Chapter 28
Research Needs Towards a Resilient Community

Vulnerability Reduction, Infrastructural Systems Model, Loss Assessment, Resilience-Based Design and Emergency Management

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Abstract Most of the literature on resilience is devoted to its assessment. It seems time to move from analysis to design, to develop the tools needed to enhance resilience. Resilience enhancement, a close relative of the less fashionable risk mitigation, adds to the latter, at least in the general perception, a systemic dimension. Resilience is often paired with community, and the latter is a system. This chapter therefore discusses strategies to enhance resilience, endorses one of prevention rather than cure, and focuses in the remainder on the role played by systemic analysis, i.e. the analysis of the built environment modelled beyond a simple collection of physical assets, with due care to the associated interdependencies. Research needs are identified and include challenges in network modelling, the replacement of generic fragility curves for components, how to deal with evolving state of information.

28.1 Increasing Resilience

28.1.1 Resilience Definition and Quantification

The term resilience originated in Mechanics, was adopted in Ecology and has recently seen increasing use, alongside the term sustainability, in many other fields. Growing population and urbanization, increase in complexity of infrastructural systems, and of interconnection in general, translate into increasing and longer-lasting impacts from natural and man-made hazards and are probably behind this

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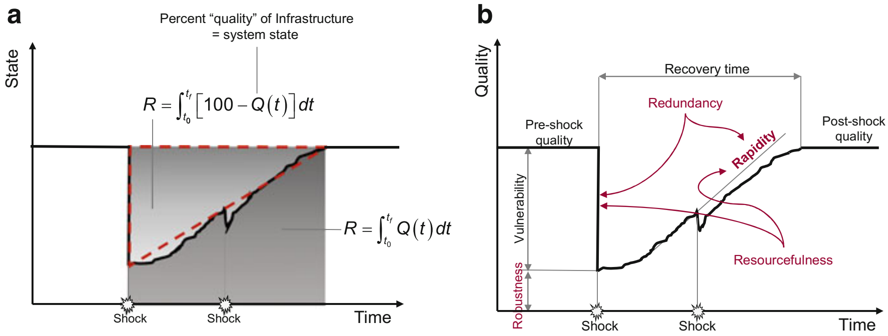

Fig. 28.1 The so-called "engineering" definition of resilience (**a**) and the "4R's" (**b**)

revival of the concept of resilience. Its widespread use in many disciplines has led to a host of different definitions, adapted to the needs or points of view in each particular field. Many papers are devoted just to the collection of these definitions. Herein the definition of resilience evolved from that first given in (Bruneau et al. 2003) is adopted. This definition, graphically illustrated in Fig. 28.1a, is by now well accepted in the civil engineering field, even though interesting alternative proposals have been advanced (Sun et al. 2015).

Resilience is a system property defined in terms of the evolution of system state over time in the presence of a disturbance. If a meaningful global variable describing state at the system level is found, called quality in (Bruneau et al. 2003), then resilience can be defined with respect to the variation (fall and recovery) of Q over time, due to one or more shocks. R can be related to either the area above the recovery path (sometimes referred to as the "resilience triangle", in dashed red in the figure), or below. Figure 28.1b introduces a number of properties related to Q and R: the fall in Q due to the shock, measure of the immediate impact of the disturbance, is called vulnerability; conversely, its complement is the system "Robustness"; the average slope of the recovery path is the "Rapidity", whose increase reduces the recovery time; "Redundancy" in the system, as well as "Resources" invested in the system or in recovery actions, decrease vulnerability and increase rapidity. Robustness, rapidity, redundancy and resources are also evocatively known as "the 4Rs".

Within this context, it can be observed that the main problem to be solved in order to assess resilience in a quantitative manner, is the formulation of an effective, computable and descriptive measure of system state, i.e. the variable Q, along with the development of tools to describe in a reliable manner its evolution over time. Resilience then follows. The issue is not trivial to solve and much work has been devoted to it, e.g. by Bruneau and co-workers (Cimellaro et al. 2010), as well as others (Bocchini et al. 2014). Just to give two examples, difficulties stem from prediction of the sequence of shocks (in the context of earthquake engineering, seismic sequences), which are random in both intensity, position of each shock and occurrence time and require refined tools not yet mature (see e.g., Iervolino et al. 2014), or the analysis of cumulative damage to system components (e.g., among many others, Franchin and Pinto 2009).

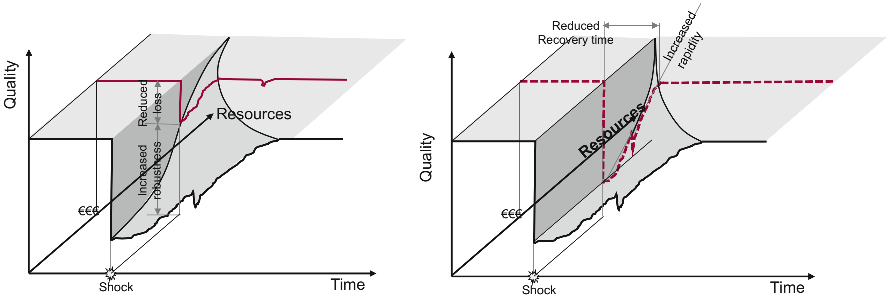

Fig. 28.2 Resilience enhancement: investment of resources in vulnerability reduction (**a**) versus recovery actions (**b**)

28.1.2 Resilience Enhancement

Leaving aside for now the problems related to the definition and quantification of Q and hence R, one can examine, still in abstract terms, what are the strategies to increase the resilience of a system.

Figure 28.2 illustrates the two extreme strategies, which are not mutually exclusive. Panel (a) shows investment of resources into increasing robustness or, conversely, reducing vulnerability. This is pure prevention. With increasing resources put into enhancement of the existing system components and in higher performance of the new ones, the initial impact goes progressively to zero. Decreased damage obviously translates in faster recovery, as well as in overall lower loss. Panel (b) shows investment of resources into recovery actions. The latter leaves the initial impact unaltered but increases rapidity reducing recovery time and loss, even though, most likely, not to the extent achievable by prevention. As an old advertisement said, it appears that prevention is better than cure. Why a society, or system administrator would want to incur damage in the first instance?

The answer to the question, as well as more arguments in favour of prevention, require consideration of one aspect of paramount importance: uncertainty. Figures 28.1 and 28.2 show qualitative diagrams of Q that represent one possible sequence of shocks, with one possible initial impact, followed by one recovery path. The reality is, just focusing on the cause, that the number, intensity, position and time of occurrence of earthquake in a seismic sequence cannot be deterministically predicted. Moving on to the effects, components' damage given intensity is also uncertain. Even more uncertain is the path of recovery, which is affected not just by physical (cumulative) damage but also by the recovery strategy. One could speculate about the very possibility of predicting the latter. Recent examples have shown unpredictable political decisions can lead to completely unforeseeable outcomes (Calvi and Spaziante 2009). Therefore, prediction of recovery path and time are affected by large uncertainty. This is all shown in Fig. 28.3a. Further, the new stable state to which the recovery curve tends is almost never equal to the pre-shock

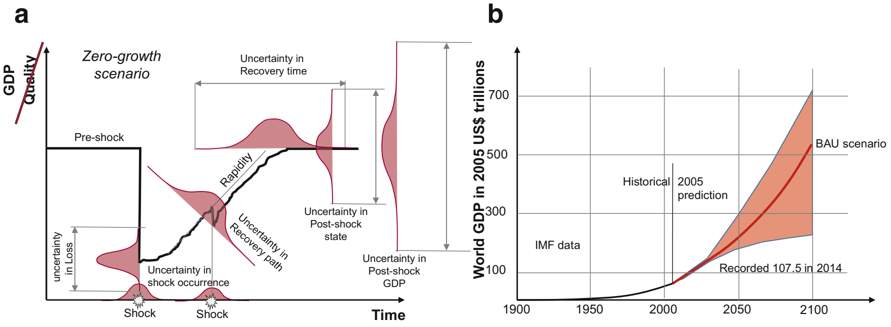

Fig. 28.3 Uncertainty in impact, recovery path and time and post-shock state (**a**); Uncertainty in world GDP up to 2100 AD

one, as simplistically shown in Fig. 28.3a as well as in both Figs. 28.1 and 28.2. Thus, further uncertainty characterizes the post-shock state.

All of the above is further exacerbated when the system is a “community” or “society”. While it is probably still manageable to constrain uncertainty in post-shock state for a “simpler” physical system such as a transportation or water distribution network, when the system has also social and economic dimensions, like a community does, the issue complicates considerably. What is quality for a community? The very simple answer, which avoids the debate and adopts the default choice of an economic measure, is to measure quality by the gross domestic product (GDP), whole, per capita, purchasing power parity, etc.[1] The associated uncertainty of prediction of the post shock state is much larger, as indicated in Fig. 28.3a. The reason for this increased uncertainty is that the very trend line, i.e. the evolution over time of GDP in the absence of shocks, is highly uncertain, as shown by Fig. 28.3b, which reports a 2005 prediction from International Monetary Fund (IMF). Interestingly enough, the latter figure shows that, according to all predictions, GDP will keep increasing (which is why Fig. 28.3a, where for simplicity the GDP baseline is flat, is denoted as a “zero-growth” scenario). Certainly these predictions reflect the dominant line of thought among economists of our time, and one wonders how much sustainability enters into these considerations (Meadows et al. 2004).

Going now back to the initial question of prevention versus cure, one can say that, due to the large uncertainty in occurrence time and place of earthquakes, as well as on the associated damage, and considering the stark difference in time horizon between this class of natural hazards and the next political election, it may appear more convenient to put resources in more pressing matters than in a possibility of future loss. This view is supported by observation of different approaches to the problem of prevention in different countries. Quite invariably and expectedly the countries that invest more are those where frequency and intensity of earthquakes are larger. Indeed, to cite the Italian case, only due to a number of seismic events closely

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[1] The reader is warned that what follow are amateurish economic considerations.

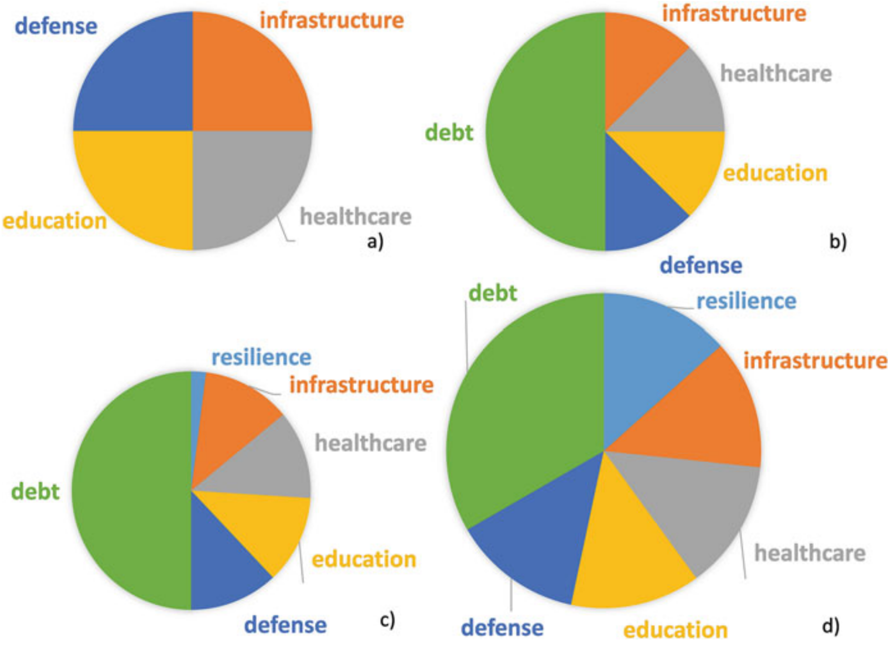

Fig. 28.4 Public expenditure and budget constraints to resilience investment

spaced in time (L'Aquila 2009; Emilia 2012 and Central Italy 2016–2017, (Dolce 2018)), measures towards prevention through state-subsidized strengthening have started being adopted, e.g. the "Sismabonus" scheme (Dolce 2017). The problem, however, remains. Economic boundary conditions are not favourable, as qualitatively illustrated in Fig. 28.4. In ideal conditions (panel (a)) public expenditure covers a number of functions (e.g. education, defence, healthcare, infrastructure). In real conditions, public expenditure is partly absorbed by interests on debt (panel (b)). Investment in resilience, a long term goal which requires vision, competes with running expenses associated with strong social interests. In a way, the situation with resilience is similar to that of education. In both cases the return on the investment is postponed and requires more political will and long-term vision. One possibility is to integrate resilience-oriented actions, like seismic strengthening, into ordinary maintenance programs of infrastructures (panel (c)). Of course a generous GDP growth (panel (d)) would allow larger investments, but, once again, current economic boundary conditions are different. It is obviously easier to divert budget to resilience (emergency management plus repair/reconstruction for higher performance) at the time an earthquake strikes, when public attention is high and opposition could be easily pointed as morally unjustified in view of the disaster victims.

The argument of high uncertainty can actually support an opposed point of view, a strong position in favour of prevention, since all the prediction problems related to the post-shock state (the entire recovery path ending with the new state) are greatly reduced by limiting initial damage, or simply eliminated together with it. The issue is

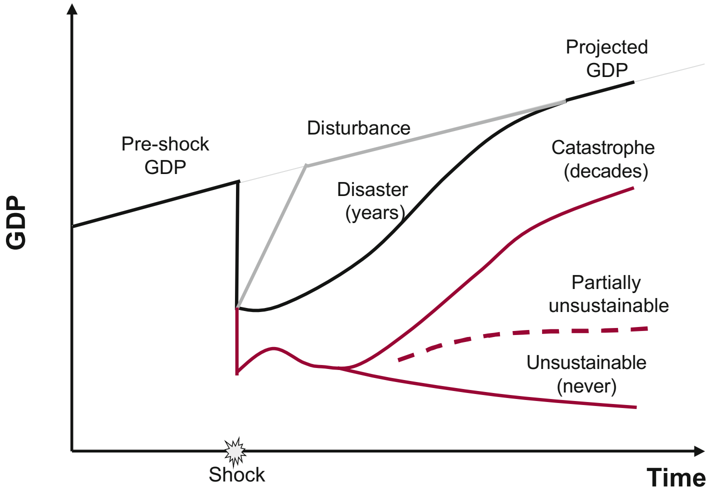

Fig. 28.5 Sustainable vs unsustainable outcomes following a shock (adapted from Davis (2015))

not one of academic nature, of avoiding a difficult (impossible?) modelling problem, but, rather, one of the utmost practical relevance. As shown in Fig. 28.5, recovery paths, as they are called, could well be characterized by no recovery at all. Impact may be so large that it takes decades to attain a new state that is below the previous trend line (a catastrophe), or even large enough to be partially or totally unsustainable, with a community being hit too hard to ever recover resulting in a large-scale outmigration. Think of Pompeii (79 AD), or, more recently, of the situation after Tohoku earthquake (2011) in some regions of Japan or in Christchurch after the 2010 Canterbury earthquake sequence (Newell et al. 2012).

In sum, informed decision-making requires reliable predictions. When uncertainties are of the order of magnitude illustrated, and contributed by sources other than physical, requiring specialist knowledge from different disciplines, including softer ones like economy or sociology, it can be argued from the limited perspective of an engineer that vulnerability reduction is the safer, more reliable way towards resilience enhancement. This is especially true when the range of possible outcomes includes extreme unsustainable ones as shown in Fig. 28.5 (which is not always the case, for instance in regions of medium seismicity).

28.1.3 Resilience-Based Design, or Performance-Based Design with Resilience-Based Targets

If this “engineering take” on resilience enhancement is adopted, the next question arising is how to relate a global system-level objective like resilience (which, as shown in Fig. 28.1, is computed in terms of the system state) to individual safety levels for the elements of the built environment. In other words, what seismic risk should we be designing new structures or retrofitting existing ones for, in order for our communities to meet predefined resilience targets? This theme is attracting some interest, ranging from attempts to answer the preliminary question of what is the risk implied by our current design procedures (Iervolino 2018), to attempts to link component safety to system safety through classical reliability methods (Lin et al. 2016). Actually, the most interesting approach to this problem is the one put forward in (Mieler et al. 2013, 2015).

Mieler et al. (2013, 2015) start by analysing the regulatory framework within which critical systems like nuclear power plants (NPPs) are designed, and end up comparing it with the regulatory framework for the system of interest in our case, i.e. a Community.[2] They draw an analogy between NPPs and communities, highlighting differences. The main difference, however, does not require to enter into the details. It is in the design philosophy. NPPs are designed top-down, starting from a clear explicit statement of the system-level goal, or undesired outcome to avoid. For NPPs these are core damage and radioactivity release, as shown on top of Fig. 28.6a. Next, functions vital for the plant and associated failure modes related to the undesired outcome are described through event tress and linked to the performance, or damage, of each of the physical system in the system of systems that represents the NPP (these are divided in primary and secondary, or support systems). On the contrary, the design philosophy behind communities is obviously bottom-up, with a fragmented and often non-consistent regulatory framework. Systems can also be subdivided into primary, essentially the buildings housing the vital community functions (VCFs) identified in analogy with those of a NPP, and secondary, i.e. the lifelines satisfying the demands for energy, transportation, communication, goods and services. These systems, however, are designed according to codes and guidelines that are drafted and maintained by non-coordinated bodies. Often, with reference to the specific problem of resilience to earthquakes, the seismic action is not considered at all in some systems or considered in non-consistent manner across different systems. As a result, the probability of occurrence of the undesired outcome, i.e. an unsustainable outmigration, is not a target but the end result of an uncontrolled process.

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[2] A system is a dynamic entity comprising a collection of interacting components assembled to perform an intended function. As such, a community can be described as a system, albeit an incredibly large and multi-faceted one. It is a complex dynamic system of people and organizations with relationships and interactions. Most of these relationships and interactions are physically supported by the community's built environment, which plays a crucial role in enabling a community to successfully function: it provides the physical foundations for much of the economic and social activities that characterize a modern society. Natural and man-made hazards can damage the built environment, thus disrupting the security, economy, safety, health, and welfare of the public. In response, regulatory frameworks were developed and implemented to ensure minimum levels of performance for individual parts of the built environment.

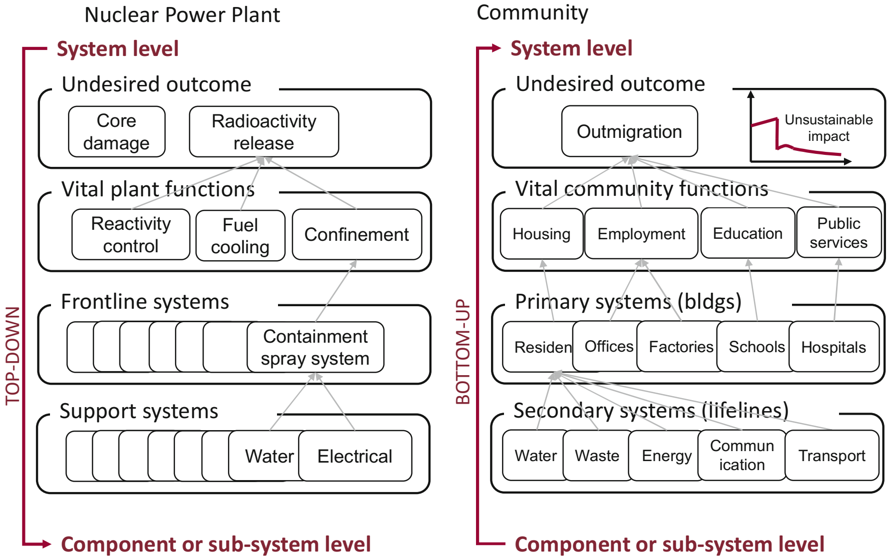


Fig. 28.6 The analogy between a NPP and a community and the opposite approach in design between the two systems

It would be sensible to adapt the NPPs regulatory framework to communities, but a number of differences pose challenges to this operation:

1. Physical scale. Communities occupy much larger geographic areas than NPPs, thus subsystems and components such as lifelines are spatially distributed over a potentially large area. As a result, it becomes necessary to account for partial failures of these subsystems and components. For example, an earthquake may cause damage to portions of an electric power grid, resulting in service disruptions to particular neighbourhoods or city blocks only. The evaluation of NPPs does not account for partial failures: components and sub-systems are either functional or non-functional.
2. External boundaries of the system. Most components and subsystems in a NPP reside within the well-defined physical boundaries of the plant. A community, on the other hand, can rely on components and subsystems that fall outside its jurisdictional boundaries. An electric power grid can draw electricity from a generating station far away and events disrupting the functionality of the station may cause service disruptions in the community, even though its power grid is not directly affected by the event. This issue of where to draw the boundary of the system is a difficult one, and in one case this led to modelling at very large scale (the entire US in (Karaca 2005)).
3. Time scale. A community's built environment is constructed over time, over decades or even centuries, especially in Europe. Individual components have likely been designed and constructed using substantially different specifications

and standards (the problem of existing buildings and other physical assets), meaning that the expected performance of similar components (e.g., residential buildings or highway bridges) within a community can vary drastically. In comparison, NPPs are built over a relatively short period of time.

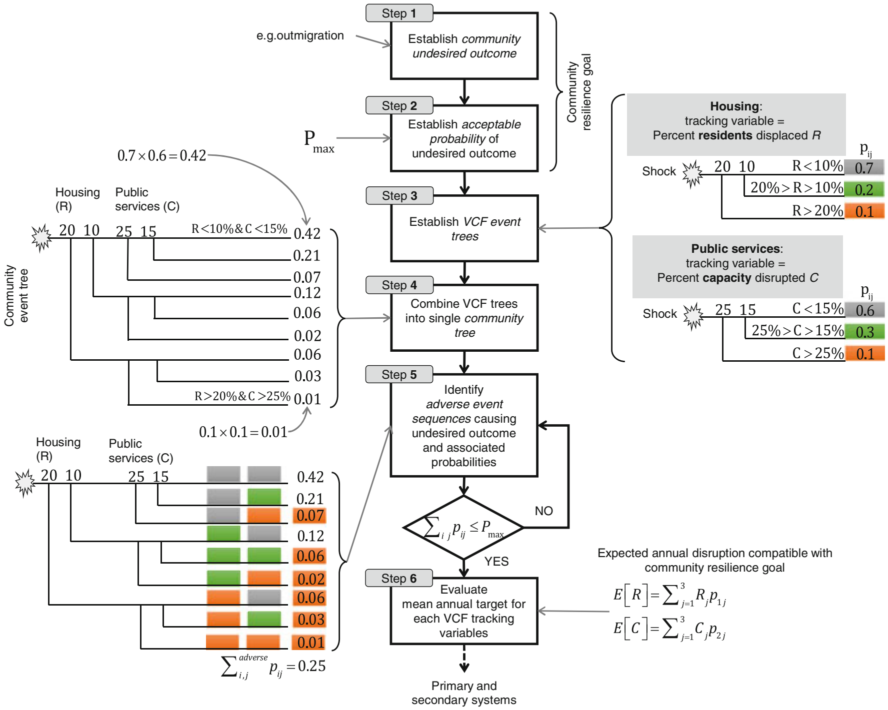
This said, the overall approach conceptually set out in Mieler et al. (2013, 2015) is rational and can be considered possibly the more solid base for developing the next generation design guidelines. This is indeed the basis for resilience-based design (RBD), which, in the view of the author, is nothing else than performance-based design (PBD) with resilience-based performance targets. Of course, while concepts of PBD still struggle to make their way into codes (Fardis 2018), and, when they do, they really are watered down versions of PBD, devoid of any explicit consideration of probability (Vamvatsikos 2017), PBD methods are being developed, extended, improved (Vamvatsikos et al. 2015) (Franchin et al. 2017) and at some point they will be ready for practical application. At that time the missing link will be proper resilience-based performance targets. Research is needed in this direction because the framework put forward by Mieler et al. is not operational.

28.1.3.1 Setting Resilience-Based Performance Targets for Individual Physical Assets

In this section an idea is presented on how to operationalize Mieler et al. framework to establish the performance target for an individual structure. This is one of the research needs mentioned in the title and this section identifies specific aspects that need focused research efforts.

Figure 28.7 illustrates the flow chart of the procedure from the community resilience goal to the performance targets for the vital functions. Step 1 requires defining an undesired community-level outcome (outmigration, or any other). Step 2 requires establishing an accepted threshold value for the probability (e.g. annual, or mean annual frequency) of the undesired outcome, P_{max}. The undesired outcome and the associated P_{max} jointly represent the community resilience goal. Step 3 involves establishing VCFs event trees and associated (tentative) target performances. In the figure for illustration purposes, only two VCFs are considered, Housing and Public services, with three possible events (partial functioning states) defined in terms of an appropriate tracking variable. Probabilities are assigned to each state j of each function i (these are desired targets), p_{ij}.

Step 4 involves combing the VCFs trees into the Community tree. In the example the probabilities of each sequence resulting from the combination of VCF events are computed by simple multiplication assuming statistical independence, like the 42% probability of the percent residents displaced, R, and the percent capacity disrupted, C, being lower than their lowest respective thresholds. This is beyond doubt an aspect where substantial improvement is needed, since obviously capacity disruption in services and percentage of residents displaced are not statistically independent, being caused by damage to common systems due to a common cause.



$$\sum_{i\,j} p_{ij} \le P_{max}$$

$$\sum_{i,j}^{adverse} p_{ij} = 0.25$$

$$E[R] = \sum_{j=1}^{3} R_j p_{1j}$$

$$E[C] = \sum_{j=1}^{3} C_j p_{2j}$$

Fig. 28.7 How to establish the target annual disruption in vital community functions compatible with predefined community resilience goals, according to the framework by Mieler et al. (2013, 2015)

Step 5 requires the identification of adverse event sequences leading to the undesired outcome, as well as of the associated probabilities. Identification of adverse sequences is done in the figure according to the simplified rule used in Mieler et al., i.e. a sequence leads to the undesired outcome when at least one VCF "is in the red", or two VCFs "are in the orange". This is obviously one more aspect that needs to be formalized and tackled in a more robust manner for operationalization. The sum over all adverse event sequences provides the total undesired outcome probability, which must be lower or equal than the target. Once, after iteration, this condition is positively verified, the target mean annual value of the tracking variable of each VCF is obtained (Step 6).

Even considering the problem of statistical dependence in Step 4 or that of identifying adverse sequences in Step 5, the procedure in Fig. 28.7 is well defined and provides a link from the community resilience goal, to the VCF performance targets. The next step, however, is not trivial. Herein, one idea is put forward on how this last link to the performance of an individual physical asset can be established. The idea is illustrated with reference to the hypothetical problem of determining the target performance for a new hospital, in terms for instance of ratio of post-event to pre-event beds or operating theatres available. The hospital is one of the primary systems upon which the health-care service depends. The latter is part of the "Public Services" vital

Service importance matrix (1×n) $\mathbf{I}_{service}$	Service		
	Police	Health-care	Food
Public services	0.3	0.3	0.4

a)

System importance matrix (n×m) $\mathbf{I}_{system}$		Systems						
		Primary			Secondary			
		Police stations	Hospitals	Stores	Water	Electric power	Fuel (oil)	Roads
Services	Police	0.4				0.2	0.2	0.2
	Health-care		0.5		0.1	0.2	0.1	0.1
	Food			0.5	0.1	0.1	0.1	0.2

b)

Fig. 28.8 Matrices linking functions to services (**a**) and services to systems (**b**)

function. A relation is needed between the "Public Services", for which a target disruption value compatible with community resilience goal, E[C] in Fig. 28.7, is now available, and each service, as well as between the latter services and the primary and secondary systems. According to the proposed framework these relationships can be expressed with service and systems importance matrices, denoted in Fig. 28.8 by $\mathbf{I}_{\text{service}}$ and $\mathbf{I}_{\text{system}}$, respectively. The "Public Services" VCF is over-simplified in the figure for the sake of illustration and is reduced to the police, health-care and food services. Also, the list of supporting systems, primary and secondary, is also reduced for the sake of the example, and the actual numbers in the matrices are made up, their sound selection process representing one more important aspect that requires focused research efforts. With reference to the health-care service, the figure shows that it strongly depends on the service level of hospitals (a weight of 0.5) and to a minor extent on the service level of lifelines such as the potable water, electric power and road networks (weights between 0.1 and 0.2).

With the above matrices in place, the total disruption in public services D_{tot} can be linked to the disruption in the primary and secondary systems. Further, by partitioning the matrices, the total disruption can be divided into a contribution coming from the new hospital to be designed (system 1) and a contribution coming from all the surrounding systems:

$$\begin{aligned} D_{tot} &= \underbrace{\mathbf{I}_{service}}_{1\times n}\,\underbrace{\mathbf{I}_{system}}_{n\times m}\,\underbrace{\mathbf{D}_{system}}_{m\times 1} = \mathbf{I}_{service}\left[\mathbf{I}_{system,1}\;\;\mathbf{I}_{system,2}\right]\begin{bmatrix} D_{system,1} \\ \mathbf{D}_{system,2}\end{bmatrix} = \\ &= \underbrace{\underbrace{\mathbf{I}_{service}}_{1\times n}\,\underbrace{\mathbf{I}_{system,1}}_{n\times 1}}_{1\times 1}\,\underbrace{D_{system,1}}_{1\times 1} + \underbrace{\underbrace{\mathbf{I}_{service}}_{1\times n}\,\underbrace{\mathbf{I}_{system,2}}_{n\times(m-1)}\,\underbrace{\mathbf{D}_{system,2}}_{(m-1)\times 1}}_{1\times 1} \end{aligned} \tag{28.1}$$

By equating this disruption to the annual percent capacity disruption compatible with the community resilience goal, E[C] in Fig. 28.7, one could obtain the target unknown maximum disruption for the new hospital $D_{system,1}$:

$$D_{system,1} = \frac{E[C] - \mathbf{I}_{service}\mathbf{I}_{system,2}\mathbf{D}_{system,2}}{\mathbf{I}_{service}\mathbf{I}_{system,1}} \qquad (28.2)$$

The missing item in the above equation is the disruption due to seismic events to all the other systems of the built environment supporting the community, $\mathbf{D}_{\mathrm{system},2}$. The latter requires a systemic analysis of the entire built environment, i.e. an analysis to assess the impact of an earthquake event at the regional or urban scale. While this is one further aspect where research is needed, unlike the aspects previously mentioned, systemic analysis has already attracted considerable attention in the last decade at least, and several frameworks or partial models exist. The next main section is thus devoted to this topic and to identify some of its research gaps.

28.2 Systemic Analysis of the Built Environment

28.2.1 Existing Frameworks

Among the many available, the definition of infrastructure given in (PCCIP 1997) as the "network of distinct man-made systems and processes that function collaboratively and synergistically to produce and distribute a continuous flow of essential goods and services", is adopted. From a system-theoretic point of view, the infrastructure is thus a system of systems (SOS) (Rinaldi 2004), a super-system containing all other systems (buildings, lifelines, critical facilities, etc.) and constitutes the physical layer supporting the life of our society, the built environment, i.e. the two bottom layers in Fig. 28.9a. The term infrastructural system is thus used to indicate any of the component systems in Fig. 28.9a. Analysis of the impact of an earthquake on infrastructural systems has started with the analysis of single systems. Most of the research in earthquake engineering still focuses on the characterization of the single-site point assets in these systems, like buildings or bridges, which are themselves (structural) systems but, at the scale of interest herein, are just components. This component-oriented point of view dominates the scene and this is reflected, just to give an example, in the HAZUS collection of components' fragility curves (NIBS 1999). Of the much smaller proportion of research that looks into the spatially distributed portion of these systems, most work focused initially on road networks, e.g. (Shinozuka et al. 2003), with fewer works devoted to other lifelines, like power networks (Vanzi 1996) or water networks (Wang et al. 2010).[3] Studies dealing with two or more systems are even scarcer and typically referring to the power and another dependent network, e.g. (Dueñas-Osorio et al. 2007) (Poljanšek et al. 2012), while those aiming at modelling consequences beyond simple physical damage are rare (Cho et al. 2001) (Karaca 2005). To the knowledge of the author, the

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[3] This chapter is not a state-of-the-art on either resilience or the assessment of infrastructural systems, but, rather, a point of view on some research gaps in the field. For this reason, only a subjective, partial selection of examples is given here, before focusing from the next section on the framework developed by the author and co-workers.

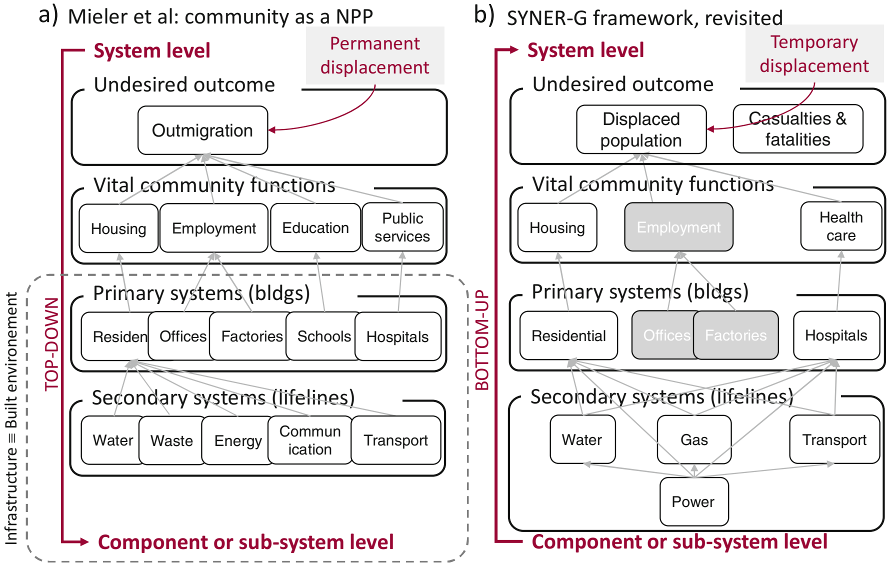

Fig. 28.9 The representation of a Community as a NPP by Mieler et al. (2013, 2015), with identification of the supporting system of systems (primary+secondary) at its base (**a**) and the analogy with the SYNER-G framework (grey fill indicate the considered systems, implemented in OOFIMS)

first notable large scale effort to model the problem of the impact of an earthquake at urban or regional scale from a systemic point of view originated on the US East Coast under the umbrella of the MCEER and later of the MAE. This is the research the led to seminal works like that by Bruneau et al. (2003).

More recently, in Europe, the author and co-workers contributed to the development of a framework for the analysis of interdependent infrastructural systems, within the context of the SYNER-G project (2009–2013). This project is described in a number of papers and in two dedicated books (Pitilakis et al. 2014a, b). In particular, the systemic framework and the general object-oriented model developed to support it are described in (Franchin 2014). The framework presents high similarity with that put forward in (Mieler et al. 2013) and can be described in the same way, as shown in Fig. 28.9b. The main difference is in the perspective, a top-down design one versus a more traditional bottom-up, assessment perspective in SYNER-G. On the other hand, the SYNER-G framework, implemented in an open-source software, namely Object-Oriented Framework for Infrastructure Modelling and Simulation (OOFIMS), is fully operationalized and considers already an important subset of the primary and secondary systems, with their interactions. In this respect, this model, or other similar in capabilities, are good candidates for the evaluation of systemic impact needed in Eqs. (28.1) and (28.2).

Figure 28.10 illustrates qualitatively the main features of this systemic model. It is multi-layered, with some layers in the physical space (collectively denoted as

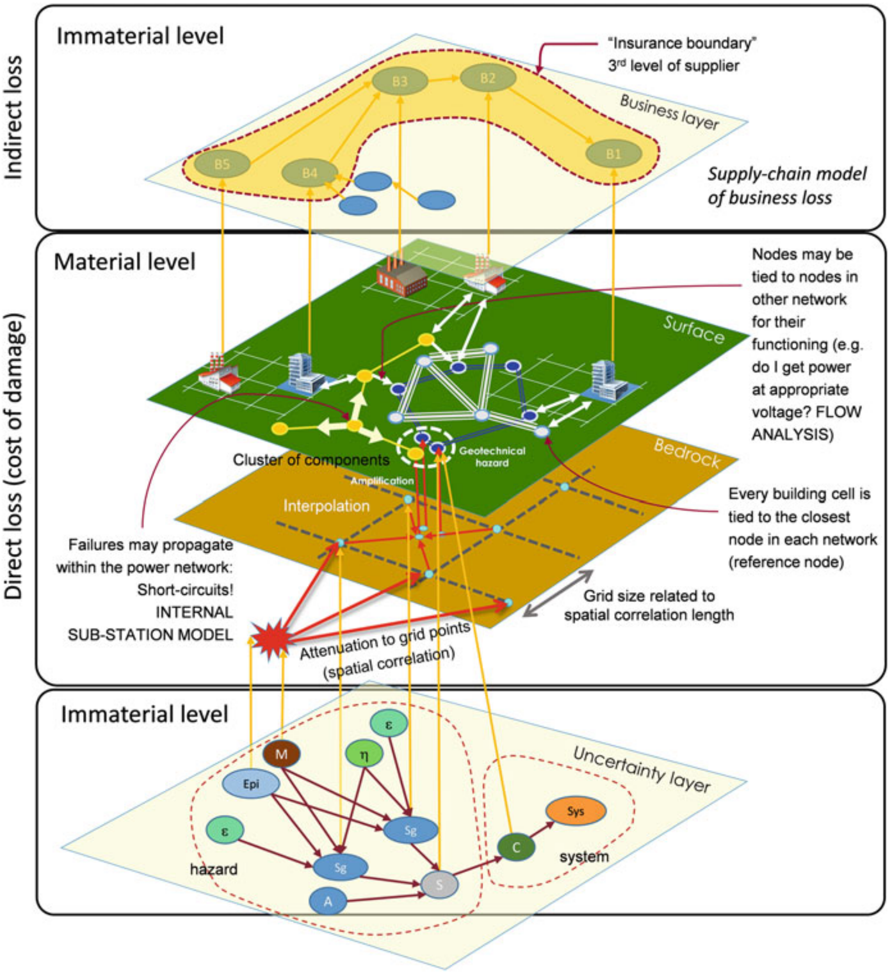

Fig. 28.10 The model developed within the SYNER-G project and implemented into the OOFIMS software, and its possible extension to consider indirect loss due to business interruption

"material level"), while others are non-material. Thus, for each physical quantity needed at the material level, there is a corresponding random variable in the Uncertainty layer (links in this non-physical network denote statistical dependence). At the bottom lies a probabilistic model of spatially distributed seismic hazard, described in detail in (Weatherill et al. 2014), which allows prediction of consistent seismic intensity fields (or maps). The separation of inter- and intra-event errors in the prediction of simultaneous intensity at different sites (Bommer and Crowley 2006), and of spatial correlation (Jayaram and Baker 2009), by now a consolidated acquisition, wasn't immediately recognized in its importance. For quite some time most so-called regional studies, which generally where portfolio loss assessments with no consideration of interactions whatsoever, used design maps. The model in Fig. 28.10 generates scenarios starting from magnitude and location, it then predicts local intensities S_g on a regular grid (considering inter-event η and correlated intra-event ε errors), from which values S at the location of individual components are interpolated. When spatially consistent values at the bedrock under each component are determined, surface values are obtained via site-dependent random amplification (A), and values of other intensity measures, needed for components of different types clustering at the same site, are also obtained in a probabilistically consistent manner.

The innovative portion of the model begins where the hazard ends, i.e. in the system portion where the components states (C) are propagated into the system states (Sys). The focus in its development was on the capability to include interactions, on the possibility of integrating different system models with non-consistent granularity of the input data, and on refinement of each system internal model. Thus, just to give an example, the primary systems (buildings) are automatically tied to the closest node in each of the secondary, establishing a two-way relationship with each of them (assembly of demand from the buildings to the system, loss of service from the system to the buildings). Other building-system interactions include, e.g., obstruction of road segments due to building damage. Ties exist also between nodes of the secondary systems, so that loss of power due to a failure in the electric power network cascades into failure of the connected systems. But the main important difference with other models is in the refinement of the individual network system models. All models are analysed in terms of flows, rather than simple connectivity. This aspect is one that has been shown to change the results of the assessments (Cavalieri et al. 2012, 2014) (Franchin and Cavalieri 2015), and is considered in the next section.

Before moving on, however, let's consider once more Fig. 28.10. The top portion of the figure shows a layer, denoted as "business layer", where another non-physical network lies. Nodes B_i in this network are businesses, and the network of links connecting them represent the chains of supply and demand from prime sources to the final customer. This portion of the model is just an idea and, to the best knowledge of the author, a complete full-blown systemic view of this type (i.e. with a consistent level of completeness at all levels, from hazard, to physical behaviour of the interconnected systems, to the organizational aspects of business) is still missing and probably beyond the current modelling capabilities. Nonetheless, it shows one possibility to go beyond the simple summation of direct loss and venture into that of indirect loss armed with the capability of modelling business interruption due to a range of causes, many of which non-local. This kind of studies may never reach the point where they provide accurate assessments, but will serve the purpose of exploring complex patterns. It may be of interest to the insurance industry (for instance to choose where to trace their boundary for liability, the figure shows, as an example, the boundary of business B_1 stopping at third-order suppliers).

28.2.2 Challenges in Network Modelling

The production and distribution of essential goods and services mentioned before requires a number of specialised networked systems, consisting of production, exchange and consumption sites, connected by links. From a mathematical point of view, they can all be regarded as graphs consisting of nodes or vertices, and edges. At a basic level, where most physical differences among networks are disregarded and the focus is only on connectivity, this graph theoretic point of view, and the associated mathematical apparatus, is all that is needed to assess the impact of damage. Figure 28.11a shows a simple network, with $n_V = 4$ vertices and $n_E = 5$ edges connecting them. Whatever is conveyed by the network, can travel along edges in both directions, depending on what drives or directs the flows. This situation arises, e.g., in power networks, where flow can occur in both directions depending on the voltage at the edge ends. The corresponding graph is called undirected, and its mathematical representation can be through a symmetric adjacency matrix **A**. Alternatively, an incidence matrix **I** can be used, where each row indicates which nodes are connected by the corresponding edge. When edges cannot be necessarily travelled in both directions, like e.g. with one-way roads in transportation networks, the graph is directed and **A** is not symmetric any more. Damage is modelled at the network level, by an update of either **A** or **I**, as shown for instance by removal of the third and fifth row of **I** in Fig. 28.11c. At this basic level, the physical differences between networks enter only into the way damage to components is predicted: for each system a different set of fragility curves is considered.

The limits of this basic modelling level can be easily exposed, both at the global and the local level. Figure 28.12a shows the same network as Fig. 28.11a, but now the four nodes are divided into $n_S = 2$ sources (v1 and v2) and $n_D = 2$ demand nodes (v3 and v4). An often used connectivity-based global measure of network

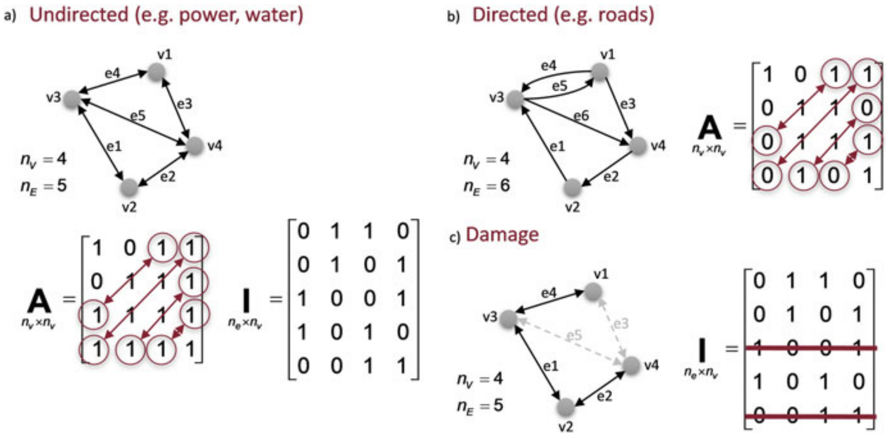

Fig. 28.11 Graph representation of networks: undirected (**a**) and directed (**b**). Damaged network (**c**)

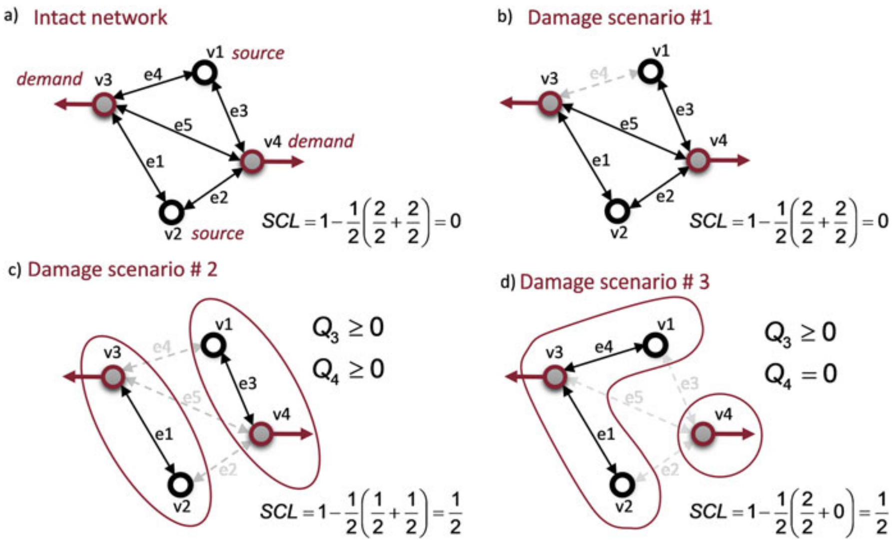

Fig. 28.12 Sources and demand nodes in the network of Fig. 28.11(**a**). Different damage scenarios (**b**) to (**d**)

performance is the so-called simple connectivity loss (SCL), defined as (Franchin and Cavalieri 2013):

$$SCL = 1 - \frac{1}{n_D} \sum\nolimits_{i=1}^{n_D} \frac{N_{Si,0}}{N_{Si,s}} \tag{28.3}$$

where N_{Si} is the number of sources connected to the i-th demand node, and the subscript "0" and "s" denote the "zero", undamaged, reference conditions, and the "seismic", damaged one. It clearly takes upon the value 0 in the initial condition where, for any demand node, $N_{Si,\,s} = N_{Si,\,0}$. Figure 28.11b shows a damage scenario where edge 4 is removed from the network. Even though not directly, demand node v3 is still connected through node v4 to the source v1. As a result, SCL = 0, as for the intact conditions. According to the connectivity approach this damage goes undetected. Two more damage scenario, shown in Fig. 28.11c, d, are also assigned the same value of SCL of 0.5, even though in case (c) both demand nodes are still connected to one source, while in case (d) demand node v4 is disconnected and therefore its demand cannot be satisfied ($Q_4 = 0$).

The situation in Fig. 28.11b is worth considering again. It should be stressed that being still connected to a source is a necessary but not sufficient condition to satisfy a node demand. What matters is the actual flow delivered. For instance, a number of pipes may connect a source with a demand node, but leaks along the path may reduce pressure to the point that the water head is below the height of the buildings served by the demand node. No water would get out of the tap, especially at higher floors, without any broken pipe in between. Similarly, electric apparatuses are not very tolerant to voltage, and power provided with voltage lower than 90% the regular working condition would make them unusable. These are good reasons to go for flow modelling, one more is given later on (flow can be measured after the event). Against this approach is the elegant and efficient reliability methods available for connectivity-only models. Solving the real problem, however, remains for now a matter of brute force and Monte Carlo-like simulations. In the view of the author, efforts to devise more efficient, affordable schemes to reduce the burden of Monte Carlo simulations, like e.g. the reduction of seismic scenarios to be analysed (Chang et al. 2000) (Jayaram and baker 2010), are more appreciable than those trying to push the limits of connectivity-based methods. It is probably wise, however, to keep pursuing both, given the stark difference in computational effort. For instance, while it has been shown that simple connectivity models cannot predict the correct retrofit priorities for power-network components, enhanced connectivity approaches like hierarchical decomposition come closer to the flow-based results (Cavalieri et al. 2014).

Table 28.1 reports, for the five of the many networked systems implemented so far in OOFIMS (Cavalieri et al. 2012, 2014a, b, 2016, Esposito et al. 2014 and Cavalieri 2017), the topology, i.e. whether edges form closed loops as in grid-like systems or they don't, as in tree-like ones, and which portion of each network has one topological structure or the other. The table then provides information on damage, and finally on flow. For what concerns damage, in order to describe it fully, models for damage and its consequence should be formulated and implemented for both nodes and edges. For nodes, damage at the sources (S) and in intermediate junction nodes (J, in general, denoted TD/D for power, where voltage transformation can occur, or Re/ReMe for gas, where pressure reduction can happen) should be modelled. Junction in road networks are more complex. They can be at-grade, in which case they are basically not vulnerable, or interchanges, made up of ramps and bridges, tunnels, in which case they resemble those in power or gas networks, where they are themselves systems. In OOFIMS node damageability, with the exception of TD/D and Re/ReMe substations, is not modelled, as indicated by the italic in the table. On the other hand, damage to edges is modestly modelled. It can be continuous (with progressive reduction of flow capacity), as in all system with pipes (water, gas, etc), or discrete, binary (fail,safe), as for power lines, or multi-level as in road networks, for lanes that can be closed to limit vertical load on damaged structures. Furthermore, damage can be direct, for all components, or indirect, as when a power line (especially an overhead one that, contrarily to buried one is almost insensitive to seismic motion) is damaged due to overcharge. The consequences of damage are for all networks a decrease in flow for direct damage (consequence on the damaged edge) and a possible increase in flow for indirect damage (consequence of damage to other edges, causing change of flow patterns).

Coming finally to the lower portion of Table 28.1, dedicated to flow, the table first reports the quantity whose gradient drives flows through the network, and the quantity flowing. In all cases, with the exception of road networks, the flow equations express flow of a physical quantity under physical constraints. Road networks are complicated by the fact that drivers are (still) human, and elements of behaviour modelling are included. Without entering into the details, several

Table 28.1 Networked systems: topology, flow and damage type and consequences

System		Power	Gas	Freshwater	Stormwater/ Wastewater	Roads
Topology	Grid-like	Transmission/ distribution	Transmission/ distribution	Transmission/ distribution	N/A	Yes
	Tree-like	Distribution (LV)	Distribution (LP)	Distribution	Collection	Yes
Damage	Nodes	*S*, TD&D	*S*, Re, ReMe	S, J	J	No
	Edges	Binary.Buried, direct. O*verhead, indirect.*	Continuous. Pipes, direct (leaks/ breaks).	Continuous. Pipes, direct (leaks/ breaks).	Continuous. Pipes/channels, direct (leaks/ breaks).	Discrete. Bridges/ embankments/ trenches/ tunnels, direct.
	Consequence (direct)	Zero current	Flow decrease	Flow decrease	Flow decrease	Flow decrease
	Consequence (indirect)	Current increase (overcharge)	Flow increase	Flow increase	Flow increase	Flow increase (traffic congestion)
Flow	Driver	Voltage V	Pressure P	Hydraulic head $h = z+P/\gamma_w$	Head	Trips (O/D matrix)
	Quantity	Power (complex)	Gas (compressible)	Liquid	Liquid	Vehicles
	Equations(line loss)	Multiple voltage ranges	Multiple pressure ranges	Single pressure range	Free surface gravity flow	Single speed range
	Equations(line capacity)	*Yes*	No	No	*Yes*	Yes

S = Source node; D/TD = Distribution or Transformation-distribution sub-station (power); Re/ReMe = pressure Reduction or Reduction-Measurement sub-station (gas); J = generic Junction (where more edges converge) algorithms exist to determine flow, looking for an optimum either from the user or the system perspective. Perhaps in the future, with the advent of autonomous and coordinated vehicles the predictability of these networks will improve considerably. Herein, however, what is relevant is that the demand on the road network is the end result of another analysis whose output is the so-called origin-destination (O/D) matrix, which expresses the amount of vehicles leaving each node (traffic analysis zone) for each possible destination. Most studies in the field of seismic assessment of road networks used and still use so-called static O/D matrices, i.e. use pre-earthquake demand on post-earthquake damaged network. Attempts to use so-called dynamic O/D matrices, linking the change in traffic demand to damage in residential buildings and economic activities, are scarce and seem not to have drawn enough attention (Cho et al. 2004). This is one more aspect that requires considerable improvement and seems to have defied researchers' efforts so far. On the other hand, perhaps because flow-based assessments and multi-system studies are still a minority in lifelines research, it may have escaped the attention that the same problem afflicts also power, water or gas systems. All these systems have demand proportional to population needs, and if the population is displaced and economic activity pattern is altered after the event, the demand pattern should reflect it. In this respect the automatic link between buildings and demand nodes in the SYNER-G framework represents a solution, at least for these systems (no progress has been made instead on the post-earthquake travel demand front).

The last portion of the table provides information on the actual flow equations. In light of the differences in the conveyed quantities, equations are much simpler where water is involved, than in the case of electricity or gas. Flow models include two types of equations, balance equations expressing flow continuity at the nodes, and resistance equations expressing line loss. For freshwater networks these are written as:

$$\begin{array}{l} \begin{cases} \mathbf{I}_D^{*T}\mathbf{q} - \mathbf{Q} = \mathbf{0} \\ \Delta\mathbf{h} - \mathbf{r}(\mathbf{q}) = \left(\mathbf{I}_S^{*}\mathbf{h}_S + \mathbf{I}_D^{*}\mathbf{h}_D\right) - \mathbf{r}(\mathbf{q}) = \mathbf{0} \end{cases} \\ \mathbf{r}(\mathbf{q}) = \mathbf{R}\mathbf{q}\circ|\mathbf{q}| \end{array} \tag{28.4}$$

where $\Delta\mathbf{h}$, $\mathbf{r}$ and $\mathbf{q}$ are the $n_E \times 1$ vectors of node head difference, resistance (function of the edge flow) and edge flows, $\mathbf{Q}$ is the $n_D \times 1$ vector of node demands (zero if the node is a junction) and $\boldsymbol{I}_S^*$ and $\boldsymbol{I}_D^*$ are the partitions of the incidence matrix related to source nodes and demand nodes, respectively. With reference to the simple network in Fig. 28.11a, the incidence matrix is expressed as:

$$\underset{n_e \times n_v}{\mathbf{I}^*} = \left[\begin{array}{cc|cc} 0 & -1 & 1 & 0 \\ 0 & -1 & 0 & 1 \\ -1 & 0 & 0 & 1 \\ -1 & 0 & 1 & 0 \\ 0 & 0 & -1 & 1 \end{array}\right] = \left[\begin{array}{c|c} \underset{n_e \times n_S}{\mathbf{I}_S^*} & \underset{n_e \times n_D}{\mathbf{I}_D^*} \end{array}\right] \tag{28.5}$$

It is important to note that within the flow analysis, although the water network is undirected, the incidence matrix must reflect the actual edge directions as specified in the network connectivity matrix, and thus it has 0, +1 and -1 entries.

For gas networks, pressure ranges are large enough that a single set of equations does not suffice (line loss changes its proportionality), so that equations for multiple levels of pressure, including the transformation from one level to the other are needed:

$$\begin{cases} \mathbf{I}_D^{*T}\mathbf{q} - \mathbf{Q} = \mathbf{0} \\ \Delta\mathbf{p} - \mathbf{r}(\mathbf{q}) = (\mathbf{I}_S^{*}\mathbf{p}_S + \mathbf{I}_D^{*}\mathbf{P}_R\mathbf{p}_D) - \mathbf{r}(\mathbf{q}) = \mathbf{0} \end{cases}$$
$$\mathbf{r}(\mathbf{q}) = \begin{cases} r_{ij}(q_{ij}) = p_i - p_j = K_L q_{ij}^2 & \text{low}-\text{pressure} \\ r_{ij}(q_{ij}) = p_i^2 - p_j^2 = K_M q_{ij}^2 & \text{medium(high)}-\text{pressure} \end{cases} \tag{28.6}$$

where the pressure vector **p** replaces the head difference vector **Δh**. The difficulty arises when one realizes that the above equations are design equations, not assessment equations. They are routinely used in design of new systems where demand satisfaction is a requirement. This is a simplification akin to that of modelling structures linearly, or with simple bilinear models neglecting post-peak behaviour, since no such extreme behaviour would be acceptable for a new structure (Fardis 2018). But in a damaged network system loss can be so large that demands are not met at many nodes. Head-driven (or pressure-driven, etc), rather than demand-driven equations are thus needed, such as:

$$\begin{cases} \mathbf{I}_D^{*T}\mathbf{q} - \mathbf{Q}(\mathbf{h}_D) - \mathbf{Q}_{seismic}(\mathbf{h}_D) = \mathbf{0} \\ (\mathbf{I}_S^{*}\mathbf{h}_S + \mathbf{I}_D^{*}\mathbf{h}_D) - \mathbf{r}(\mathbf{q}) = \mathbf{0} \end{cases} \tag{28.7}$$

for water networks, or:

$$\begin{cases} \mathbf{I}_D^{*T}\mathbf{q} - \mathbf{Q}(\mathbf{p}_D) - \mathbf{Q}_{seismic}(\mathbf{p}_D) = \mathbf{0} \\ (\mathbf{I}_S^{*}\mathbf{p}_S + \mathbf{I}_D^{*}\mathbf{P}_R\mathbf{p}_D) - \mathbf{r}(\mathbf{q}) = \mathbf{0} \end{cases} \tag{28.8}$$

where $\mathbf{P}_\mathrm{R}$ is the pressure reduction vector (Cavalieri 2017). In the above equations, node demands are reduced as a function of driving pressure, and additional "seismic" demands are added to nodes, lumping line loss from each pipe segment in its end nodes and summing up. This is the type of equations implemented into OOFIMS. Alternatives include the use of a third-party software in an iterative manner, adjusting water head and demands until satisfaction, like done for instance by GIRAFFE with EPANET. It could then be added that the above equations are still only stationary ones, assuming that the state of damage, supply and demand are fixed in time. Just to give an example, and not considering multiple shock sequences causing incremental damage, in the presence of variable head sources, with important network damage and associated loss, the problem of computing the sustainability of demand in the absence of repair and during a dry season become of very high relevance (studies like these have been performed for instance for Wellington, in New Zealand).

The situation for power networks is even more complicated, since, to the best knowledge of the author, available flow equations are not still demand-driven. But there is more than that, the problem being that since power cannot (could not?) be easily stored, power networks are operated with continuous adjustments to balance demand and capacity, trying to solve the so called Alternate Current Optimal Power Flow (ACOPF) problem, which is a nonlinear (non-convex) constrained optimization problem, the constraints being posed by limited line capacity or generators power limits. The problem is so tough that, formulated in 1962 (Carpentier 1962), it still awaits to date a robust and fast solution. It is solved on a yearly, monthly, daily and hourly basis for the needs of the operators and to adjust market prices (it is also indeed called the Security-Constrained Economic Dispatch or SCED), and depending on the case, solution of increasing efficiency (speed) and simplification are adopted. The alternatives include using the Economic Dispatch, i.e. solving the optimization problem without constraints, or solving nonlinear quadratic AC equations that yield mathematically but not necessarily physically feasible solutions, nor optimal ones. The latter are those used already in the (pioneering?) study in (Vanzi 1996) and implemented in OOFIMS. Most risk assessment studies have not even tried this, and when flow was considered, it was in the simplified linearized direct current (DC) variant, only recently moving on (Li et al. 2017).

In conclusion, difficulties in flow-based analysis are not related exclusively to the increased computational burden but also to the improvement and adaptation of flow models to the case of assessment of damaged networks. This is one more research gap towards the capability of designing resilience of communities in the real world.

28.2.3 Components' Fragility: Beyond Generic Fragility Models

The previous section discussed the merits and difficulties of flow-based analysis at the network level to determine functional consequences of physical damage. This section goes back to the previous step of evaluation of the components' state of damage. Damage is usually determined sampling from a damage state distribution, which is obtained at the local intensity level in each scenario event from the set of the component fragility curves. In the simplest of cases, with so-called binary components, a single curve is used, separating functional from non-functional state. In general, at least two curves are considered, as shown for instance in Fig. 28.13, with three resulting state: intact, damaged and collapsed. This allows modelling intermediate states of partial functioning. Systemic studies and simpler portfolio loss assessments make extensive use of so-called generic fragility curves, the main source of which is the already recalled HAZUS collection (NIBS 1999). The applicability of these literature fragility is seldom if ever questioned, the aim of the

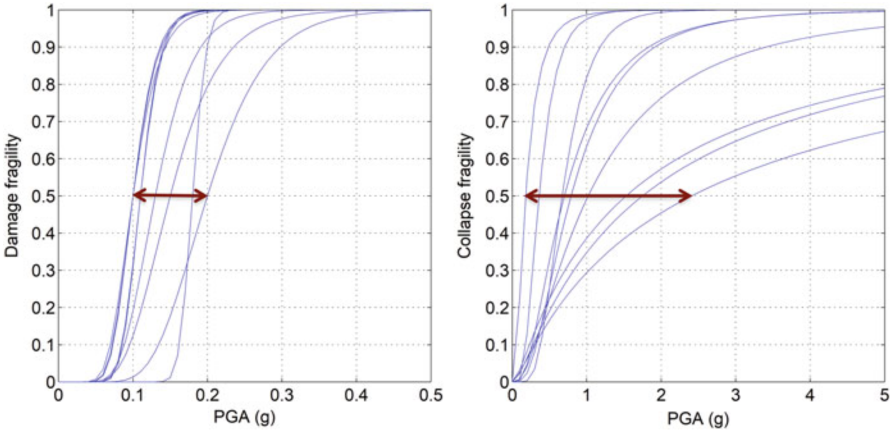

Fig. 28.13 Damage and collapse fragility for a set of bridges belonging to the same class (Adapted from Borzi et al. 2015)

analysis being testing the systemic part, rather than realism in the results. Sometimes, applicability issues are considered and project specific fragilities, which may include literature ones, are collected/derived, as done for instance during the SYNER-G project (Pitilakis et al. 2014a) or for cases where previous experience on structural behaviour is not available (Crowley et al. 2017). The problem, however, with generic fragility curves, is that they are conceptually questionable.

Fragility is well-known to be site-specific (Veneziano et al. 1983), meaning that the same structure at different sites will have a different fragility curve. This is because the fragility is not a property of the structure. This by itself would be enough to say that generic fragility curves are a nonsense, but there is more to add. During a nation-wide assessment of 485 bridges in Italy, with refined inelastic response history analyses of 3D models carried out in a consistent manner across the bridge stock, damage and collapse fragility curves where obtained (Borzi et al. 2015). The important finding of interest here is that these curves allowed to challenge the usual classifications of bridges used for the purpose of generic fragility developments. Figure 28.13 shows the fragility curves of a set of nine bridges that were obtained querying the 485 bridges data base with the criteria: multiple simply supported spans, single-stem hollow-core piers of height between 5 m and 30 m, rubber bearings. The HAZUS, Turkish and Greek typological classification would attach to all bridges the same fragility curve. The results in the figure speak for themselves. Variation only in the median collapse intensity is more than 2 g.

In sum, fragility is only an intermediate step in the evaluation of risk (or damage probability), it does depend on the site and, most importantly, on the structure properties in a stronger manner than assumed by lumping “similar” structures into the same bin for the purpose of assigning a fragility curve. What is shown in Fig. 28.13 for girder bridges can be easily extended to buildings. Can we expect that all 5-storeys regular RC buildings have the same fragility curve? There is a strong need for improved tools for damage prediction. Generic fragility curves should be replaced by more flexible fragility models that yield structure and site specific fragility curves. A first attempt in this direction, more of a demonstration study, is the Bayesian-network-based fragility model for girder bridges developed based on the data from the above mentioned 485 bridges (Franchin et al. 2016), capable of predicting a structure and site-specific fragility, even when values are assigned just to a portion of its random variables (a considerable advantage of using Bayesian Networks over alternative methods). Something along these lines, however, is needed for all types of components, if a higher level of reliability of results of systemic analysis is sought. This is an entire area of work that needs fresh concerted efforts.

28.2.4 Evolving State of Information and Emergency Management

Approaching the conclusion of this chapter, one last issue is worth mentioning. A systemic model, like the one illustrated so far, can also be used beyond planning for resilience enhancement (or risk mitigation, as it used to be called). Such a model, if a sufficient level of realism was attained (e.g. by limiting its use to a subsystem that can be more reliably predicted), could be used to inform the construction of a decision support system (DSS) for emergency management purposes. Research in this direction is ongoing, and efficient management of the post-event phase is another action towards higher resilience.

A promising tool for building DSSs is represented by Bayesian Networks. These are network of random variables used to represent in an efficient manner the uncertainty in a problem and for which efficient methods have been developed to perform Bayesian inference (Nielsen and Jensen 2009). The latter, i.e. the capability of quickly updating probabilities in response to changes in the state of knowledge, makes BNs a natural candidate for DSSs. Work in this direction in the field of seismic risk of distributed civil systems has mainly looked into connectivity-based modelling of systems, e.g. (Bensi et al. 2013). After developing a BN for the hazard portion of the problem (compare the uncertainty layer in Fig. 28.10 with Fig. 28.14a), Bensi et al. worked in order to improve the system part. The easiest way to describe the latter is the converging structure where all components are linked to the system, as in Fig. 28.14b. This structure is straightforward to obtain and for this reason is called Naïve formulation. Without entering into the theoretical details, the computational burden associated with Bayesian inference on a BN increases, among other things, with the number of incoming links to a variable, making the Naïve formulation intractable with any realistic system. This reason led to the formulation of alternative system descriptions, like the minimum link set formulation (MLS) shown in Fig. 28.14c, where components are linked to the MLS they belong, and these in turn are linked to the system, or the Efficient MLS formulation,

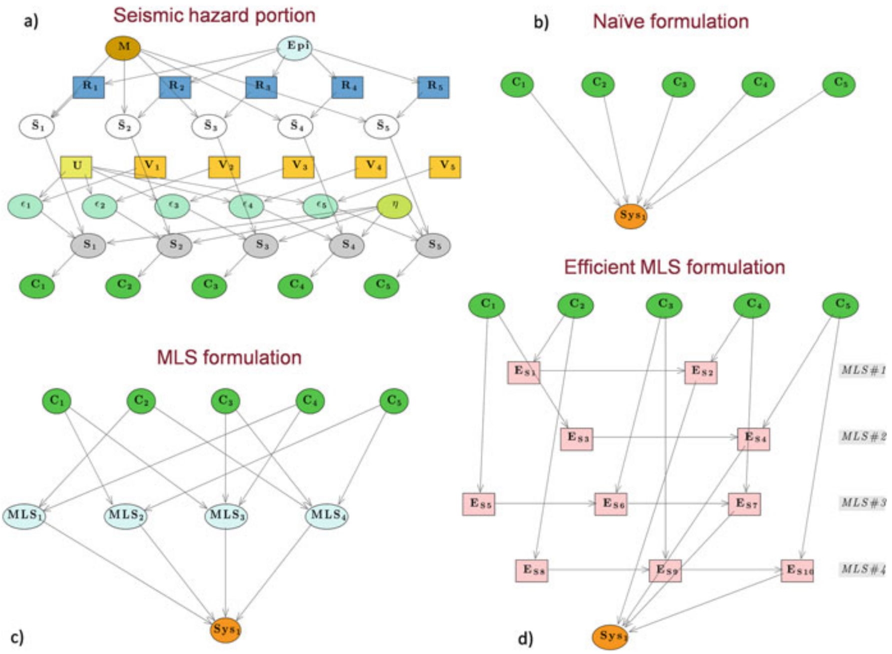

Fig. 28.14 BN for the hazard (**a**) acting on a 5-components system, and alternative formulations for the system portion of the BN (**b**) to (**d**) (Modified from Cavalieri et al. 2017)

where the number of incoming links to each variable is further reducing introducing survival path sequences (Fig. 28.14d).

The above efficient formulations, however, cannot be extended to handle the case of systems where flows are of interest, as shown in (Cavalieri et al. 2017). On the other hand, the naïve formulation, in its simplicity does not impose limitations on the type of performance metrics used to describe the system's and components' states, allowing treatment of the flow problem. For this reason, an improved Naïve formulation has been devised in (Cavalieri et al. 2017), whereby the number of incoming links is kept below a manageable threshold by eliminating edges corresponding to low correlation between component and systems states, as illustrated in Fig. 28.15a. The key to this operation is a pre-event systemic analysis to establish a set of component-system state vectors to establish these correlations. There are several advantages to this approach, besides the fact that it can solve the actual problem, rather than its connectivity simplification. First of all, as it can be seen by comparing Fig. 28.15a, b, the BN is much simpler than that obtained with the efficient MLS formulation (the figure refers to a connectivity case, where both approaches can be applied, and where inference results of the improved Naïve model have been compared to the exact MLS-based results showing excellent accuracy). This simplicity makes it also possible for the BN to be set up automatically based on the systemic simulation results, a welcome feature when dealing with real size complicated systems. Further, the BN size scales up linearly with the system size, while the

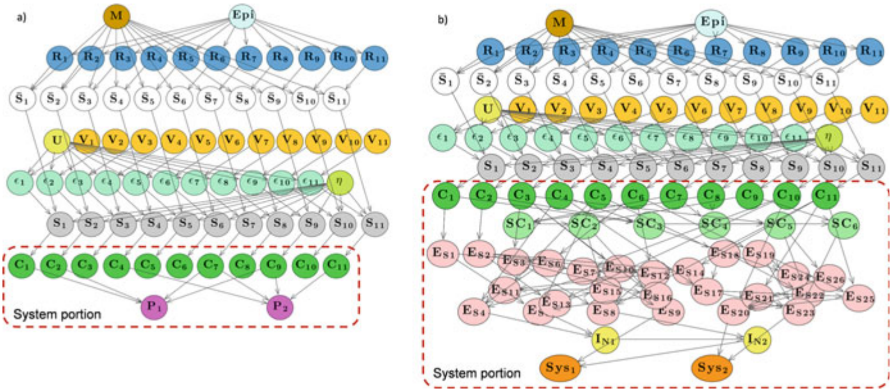

Fig. 28.15 BN for an 11-components system, thrifty-Naïve formulation (**a**) versus Efficient MLS formulation (**b**) (Modified from Cavalieri et al. 2017)

MLS-based formulations grow exponentially. This makes the improved (or thrifty, as it has been called) Naïve formulation tractable even for large systems (Gehl et al. 2017). Last but not least, since the goal is to perform Bayesian inference on the BN, it is of high practical relevance to choose a system model where performance is described in measurable terms. Flow is such a quantity: water coming out of a tap can be measured locally, without knowledge of the state of damage of the entire system. On the contrary, disconnection from or connection to a source, are information that require an analysis of the system and knowledge of the damage in all components, which is exactly what one wants to infer from a limited set of measurements.

Once again, this an instance of the problem of choosing between elegance and efficiency of the reliability method, and the solution of a realistic problem. If the latter is chosen, the only alternative seems to be trying to improve the efficiency of lower-level methods (before it was Monte Carlo, now it is the Naïve system representation), which in their simplicity exhibit the necessary flexibility to accommodate the more accurate description of system performance. This is the last of the research directions for improvement of systemic analysis towards resilience identified in this chapter.

28.3 Conclusions

Based on the previous discussion, the author's personal opinions on some of the research efforts needed towards resilience are the following:

- Investing in resilience before the event, by reducing vulnerability of existing infrastructure and designing new assets for higher performance, is the best way to

enhance resilience, associated with less uncertainty and therefore higher confidence in the end result, possibly avoiding unsustainable outcomes.
- Non-technical obstacles against this action are the lack of political will and, of course, but to a lesser extent, the unfavourable economic conditions. After all, when money is short, it should be spent wisely. Public regulators, instead, tend to reward efficiency rather than redundancy/robustness, thus fostering a more fragile infrastructure. The problem is that investment in resilience can only be made concurrently with other current public expenses and the temporal horizon of politicians (the next election) is not as long as recurrence period of natural hazards. A healthy growth of the economy would help, but sustainability issues cannot be disregarded and it may be time to start thinking to solutions that do not necessarily imply or rely on an indefinite growth of the economy.
- On the technical side, much work is needed to improve systemic analysis, so that performance targets for each asset, to be retrofitted or newly built, can be set in a rigorous manner to attain community resilience goals. It is not anticipated that this will ever become a mainstream tool, but it is important that the idea informs decision-maker at a higher level, to move on the discussion on the acceptable seismic risk levels of structures.
- In order to improve systemic analysis, network modelling should be flow-based, or at least new smart connectivity-based methods that mimic flow-based solutions should be devised. Flow is better because survival of connection does not guarantee a satisfactory level of service at demand nodes, the importance of components is ranked differently based on connectivity or flow, and, last but not least, flow can be measured and used as evidence input to BN-based decision-support systems for emergency management, while connectivity cannot.
- The obstacles against this generalized adoption of flow-based modelling are that: flow on damaged networks cannot be computed as in undamaged ones; in many cases, appropriate flow equations still need to be developed; flow forces to use Monte Carlo-like simulation, the least efficient among reliability methods.
- Fragility of components is only an intermediate step in the evaluation of damage. It does depend on the site and, most importantly, on the structure properties in a stronger manner than usually assumed. There is a strong need for improved tools for damage prediction. Generic fragility curves should be replaced by more flexible fragility models that yield structure and site specific fragility curves. This is an entire area of work that needs fresh concerted efforts.
- Improvements in systemic analysis will also benefit the other side of resilience, i.e. the post-event management phase, possibly leading to useful decision support systems informed based on comprehensive pre-event simulations.

Finally, a remark is due that is not based on what has been presented so far, but it arises naturally in every discussion about these type of analyses, especially when the background of the researchers is a “hard” one, like e.g. structural mechanics. For systemic analysis to provide useful input to all of the above, there is a strong need for validation studies and sensitivities to plug-in models. The latter is relatively easier to obtain, since it requires only running analyses with different models for each sub-system and component, assessing the sensitivity of the results to each. The former represents instead the greatest of challenges. The problem is one of scale, spatial and temporal. It is easy to calibrate a model for confined strength of concrete, by crushing concrete samples. It is probably impossible to calibrate a system of systems model at regional scale. The issue is one of spatial scale, as much as it is one of temporal scale, since even if one could measure "everything" in a region of interest during a single event, the recurrence time between damaging events is such that acquiring a reliable (multi-event) dataset would be practically impossible. The only way out at present is to accept this impossibility and be content with partial validations, i.e. validations of the intermediate models, like the ground motion prediction equations or the magnitude recurrence laws used in predicting the seismic intensity, or the fragility models for the components, and relying on the rationality of the framework used to combine them. In this respect, the sensitivity studies to the input models are essential to determine their importance and better focus validation on those that are most relevant. Designing good validations is the last important step needed in this research field.

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