability loss, if such risks occur, is acceptable. This enables management to better target risk resolution resources to those supplier programs that face high risk and are most critical to the operational capabilities of a portfolio

Functional Dependency Network Analysis (FDNA)

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Functional Dependency Network Analysis (FDNA)

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