Field Technical Surveys: An Essential Tool for Improving Critical Infrastructure and Lifeline Systems Resiliency to Disasters

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***Abstract*—This paper explores critical infrastructure resiliency. The discussion initially introduces concepts and notions that are important for the analysis. Disasters are not seen as a single event but rather as cycles with distinct phases. These concepts and notions support the conclusion that critical infrastructures are cyber-physical-social systems that have not only interconnected physical components but also include processes as an integral constituting part. The discussion also indicates that the reliability concept of availability can be used as a metric for resiliency and for characterizing degree of dependence among infrastructures. Such metric allows a quantifiable approach for critical infrastructures planning and operation. Field technical surveys are then seen as a key tool to be able to quantify availability and, thus, assess resiliency. Finally, this paper explains approaches to conduct field technical surveys and their steps.**

Keywords—Availability, Critical Infrastructure, Cyber-physical Social Systems, Extreme Events, Field Technical Surveys, Interdependence, Lifeline, Natural Disasters, Resiliency.

I. INTRODUCTION

Critical infrastructures (CI) are systems that are essential in order to support society's functions and services. Their operation under all conditions, including after natural disasters, constitutes a basic fabric of current modern societies and support humanitarian efforts to enable growth in under development countries. Each of these infrastructures are dependent for their operation on other infrastructures, called lifeline systems (LS), which are formed by physical assets, human resources and processes. Due to their societal importance, it is critical to improve CI and LS resiliency—capacity to recover quickly—to disasters. The importance of effective field technical surveys of CI and LS conditions as a tool to improve their resiliency to natural disasters have been identified in several recent conferences and meetings, such as the 2013 IEEE Power and Energy Society General Meeting [1], the 2013 US Federal Communications Commission Network Resiliency Workshop [2] and the 1st INTELEC Workshop Preparing Information and Communication Technologies Systems for an Extreme Event [3]. However, these same meetings identified the area of field surveys applied to improving resiliency as a new infant application leading to important gaps in understanding how to apply and conduct these surveys in order to achieve the desired goals. This paper describes how to improve societal resiliency to disasters by bridging these gaps through:

-Defining key concepts, such as disaster cycle, resiliency and resistance, and discussing a quantitative mathematical model to measure resiliency

-Relating resiliency with technological and human aspects of CI and LS—for example, a more resistant LS would reduce the restoration logistical needs after a disasters and, thus, allow for more resources being available and simplify logistical management, leading, in turn, to a shorter restoration time

-Discussing how pre-disaster field surveys can be used to improve disaster preparedness through a baseline evaluation of CI and LS in order to identify and mitigate vulnerabilities, and plan disaster response. These surveys includes a field evaluation of installed technologies and an assessment of existing key organizational and operational processes, such as personnel training and disaster response protocols—e.g. management of equipment logistics and repair crews.

-Discussing the use of post-disaster field technical surveys to improve CI and LS resiliency. These assessments include an evaluation not only of technology performance but also of management processes execution.

-Explaining techniques and strategies to conduct pre and post-disaster surveys

Field technical surveys are, then, seen here as fundamental components associated to each of the phases in which a disaster can be divided. That is, the implicit view is that CI evolution is a dynamic process influenced by the observations made during natural disasters. The analysis in this paper is supported by photographic material and data collected by the author during the author's field technical surveys and damage assessments after notable disasters [2] [4] – [8] (e.g. hurricanes Katrina, Ike and Sandy, and the 2010 earthquake in Chile, the February 2011 earthquake in Christchurch, NZ and the 2011 earthquake and tsunami in Japan). Hence, the discussion will follow a practical approach with actual information from past disasters. In order to provide a practical context the discussion focuses on electric power grids and communication networks as key CIs, because of the critical role than electric power and communications play for modern societies and to support humanitarian efforts.

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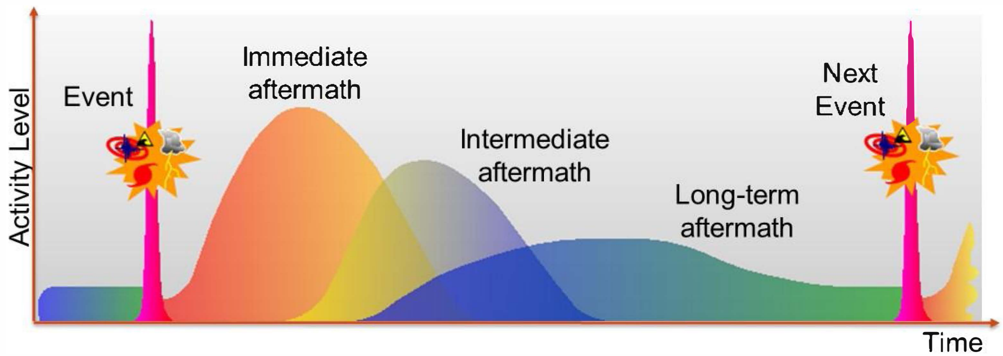

Fig. 1. Representation of a typical natural disaster cycle and its phases.

II. Definitions and Concepts

A. Disaster cycle

From a CIs planning and operation perspective, natural disasters are not merely a single event, such as the period when a hurricane's wind or an earthquake's shaking affects a given area. As Fig. 1 represents, natural disasters are a succession of four phases that form a cycle. Such cycle begins when a disaster *affects* an area and concludes when the next disaster affects the same area. The event of having a disaster affecting an area is what is commonly associated with the event of having a disaster striking an area but, in reality, a disaster lasts longer than just the event itself. This characteristics of disasters originate in the fact that disasters may affect an area directly or/and indirectly. A given area is directly affected by a disasters when the area experiences the damaging actions of such disaster, such as shaking from an earthquake or waves from a tsunami. But disasters can affect areas indirectly, too, usually because resources—economic, human, and others—need to be diverted from their common use domain to address issues caused by the disaster. For example, after a disaster strikes, government funds that were intended for some other use may need to be reassigned to fund recovery activities or a government may need to take debt that would be paid by all citizens in order to reconstruct a portion of a country affected by a disaster. Since disasters may affect areas directly or/and indirectly, then their duration spans, from a practical perspective, beyond the event itself when damaging actions are observed.

Disasters may also affect infrastructures directly and/or indirectly. For example, during the earthquake and tsunami that affected Japan in 2011, direct damage to the power grid occurred when the tsunami damaged the Fukushima #1 nuclear power plant resulting in the destruction of 4 reactors and their associated power generation capacity. However, the consequences of such direct damage had indirect effects when all nuclear power plants in Japan were taken offline due to safety concerns. As a result of this loss of generation—some of it caused directly and some caused indirectly by the tsunami—Japan needed to implement energy conservation measures that affected the country's economic activity. Moreover, eventually the loss of nuclear generation was in part replaced by power generation with a higher cost, such as natural gas power plants, or a more significant environmental impact, such as coal fired power plants, than that observed with normal operation of nuclear power plants, so the indirect effects of the tsunami are still being felt several years after the main event happened.

Although it can be claimed that the loss of electric power generation observed during the 2011 tsunami in Japan is an uncommon event, indirect effects of disasters are observed in all disasters. These indirect effects support the notion of disasters not being just a given isolated event affected an area. Power grids are commonly affected by disasters by loss of load. As Fig. 2 represents, such loss of load caused by destroyed houses or business or economic downturn caused by the disaster, usually last much longer than the time required to repair damaged assets. This loss of load may require power grid operators to adjust the normal system configuration by, for example, changing the normal voltage regulation patterns. Such loss of load may also cause negative economic effects to utilities. Communication networks may also be affected indirectly when traffic needs to be rerouted due to damage in the area directly affected by the disasters or when networks experience saturation due to excessive call volume. Indirect effects of disasters affecting CIs are also observed in their processes when restoration crews or physical resources need to be relocated from areas not directly affected by the event to the areas directly affected by the event in order to assist with repair and service restoration activities. These human and physical resources are, then, diverted from their normal duties or applications affecting CI operations in other areas.

As a result of this complex interaction between disasters and CIs, it is possible to distinguish four phases in a disaster (Fig. 1):

- Phase 1 (during the main event): This phase may last from a few minutes to a few days. Activities during this phase are focused on survival and targeted response. For some disasters, such as with aftershocks following an earthquake, the main event may repeat itself.
- Phase 2 (immediate aftermath): This phase may last from a few days to a few weeks. Activities during this phase focus on stabilization, recovery, and evaluation of system status through field assessments: Other important activities in this phase includes infrastructure restoration, repair and reconstruction. This phase concludes when these activities are mostly completed.
- Phase 3 (intermediate aftermath): This phase may typically last from a few weeks to several months. Activities conducted during this phase include forensic analysis (including field studies), and social recovery. This phase overlaps with phase #3 as recovery and

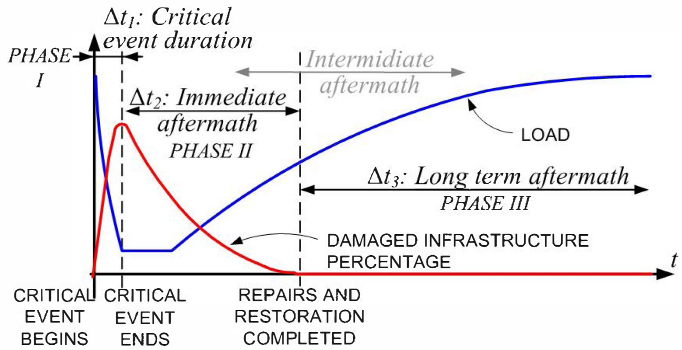

Fig. 2. Activities and load evolution associated with typical effects of a disaster on a power grid.

repair activities wind down and with phase #4 as the focus turns into preparing for the next event.

- Phase 4 (long-term aftermath): This phase may last from a few months to several years. The activities focus on preparing for the next event through planning and mitigation. During this phase infrastructures may be modified physically or through the associated processes in order to make them more resilient for a next event or to adapt to lingering effects of the last event, such as economic effects of a reduced load in power grids. The key tool for planning infrastructure modifications is risk assessments supported by vulnerability and resiliency assessments through field surveys. Preparedness activities for the next event are also included in this phase. Exercises are a key technique to evaluate processes.

B. Resiliency

Resiliency is defined by the National Academy of Sciences (NAS) [9] as the "ability to prepare and plan for, recover from, and more successfully adapt to adverse events." This definition is broader than the general concept of resiliency found in dictionaries which indicate that resiliency is the ability to recover readily from some adversity but the broader NAS definition includes this aspect and, at the same time provides a context for resiliency that fits within the characteristics of a disaster that were explained in Section A. Moreover, resiliency as defined in [9] relates the concept of resiliency with that of adaptability as a continuous process of improvement based on learning from experiences which ultimately would support a sustainable concept for CIs planning and design. In this context sustainability is, then, understood as a characteristic associate with the ability of sustain failures and recover from them through a process of continuous improvement based on learning.

One important challenge when discussing infrastructure resiliency is how to measure and quantify resiliency. In fact, most past studies involving resiliency consider resiliency as a qualitative aspect, thus, providing a limited value to any resiliency assessment in order to improve it within the context of [9]. Instead, in here it is proposed to use the concept of system availability from reliability theory in order to quantify CIs resiliency. Availability is a concept from reliability theory that can be defined as the expected portion of the time that a system performs its required function. Hence, availability of a system or a portion of a system can be calculated from

$$A = \frac{(MUT)}{(MUT)+(MDT)} \quad (1)$$

where MUT (mean up time) is the expected time a system is working meeting its operational goals and MDT (mean down time) is the expected "off-line time." The inverse of the MUT is the failure rate λ which tends to depend primarily on hardware-related aspects (such as construction practices, architecture design, etc.). The inverse of the MDT is the repair rate μ, which although it is also related to hardware-related aspects, it is also influenced by human-centered processes and activities, such as maintenance policies, and logistical and repairs management. Unavailability (U) equals $1 - A$.

Availability seems a suitable measure of resiliency within the context of [9] through the dependence on the MUT and MDT. Speed of service recovery is directly related with the definition of MDT. The faster a system can recover from a failure, the smaller MDT is. Resistance to the effects of a disaster affects availability by increasing the MUT. Such higher resistance would also lead to fewer failures, which, in turn, would free up resources that could be used to address the fewer failures that occur due to the higher resistance much faster and, thus, with a lower MDT. In this context, resistance can be understood as the opposite to vulnerability which can broadly be interpreted as the manifestation of a failure susceptibility that can result in a system loss of service (adapted from [10] and [11]). Still, it is also important to mention that strictly speaking, the definition of availability in (1) considers a "steady-state" terminal calculation after infinite number of cycles with failures and repairs, whereas during disasters only a relatively small number of failure/repair cycles occur between two consecutive disasters or during each disaster phase. Moreover, during phases 1 to 3 of a disaster, failure and repair rates are typically time dependent functions and not constant as assumed in (1). Hence, the availability calculation in (1) should be considered as an approximation from a time dependent availability well known in reliability theory. Nevertheless, if a more exact calculation is desired, there are mathematical techniques which are out of the scope of this paper, such as considering the Markov process associated to the availability of a given system under study, that allow to calculate availability as a function of time even when failure and repair rates are time dependent. Such techniques may involve numerically solving the time-dependent differential equation related to the Markov process associated to the availability of the system under study

C. Critical infrastructure and Lifeline Systems. Dependencies

The concept of a CI expands beyond the conventional view that it is a group of physical components (or assets) that are interconnected in a given way, usually a network. Critical infrastructures is an integrated concept that considers the physical components and its interconnections, and the human resources and processes used to build, operate and maintain such infrastructure. That is a CI is a system that includes cybernetic, physical and social aspects integrated within a single entity. Lifeline systems can be considered a CI that is necessary for the operation of another infrastructure. This definition of lifeline includes the concept of functional dependency because it indicates that a given dependent CI may not be able to operate

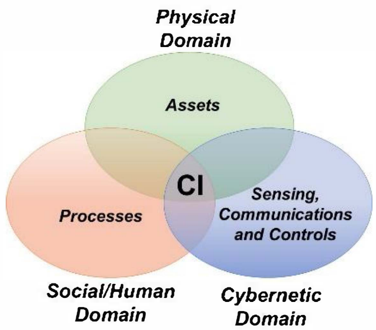

Fig. 3. Critical infrastructure components forming a cyber-physical-social system.

for long periods of times if its lifeline is not operational. Still, traditionally, dependencies have been established based on physical/topological relationships and/or based on cyber/services/functional dependencies. Although both types of interactions may be established separately, they are commonly observed to occur concurrently. This framework seems to initially indicate that CIs are a complex cyber-physical system of systems. However, this view neglects the influence of human decision processes affecting operational performance among CIs through their influence on the *MDT*. That is, the system under study are, actually, a cyber-physical-social system of systems. As a result, the three areas constituting such system—cyber, physical and social—need to be represented when studying this problem (Fig. 3).

Traditionally, dependencies between two infrastructures have been established based on physical/topological relationships and/or based on cyber/services/functional dependencies. In the latter dependency, one infrastructure transfers some "thing" necessary for the operation of the other infrastructure. States of infrastructures can be identified based on their performance and on a quality of service level at a local, regional or system-level. For some infrastructures their state can be defined in a discrete way based on their operational condition. In this state definition, an infrastructure (or a portion of it) is in an operational state when it is able to transfer some "thing"—e.g. electric power in the case of a power grid or information in the case of a communication network—to another infrastructure or user that needs it for its operation. If such direct transfer is not occurring, then the infrastructure transferring such thing is in a failed condition. One example of this direct functional dependency is observed in many disasters when transportation networks are needed in order to deliver diesel fuel (the exchanged thing) to keep communication sites operational. However, a functional dependency can also be established indirectly. In these other cases, the recipient of the exchanged thing is a human. Such is the case when the exchanged entity is information necessary to manage logistics for restoring service or maintaining service in an infrastructure system. In these cases, human actions influence the performance of another infrastructure. That is, humans are active interfaces between two indirectly coupled infrastructures with an indirect dependency. Thus, the state of an infrastructure can be associated to a quality of service level. Hence, a difference can be identified between direct and indirect functional dependencies: while the identification of an infrastructure state in the former is based on a discrete concept, in the latter it is based on a continuous scale.

It is also possible to establish another difference between direct and indirect functional dependency. In a direct functional dependency a failure of one infrastructure may not necessarily lead to an immediate failure in a dependent infrastructure because local storage of the exchanged entity or "thing" by the dependent infrastructure delays the propagation of an infrastructure failure into its dependent infrastructure. This is the case of energy being stored in batteries and diesel fuel in communication sites to allow the site to continue operating during power grid outages of a given maximum duration—notice that in this case the exchanged entity is "energy." That is, buffers can be established to manage the diffusion process of how a failure or stress condition, as it would apply for quality of service measurements, propagates across infrastructures. However, in the case of indirect functional dependency, such entity storage may not be established because humans are effectively the interface between the two interdependent infrastructures and, hence, an issue in one infrastructure may propagate immediately into its dependent infrastructure.

An example of this situation is what happens when information is needed for humans to manage some activity influencing stress levels in an infrastructure. Let's assume that such information is received by the intermediate human(s) with an acceptable quality of service. Then, when the information is received by the human recipient(s), the process of transferring the exchanged entity to the intermediary is completed and a potential failure in the dependent infrastructure will be caused by human error and not by an issue in the communications infrastructure used to transfer the information. Such issue related to human issues affect CI through processes implementation. Processes without the necessary measures to mitigate human errors are a vulnerability component and highlights the importance of human behavior in CI resiliency assessments and the participation of processes as integral components in LS in order to assess resiliency.

The discussion in the past paragraphs and sections establishes three basic aspects influencing how infrastructure resiliency can be characterized and modelled. These aspects are CI operational condition (locally or globally), failures propagation from a lifeline to its dependent CI, and recovery speed. In order to quantify CI resiliency it is necessary define metrics for these three aspects. Some of these metrics have already been identified. In particular, recovery speed is the *MDT*, which in turn is related to availability as a resiliency metric. Operational condition has already been discussed and could be associated to a *MUT* once a minimum quality of service level has been defined or when failure modes have been identified. Hence, the operational condition metric can also be associated with availability assessments.

The other related time-based aspect influencing resiliency is failures propagation from a lifeline to its dependent CI. In order to understand this aspect consider the case of the relationship existing between electric power grids and communication networks. Each communication site (a node) requires electrical power provided by a power grid in order to operate. If there is a power outage in a given area, communication nodes may not necessarily fail because communication sites are typically equipped with batteries and other forms of local energy storage in order to keep them operating when their portion of the power grid is experiencing an outage. This power grid outage can be associated with the power grid *MDT*, which is practically related with how repair crews and logistical operations are managed. Evidently, this MDT will influence the capacity of the energy storage planned for the site. As a result, the choice for total energy storage capacity in each communication site is influenced by the availability goal at the site and the power grid *MDT* at the tie point at each evaluated communication site. In turn, this *MDT* is related in part to human behavior dependent activities, such as logistics and personnel management.

The previous example suggests that the amount of local storage of the "thing" establishing a dependency between two CIs (in the previous example is electrical energy) affect the degree of dependence of one infrastructure on another. In an extreme example, if communication sites had infinite local energy storage then they would not be dependent on the power grid for electrical power. That is, local storage may allow to decouple one infrastructure from its dependence on another infrastructure. Storage also affects the calculation of availability. With storage, availability A_S of a system is calculated from

$$A_S = 1 - U_{N/S} e^{-\mu T_S} \quad (2)$$

where $U_{N/S}$ is the unavailability without storage calculated based on (1), T_S is the storage capacity and μ is the sum of the repair rates related to a direct transition from a failed state into an immediate state representing the system in an operating condition. Thus, (2) seems to suggest that it is possible to quantify the degree of dependence between two CIs based on the storage level necessary to achieve a given availability target [12]. Although this observation seem to be applicable to most critical infrastructures, some exchanges among critical infrastructures may not allow for storage of the exchanged entity. One example of this situation applies to the information transmitted through communication networks in the form of coordination messages used by repair crews of a given critical infrastructure during a period in which their system is not in operation. Equations (1) and (2) show that operational condition, dependency and resiliency are inherently related because management of failure propagation processes through local storage may allow a dependent infrastructure to avoid its failure when its lifeline (the infrastructure providing the needed entity for the dependent infrastructure to operate) fails provided that the restoration process of the lifeline (influenced by human activities) is much shorter than the capacity of the stored energy—i.e., failure of the dependent infrastructure can be avoided if the *MDT* of the lifeline is much less than T_S. That is, the concepts of resiliency and dependency are inherently integrated.

III. Field Technical surveys

The previous sections have provided the basis for recognizing the need for field technical surveys and a broader definition of them. In reality, the previous discussion suggests that field damage surveys are not merely about assessing damage but are more about an evaluation of CI condition which includes the physical components and processes. For that reason the term used in this work is that of field technical surveys (FTS) instead of field damage assessments, which are a subset of FTS. These FTS are viewed as essential tools that need to be applied in all phases of a disaster if the goal is to achieve a resilient CI. The notion of FTS tends to be closer to that of field damage assessment when applied during the immediate and the intermediate aftermath. Still, the focus should not be only on physical infrastructure components but also include processes as a continuous feedback examining execution of the activities. Hence, although the broader definition of FTS expands the scope in [13] some elements and techniques are common. In particular, the questions that FTS attempt to answer are:

a) What physical elements failed and what did not fail or what worked or did not work in terms of process execution? Why?

b) In the cases when a given infrastructure element under study failed and/or was damaged, how was operation restored? In the cases when issues were observed with the execution of a process, how did the task associated with such process in trouble was eventually accomplish?

The application of these questions need to be a part of an established formal process integrated to the operation of a CI. That is, FTS are themselves part of a CI system as a process that creates a feedback loop of information that, in turn, enables adaptation through continuous improvement for improved resiliency. That is, the main focus of FTS is on information collection, analysis and recording in order to achieve a continuously improvement process for CI operation and planning.

The questions indicated above also support the need for quantifying the application of the FTS process by collecting data that will allow to calculate availability, which is the key metric presented in here to measure resiliency and dependency. In particular. The set of questions (a) aims at learning primarily how to achieve higher *MUT*, whereas the set of questions (b) targets at identifying ways of reducing *MDT*s recognizing that this is a metric highly influenced by human aspects and process execution.

Field technical surveys are applied in all phases of a disaster. During the immediate and intermediate aftermath of a disaster FTS tend to be more focused on identifying issues both with physical components and processes in order to shorten restoration time (i.e. reduced *MDT*) but as the intermediate aftermath activities begin to transition into long term aftermath activities, the FTS activities focus more on how to extend the *MUT* by adapting CIs physical components and processes to make them more resistant to future disasters. Hence, predictive maintenance processes are part of FTS during long term aftermaths. Field technical surveys during the long term aftermath may also serve to build a comprehensive inventory of existing physical components and processes. One key process that is also applied during the long term aftermath is training, including preparing employees to do FTS during all phases of a disaster.

Field technical surveys performed during various phases of a disaster can serve to exemplify some of the notions presented in this paper and highlight the value of this tool. For example,

Fig. 4 shows a large group of utility restoration crews waiting for flood waters from Hurricane Isaac (2012) to reside in order to repair damaged portions of the electric grid along Highway 23, near Port Sulfur, LA. These crews were deployed after Isaac struck the coast from sites as far as Michigan and Indiana based on agreements set up before any hurricane affected the Gulf Coast. Such agreements could be enhanced by conducting joint exercises among all participating utilities. A cable TV (CATV) node near Yscloskey also serve as an example of the integral nature of physical components and processes and the tradeoffs related to increasing resiliency at an acceptable cost. As Fig. 5 (left) shows, this node had a pad mounted generator that was destroyed by Katrina in 2005. Since this area is not protected by levees it was considered too risky to replace such natural gas generator for a new one. The solution, as Fig. 5 (center and right) exemplifies, was to rely on the deployment of portable generators to the site after a hurricane strikes the area. This alternative approach integrates the process of deploying the portable generators as a conventional solution to power this site after a hurricane and, thus, it reduces the MDT from weeks down to days, for an equal MUT. Thus, availability is improved and resiliency is enhanced. Infrastructure evolution to support adaptation for enhance resiliency can be documented by performing FTS in all phases of disasters. Such adaptation is exemplified in Fig. 6 to 8 following the infrastructure evolution of Saint Bernard Central Office from 2005 to 2012. In 2005, this communication facility was flooded and destroyed by Hurricane Katrina. This is the condition shown in the immediate and intermediate aftermath of Katrina in Fig. 6. Due to the loss of load and the need for a lower capacity and more flexible solution, service was restored with a digital loop carrier system (DLC) shown in Fig. 7 during the long term aftermath of Hurricane Gustav which affected this area in 2008. To prevent damage from flooding, the equipment was located on an elevated platform and a permanent gas generator was located on site to power the DLC during long power outages. The choice of natural gas was made because of the lower probability of loss of service during a hurricane compared to the power grid and other solutions. Such choice highlights the importance of assessing the dependencies when planning for enhanced resiliency [16] - [18]. The effectiveness of this technology evolution for achieving an improved resiliency through adaptation was once again validated when this site maintained operation after Hurricane Isaac in 2012 (Fig. 8). This continuous use of FTS over all disaster phases also allows for an effective infrastructure planning because during the FTS in the long term aftermath it is possible to identify and mitigate vulnerabilities, and plan disaster response without priorities concerns that exist in the previous disaster phases.

Field technical surveys may be conducted based on various techniques, but the two most relevant ones are field trips and exercises. The latter is, in particular, important in order to evaluate processes and identify vulnerabilities during the long term aftermath phase of a disaster. Due to length limitations, it is not possible to include a detailed description of how to conduct FTS here. However, such detailed description has been

Fig. 4. A large number of electric utility restoration trucks deployed to restore electric service after Hurricane Ike.

Fig. 5. The same CATV outside plant equipment discussed in [8] and [14]-[15] in October 2005 (left), and on Sept. 3, 2013 while a camping-style portable genset was being installed (middle) and after installation was completed (right)

Fig. 6. Saint Bernard Central Office in October 2005 after Hurricane Katrina

Fig. 7. The DLC system located on a platform outside the abandoned former St. Bernard Central Office Building in October 2010. The permanent natural gas generator is on the right corner of the platform

Fig. 8. The former St Bernard central office building and DLC in the immediate aftermath of Hurricane Isaac in September 2012.

presented in the past in [13] or in the very complete guide in [19]. For additional detailed understanding of how different types of FTS could be conducted, readers can resort to some case studies detailed in the past by the author of this paper and other experts including exercises [20], damage assessments in the first phases of a disaster [8], [13], [21], and infrastructure evaluations in the long term aftermath of a disaster [14]. Details about how to organize field infrastructure evaluations in order to prepare a baseline of information to help plan resource allocation in preparation for a disaster can be obtained from [3] and [22].

As explained in [13], implementation of FTS span four main steps:

1) Data and Information Collection
2) Data and Information Examination
3) Analysis
4) Reporting

The data and information collection step can be divided in two phases. The first phase is preparation and planning. The second phase is execution. In the case of assessing physical components during field trips, the final outcome for this preparation phase is a plan that lists activities and locations to visit each day with details about specific things to look at each location—e.g. through a checklist. In case of exercises the plan describes what infrastructure components or processes are going to be tested and in which way those tests would be performed—e.g., through specific scenarios. In addition, for all FTS the plan should list logistical details and the intended schedule. Hence, two key decisions to be made as part of this phase are to organize the damage assessment trip logistics and determine its schedule. In the case of exercises, the outcome is also a plan that lists activities and offices/personnel involved with the exercise. A key concern during this step, particularly during the immediate and intermediate aftermath of a disasters, is on data and information preservation and recording because of the volatile nature of these data an information. Important factors affecting the plan developed in this step and the necessary prioritization that needs to be done are information value, data volatility, and effort. Timing, duration and scope of the intended trip or exercise may usually depend on the type and intensity of the disaster that happened or is expected. In the second phase of data and information collection there are two approaches in the particular case of field damage assessments: a fast area sweep that maximizes covered area and visited locations by minimizing the time spent at each site, and the other that could be identified with a targeted focus in which fewer locations are examined but with each site evaluated in more detail. Evidently, in this last approach more time is spent at each site. Since the ultimate goal of the FTS is to build a comprehensive record of processes outcomes and physical infrastructure performance or condition, data and information collection needs to include lifelines, too. Collected data may take various forms but, usually, photographic and video records are extremely useful for later steps and become evidence that may be needed in later proceedings. In the case of exercises, the data and information collected would necessary include a chronological record of actions taken by the participants during the exercise.

Data and information examination is intended as an initial step for answering the aforementioned set of questions (a) and (b) and identify potential gaps that need to be addressed for the next step involving a more comprehensive analysis in the analytic step in which the set of questions (a) and (b) are answered. The final step of the process is to prepare a report that details all the collected information and the process that was used to collect such information. The report also examines the collected data and presents the observations made from the analysis of the information. In this step it is important to consider measures to ensure that data, information and the report are documented appropriately.

As it was aforementioned, there are different types of FTS, including, but not limited to, conventional field damage assessments, or infrastructure evaluations during the long term aftermath or exercises. As a result, a detailed description about how to conduct these assessments beyond what was already discussed in this section requires a discussion that is too extensive for this paper length requirements and it is not within the scope of this work. However, it is possible to identify some additional common characteristics of the different types of FTS that provides more details about how to conduct FTS. One of such common elements is related with the stakeholders and the ones conducting FTS. Within the context of infrastructure assessments, typical stakeholders providing information for the FTS and receiving their results are infrastructure operators, contractors, technology vendors, government officials and the general public—i.e., users act as stakeholders at an aggregated level and not generally as individuals. Since people typically act as groups and not individuals, it is not common to have extensive interactions between surveyors and people, within the context of FTS for infrastructure assessments because most of those interactions tend to provide more an anecdotal data point instead of an objective expert information.

A key element of FTS are those who need to conduct those assessments. Ideally, it is desirable that FTS are conducted by independent surveyors—consultants, academic researchers, standardization agencies professionals or technology organizations—not necessarily only because of the benefits of unbiased analysis but also because independent surveyors have the advantage of being able to interact with competing infrastructure operators without conflicts. Typically, surveying agencies or groups would lead the FTS and supervise the field personnel which could be permanently hired professionals, contractors or in some cases volunteers. Part of the preparation for performing FTS would involve training and certification of field surveyors. The required training will depend on the type of FTS to be conducted. For example, field damage assessment after disasters will require surveyors to learn about infrastructure and lifelines technologies, planning and operation, as well as knowledge of processes used to manage such infrastructure.

Finally, the value of isolated FTS is usually limited. In the same way that disasters have cycles, it is important to have FTS conducted periodically so data and information can follow cyclic patterns and the report of a given FTS can be used as feedback for a next FTS. That is, typical flow of data in FTS starts in stakeholders providing information to surveyors. This information is usually combined with additional data collected by surveyors. All these information and data is eventually returned to the stakeholders through the report so FTS can be used, as it was explained above within the context of [10], as the basis of a continuous process of improvement and adaptation to improve resiliency.

IV. Conclusions

This paper has explored fundamental concepts and techniques associated to improving critical infrastructure resiliency to natural disasters. This goal is seen as a fundamental goal in order to support humanitarian efforts after disasters and to enhance societal sustainability. Natural disasters are seen not as single events but rather a succession of cycles in which natural disasters can be separated in phases: the main event, immediate aftermath, intermediate aftermath and long term aftermath. The discussion presents a transformational view of critical infrastructures and explains why they are cyber-physical-social systems that are not limited to the mere interconnection of some physical components because processes are also an integral part of how they are constituted.

Another novel aspect of this paper is to present a metric for resiliency based on the reliability theory concept of availability. This metric allows to mathematically understand how resiliency are direct dependencies of infrastructures are related. This metric also enable quantifiable techniques for planning and operating critical infrastructures. Then this paper presents field technical surveys as a fundamental tool for enhancing critical infrastructure resiliency because these assessments are a key tool in order to identify the values that allow quantifying resiliency and degree of dependency. The final portion of the paper describes strategies to performing field technical surveys. These assessments include damage assessments done in the immediate and intermediate aftermaths of disasters and exercises conducted during the long term aftermath to evaluate both condition of physical components and of processes.

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