Modeling of Cyber-Physical Intra-Dependencies in Electric Power Grids and Their Effect on Resilience

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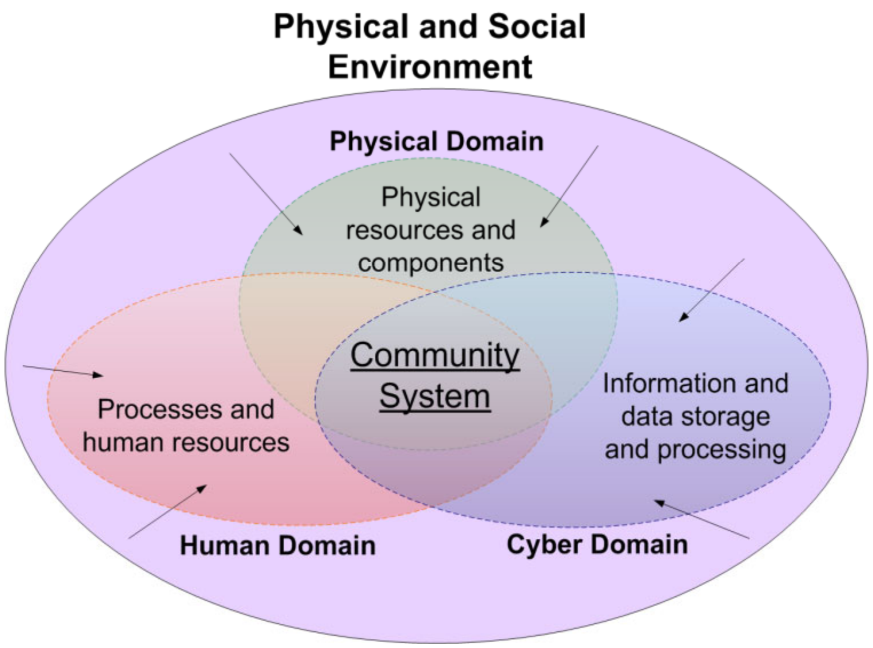
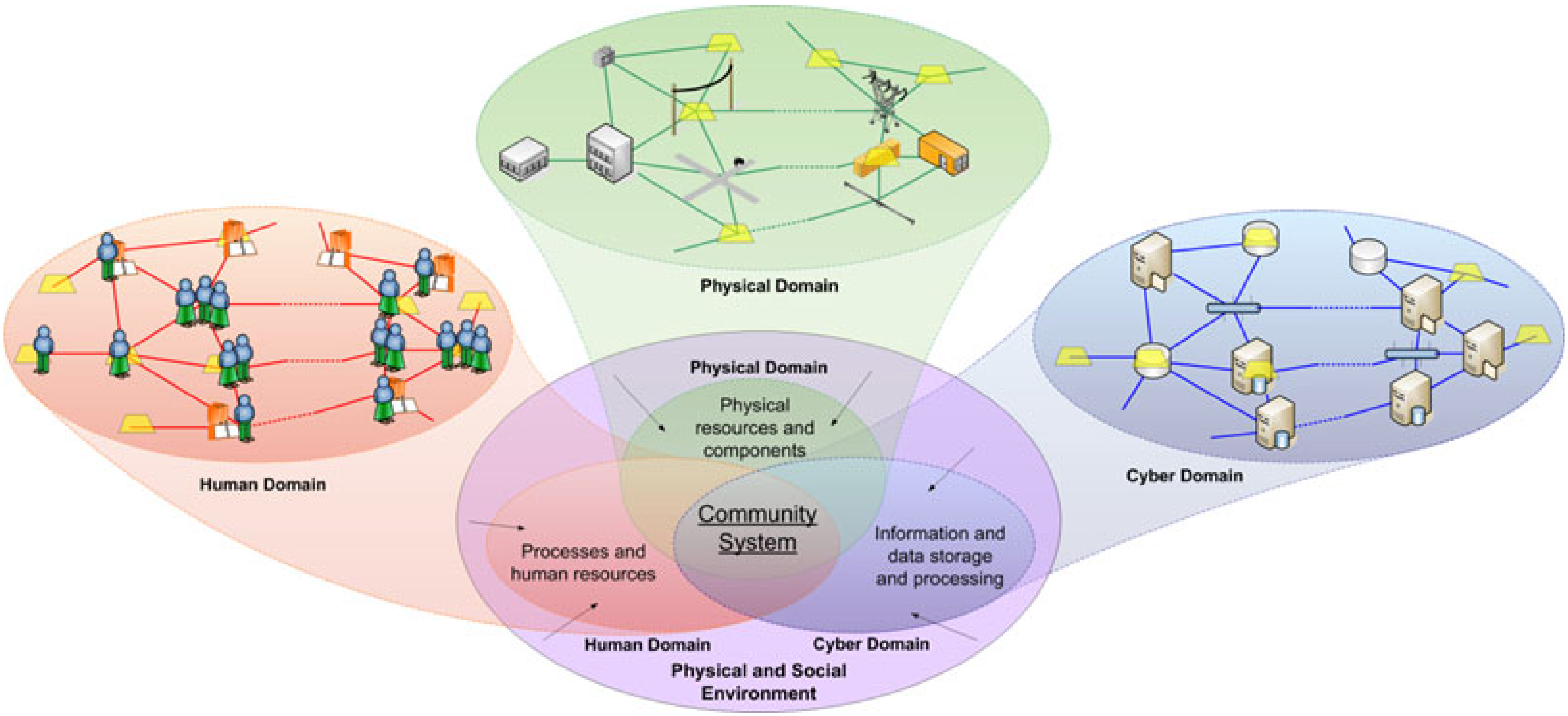
Critical Infrastructure Systems

- Critical infrastructures (including power grids) are an integrated concept of a system that includes the following domains:
  - Physical domain: Physical components and its interconnections
  - Cyber domain: databases, information, communications and control and operations algorithms.
  - Human/organizational domain: processes, policies, procedures, regulations as well as the human system operators and administrators necessary to manage, administrate and operate the system
- Infrastructures are networked systems and are characterized by the services they provide. Electric power grids' service is the **provision of electric power**.



Resilience model

- Each domain is modeled as a graph in which each component is connected to other components of the same domain through the provision of services within the system.
- Hence, each node or vertex represents a component or group of components necessary to provide a service whereas the connections or edges between vertices represent the provision of such service.



Resilience model

- Vertices can be classified into sink vertices and source vertices.
- **Sink vertices** represent the receiving end of a service. I.e., electric loads are the sink vertices in the physical domain of the graph representing the provision of electrical energy by power grids. Another example of a sink vertex, this time in a power grid cyber domain is control commands into power plants.
- **Source vertices** represent the originating end of a service. Hence, power plants within a power grid are source vertices for the electric power provision service in the physical domain of a power grid. Another example of a source vertices in a power grid cyber domain are voltage, current and power measurements used state estimation.Source vertices transform services and resources into another service.
- It is also possible to distinguish a third type of vertices: passing, transfer or transmission vertices, in which an input service is passed or transferred to other vertices without changing the service being provided.

Dependencies

- Source vertices need for services establish dependencies.
- That is, **dependencies are established with respect to services and not with respect to infrastructures**.
- Even when a service is primarily provided by a infrastructure system, such service may or may not be always provided by such infrastructure.
- For example, a communications site needs the provision of electric power for its operation. However, such power may be provided by a power grid, or local renewable energy sources or, temporarily, by batteries.
- If the service to a given infrastructure vertex is provided by another infrastructure, then the former infrastructure system is a lifeline of the latter infrastructure system.
- Interdependencies exist when dependencies of services provided by a pair of infrastructures or community systems are reciprocal.
- Power grids do not use public communication networks for their SCADA system so it may not be possible to establish in this case an interdependency. (This can change in the future with smart grids).
- Intra-dependencies (dependencies within a given infrastructure system) can be identified in power grids because it is a cyber-physical system with its own communications network used to transmit control and sensing signals.

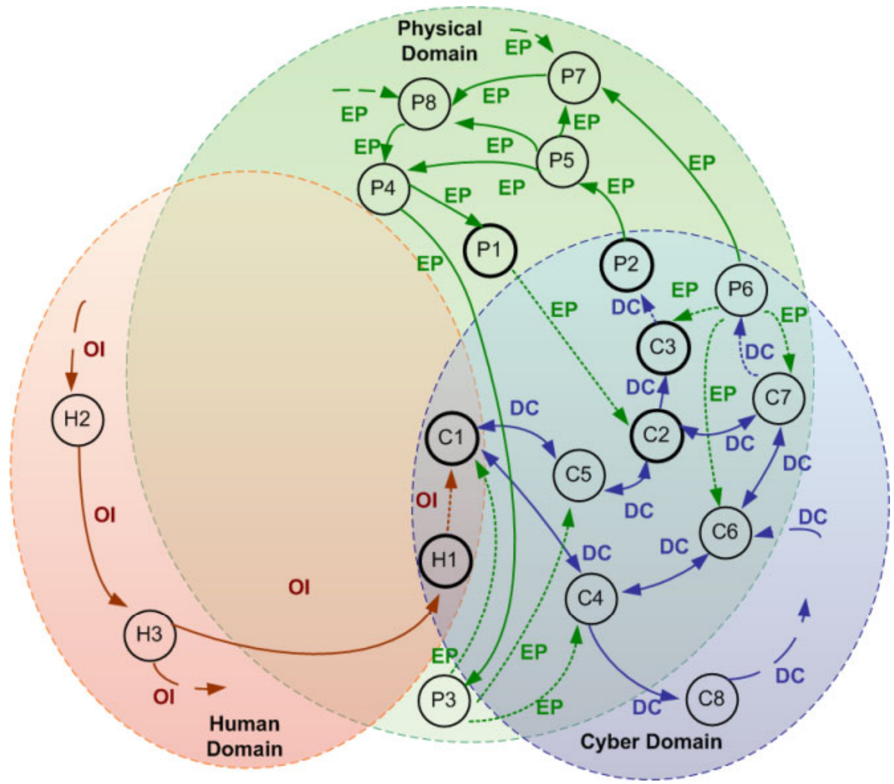
Dependencies

- **Service buffers**:
  - They are part of vertices receiving a service.
  - Buffers have the ability for temporarily provide its associated service to its vertex if the service being provided by another vertex is disrupted.
  - One key attribute of buffers is their autonomy which is the maximum time they can temporarily provide the service they are buffering.
  - Examples of buffers:
    - Energy storage in batteries for buffering the service provision of electrical energy.
    - Waiting time for a communications link to be reestablished as a buffer for the service data connectivity.
    - Cash savings as a buffer for the service provision of funds.

Cyber-physical Intra-Dependencies

- Assume that P2 is a power generator and that a person at a dispatch center represented by H1 needs to send a command to that power generator.

- There are three services creating intra-dependencies
  - EP: Electric power provision (main service supported by the other two)
  - DC: Data connectivity.
  - OI: Operations instruction.



Cyber-physical Intra-Dependencies

- From the Presidential Policy Directive 21 the term 'resilience' means the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions.
- Resilience for a single load (or, in general, a sink vertex) is

$$R_{SL} = \frac{T_U}{T_e}$$

where T_U is the period of time that is part of the total event duration T_e when the load is receiving power. In this resilience metric, the total event duration, T_e, equals the sum of T_U and T_D (the period of time that is part of T_e when the load is not receiving power).

- In general,

$$R_{Vj} = R_{Vj,i} \prod_{k=1}^{K} \left(1 - (1 - R_{Vk}) e^{-\frac{T_{BVj,Vk}}{T_{D,Vk}}}\right)$$

where the K vertices V_k are the set of vertices immediately preceding vertex V_j in the service path to V_j—i.e., the K vertices V_k are those directly providing services to V_j—$T_{BVj,Vk}$ is the autonomy for the service buffer at vertex V_j for the service provided by V_k and $T_{D,Vk}$ equals the difference between T_e and $T_{U,Vk}$

Cyber-physical Intra-Dependencies

- Let's calculate R_{P2}

$$R_{P2} = R_{P2,i}\left(1-(1-R_{C3})e^{-\frac{T_{BC,P2}}{T_e(1-R_{C3})}}\right)$$

- So, we need R_{C3}

$$R_{C3} = R_{C3,i}\left(1-(1-R_{C2})e^{-\frac{T_{BC,C3}}{T_e(1-R_{C2})}}\right)\left(1-(1-R_{P6})e^{-\frac{T_{BP,C3}}{T_e(1-R_{P6})}}\right)$$

- So, we need R_{C2} and R_{P6}. Let's calculate R_{P6} first

$$R_{P6} = R_{P6,i}\left(1-(1-R_{C7})e^{-\frac{T_{BC,P6}}{T_e(1-R_{C7})}}\right)$$

Cyber-physical Intra-Dependencies

- Since C2 has two of the same service inputs (DC) and one input for EP service from P1:

$$R_{C2} = R_{C2,i}\left(1-(1-R_{P1})e^{-\frac{T_{BP,C2}}{T_e(1-R_{P1})}}\right)R_{C,C5-C7}$$

where

$$R_{C,C5-C7} = \left(1-(1-R_{C5-C7})e^{-\frac{T_{BC,C2}}{T_e(1-R_{C5-C7})}}\right)$$

where

$$R_{C5-C7} = R_{C5} + R_{C7} - R_{C5}R_{C7}$$

Cyber-physical Intra-Dependencies

- Next let's calculate R_{C1}

$$R_{C1} = R_{C1,i}\left(1-(1-R_{H1})e^{-\frac{T_{BH,C1}}{T_e(1-R_{H1})}}\right)\left(1-\ (1-R_{P3})e^{-\frac{T_{BP,C1}}{T_e(1-R_{P3})}}\right)$$

- Calculation of R_{H1} could be a complex process as human made decisions and interactions among humans and cyber-machines need to be considered.
- The concept of $T_{BH,C1}$ as a buffer that could temporarily provide the operations instruction service when vertex H1 is not providing such service is a priori non-existent.
- Thus, a priori $T_{BH,C1}$ equals zero, which makes vertex H1 specially critical.

Cyber-physical Intra-Dependencies

- Still, C1 acting as an interface between the human and a cyber domain is an important vulnerable point not only for resilience but also for cyber-security.

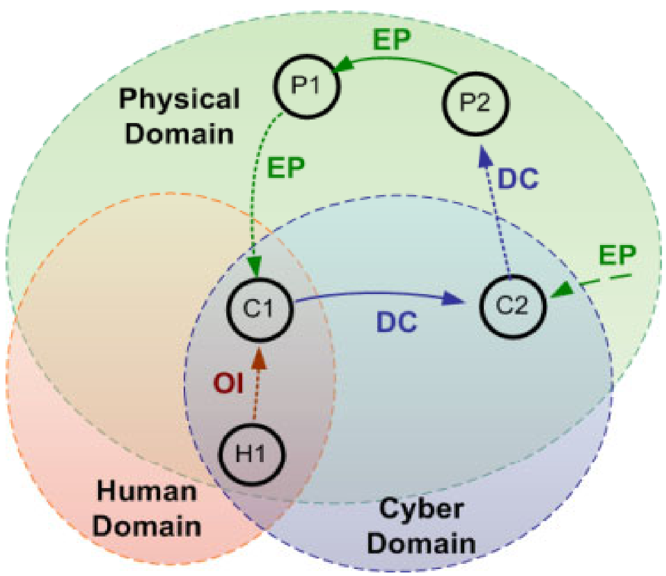
- A last step of interest for this discussion is to calculate R_{P1} considering that the only received service is the provision of electric power from P4. Although it is uncommon because of the high cost, the addition of energy storage in the grid may limit outage cascading by adding energy storage in P1 with an autonomy given by $T_{B,P1}$. Instead, since power levels in the cyber vertices are generally lower than those in the physical domain, it is typically more cost and operationally effective to add energy storage at the cyber vertices, as was exemplified with C2.

- The same approach taken up to here should be followed to calculate the other vertices resiliencies affecting R_{P2}

Cyber-physical Intra-Dependencies

- Let's use another example to further study cyber-physical intra-dependence within power grids.

- For simplicity assume that
  - vertex C2 is powered from a combination of renewable and alternative sources with a perfect resilience.
  - The provision of services from the human domain is assumed to be perfectly resilient.



Cyber-physical Intra-Dependencies

- The previous system has the following equations

$$
\begin{aligned}
f_1(\boldsymbol{R}_V) = R_{P2}\Bigg(1 - R_{P2,i}R_{C2,i}R_{C1,i}R_{P1,i}\,e^{-\frac{T_{B,P2}}{T_\theta(1-R_{C2})}}e^{-\frac{T_{B,C2}}{T_\theta(1-R_{C1})}}e^{-\frac{T_{B,C1}}{T_\theta(1-R_{P1})}}e^{-\frac{T_{B,P1}}{T_\theta(1-R_{P2})}}\Bigg)\\
- R_{P2,i}\Bigg(1 - e^{-\frac{T_{B,P2}}{T_\theta(1-R_{C2})}} + R_{C2,i}\,e^{-\frac{T_{B,P2}}{T_\theta(1-R_{C2})}} - R_{C2,i}\,e^{-\frac{T_{B,P2}}{T_\theta(1-R_{C2})}}e^{-\frac{T_{B,C2}}{T_\theta(1-R_{C1})}}\\
+ R_{C2,i}R_{C1,i}\,e^{-\frac{T_{B,P2}}{T_\theta(1-R_{C2})}}e^{-\frac{T_{B,C2}}{T_\theta(1-R_{C1})}} - R_{C2,i}R_{C1,i}\,e^{-\frac{T_{B,P2}}{T_\theta(1-R_{C2})}}e^{-\frac{T_{B,C2}}{T_\theta(1-R_{C1})}}e^{-\frac{T_{B,C1}}{T_\theta(1-R_{P1})}}\\
+ R_{C2,i}R_{C1,i}R_{P1,i}\,e^{-\frac{T_{B,P2}}{T_\theta(1-R_{C2})}}e^{-\frac{T_{B,C2}}{T_\theta(1-R_{C1})}}e^{-\frac{T_{B,C1}}{T_\theta(1-R_{P1})}}\\
- R_{C2,i}R_{C1,i}R_{P1,i}\,e^{-\frac{T_{B,P2}}{T_\theta(1-R_{C2})}}e^{-\frac{T_{B,C2}}{T_\theta(1-R_{C1})}}e^{-\frac{T_{B,C1}}{T_\theta(1-R_{P1})}}e^{-\frac{T_{B,P1}}{T_\theta(1-R_{P2})}}\Bigg) = 0
\end{aligned}
$$

$$
\begin{aligned}
f_2(\boldsymbol{R}_V) = R_{P1}\Bigg(1 - R_{P1,i}R_{P2,i}R_{C2,i}R_{C1,i}\,e^{-\frac{T_{B,P1}}{T_\theta(1-R_{P2})}}e^{-\frac{T_{B,P2}}{T_\theta(1-R_{C2})}}e^{-\frac{T_{B,C2}}{T_\theta(1-R_{C1})}}e^{-\frac{T_{B,C1}}{T_\theta(1-R_{P1})}}\Bigg)\\
- R_{P1,i}\Bigg(1 - e^{-\frac{T_{B,P1}}{T_\theta(1-R_{P2})}} + R_{P2,i}\,e^{-\frac{T_{B,P1}}{T_\theta(1-R_{P2})}} - R_{P2,i}\,e^{-\frac{T_{B,P1}}{T_\theta(1-R_{P2})}}e^{-\frac{T_{B,P2}}{T_\theta(1-R_{C2})}}\\
+ R_{P2,i}R_{C2,i}\,e^{-\frac{T_{B,P1}}{T_\theta(1-R_{P2})}}e^{-\frac{T_{B,P2}}{T_\theta(1-R_{C2})}} - R_{P2,i}R_{C2,i}\,e^{-\frac{T_{B,P1}}{T_\theta(1-R_{P2})}}e^{-\frac{T_{B,P2}}{T_\theta(1-R_{C2})}}e^{-\frac{T_{B,C2}}{T_\theta(1-R_{C1})}}\\
+ R_{P2,i}R_{C2,i}R_{C1,i}\,e^{-\frac{T_{B,P1}}{T_\theta(1-R_{P2})}}e^{-\frac{T_{B,P2}}{T_\theta(1-R_{C2})}}e^{-\frac{T_{B,C2}}{T_\theta(1-R_{C1})}}\\
- R_{P2,i}R_{C2,i}R_{C1,i}\,e^{-\frac{T_{B,P1}}{T_\theta(1-R_{P2})}}e^{-\frac{T_{B,P2}}{T_\theta(1-R_{C2})}}e^{-\frac{T_{B,C2}}{T_\theta(1-R_{C1})}}e^{-\frac{T_{B,C1}}{T_\theta(1-R_{P1})}}\Bigg) = 0
\end{aligned}
$$

Cyber-physical Intra-Dependencies

$$
\begin{aligned}
f_3(\boldsymbol{R}_V) = R_{C1}\Bigg(1 &- R_{C1,i}R_{P1,i}R_{P2,i}R_{C2,i}e^{-\frac{T_{B,C1}}{T_e(1-R_{P1})}}e^{-\frac{T_{B,P1}}{T_e(1-R_{P2})}}e^{-\frac{T_{B,P2}}{T_e(1-R_{C2})}}e^{-\frac{T_{B,C2}}{T_e(1-R_{C1})}}\Bigg) \\
&- R_{C1,i}\Bigg(1 - e^{-\frac{T_{B,C1}}{T_e(1-R_{P1})}} + R_{P1,i}e^{-\frac{T_{B,C1}}{T_e(1-R_{P1})}} - R_{P1,i}e^{-\frac{T_{B,C1}}{T_e(1-R_{P1})}}e^{-\frac{T_{B,P1}}{T_e(1-R_{P2})}} \\
&+ R_{P1,i}R_{P2,i}e^{-\frac{T_{B,C1}}{T_e(1-R_{P1})}}e^{-\frac{T_{B,P1}}{T_e(1-R_{P2})}} - R_{P1,i}R_{P2,i}e^{-\frac{T_{B,C1}}{T_e(1-R_{P1})}}e^{-\frac{T_{B,P1}}{T_e(1-R_{P2})}}e^{-\frac{T_{B,P2}}{T_e(1-R_{C2})}} \\
&+ R_{P1,i}R_{P2,i}R_{C2,i}e^{-\frac{T_{B,C1}}{T_e(1-R_{P1})}}e^{-\frac{T_{B,P1}}{T_e(1-R_{P2})}}e^{-\frac{T_{B,P2}}{T_e(1-R_{C2})}} \\
&- R_{P1,i}R_{P2,i}R_{C2,i}e^{-\frac{T_{B,C1}}{T_e(1-R_{P1})}}e^{-\frac{T_{B,P1}}{T_e(1-R_{P2})}}e^{-\frac{T_{B,P2}}{T_e(1-R_{C2})}}e^{-\frac{T_{B,C2}}{T_e(1-R_{C1})}}\Bigg) = 0
\end{aligned}
$$

$$
\begin{aligned}
f_4(\boldsymbol{R}_V) = R_{C2}\Bigg(1 &- R_{C2,i}R_{C1,i}R_{P1,i}R_{P2,i}e^{-\frac{T_{B,C2}}{T_e(1-R_{C1})}}e^{-\frac{T_{B,C1}}{T_e(1-R_{P1})}}e^{-\frac{T_{B,P1}}{T_e(1-R_{P2})}}e^{-\frac{T_{B,P2}}{T_e(1-R_{C2})}}\Bigg) \\
&- R_{C2,i}\Bigg(1 - e^{-\frac{T_{B,C2}}{T_e(1-R_{C1})}} + R_{C1,i}e^{-\frac{T_{B,C2}}{T_e(1-R_{C1})}} - R_{C1,i}e^{-\frac{T_{B,C2}}{T_e(1-R_{C1})}}e^{-\frac{T_{B,C1}}{T_e(1-R_{P1})}} \\
&+ R_{C1,i}R_{P1,i}e^{-\frac{T_{B,C2}}{T_e(1-R_{C1})}}e^{-\frac{T_{B,C1}}{T_e(1-R_{P1})}} - R_{C1,i}R_{P1,i}e^{-\frac{T_{B,C2}}{T_e(1-R_{C1})}}e^{-\frac{T_{B,C1}}{T_e(1-R_{P1})}}e^{-\frac{T_{B,P1}}{T_e(1-R_{P2})}} \\
&+ R_{C1,i}R_{P1,i}R_{P2,i}e^{-\frac{T_{B,C2}}{T_e(1-R_{C1})}}e^{-\frac{T_{B,C1}}{T_e(1-R_{P1})}}e^{-\frac{T_{B,P1}}{T_e(1-R_{P2})}} \\
&- R_{C1,i}R_{P1,i}R_{P2,i}e^{-\frac{T_{B,C2}}{T_e(1-R_{C1})}}e^{-\frac{T_{B,C1}}{T_e(1-R_{P1})}}e^{-\frac{T_{B,P1}}{T_e(1-R_{P2})}}e^{-\frac{T_{B,P2}}{T_e(1-R_{C2})}}\Bigg) = 0
\end{aligned}
$$

Cyber-physical Intra-Dependencies

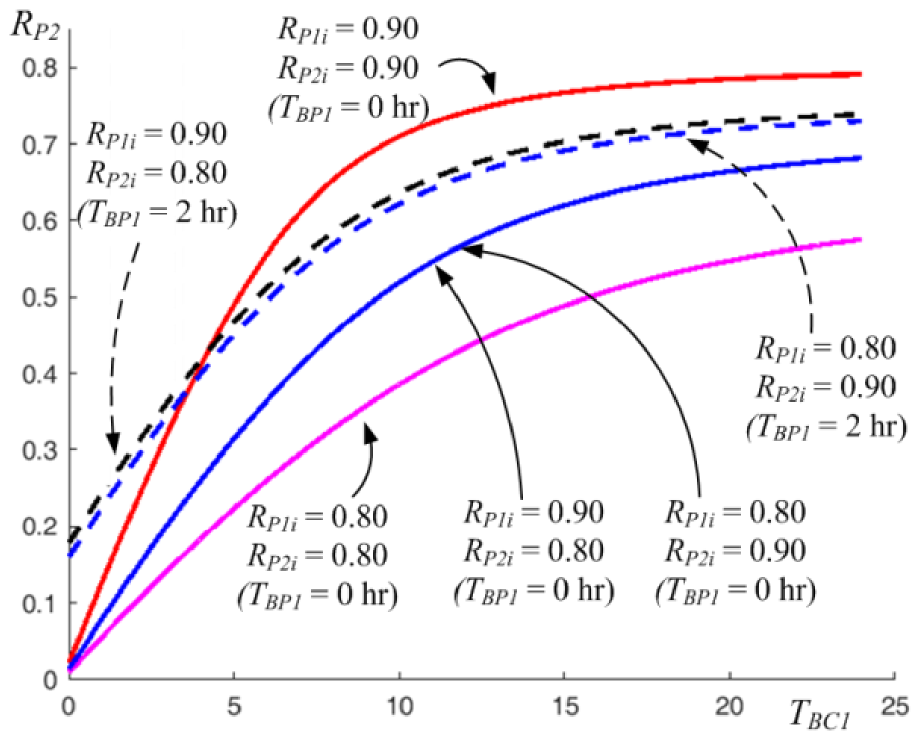
- Buffers for the EP and DC services:
  - Buffer for EP = physical service buffers = energy storage devices
  - Buffer for DC…. the service that is being buffered is data connectivity. Hence, the purpose of the buffer for this cyber service relates to the time that the sink vertex can wait for data connectivity to be reestablished before the vertex can no longer provide its output service.
  - DC service buffer autonomy is maximum waiting time for connectivity to be reestablished.
  - E.g., $T_{B,P2}$ is how long the power generation unit at P2 can operate without commands due to data connectivity loss. Waiting time depends on inertia and on the contribution that hierarchical de-centralized controllers, such as droop controllers, play in maintaining operation.
  - Still, waiting times are usually negligible or null in comparison to the time it takes to reestablish data connectivity.
  - Thus, failures in the provision of the cyber service data connectivity may cascade almost instantaneously.

Cyber-physical Intra-Dependencies

- A few more assumptions:
  - Consider an event with T_e = 36 hours
  - Initially, both R_{C1i} and R_{C2i} equal to 0.99.
  - As it is typical in conventional power grids in which sufficiently large energy storage devices are not part of electric utilities assets T_{BP1} = 0.
  - Since it is uncommon that cyber vertex include any meaningful waiting time in case of a failed communication link, T_{BC2} also equals 0.
  - It is also assumed that the electric power generator represented by vertex P2 has its cyber services buffer providing an autonomy of 0.2 hours due to the combination of a decentralized controller and its machine inertia.

Cyber-physical Intra-Dependencies

- Some lessons……



- Increased stored energy at vertex C1 mitigate the intra-dependencies effects on R_{P2} and improves resilience.

Cyber-physical Intra-Dependencies

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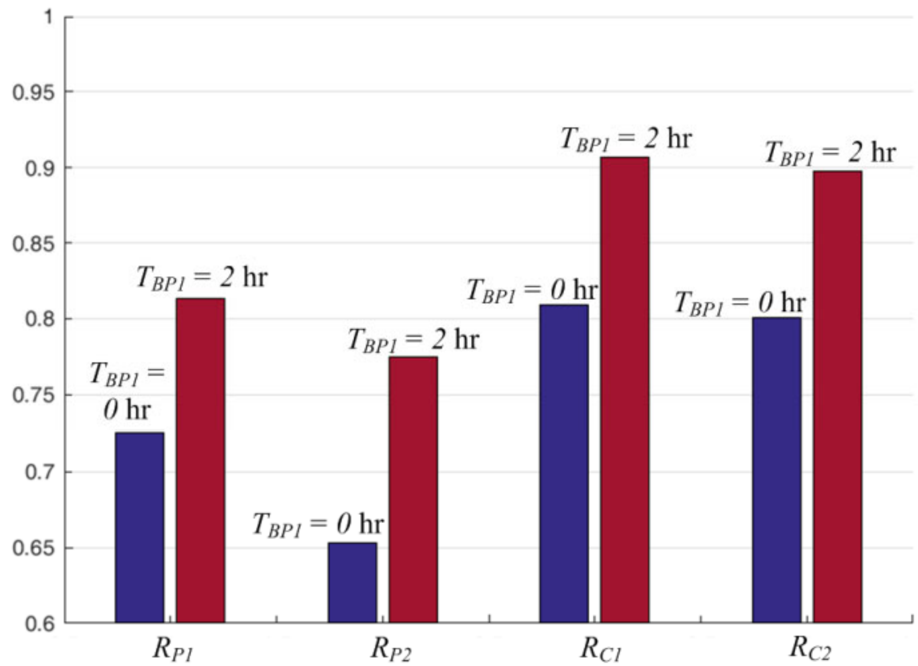
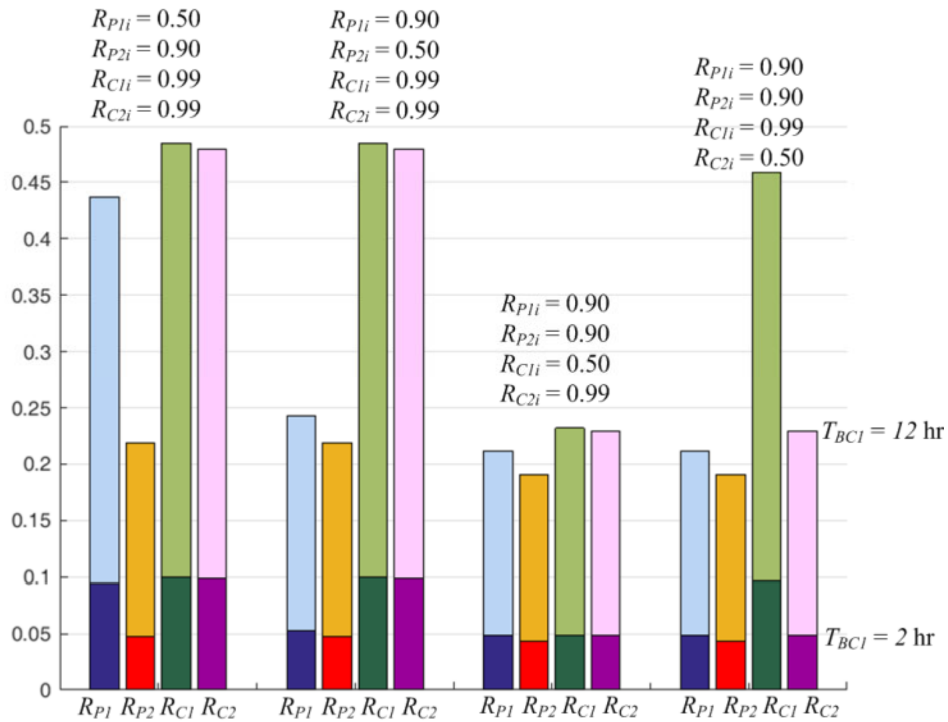
- Some lessons……



- Here, R_{C1i} and R_{C2i} are assumed to be kept at 0.99 and R_{P1i} and R_{P2i} are made equal to 0.90 while T_{BP1} changes from 0 to 2hrs.
- The addition of this stored energy at P1's input increases resilience of all vertices.
- Although adding such levels of energy storage in conventional power grids is extremely unusual, such solution have been proposed for microgrids, which potentially provides them with a design advantage in terms of resilience.

Cyber-physical Intra-Dependencies

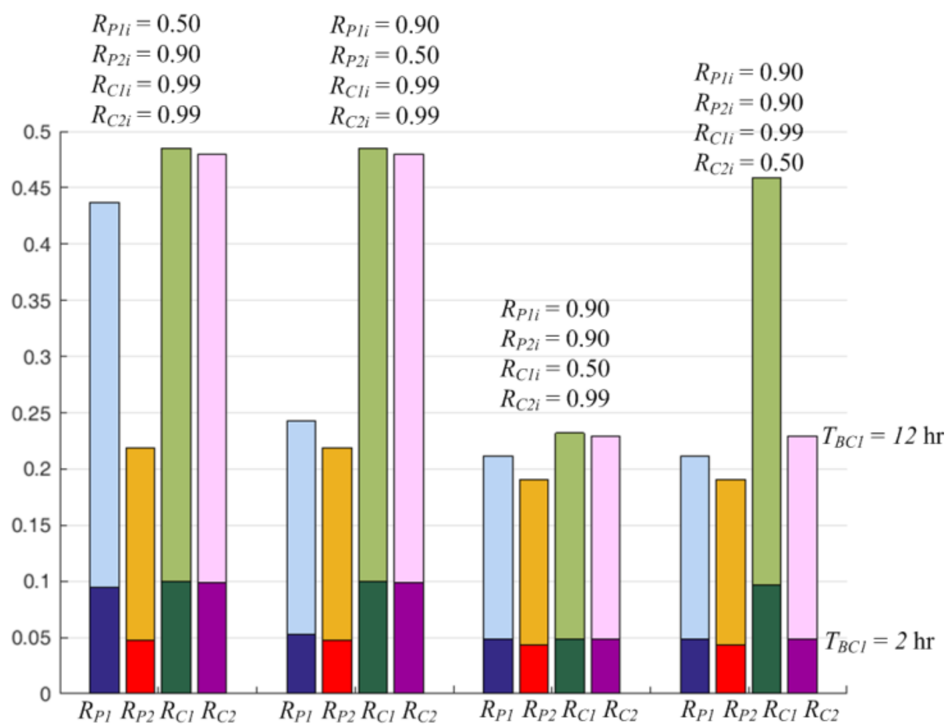
- Some lessons……



- Resilience is negatively impacted the most when one of the vertices in the cyber domain have lower internal resilience
- Hence, vertices in the cyber domain seem more critical than those in the physical domain. This observation is explained by the very limited autonomy that practically exists for the data connectivity service provided by the cyber domain components.

Cyber-physical Intra-Dependencies

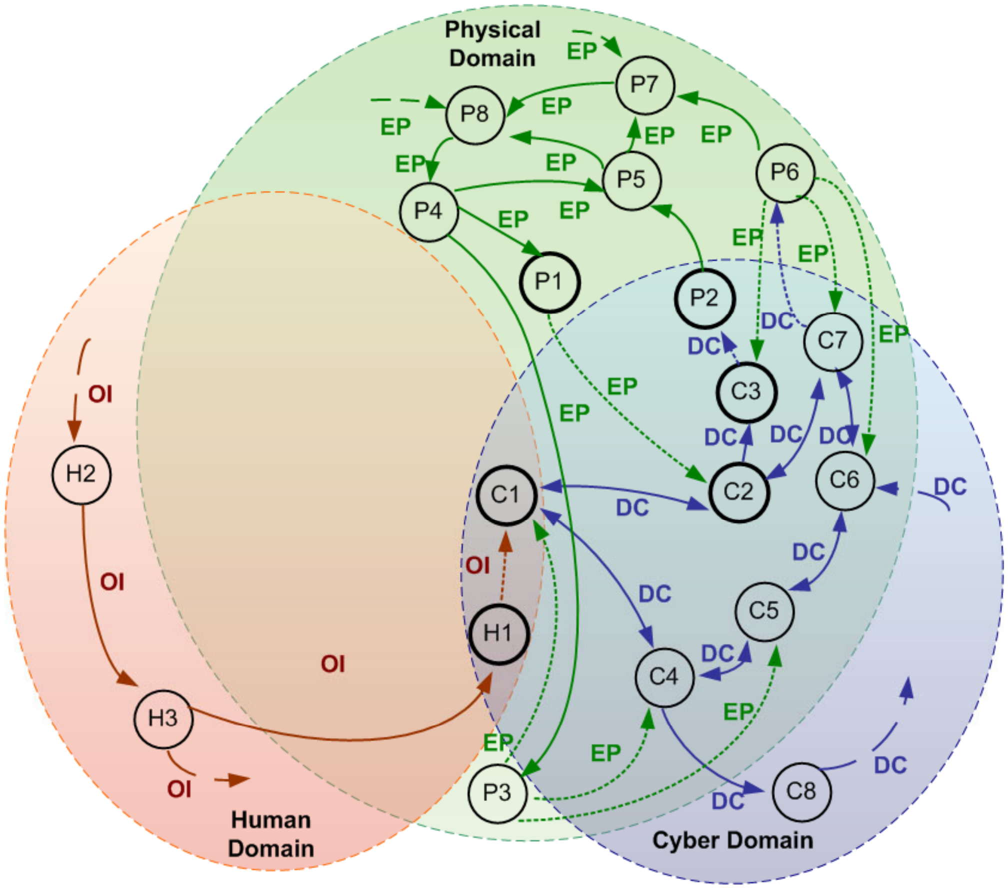
- Some lessons……



- Notice also the important role of added energy storage buffering in vertex C1 for the service provided by P1.
- Such buffer reduces the impact of a vertex lower internal resilience except for the case of lower internal resilience in C1 because a failure in C1 is not buffered into C2 by the buffer at C1.

Cyber-physical Intra-Dependencies

- Some more lessons from the more complex example……
- Operation of vertex C2 is specially critical because it is the only vertex in the cyber domain providing services to vertex C3, which, in turn, is the only vertex in the cyber domain providing data connectivity services to vertex P2, which is a source vertex (i.e., a power generator) in the physical domain.



Cyber-physical Intra-Dependencies

- A first approach to improve resilience is to provide a longer energy storage autonomy to vertex C2.
- Resilience can be further improved if vertex C3 is included in the ring of vertices in the cyber domain so there are two alternative paths for vertex C3 to receive data connectivity services.
- Hence, service provision bi-directionality capability is an important edge attribute in order to establish diverse service provision paths to enhance resilience.
- Although such bi-directionality is almost always found in data connectivity services and it is also observed at the transmission level of power systems, such characteristic is commonly lacking at the distribution level of power grids, which makes this portion of the grid especially vulnerable to natural disasters.