ABSTRACT

Civil infrastructure systems (CISs), such as the electric power supply systems, the water supply and distribution systems, and the cellular communication systems, are the backbones of contemporary societies. Resilient CISs are essential for resilient communities. The Re-CoDeS resilience quantification framework (Resilience-Compositional Demand/Supply framework) allows the assessment of the resilience of CISs in a holistic community demand/CIS supply approach. The framework considers (disaster) impact on both the evolution of the CIS service demand and the CIS service supply. An extension of the Re-CoDeS framework allows to quantify the effect of interdependency of different CISs on community resilience. A potential Lack of Resilience can be quantified on a macro or system level, and decomposed on a micro or node level, considering the influence of the demand and supply interdependence of the CISs on each other. Finally, the economic and social impact of interdependency of various CISs on community resilience can be assessed.
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Civil infrastructure systems (CISs), such as the electric power supply systems, the water supply and distribution systems, and the cellular communication systems, are the backbones of contemporary societies. Resilient CISs are essential for resilient communities. The Re-CoDeS resilience quantification framework (Resilience-Compositional Demand/Supply framework) allows the assessment of the resilience of CISs in a holistic community demand/CIS supply approach. The framework considers (disaster) impact on both the evolution of the CIS service demand and the CIS service supply. An extension of the Re-CoDeS framework allows to quantify the effect of interdependency of different CISs on community resilience. A potential Lack of Resilience can be quantified on a macro or system level, and decomposed on a micro or node level, considering the influence of the demand and supply interdependence of the CISs on each other. Finally, the economic and social impact of interdependency of various CISs on community resilience can be assessed.

Introduction

Civil infrastructure systems (CISs), such as the electric power supply systems, the water supply and distribution systems and the cellular communication systems, provide valuable services to modern communities. Resilient CISs are crucial to maintain the living standards of contemporary societies. The components of these systems are, however, fragile when submitted to demands imposed by natural hazards (e.g. earthquakes, floods, storms), or threats like terrorist or cyber attacks. In addition to direct damage to the components, the functioning of many CISs depends on the availability of services provided by other CISs. Examples for such functional interdependency [1-14] include, for example, the water pumps of the water supply systems, or the base transceiver

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stations of the cellular communication systems, which require electric power to be functional, and are, thus, dependent on the performance of the electric power supply systems. On the other hand, the functioning of the electric power supply systems may depend on the performance of parts of the water supply system (for example in the case of hydropower stations) or of the cellular communication system (for example, to remotely control the switches, to organize recovery work in the aftermath of a disaster, or to transmit operational or repair instructions to a technician via mobile phone). These CISs are, thus, functionally interdependent. The Re-CoDeS framework [15] (Resilience-Compositional Demand/Supply framework) allows to assess and quantify the resilience of CISs using a demand/supply approach. In the following, the framework is adapted to quantify the resilience of interdependent CISs that supply the demand for service of a community, composed of its inhabitants, building stock and multiple CISs.

Adapting the Re-CoDeS framework to Interdependent CISs

The Re-CoDeS framework allows to assess the resilience of different types of CISs using a demand/supply approach and to quantify a potential Lack of Resilience (LoR) of a CIS over a given period of time. A LoR can be observed if, at any moment in time, the demand of the community for the services of a CIS cannot be fully supplied: there is a supply deficit. The supply deficit can, for example, be related to damage to the components of the systems due to natural disasters, human-made attacks, or long-term degradation of the components (e.g. due to wear and tear, poor maintenance or environmental stressors), or due to the unavailability of services of other CISs (e.g. electric power), required to operate the CIS of interest. The interdependency of two systems can potentially lead to (negative) feedback loops or cascading failures. On the other hand, changes in the demand, e.g. due to damage to the building stock and population movements, can lead to a LoR, if the service supply of the CIS cannot be adjusted accordingly.

Service Demand, Supply and Consumption of Interdependent CISs

To quantify the resilience of a set of interdependent CISs supplying their services to a community, the metrics of aggregated demand, available supply and consumption need to be determined.

The aggregated demand for the service or resource \( r \) provided by a CIS at a given demand node \( i \) at time \( t \), is designated as \( D_{i,r}(t) \), where \( i \in \{1, ..., I\} \) is the index of the demand node of interest and \( r \) is the service or the resource that is demanded (e.g. electric power, potable water). Then:

\[
D_{i,r}(t) = \sum_u D_{i,r,u}(t)
\]  

where \( D_{i,r,u}(t) \) is the demand of a user \( u \) for a resource or service \( r \) at node \( i \) at time \( t \). Users or consumers are, for example, other CISs or citizens of the community inhabiting the building stock.

The demand at a given node can change, for example, due to the fragility of the users (e.g. building stock damage usually causes a reduction of the electric power demand, since the electric appliances in the buildings might get damaged, or cannot be used anymore), a change of the demand pattern (e.g. water conservation measures after a large natural disaster, or a higher demand to the cellular communication system during emergency situations), or due to the (post-disaster)
recovery of the users (e.g. a damaged building is repaired and reoccupied). The total demand of a certain user $u$ for the resource or service $r$ provided by a CIS at time $t$, $D_{sys,r,u}(t)$, can be determined as:

$$D_{sys,r,u}(t) = \sum_i D_{i,r,u}(t)$$  \hspace{1cm} (2)

The total service or resource demand at time $t$ to the CIS of interest, $D_{sys,r}(t)$, is the sum of the resource or service demand of all users to all nodes of that system at time $t$:

$$D_{sys,r}(t) = \sum_i D_{i,r}(t) = \sum_i \sum_u D_{i,r,u}(t)$$  \hspace{1cm} (3)

If a system of systems composed of the building stock (BS), the electric power supply system (EPSS), the water supply system (WSS) and the cellular communication system (CCS) is considered, Eq. 1 to determine the demand for electric power at a node $i$ at time $t$, $D_{l,EPSS}(t)$, can be written as:

$$D_{l,EPSS}(t) = D_{l,EPSS,BS}(t) + D_{l,EPSS,WSS}(t) + D_{l,EPSS,CCS}(t) + D_{l,EPSS,EPSS}(t)$$  \hspace{1cm} (4)

where $D_{l,EPSS,BS}(t)$ is the demand of the building stock for electric power at node $i$ at time $t$, $D_{l,EPSS,WSS}(t)$ is the demand of the water supply system for electric power at node $i$ at time $t$, $D_{l,EPSS,CCS}(t)$ is the demand of the cellular communication system for electric power at node $i$ at time $t$, and $D_{l,EPSS,EPSS}(t)$ is the demand of the electric power supply system for electric power at node $i$ at time $t$ (e.g. to run the computers operating the system or certain components).

The available supply of a service or resource $r$ of a given CIS at node $i$ at time $t$ for a certain user $u$ is designated as $S_{l,r,u}^{av}(t)$. The available supply depends on the evolution of the supply capacity of a service or resource $r$, $S_{l,r}^{C}(t)$, at the different supply nodes $j \in \{1, \ldots, J\}$ of the CIS (and their vulnerability and recovery), the topology of the system, the dependence on resources or services (e.g. of other CISs) needed to operate the components (e.g. electric power to operate a water pump of the water supply system) and on the system service model.

The supply capacity $S_{l,r}^{C}(t)$ is the supply generated, created or entering the CIS at supply node $j$ at time $t$ (note that supply and demand nodes may coincident for certain CISs):

$$S_{l,r}^{C}(t) = S_{l,r}^{C,\text{max}}(t) - S_{l,r}^{C,\text{loss}}(t)$$
$$= S_{l,r}^{C,\text{max}}(t) - S_{l,r}^{C,\text{loss,\text{damage}}}(t) - S_{l,r}^{C,\text{loss,\text{int}}}(t) - S_{l,r}^{C,\text{loss,\text{other}}}(t)$$  \hspace{1cm} (5)

where $S_{l,r}^{C,\text{max}}(t)$ is the maximal possible supply capacity of service or resource $r$ at supply node $j$ at time $t$, if there were no losses, and $S_{l,r}^{C,\text{loss}}(t)$ the aggregated loss in supply capacity of service or resource $r$ at supply node $j$ at time $t$. $S_{l,r}^{C,\text{loss,\text{damage}}}$ are the losses in service supply capacity of service or resource $r$ at supply node $j$ at time $t$ associated to damage to the components (e.g. as consequence of a natural disaster or a continuous degradation), $S_{l,r}^{C,\text{loss,\text{int}}}$ are the losses in the supply capacity of service or resource $r$ at supply node $j$ at time $t$ associated to the unavailability
of the resources required to operate the supply node (e.g. electric power for pumps or cellphone towers), and \( S^{C,loss,other}_{j,r} \) are the losses in the supply capacity of service or resource \( r \) at supply node \( j \) at time \( t \) associated to other factors (e.g. operational considerations to reduce service capacity for economic or system protection reasons). Consider, for example, a water pump at a water aquifer located outside of a city that requires electric power to operate and a cellular connection to receive regulation or control signals, \( S^{loss,int}_{j,WSS} \) is the loss of supply capacity of potable water at node \( j \) at time \( t \) decomposed into:

\[
S^{C,loss,int}_{j,WSS}(t) = S^{C,loss,EPSS}_{j,WSS} + S^{C,loss,CCS}_{j,WSS}
\]

where \( S^{C,loss,EPSS}_{j,WSS} \) is the loss in supply capacity of potable water due to the unavailability of electric power, and \( S^{C,loss,CCS}_{j,WSS} \) is the loss in supply capacity of potable water associated to the unavailability of the cellular communication system, at node \( j \) at time \( t \), respectively.

The supply capacity of the entire CIS for a service or resource \( r \) at time \( t \) is:

\[
S_{sys,r}(t) = \sum_j S_{j,r}(t)
\]

(7)

For example, \( S_{sys,EPSS}^C(t) \) would be the amount of electric power generated at all the electric power generation plants of the electric power supply system at time \( t \). The supply is, then, distributed through the distribution network and allocated and made available to the different users at the different demand nodes of the CIS. The system service model determines the allocation of the supply capacity to the users at different demand nodes. It depends on the topology of the service distribution system (e.g. failure of links can make certain demand nodes unattainable), the physics laws and technical operation mode of the system (e.g. hydraulic flow equations for a water distribution system), and on the service allocation priority determined by the system operator (e.g. an operator might choose to first provide electric power to the hospital, and only at a later point to the residential building stock and the industry).

The available supply of a service or resource \( r \) at node \( i \) at time \( t \) for a certain user \( u \), \( S^{av}_{i,r,u}(t) \), can be determined as follows:

\[
S^{av}_{i,r,u}(t) = \varphi \left( S^C_{i,r}(t) \ldots S^C_{i,r}(t), \forall u: C_{i,r,u}(t) \ldots C_{i,r,u}(t), \forall u: D_{i,r,u}(t) \ldots D_{i,r,u}(t), S^{loss}_{i,r,u}(t) \ldots S^{loss}_{i,r,u}(t) \right)
\]

(8)

where \( \varphi(\cdot) \) is the system service model, \( S^{loss}_{i,r,u}(t) \) are the aggregated losses associated to the distribution of resource or service \( r \) to user \( u \) at node \( i \) at time \( t \), and \( C_{i,r,u}(t) \) is the consumption of resource or service \( r \) by user \( u \) at node \( i \) at time \( t \) (see below). \( S^{loss}_{i,r,u}(t) \) can, for example, be the loss in available supply of potable water to a high-rise building due to the inoperability of a local water pump at a demand node needed to pump the water to the higher floors. This inoperability can, for example, be caused by a loss of electric power supply, or damage to the pump, or other factors. In such a case, the loss of available supply of potable water to the building stock associated to the demand node \( i \) at time \( t \), \( S^{loss}_{i,WSS,BS}(t) \) could be written as:
\[
S_{i,WSS,BS}^{\text{loss}}(t) = S_{i,WSS,BS}^{\text{loss,damage}}(t) + S_{i,WSS,BS}^{\text{loss,int}}(t) + S_{i,WSS,BS}^{\text{loss,other}}(t)
\]  

(9)

where \( S_{i,WSS,BS}^{\text{loss,damage}}(t) \) is the loss of available supply of potable water to the building stock due to damage to the components of the water supply system at a demand node level, \( S_{i,WSS,BS}^{\text{loss,int}}(t) \) is the loss of available supply of potable water to the building stock due to the unavailability of resources provided by other CISs required to operate the water supply system at a demand node level, and \( S_{i,WSS,BS}^{\text{loss,other}}(t) \) is the loss of available supply of potable water to the building stock at a demand node level due to other factors, at node \( i \) at time \( t \), respectively.

Note that [2]:

\[
S_{SYS,r}^{C}(t) \neq \sum_{i} \sum_{u} S_{i,r,u}^{av}(t)
\]  

(10)

Furthermore, note that \( S_{SYS,r}^{loss}(t) \) are losses associated to supply nodes, and \( S_{i,WSS,BS}^{loss}(t) \) are losses associated to a certain user at a demand node level. Both influence directly and indirectly the service supply available to a given user.

The **consumption** of service or resource \( r \) by user \( u \) at demand node \( i \) at time \( t \) is designated as \( C_{i,r,u}(t) \). The consumption of a certain resource or service \( r \) by a certain user \( u \) is the minimum of the available supply of that resource for user \( u \) at node \( i \) and time \( t \) and the demand for that resource or service \( r \) by user \( u \) at node \( i \) and time \( t \):

\[
C_{i,r,u}(t) = \min(S_{i,r,u}^{av}(t), D_{i,r,u}(t))
\]  

(11)

The total consumption \( C_{i,r}(t) \) of a given resource or service \( r \) at node \( i \) at time \( t \) is then:

\[
C_{i,r}(t) = \sum_{u} C_{i,r,u}(t)
\]  

(12)

and the total consumption at time \( t \) of a given service or resource \( r \) by all the users in the considered system of system (community), \( C_{SYS,r}(t) \), is:

\[
C_{SYS,r}(t) = \sum_{i} C_{i,r}(t) = \sum_{i} \sum_{u} C_{i,r,u}(t)
\]  

(13)

**Lack of Resilience of Interdependent CISs**

Using the metrics defined above, the \( \text{LoR} \) of a certain CIS that provides a service or resource \( r \) at a node \( i \) over a period \( t_0 \leq t \leq t_f \) associated to a given user \( u \) can be quantified as:

\[
\text{LoR}_{i,r,u} = \int_{t_0}^{t_f} \langle D_{i,r,u}(t) - S_{i,r,u}^{av}(t) \rangle = \int_{t_0}^{t_f} \left( D_{i,r,u}(t) - C_{i,r,u}(t) \right)
\]  

(14)

where \( t_0 \) and \( t_f \) are the starting and ending time of the resilience assessment, respectively. \( \langle \cdot \rangle \) is the singularity function, which returns the argument if it is positive (i.e. \( D_{i,r,u}(t) - S_{i,r,u}^{av}(t) \) in this
case), and 0 otherwise.

The LoR associated to all users \( u \) at a node \( i \) of a given CIS delivering a service or resource \( r \), over a period \( t_0 \leq t \leq t_f \), \( \text{LoR}_{i,r} \), is then:

\[
\text{LoR}_{i,r} = \sum_u \text{LoR}_{i,r,u} = \sum_u \int_{t_0}^{t_f} (D_{i,r,u}(t) - S_{i,r,u}^\text{av}(t)) = \sum_u \int_{t_0}^{t_f} (D_{i,r,u}(t) - C_{i,r,u}(t)) \quad (15)
\]

and the LoR at a system level of the entire CIS delivering a resource or service \( r \) over a period \( t_0 \leq t \leq t_f \), \( \text{LoR}_{\text{sys},r} \), is:

\[
\text{LoR}_{\text{sys},r} = \sum_i \sum_u \text{LoR}_{i,r,u} = \sum_i \sum_u \int_{t_0}^{t_f} (D_{i,r,u}(t) - S_{i,r,u}^\text{av}(t)) = \sum_i \sum_u \int_{t_0}^{t_f} (D_{i,r,u}(t) - C_{i,r,u}(t)) \quad (16)
\]

The LoR associated to a resource or service \( r \), depending on the influence of a user \( u \) on a system level, \( \text{LoR}_{\text{sys},r,u} \), is:

\[
\text{LoR}_{\text{sys},r,u} = \sum_i \text{LoR}_{i,r,u} = \sum_i \int_{t_0}^{t_f} (D_{i,r,u}(t) - S_{i,r,u}^\text{av}(t)) = \sum_i \int_{t_0}^{t_f} (D_{i,r,u}(t) - C_{i,r,u}(t)) \quad (17)
\]

The different LoR metrics can be normalized by the demand [15] to obtain a measure included in the range [0,1] to allow a comparison of the resilience of different nodes and CISs.

The normalized LoR of a certain CIS, providing a resource or service \( r \), at a node \( i \), over a period \( t_0 \leq t \leq t_f \), associated to a given user \( u \), \( \text{LoR}_{i,r,u} \), is:

\[
\begin{align*}
\text{LoR}_{i,r,u} &= \frac{\int_{t_0}^{t_f} (\text{LoR}_{i,r,u}(t) - S_{i,r,u}^\text{av}(t))}{\int_{t_0}^{t_f} \text{LoR}_{i,r,u}(t)} = \frac{\int_{t_0}^{t_f} (D_{i,r,u}(t) - C_{i,r,u}(t))}{\int_{t_0}^{t_f} D_{i,r,u}(t)} \quad (18)
\end{align*}
\]

The normalized LoR at a node \( i \) of a given CIS delivering a service or resource \( r \) considering all users \( u \), over a period \( t_0 \leq t \leq t_f \), \( \text{LoR}_{i,r} \), is then:

\[
\begin{align*}
\text{LoR}_{i,r} &= \sum_u \text{LoR}_{i,r,u} = \sum_u \int_{t_0}^{t_f} (D_{i,r,u}(t) - S_{i,r,u}^\text{av}(t)) = \sum_u \int_{t_0}^{t_f} (D_{i,r,u}(t) - C_{i,r,u}(t)) \quad (19)
\end{align*}
\]

and the normalized LoR of the entire CIS delivering service or resource \( r \) at a system level over a period \( t_0 \leq t \leq t_f \), \( \text{LoR}_{\text{sys},r} \), is:

\[
\begin{align*}
\text{LoR}_{\text{sys},r} &= \sum_i \sum_u \text{LoR}_{i,r,u} = \sum_i \sum_u \int_{t_0}^{t_f} (D_{i,r,u}(t) - S_{i,r,u}^\text{av}(t)) = \sum_i \sum_u \int_{t_0}^{t_f} (D_{i,r,u}(t) - C_{i,r,u}(t)) \quad (20)
\end{align*}
\]
The normalized $LoR$ associated to a service or resource $r$, depending on the influence of a user $u$ on a system level, over a period $t_0 \leq t \leq t_f$, $\overline{LoR}_{sys,r,u}$, is:

$$\overline{LoR}_{sys,r,u} = \frac{\sum_{i} LoR_{tr,u}}{\sum_{i} t_{f} d_{t,r,u}(t)} = \frac{\sum_{i} t_{f} (D_{tr,u}(t) - c_{tr,u}(t))}{\sum_{i} t_{f} d_{t,r,u}(t)}$$

(21)

Note that:

$$\overline{LoR}_{t,r,u} \neq \overline{LoR}_{r,u,t}$$

(22)

and

$$\overline{LoR}_{sys,r,u} \neq \overline{LoR}_{sys,u,r}$$

(23)

In fact, the dependence of one system on the services or resources of another system might be different in the two directions. One CIS might rely heavily on the resources or services of the other CIS, while the other CIS may be almost completely independent of the supply of services by the first CIS.

Finally, the $LoR$ of a system of systems, or a community composed of interdependent CISs (e.g. building stock, BS; electric power supply system, EPSS; water supply system, WSS; cellular communication system, CCS; ...), can be expressed as:

$$LoR_{community} = f(LoR_{sys,BS}, LoR_{sys,EPSS}, LoR_{sys,WSS}, LoR_{sys,CCS}, ...)$$

(24)

or, using the normalized metrics:

$$\overline{LoR}_{community} = f(\overline{LoR}_{sys,BS}, \overline{LoR}_{sys,EPSS}, \overline{LoR}_{sys,WSS}, \overline{LoR}_{sys,CCS}, ...)$$

(25)

**Discussion**

The determination of the $LoR$ of individual CISs and of a system of systems of interdependent CISs is a challenging and complex task. In fact, this quantification requires detailed knowledge on the operations and the demand of the individual CISs and on their functional relationships, both on the supply and the demand sides. The proposed extension of the Re-CoDeS framework allows to consider the influence of interdependency using a demand/supply approach, and to quantify its effect on the resilience of communities.

The proposed framework allows a resilience quantification at different levels: on a micro or node level, considering the $LoR$ associated to a specific CIS service and a specific consumer or user group, and on a macro or system level. The share of each partial $LoR$ for the different nodes of a CIS and for a certain service or resource can be computed to determine the exact influence or interdependency of the different CISs on each other, as well as the aggregate effect on community resilience. Importantly, normalized metrics allow to compare different nodes and different CISs.
For example, Eqs. 1 and 2 can be used to determine the dependency of one CIS on the demand of another CIS, and Eqs. 6 and 9 can be used to determine the dependency of one CIS on the supply of another CIS. Finally, the use of Eqs. 17 and 21 allows the quantification of the interdependence of two systems using the demand/supply approach. The proposed resilience quantification can, for example, be used to design a targeted resilience measure for a specific user group, or for a specific demand node (e.g. to design a CIS in a way to minimize the LoR associated to hospitals). The framework needs, however, to be tested for robustness in a real or virtual case study of a community.

Furthermore, the use of Eqs. 24 and 25 makes it possible to quantify the economic and to approximate the societal impact of a LoR at the community level. However, while computing the interdependent LoR is already complex, determining the exact social or economic impacts and consequences might increase the complexity of this process even further. In a simplified procedure, Eq. 24 can be linearized using the equilibrium (market) price of the different commodities at $t_0$ to approximate the economic costs of a LoR imposed on a community composed by a building stock, an electric power supply system, a water supply system and a cellular communication system:

$$
\text{LoR}_{\text{community}} = P_{BS}(t_0) \cdot \text{LoR}_{\text{sys,BS}} + P_{EPPS}(t_0) \cdot \text{LoR}_{\text{sys,EPPS}} + P_{WSS}(t_0) \cdot \text{LoR}_{\text{sys,WSS}} + P_{CCS}(t_0) \cdot \text{LoR}_{\text{sys,CCS}}
$$

where $P_{BS}(t_0)$ is the equilibrium price of a unity of building stock (e.g. a square feet of residential space) at $t_0$, $P_{EPPS}(t_0)$ is the equilibrium price of a kWh of electric power at $t_0$, $P_{WSS}(t_0)$ is the equilibrium price of a liter of potable water at $t_0$, and $P_{CCS}(t_0)$ is the equilibrium price of a unity of a cellphone call at $t_0$. $\text{LoR}_{\text{sys,BS}}$, $\text{LoR}_{\text{sys,EPPS}}$, $\text{LoR}_{\text{sys,WSS}}$, and $\text{LoR}_{\text{sys,CCS}}$ are the LoR associated to the different CISs considered in the analysis. The best way to determine the economic and societal impact of a LoR on the community requires future research.

Conclusions

Re-CoDeS is a framework to assess and quantify the resilience of CISs using a demand/supply approach. The framework has been extended in this paper to assess the disaster resilience of a system of systems, composed of various interdependent CISs that supply their resources and services to a community composed of the buildings stock and other CISs. The dependency of one CIS on another CIS can be determined considering the resource or service demand, the resource or service supply, and the coupling of these two metrics.

The integrated resilience assessment of such a system of systems increases, however, the complexity of the resilience assessment considerably: it grows exponentially with the number of CISs considered. The proposed framework also needs to be tested in real and/or virtual case studies to confirm the robustness of the proposed metrics. The incentive is clear: the extended Re-CoDeS framework makes it possible to quantify the systemic (disaster) resilience of communities supplied with resources or services from multiple interdependent CISs and enables design and testing of engineering, financial and public policy measures that lead to more resilient communities.
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