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Complexity Mapping for Resilient and Sustainable Infrastructure: The Doppler Radar in Puerto Rico Case Study

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***Abstract*— The Doppler radar located in Cayey, Puerto Rico is a critical tool in early weather forecasting. During Hurricane Maria in September 2017, the radar was destroyed as the result of the strong winds. An X-band radar was used as a temporary solution. X-band radar have limited range in comparison with Doppler radars. On June 2018, a new Doppler radar was built and forecasting services were fully restored. This paper uses a five-dimensional project management model (5DPM) and complexity maps to identify and manage the sources of complexity in restoring the radar's functionality and maintaining capacity. When looking at the radar individually, it can be concluded that the radar is fully restored. However, rebuilding the radar is different than providing a resilient and sustainable capacity. In order to ensure that the radar remains functional during and after an adverse natural event, ensuring that the radar suffers no damage is not enough. One has to expand the project´s footprint and use a whole systems approach to look at the project within the framework of supporting critical infrastructure, thus increasing the project´s complexity. For example, the radar has a power generator to supply energy in case of an electrical power failure. During a prolonged power failure, the radar may run out of fuel. If the roads and bridges are damaged, access to the site may be blocked, which compromises the radar's functionality. Based on the complexity analysis, it can be concluded that while the reconstruction of the Doppler radar to restore its functionality has finished, ensuring that it maintains capability to adequately warn Puerto Rico residents of weather events during and after a natural disaster still needs to be addressed. Hurricane Maria increased awareness regarding Puerto Rico's critical infrastructure vulnerabilities. The lessons learned from the natural disaster can be used to develop and implement a whole systems approach to design and build resilient and sustainable infrastructure. This paper contributes to the body of knowledge by demonstrating the concept of applying 5DPM to both individual projects and integrated systems. It moves restoration of services from a project specific basis to capacity maintenance mode, which looks at whole systems approach thus expanding the complexity footprint. This global focus ensures that critical infrastructure is resilient and sustainable.**

Keywords*— *Complex project management, emergency restoration of services, resiliency, critical infrastructure, Doppler radar, hurricane.

I. INTRODUCTION

Hurricane Maria made landfall on September 20, 2017 in Puerto Rico and brought strong winds, extreme precipitation, floods and landslides. The island's critical infrastructure suffered major damage and an emergency declaration was issued. When it made landfall, Hurricane Maria took a course that bisected the island from the Southeast to the Northwest, as if a 60-mile-wide tornado passed through the entire island. As a matter of fact, it was worse than a gigantic tornado because these do not come with a massive amount of rain. After the hurricane, restoring the critical services became a priority. The limited amount of time that could be devoted for planning combined with pressure from the media and other stakeholders scrutinizing every decision regarding the restoration of services increased the complexity of restoring critical services [1].

Standard project management theory requires three dimensions to be managed in order to complete a project successfully: 1) Technical (project scope and quality), 2) Schedule (the project´s duration) and, 3) Cost (the amount of money needed to complete the project´s scope). Complex projects include high levels of "uncertainty about what the objectives are, and/or high uncertainty in how to implement the objectives"[2]. Therefore, emerging complex management theory requires two additional dimensions to be managed: 4) Context and, 5) Financing. This management theory is referred to as 5-Dimensional Project Management (5DPM) [3]. The Context dimension includes the external influences and factors that impact the project. Context includes stakeholders, resource availability, local and global issues, legal and legislative requirements, environmental issues, unusual conditions and other factors that are difficult to predict and plan for during the design and construction [3]. The Finance dimension includes the source of the funds, the schedule of fund availability and the cash flow [3]. 5-

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Dimensional Project Management (5DPM) uses complexity maps as tools to quantity a project's complexity footprint.

Natural disasters caused by hurricanes, earthquakes, fires and tsunamis cause damage both to nodes (individual design and construction projects) as well as to the network that connects these nodes. In order to restore services after a natural disaster, an integrated systems approach to manage assets is needed. An integrated systems approach to manage public infrastructure assets, such as roads, bridges, utilities and water treatment facilities, includes the life cycle to maintain, rehab and replace the facilities [4]. Thus, when designing and building critical infrastructure it is essential to ensure that the infrastructure is resilient and sustainable. In this paper, resiliency is defined as the capacity to withstand the impact of natural events and recover rapidly if damage occurs [5]. Sustainability is defined as the ability to maintain capacity.

The purpose of this paper is to demonstrate the concept of applying 5DPM to both individual projects and integrated systems. It moves restoration of services from a project specific basis to capacity maintenance mode, which looks at whole systems approach thus expanding the complexity footprint. This global focus ensures that critical infrastructure is resilient and sustainable.

METHODOLOGY

This investigation uses case study research to look in-depth at a project. According to Yin, case studies are particularly useful to understand how things are done in detail [6]. The authors used multiple sources of information which include archival project documents, public records, news and trade publications. The results were triangulated to gain an in-depth understanding of the information examined. After all the information was analyzed, the complexity maps were created by examining the sources of complexity of each dimension. Then each of the five dimensions was ranked in order of complexity with 5 being the most complex dimension and 1 is the least complex dimension. Then a relative complexity value was assigned to each dimension. If it was determined that the project was as complex and a routine project in a particular dimension, a score of 50 was assigned. If it was determined that the complexity was higher that of a routine project, a score higher than 50 was assigned. The final step was to plot the data into a radar diagram and calculate its area [3].

II. THE DOPPLER RADAR CASE STUDY

A. Damage Assessment

A Doppler radar is a specialized radar that uses the Doppler effect to measure the precipitation in a thunderstorm and the motion (i.e. to measure wind speed) of the severe weather along the rotating radar beam [7]

The Doppler radar in Cayey, Puerto Rico is supported by a 3-D steel truss with diagonals placed in a Chevron bracing configuration, as shown in Figure 1. The radar is located two thousand eight hundred feet above sea level [8]. Unfortunately, Hurricane Maria destroyed the thirty nine foot wide protective dome that surrounds the sensitive electronic equipment inside [9]. According to Scott [10], that radar was designed to withstand maximum winds of 116 knots (133 miles per hour). During hurricane Maria, the wind exceeded the design speed. An X-band radar was used as a temporary solution. X-band radar have limited range in comparison with Doppler radars [11]

Fig. 1: Steel truss supporting the radar

(source: Picture taken by Dr. Luis Suarez)

Fig. 2: Damages in the Doppler's dome

(source: Pictures taken by Dr. Luis Suarez)

Table 1: Timeline of the Radar's damage and reconstruction

Date	Description
September 20, 2017	The Doppler radar was destructed as a result of Hurricane Maria.
October 21, 2017	Two X-band temporary radars arrived.
Late-April, 2018	The radar tower was restored.
June 18, 2018	The new radar started functioning

In order to access the radar's site, one has to exit highway PR-52 on exit 32 and continue on to a rural road (PR-184) for 6.2 miles. PR-184 is a narrow road that crosses several bodies of water and was inaccessible after the hurricane due to trees and other debris blocking the road. It took the PR National Guard three weeks after the hurricane hit the island to clear the road and allow access to Guavate, where many communication towers were damaged [12]. From PR-184, one has to turn right on PR-179 and shortly after to an even narrower road called "Los Baldíos" and continue for 1800 feet. In the right is the radar's site using Google Maps. As it can be seen in Figure 3, "Los Baldíos" suffered landslides during the hurricane and, as of March 1, 2019, the road has yet to be repaired. Thus, even though the radar is in operation, its continued operations are dependent on the ability to deliver fuel to the generator that provides its power. If the road in Figure 3 is further undercut by the normal rainfall in this area and fails, the radar will go out of operation because of the support infrastructure failed. This leads to believe that 5DPM theory for emergency restoration of service projects needs be expanded to include the network of support infrastructure necessary to keep the critical piece of infrastructure operating on a long-term basis. Said another way, repairing the radar is not enough in this specific case.

Fig. 3: Rural road "Los Baldíos" near radar's site (March 1, 2019)

(source: Picture taken by Dr. Luis Suarez)

B. Restoration of Services Complexity Analysis

As stated earlier, looking at projects individually is not enough to maintain capacity during and after a natural event. One has to use an integrated systems approach to manage public infrastructure assets. Table 2 summarizes a list of examples of sources of complexity associated with restoring the radar site and compares it with the complexity associated with restoring the infrastructure that ensures that the radar maintains its capacity during and after a natural event.

Table 2: Comparison of examples of sources of complexity by dimension for the Radar site and its supporting infrastructure

Dimension	Radar Site	Radar's Capacity Supporting Infrastructure
Technical (Scope)	Radar	Radar Site
	Tower	Roads
	Power	Bridges
	Radome	Power
		Environmental
		Geotechnical
		Hydrology
Schedule	ASAP	ASAP
	Short-term: Temporary X-Band Radar	Short-tem: Clear roads to access site
	Long-tem: Doppler Radar	Long-term: Schedule sequence of reconstruction efforts
Cost	Scope definition - damage	Scope definition - damage assessment
		Availability of construction materials and skilled labor
Context	Stakeholders: NOAA	Stakeholders: NOAA, U.S. Army Corps of Engineers, Local and State Transportation Authorities, etc.
	PR blind to new on-coming	Social Equity
		Environmental
		Post-recovery continuity of network operations
		Ability to rebuild infrastructure better than pre-disaster condition.
Finance	Limited sources of funding	Multiple sources of funding which require coordination and tracking.
	FEMA emergency funding constraints	Eligibility for FEMA emergency funding.
		Long-term availability of operations and maintenance funding

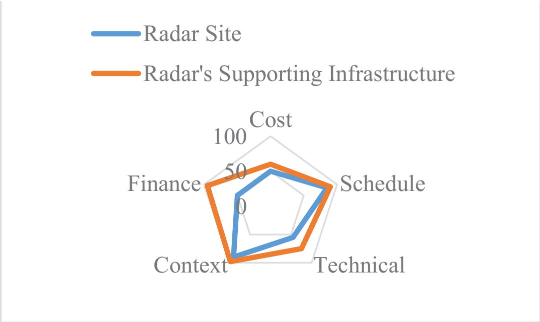
As shown in Table 2, when one expands a project's scope from the individual project to its supporting infrastructure, the complexity increases. Table 3 shows the complexity rating in each dimension as scored by the project team after an in-depth analysis of the complexity factors in each dimension. Fig. 4 shows the complexity footprint of the radar site and the supporting infrastructure. As it can be seen, the complexity area of the radar site is 10,319 units compared to the complexity area of the radar supporting infrastructure of 15,764. One can see a significant increase in complexity to ensure that the radar can maintain capacity during and after a natural event.

Table 3: Complexity Map Scores

Radar Site	
Cost	50
Schedule	85
Technical	55
Context	90
Finance	50
Area	10,319

Radar Capacity Framework	
Cost	60
Schedule	90
Technical	75
Context	98
Finance	95
Area	15,764

FIG. 4: Radar Site and Radar's Supporting Infrastructure Complexity Maps



The results of the complexity maps indicate that when the whole systems approach is considered, all the dimensions increase their complexity. In particular, the finance dimension increases from a 50, which is a routine project, to a 96 which is a very complex project. The significant increase in complexity in this dimension is due to the fact that the radar's supporting infrastructure, such as roads and bridges require multiple stakeholders which include multiple sources of funding. When multiple sources of funding are involved, one has to track every dollar to ensure that it is allocated to the right account.

CONCLUSIONS

This paper demonstrates the concept of applying 5DPM to both individual projects and integrated systems. It concludes that when 5DPM is applied to integrated systems, the complexity footprint is expanded. Complexity of rebuilding the radar is different than providing a resilient and sustainable capacity particularly in the event of a future natural event. The current approach treats projects individually, without considering the support infrastructure that must be in place to sustain a given project's operation. Hence, there is no guarantee that the critical infrastructure like the radar site discussed in this paper will work in the next emergency. In order to maintain the capacity of critical infrastructure needed in an emergency, projects have to be looked at within the framework of supporting infrastructure, thus expanding the project's footprint. This increases the complexity to rebuild the island's infrastructure. It can be concluded that while the reconstruction of the Doppler radar to restore its functionality has finished, restoring the surrounding community still needs to be addressed which increases the risk of loss of functionality of the radar and thus putting lives in danger by not being able to adequately inform residents of weather events. The results of the complexity maps indicate that even though the radar is fully functional, there is no guarantee that the radar can remain completely operational if the surrounding area is not designed and built to be resilient.

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