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Post-Disaster Infrastructure Delivery for Resilience

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Abstract: As climate change increases the frequency and intensity of disasters and associated infrastructure damage, Alternative Project Delivery Methods are well positioned to enable innovative contracting and partnering methods for designing and delivering adaptation solutions that are more time- and cost-effective. However, where conventional "build-back-as-before" post-disaster reconstruction occurs, communities remain vulnerable to future disasters of similar or greater magnitude. In this conceptual paper, we draw on a variety of literature and emergent practices to present how such alternative delivery methods of reconstruction projects can systematically integrate "build-back-better" and introduce more resilient infrastructure outcomes. Considering existing knowledge regarding infrastructure resilience, post-disaster reconstruction and project delivery methods, we consider the resilience regimes of rebound, robustness, graceful extensibility, and sustained adaptability to present the potential for alternative project delivery methods to improve the agility and flexibility of infrastructure against future climate-related and other hazards. We discuss the criticality of continued pursuit of stakeholder engagement to support further improvements to project delivery methods, enabling new opportunities for engaging with a broader set of stakeholders, and for stakeholders to contribute new knowledge and insights to the design process. We conclude the significant potential for such methods to enable resilient infrastructure outcomes, through prioritizing resilience alongside time and cost. We also present a visual schematic in the form of a framework for enabling post-disaster infrastructure delivery for resilience outcomes, across different scales and timeframes of reconstruction. The findings have immediate implications for agencies managing disaster recovery efforts, offering decision-support for improving the adaptive capacity of infrastructure, the services they deliver, and capacities of the communities that rely on them.

Keywords: post-disaster recovery; re-designing infrastructure; alternative project delivery methods; disaster resilience; stakeholder engagement

Citation: Chester, M.V.; El Asmar, M.; Hayes, S.; Desha, C. Post-Disaster Infrastructure Delivery for Resilience. *Sustainability* **2021**, *13*, 3458. https://doi.org/10.3390/su13063458

Academic Editors: Krzysztof J. Wołosz, Krzysztof Urbaniec and Neven Duić

Received: 31 January 2021
Accepted: 16 March 2021
Published: 20 March 2021

1. Introduction

The provision of infrastructure services to communities during and immediately following disasters is critical. From basic resources (e.g., food, water, energy) to shelter, health services, and access to information and communication technologies, ensuring that supporting infrastructure remains reliable when perturbed is paramount. Such action directly addresses global sustainability measures defined by the United Nations across multiple goals including Goal 9 regarding resilient infrastructure and Goal 11 regarding resilient cities and human settlements [1]. However for many urban contexts around the world, critical infrastructure continues to be vulnerable to extreme events [2]. Furthermore, approaches to managing this vulnerability are inadequate, with impacts felt keenly by poorer communities often located in more risk-prone locations or serviced by ageing or temporary infrastructure [3,4]. It has long been known that following immediate disaster response efforts, the ensuing recovery phase presents communities with a significant opportunity to reevaluate infrastructure needs, both in terms of form and services delivered [3]. Depending on the scale of actual disruption—or potential disruption—that is made visible by the disaster, infrastructure can be reconsidered with future, and perhaps different, needs in mind. It has also long been documented that this shift can improve the future resilience of infrastructure to disasters, enabling the continuation or rapid return of critical services [3–6].

In the context of this longstanding knowledge, it is an ongoing journey to improve the capacity of infrastructure to continue services during disasters, and to bring infrastructure services back online after a disaster. In spite of these insights spanning the last four decades, affected infrastructure such as roads, rail, energy, water and wastewater systems are still often repaired or rebuilt to emulate pre-existing systems, i.e., "build-back-as-before". While global agencies such as the World Bank have advocated for "stronger, faster, and more inclusive recovery" [7] and there are some efforts towards "build-back-better" (see for example [8–10]) or "bouncing forward" [11], the lived reality for local and regional authorities around the world is ad hoc and highly variable, and is dependent on local leadership and advocacy. Disaster response protocols persist in emphasizing rebuilding capacity to previous engineering standards, with any design amendments focusing on fortifying or armoring against the risk [6,12–14]. Efforts to improve this response persist in emphasizing timing priorities such as preparedness, speed and efficiency [13], with confusion amongst stakeholders regarding what measures could improve infrastructure resilience, in addition to dissonance regarding current and future risks of disruption [15,16].

Addressing this global context, resilience theory literature has evolved alongside the increasing intensity and impacts of natural disasters [17]. Furthermore, the construct of "resilience" has emerged as a key consideration for decision-makers, requiring new knowledge and skills to embed in reconstruction efforts [17]. Beyond an emphasis on risk-based robustness [18], resilience is increasingly being recognized in the literature as the capacity to adapt, also known as "adaptive capacity". Although at times armoring and strengthening an asset may be the best approach, at other times (or scales) controlled failure (i.e., "safe-to-fail"), or sustained adaptability and flexibility may be preferred [14,16,19,20].

Disasters represent a unique opportunity to build-back-better, reducing the negative impacts of future disasters. After a disaster there is often a convergence of key variables that create a window of opportunity including a need for new assets, release of resources for reconstruction, and community and political will to prevent future disasters from occurring. Yet too often, in the haste to reestablish services, decision-makers default to reinstating the same or similar infrastructure. The traditional method of delivering infrastructure projects, called design-bid-build (DBB), consists of planning and designing the asset, and then bidding out the project to a contracted entity that can build the completed design for the lowest price. Alternative approaches are emerging to "build-back-better" following disasters, called Alternative Project Delivery Methods (APDMs).

APDMs emphasize innovative design, contracting, construction, and early stakeholder engagement activities, spanning "design-build" (DB), "construction management at risk" (CMAR), "integrated project delivery" (IPD), and many others. They have developed over the past two decades to deliver projects more efficiently by engaging key stakeholders early, leveraging builders', suppliers', regulators', and operators' experiences and feeding these back into the design process. Known for their innovative design solutions and considerably faster reconstruction efforts, questions remain as to how APDMs can be implemented to improve infrastructure resilience outcomes, leveraging such diverse stakeholder insights and capabilities.

This paper aims to describe how alternative infrastructure delivery methods can support resilience. In the following sections, we step through how current and emergent innovative practices in infrastructure delivery can improve the adaptive capacity of infrastructure. Focusing on resilience theory described by Woods [20] we present our critical-thought progression in proposing Wood's theory as a useful reference to guide resilience outcomes when APDMs are adopted. This is informed by previous systematic literature reviews in that topic area [6], as well as our appreciation of APDMs as potential approaches for post-disaster infrastructure reconstruction. We draw on examples from the USA and internationally to illustrate how these methods can support resilience and rebuilding efforts. It is intended that readers use this paper to reframe post-disaster reconstruction as a critical opportunity for embedding resilience into the very systems that underpin community health and wellbeing.

2. Methods

This study adopted a qualitative research approach in the form of a conceptual paper. For several decades researchers have been contemplating what constitutes quality conceptual research academically [21] and from a publications perspective [22–24]. Common to the discourse is the need for such research to have a problem-focused approach, addressing the "what's new?" question thoroughly (distinguishing it from a review paper), "bridging existing theories in interesting ways, linking work across disciplines, providing multi-level insights, and broadening the scope of our thinking" [24]. As established and confirmed by researchers over the years, conceptual paper arguments involve assimilating and combining evidence that takes the form of previously developed concepts and theories. Instead of presenting and analyzing new empirical data, a conceptual paper provides new insights into existing concepts and knowledge, which in turn may lead to the creation of further research questions [24]. In the following paragraphs, we set the context for the conceptual paper, discussing how and why the theories, concepts and constructs on which the paper is grounded, were selected. We then summarize the two methods used to approach the study, comprising a literature review on infrastructure resilience and disaster management, and a comparison of two reconstruction project delivery methods based on case studies of post-disaster reconstruction projects.

Using the conceptual paper language described by Jaakkola [24], we began with the "focal phenomenon" observed by the authors in our research over the last several years, in the use of APDMs in post-disaster resilient infrastructure delivery. We could observe the use of APDMs in industry, but we could not see their rationale or benefits adequately addressed in the existing resilience-related research. Inductively considering differing conceptualizations of this phenomenon, we proposed that the aspect of interest—in this case the increasingly targeted use of APDMs in post-disaster infrastructure delivery to bring about resilient solutions—could be explained and informed with regard to the resilience regimes theory described by Woods [20]. In practical terms, we approached the study with the understanding that each APDM is purposefully structured to directly engage with a broader group of stakeholders to inform and improve infrastructure design decisions. Furthermore, such purposeful use appears (based on a significant body of literature) to be more effective (in terms of time, cost, and quality) than the traditional design-bid-build (DBB) approach.

As such, in this study we asked, "Could APDMs be leveraged and positioned to support resilience-based design principles for post-disaster recovery?". This involved the sub-questions of, "How do we incentivize resilient infrastructure delivery that increases the capacity of a system to handle predicted extreme events, and which can handle future surprises?" Furthermore, "If the traditional DBB process re-enforces rigidity and brittleness, then what alternative processes exist for improving the adaptive capacity?". We used Woods' resilience regimes theory for this examination of the potential for APDMs to improve the agility and flexibility of infrastructure against future climate-related hazards.

With this in mind, we focus on three topic areas in our literature review: resilience theory, disaster recovery as it relates to infrastructure reconstruction, and case studies that describe the approaches used in disaster reconstruction. In addition to the literature review of papers relating to resilience and project delivery methods, we reflected on observed industry practice to compare two widely used reconstruction project delivery methods, seeking out examples of post-disaster reconstruction projects to assist in considering alternative processes for improving adaptive capacity.

As such, the paper presents and discusses the results of the literature review using three headings that step the reader through the critical thought building process regarding: (1) the topic area of infrastructure resilience and disaster management; (2) the evolution of project delivery methods in post-disaster reconstruction; and (3) the proposed opportunity for enhancing post-disaster reconstruction with the learnings from resilience theory, in this case as described by Woods. In keeping with the usual outputs of a conceptual paper to bridge theory and review, our distilled learnings from the literature, theory and applied practice examples are also presented visually through a schematic, to prompt the consideration of resilience priorities pursue resilient infrastructure outcomes when using APDMs for post-disaster reconstruction.

3. Infrastructure Resilience and Disaster Management Literature

In this section we draw on three fields of literature to walk through the context for addressing post-disaster reconstruction and opportunities for improving infrastructure outcomes. We begin by highlighting key concepts and constructs in the field of infrastructure resilience spanning theory and practice. We illustrate progress in using reconstruction phases for working on resilient infrastructure solutions with several examples from the USA and Australia.

3.1. Infrastructure Resilience Theory

The field of infrastructure resilience is evolving in response to the complexity and uncertainty associated with emerging challenges such as climate change, which are highlighting the limitations of traditional resilience approaches [25]. Where traditional practice has focused largely on increasing robustness and rigidity—building infrastructure back "bigger, wider, stronger" after disturbance—more recent resilience theory is focusing on attributes of adaptability, flexibility and agility [6,18,25]. This approach seeks to design and construct infrastructure that can not only withstand projected disturbances, but that is able to adapt and adjust in the face of unexpected disruption [17].

In recent work by the authors, these emerging resilience attributes have been aligned to principles of resilience in natural environments, with a proposed convergence of "engineering resilience" theories with "socio-ecological resilience" theories—approaches that have traditionally been almost diametrically opposed [6,25]. Where engineering resilience has prioritized robustness, rigidity and stability, socio-ecological resilience has demonstrated flexibility, change and multi-functionality. Recent investigations have highlighted that these converging ideas have had some traction in infrastructure resilience theory [18,20,26]; however, they limited the influence on industry practice. This paper seeks to support shifts in infrastructure practice by uniting theoretical advances with project delivery models well suited to their implementation.

Built environment design professionals are well-trained in design approaches that consider a set of hazards and how infrastructure should perform when exposed to those hazards. Less familiar are design approaches that consider infrastructure systems capable of extending themselves to unforeseen conditions. Such approaches comprise differences in methods and hardware, in addition to embedding assumptions and expectations about the infrastructure managers (i.e., resources and capabilities) and the communities that rely on and support the infrastructure solution. Woods [20] provides a pragmatic approach for built environment professionals to address adaptive capacity in design solutions. Four core "resilience regimes" are identified, which can be used by all stakeholders to contextualize and discuss design priorities for dealing with known and unknown hazards:

- Rebound: the capacity to return to equilibrium after a trauma. Capacity is a function of both physical assets, resources, and community capabilities.

- Robustness: the increased ability to absorb perturbations. Increasing robustness involves expanding the disturbances that the system can protect itself against, which means that robust control is risk sensitive, but brittle at its boundaries (when surprise occurs).
- Graceful Extensibility: the ability of the system to stretch (extend adaptive capacity) to overcome surprise, when a perturbation outside of the design set occurs. It seeks to understand how systems with finite resources in changing environments stretch to accommodate events that challenge boundaries. These systems can anticipate bottlenecks, learn about changing disturbances, and can adjust responses on a case by case basis.
- Sustained Adaptability: the ability to adapt to future surprises as conditions continue to evolve. This includes the ability to manage/regulate adaptive capacities of systems as layered networks. Central to sustained adaptability is understanding what design principles should be maintained and which are needed to provide flexibility over long scales.

These four resilience regimes present an insightful framing of how to think through strategies for managing infrastructure readiness for extreme events. At various scales of the infrastructure system, different regimes could be implemented as part of the design solution. For example, a solution for improving flood resilience could include an improved drainage system (Rebound), a levee being made robust (Robustness), alongside creating a disaster response system that can deal with unforeseen hazards and infrastructure failures (Graceful Extensibility and Sustained Adaptability).

Traditional approaches of infrastructure design and delivery (pre or post disaster) tend to emphasize Rebound and Robustness, functioning within a predetermined set of conditions and unknown consequences of failure beyond [20]. They focus on principles of optimization and efficiency (informed by predicted future impacts) at a time when the environments and demands for infrastructure services are becoming more complex and less predictable [16]. Graceful Extensibility and Sustained Adaptability are the least familiar design spaces for built environment professionals, describing systems that continue to thrive when their boundary (design) conditions are exceeded. This includes, for example, considering community needs amidst changing future risks, and reconsideration of infrastructure form and services.

3.2. Resilient Infrastructure through Reconstruction Practices

Disasters have long been understood to comprise (often repetitive) events that result in a journey of mitigation planning, preparedness, response, and recovery including reconstruction [27,28]. Mitigation and preparedness occur before the disaster, while response, recovery, and reconstruction occur afterwards. The choices, resources, policies, and practices that are instituted across these phases determine the adaptive capacity of a community to respond to disasters [29]. Given the repetitive nature of disasters, the reconstruction phase that starts after a disaster in many ways determines the potential for a community to mitigate their vulnerabilities during future events. A window of opportunity occurs after a disaster, where public opinion is sensitized to the hazard and disaster, and demand is created to address the challenge, both acutely and in the future [27–29]. This window of opportunity corresponds to the timeframes of recovery and reconstruction, as new legislation and policy to deal with future disasters largely occur during these times [3,5,30]. Resources and commitments are the largest, and often the greatest flexibility exists to change disaster preparedness and response approaches.

Over the last twenty years in particular, reconstruction practices have been discussed in relation to sustainability imperatives and climate change [5,31]. Mulowayi et al. [32] document a variety of connotations of "resilience" that are being used during different phases of the infrastructure lifecycle, including a focus on mitigation and preparation during the prevention and preparedness phases, followed by a respond and recover focus during disaster response and rebuilding. Drawing on the theoretical context discussed above, Figure 1 presents an adaptation of Mulowayi et al.'s findings showing the ideal scenario, where costs of preparation and adaptation for resilience are incorporated into the response and recovery phases of infrastructure building.

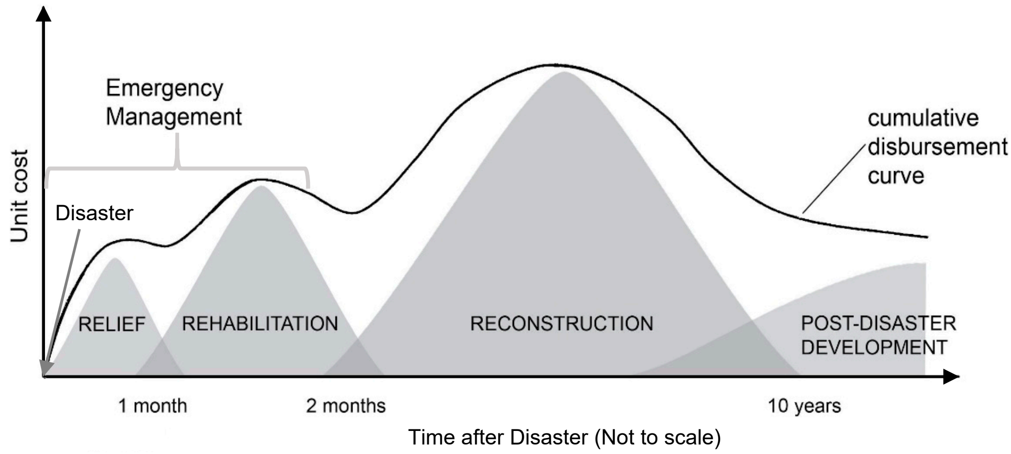

Figure 1. Disaster response phases and associated costs, towards resilient infrastructure outcomes. Adapted from [32].

Time periods of the phases vary for the structural (e.g., infrastructure changes) and non-structural activities/responses, but generally describe:

- Relief Phase: the short term—the days to weeks after a disaster when services are offline, and chaos is being managed.
- Rehabilitation Phase: the medium term—the weeks to months after a disaster when the chaos has been calmed, immediate threats reduced, and basic services are being brought back online.
- Reconstruction Phase: the long term—this typically starts months after a disaster when infrastructure and services are being rebuilt.
- Post-Disaster Development Phase: the long-term reconstruction of assets in the aftermath of a disaster under relative stability.

Within this context, improved resilience requires reconstruction processes that recognize the limitations of current infrastructure (i.e., the vulnerabilities they create). It also requires engagement with communities to design and deploy new infrastructure that reduces vulnerability through its improved agility and flexibility to future events. As such, infrastructure designers and engineers need to work directly in partnership with community stakeholders to understand evolving needs while designing systems that improve resilience outcomes.

Resilience research shows the importance of community engagement and preparation in being able to respond to a disaster, to reassess future needs and build services differently. In 2017 Patel et al. [33] documented a review of 80 studies on community resilience, concluding several common themes. One of those themes "Governance and Leadership" described the importance of public involvement and support. Patel describes how "having local participation and representation in strategic planning, response, and recovery were described as important by multiple publications. Additionally, public involvement may involve having local leaders who understand and represent a community's uniqueness and aspirations." A community's participation in the disaster recovery process is critical for its resilience to future disasters. Top-down planning that disregards a community's needs is more likely to deploy infrastructure and resources that do not consider the particular needs, vulnerabilities, and capacities of the community [34–40].

Additionally, Patel et al. [33] identify appropriate economic investments driven by community involvement as having long term repercussions in terms of equitable distribution of resources, cost-effectiveness, and improvement in the diversity of economic resources.

3.3. Example Approaches to Reconstruction for Resilient Infrastructure Outcomes

To illustrate this, the authors reference approaches to reconstruction adopted in Queensland, Australia, following a series of natural disasters in the past decade. Australia faces significant impacts from climate change, and Queensland is considered the Australian State most impacted by natural disasters [41]. From November 2010 through to April 2011, extensive flooding affected the region because of intense rainfall and multiple cyclones, with much of the State declared disaster affected, more than 70 towns evacuated and over US $15 billion in damage [42]. As a result, the Queensland Government took unprecedented steps to establish several response and funding agencies to support the emergency response and rebuilding of impacted assets and networks. This included the Queensland Reconstruction Authority (QRA), which was established within one month of the 2011 flood events to coordinate reconstruction efforts across the State, including allocation of funds received through the Federal "Natural Disaster Relief and Recovery Arrangements" (NDRRA) and synthesis of lessons learnt from post-disaster recovery to inform resilient infrastructure planning [43].

One of the primary lessons emerging from the reconstruction period is related to the capacity to rebuild for resilience in the aftermath of natural disasters [44]. At the national level, reconstruction funds were made available through the National NDRRA, and both lived experience and subsequent formal reviews highlighted limitations of the program, including a focus on "response and recovery at the expense of prevention and mitigation measures that are more cost-effective in the long term". This failure to consider rebuilding for adaptive capacity, it was argued, exacerbated a reliance on Federal support and a failure to invest in mitigation and resilience efforts [45]. In short, the Federal NDRRA typically funded only "like-for-like" replacement of existing assets, where the reconstructed infrastructure matched previous design specifications. Funds were not extended to adaptation and resilience efforts, severely impacting the likelihood of efforts to design for resilience, where these would have required often significant time and resource investments outside of the existing funding and governance arrangements [42,45,46].

Recognizing this, the Queensland Betterment Fund was created by the QRA in 2013 following Tropical Cyclone Oswald, which caused almost USD $1.7 billion in damage to public assets that had already been previously impacted by earlier disaster events and were considered vital to community wellbeing [42]. The fund was designed to support the rebuilding of assets that had been repeatedly impacted, in a way that was more disaster-resilient, as opposed to rebuilding to previous specifications. It provided projects receiving assistance from the NDRRA an opportunity to also apply for betterment funding to support rebuilding for resilience [42]. While only one betterment project was approved under the NDRRA, 220 were approved within 6 months of establishment of the Betterment Fund [42].

Projects funded under the Betterment Program included road realignment and resurfacing, flow and drainage (floodway, culverts and causeways), bridge upgrade and repair, water treatment and sewerage improvements, and a range of other infrastructure betterment projects including seawalls, embankments, levees, weirs and dams [42]. Betterment Funding, for example, was used to upgrade road infrastructure in a remote indigenous community, where the only ground access to a vital telecommunications tower was repeatedly damaged during disaster events over several years. In each instance, damage to the road left the tower inaccessible, leading to severe disruption and risk associated with a loss of essential services and communication. The betterment fund infrastructure upgrade allowed the road to withstand heavy rains and flooding in later years after many years of disruption and damage [42]. This outcome has been repeated across Betterment

Fund projects, including road infrastructure that had previously been rendered inoperable for months after disaster events, cutting freight and transport links and leading to significant repair costs. Betterment funding to raise and adapt these assets has resulted in infrastructure able to withstand major events with minimum disruption and significant reductions in ongoing repair and maintenance costs [42].

Learnings from the NDRRA scheme included recognition of limited engagement between emergency management and community development agencies and stakeholders, as well as duplicative, inefficient and at times ineffective administration arrangements, often with significant ambiguity [47]. Recommendations included alternative funding models that prioritized disaster prevention and preparedness, administrative streamlining and stronger interdisciplinary and inter-agency collaboration [47]. Recognizing the increasing interdependencies of technical and social systems, and the potential for compounding asset and network failures post-disaster, Mulowayi et al. [32] reiterate the need for inter-organizational collaboration to improve resilience in the rebuilding of infrastructure assets and networks, including through the use of alternative project delivery models to support collaboration. While single-organization responses may be well suited for responding to understood and predictable disruptions, complex high-risk contexts such as natural disasters require flexibility and external collaboration and engagement.

4. Reconstruction Project Delivery Methods

Drawing on key literature from the field of project delivery methods, and the research endeavors and lived experiences of the paper authors, in the following paragraphs we discuss conventional and emerging approaches for delivering post-disaster reconstruction. We reflect on their ability to address resilient infrastructure outcomes, discussing embedded limitations with conventional practice that are being addressed through emerging alternative project delivery methods.

4.1. Conventional Project Delivery Methods

The traditional method of delivering infrastructure projects consists of planning and designing the asset, and then bidding out the project to the contractor that can build the completed design for the lowest price [48]. This project delivery method is called design-bid-build (DBB). In the design phase, an architect or engineer develops plans and specifications to meet the agency’s needs, and engineers design the systems (e.g., structural, mechanical, electrical, etc.) Typical design milestones for an infrastructure project include conceptual design, schematic design, detailed design, and finally construction documents. Major decisions about materials and strength limits (think robustness) are made in this phase. Then comes the bidding phase where several constructors (e.g., general contractors) bid on the completed design documents; the agency now has a firm price for the project, and the construction contract normally goes to the lowest bidder. Finally, in the construction phase, a fixed price contract is signed between the agency and contractor, which generally incentivizes the contractor to minimize cost, and offers limited incentives for the contractor to increase quality beyond the minimum specifications required by the design.

Engineers and contractors are only two groups of stakeholders impacted by a project. There is a wide-ranging array of stakeholders for an infrastructure project, making broader community engagement in the project particularly valuable. Stakeholders for an infrastructure project include engineers, architects, general contractors, construction managers, specialty contractors such as electrical and mechanical contractors, vendors, material suppliers, banks, permitting agencies and governments at the local, state, and federal levels, attorneys, insurers, local businesses and communities, and many more. The traditional DBB approach to infrastructure design involves primarily architects and engineers. During the design phase critical assumptions and decisions are made as to the resilience approach (i.e., the four regimes presented earlier). DBB does not offer many of the other key stakeholders a mechanism for providing input to guide the project design, identifying problems, or contributing to solutions.

The traditional DBB process is lengthy but has been proven to work well for repetitive and non-complex projects, projects with limited room for innovation, and projects where schedule is not the main driver. But reconstruction projects after disasters do not meet any of the above criteria. In fact, time is critical and there is a considerable need for innovation to learn from the disaster, leverage the combined knowledge of all stakeholders to identify the appropriate resilience regimes, and redesign/rebuild infrastructure that is more resilient to future disasters.

In the traditional infrastructure design process, risk is codified and designed against using a historical set of risk factors, and community engagement tends to occur once an infrastructure solution has been proposed. Infrastructure and the environment are inextricably linked, yet we tend to think of the two systems as being at odds with each other, largely because of a post-modern mindset that emphasizes management of natural systems [49]. For the past century infrastructure and extreme events have largely become expressed through the relationship of what we now often loosely call the "design storm".

The design storm is a term that characterizes the frequency and intensity of an event that we codify that infrastructure must be able to withstand (e.g., a certain intensity precipitation event, or a duration/intensity of heat). It is based on historical environmental conditions, and with the uncertainty of climate change, the validity of using historical data to plan for future conditions is now in question [50]. The use of a design storm drives how engineers design against failure. It gives near worst case conditions that legally the system must be able to withstand; as such, infrastructure are fundamentally designed using risk-based approaches that favor robustness. The use of risk-based approaches in an uncertain climate future is the subject of much debate [19,51].

On the community side, it is widely recognized that community resources and networks are central to a city's ability to cope with a disaster [29,52]. Yet the infrastructure design process is one that largely separates a community's capabilities from the infrastructure service. Infrastructure are designed as fail-safe systems (to a particular level of risk) and when they fail the consequences are largely outside of the scope of training for engineers and managers [48]. As such, the process of deploying infrastructure tends to focus on first selecting the appropriate design options to provide the service, and secondly engaging with community members to identify the best design, which is often reduced to a cost-benefit analysis.

4.2. Alternative Project Delivery Methods

APDMs offer opportunities to quickly deploy new infrastructure while at the same time more rigorously engaging with communities and other key stakeholders to reassess future needs. APDMs have developed over the past two decades to deliver projects more efficiently and allow for innovation by engaging the builders and other key stakeholders early in the design phase, providing a more collaborative approach to infrastructure project delivery [53–55]. Various APDMs exist, including design-build (DB), construction management at risk (CMAR) also called construction manager/general contractor (CM/GC), integrated project delivery (IPD), and design-build-operate-maintain (DBOM), to name a few. The approaches differ in how they structure and incentivize involvement by various stakeholders earlier in the design process.

Figure 2 illustrates the timing of contractor engagement as one key difference between the traditional DBB delivery method and CMAR (and DB is even shorter). On average over the last two decades APDM projects have been delivered to the public 35% faster than the traditional DBB, and with improved cost certainty [54]. The most recent data show even greater improvements, with DB delivering projects 102% faster than the traditional DBB [53].

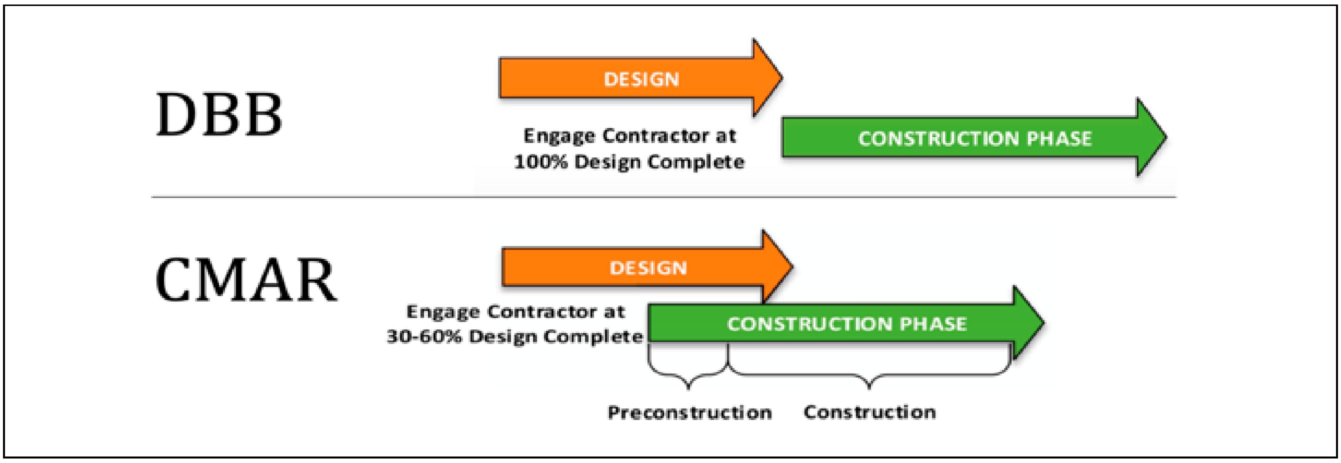

Figure 2. Visual comparison of contractor engagement time for Design-Bid-Build (DBB) versus Construction Management at Risk (CMAR).

Differences between various APDM approaches have also been previously canvassed in detail [56–59]. Given the criticality of bridges and roads for both non-disaster conditions access and post-disaster recovery, it makes sense that these infrastructure assets have been the subject of innovative delivery methods in rebuilding after their failures. APDMs have been used effectively on highway, bridge, water, transit, and other infrastructure projects. Many cases of APDM use in transportation infrastructure reconstruction exist [60]. The use of APDM in bridge and road reconstruction post-disasters tends to emphasize reconstruction speed, cost management, and minimizing future risks to the asset at hand. Recent evidence focusing on pavement projects suggests that the resulting facilities themselves may be higher performing too [61].

Table 1 provides a short summary of the two most popular APDMs (i.e., CMAR and DB) and key observed project performance outcomes in comparison to the traditional DBB delivery method, which is used here as a baseline.

Table 1. Summary comparison of DBB versus CMAR and DB project delivery methods [53,54,62,63].

Project Performance Outcomes	DBB (Baseline)	CMAR	DB
Number of contracts	Two (owner-designer, and owner-contractor)	Two (owner-designer, and owner-contractor)	One (owner-DB)
Contractor timing of engagement	After 100% of the design is complete	Between 30% and 60% of design complete	Before 30% of design complete
Project Speed	baseline	25% faster than DBB	102% faster than DBB

A disaster reconstruction effort that is trying to integrate new ideas and innovations to rebuild infrastructure differently while using significant input from new stakeholders is extremely complex. In APDMs, where the design is not complete when the constructor is appointed, team selection is critical to success. While low-bid competitions work when the design is fully completed, they are often not ideal in reconstruction efforts where more perspectives (e.g., builders, community, etc.) are needed early to inform a more resilient design. Qualifications-based selection is critical, inviting the best qualified engineers and builders that have successfully completed similar work in the past. A qualifications-based selection can include many criteria that are critical to project success, particularly those just discussed. The proposer's previous experience, safety record, proposed work plan, past work quality, the team of individuals dedicated to this project, the expected challenges identified by the proposer, the proposer's fees, the community involvement plan, and so on, can all be part of the criteria used in the procurement.

Around the world, agencies in various infrastructure sectors have been developing guides for practitioners to create teams and implement successful practices in APDM projects. Examples from the USA include the water sector [62–64], transportation sector [65,66], and for Construction Management [67,68]. Those studies and resulting guides provide some of the key tools used in APDM projects, including innovation matrixes, independent cost estimating, and over-the-shoulder design reviews. Improved schedule efficiencies and expanded opportunities for innovation have resulted in interest as to how to deploy APDM approaches after a disaster, as illustrated in these three examples:

- Following Hurricane Katrina, in in New Orleans (Louisiana, USA), the U.S. Army Corps of Engineers led efforts to rebuild infrastructure and protect against future flooding events [69]. The St. Bernard Parish Pump Stations are one example where APDMs were used to select contractors, engage with the community, and create innovations towards quality control [70]. While the regional political culture rewarded development and patronage at the expense of public safety [71], APDM innovations were enabled by constrained resources (the Army Corps had many simultaneous rebuilding projects in the region), heavy scrutiny, and goal of designing new systems that were capable of withstanding extremes beyond those that had failed. Multiphase proposals allowed the Army Corps to elicit appropriate expertise, and a local partnership team was formed to consult on the final design and operation conditions. The resultant delivery method switched from top-down management of design, to bringing in a project partner team to discuss the pros and cons of potential solutions [70].
- After its tragic collapse, the I-35W St. Anthony Falls bridge (Minnesota, USA) required replacing. Faced with ongoing landslide threats, the Minnesota Department of Transport (DOT) recognized that in-house designers lacked specific expertise to manage ongoing risk to drivers and travelers and recognized the need to clear and protect assets [72]. The agency instituted an external engagement process that asked design-builders to submit short form proposals that focused on the critical aspects of reconstruction deemed most important—opportunities created for identifying new risks and design approaches. The contract was subsequently established with a specialist geotechnical firm to both shore-up existing at-risk areas and begin reconstruction of foundational elements, thereby giving the DOT time to fully develop their reconstruction designs. Consolidation of risk management and immediate response to a single firm with specialized expertise relieves the DOT from having to multi-task across response and recovery and instead gives them additional resources to focus their efforts on long-term resilience. The new bridge project was delivered in a record time.
- Dealing with the Pentagon Reconstruction following the 9/11 terrorist attacks (Washington DC, USA), management of the reconstruction effort was overseen by Integrated Product Teams (IPT), with each team representing an area of expertise and perspectives on the project goal. This APDM was aimed at expediting construction while utilizing a broad set of expertise and involving processes for complex systems management [73]. The approach reduced development time and risk of failure, and enhanced quality, flexibility and better knowledge sharing [74].

From a resilience perspective, these examples illustrate how multiple stakeholder goals and needs can be met, alongside creating incentives for the reconstructed infrastructure to be better able to respond to a different and emerging set of hazards. APDMs are purposefully structured to directly engage with a broader group of stakeholders to steer infrastructure design decisions and appear to do so more effectively (in terms of time, cost, and quality) than the traditional DBB approach. Also common to these examples is the opportunity that the leadership took to engage early with a broader group of stakeholders. This enabled a more flexible and place-based approach to the impacts of disasters on local communities, and the realization of innovative solutions that increased the quality and context-specific appropriateness of the delivered infrastructure.

In addition, the examples point to the opportunity to incorporate insights garnered during the failure. They also demonstrate similarities (unlike the traditional DBB approach), in involving concurrent construction and design of the infrastructure, informed by a large group of stakeholders. With CMAR and DB for example, the constructor is engaged in the project before the design is complete [68,75]. This early engagement allows the constructor to provide input on the design, perform constructability analysis, share insights regarding the design decisions' impact on project cost and schedule, discuss construction means and methods that can help deliver a better facility, and so on.

Involvement of the constructor in the design phase has resulted in improved project outcomes [59]. But other APDM approaches push the collaboration even further and aggressively involve even more diverse groups of stakeholders. For instance, IPD involves facility users, maintainers, regulators, trade partners, suppliers, and others as part of key decisions early before the design has even started, leading to significant improvements in project outcomes, including higher quality projects. These key stakeholders can be part of the project's "core group" that meet every week, wherein all have an equal say on project decisions [48]. The authors propose expanding this group even further to include key community stakeholders.

5. A Framework for Enabling Post-Disaster Infrastructure Delivery for Resilience

Synthesizing the key insights from the previous two sections about improving resilient infrastructure outcomes through rethinking post-disaster reconstruction methods, in this section we discuss the opportunities that appear when overlaying Woods' infrastructure resilience principals on to post-disaster reconstruction practices and project delivery methods. Addressing the phenomenon of alternative project delivery methods that are already improving time and cost performance, we ask "could APDMs be leveraged and positioned to support resilience-based design principles for post-disaster recovery?".

5.1. Processes for Increasing Stakeholder Engagement to Handle Future Surprises

Typically, infrastructure is still designed with a risk-based mindset, so when conditions exceed those it was designed for, the consequences of failure—spanning infrastructure rehabilitation, impacts to people, the environment, and the economy—are notoriously absent from the planning process. As such, the current fail-safe paradigm divorces the costs of consequences from the benefits of the infrastructure.

The Graceful Extensibility and Sustained Adaptability resilience regimes have a commonality of calling for planning outside of a known or fixed set of design hazards. It is imperative to get a broad spectrum of stakeholders engaged in such planning of post-disaster reconstruction processes early. Given the "new normal" of climate uncertainty, novel infrastructure design processes that involve a diverse group of stakeholders are necessary to explore what could happen under situations where infrastructure fails due to unforeseen hazards [19]. This includes permitting agencies and regulators involved in addition to all stakeholders previously included in Rebound and Robustness discussions.

Application of one or more of the four resilience regimes may also allow infrastructure to go into controlled failure under some circumstances, which would mean that other governmental portfolios dealing with, for example, communities, tourism, education and agriculture may need to be engaged given the possible interdependencies involved. Given the novelty associated with two of the regimes (Graceful Extensibility and Sustained Adaptability), insurers and sureties will also need to be engaged in the planning and design process to confirm that the work is insurable.

APDMs—in particular DB and IPD—give these key stakeholders a seat at the weekly or monthly decision-making table, as new infrastructure is planned for and designed. This includes a range of procurement methods for bringing broad groups of stakeholders to the table to plan for failure due to an unknown set of hazards, thereby incorporating the costs of failure into the infrastructure design and selection process, radically altering typical cost-benefit analyses approaches. Such procurement methods allow the proposer's planned involvement with the community (asking them to provide a key input) to impact the selection of the winner. Indeed, "public involvement" was a key criterion for the I-35W bridge reconstruction project in Minnesota, discussed earlier [72].

5.2. Processes for Improving Adaptive Capacity to Handle Unforseen Hazards

In contrast to the "rigidity and brittleness" of infrastructure solutions that are reinforced by DBB delivery methods (Table 1), APDMs provide opportunities to change how and why infrastructure are designed, towards improving the adaptive capacity of the solutions to future hazards, and to the evolving needs and capabilities of the end-user community. A key challenge to adaptivity is opening up problem and solution spaces through the process of knowledge co-generation. Knowledge co-generation is a set of processes where stakeholder perspectives are diversified, creating opportunities for seeing challenges differently [76]. When it comes to post-disaster recovery and opening up solutions, a commitment to a process that involves different stakeholders to those who would generally be involved in status quo rebuilding appears to be supported by APDM.

APDMs facilitate new opportunities for bridging and aligning infrastructure and community capabilities. First, communities have unique insights into their risks should hazards occur. For example, in the aftermath of Hurricane Maria in Puerto Rico, critical infrastructure assets that led to large scale or cascading failures were revealed, and social vulnerabilities around age and health conditions were brought to light [77–79]. Community involvement in the aftermath of the disaster during the design process would bring these vulnerabilities front and center, and would allow for a reframing of the hazards towards a prioritization managing future consequences. Imagine a scenario where during rebuilding efforts in Puerto Rico local community members described where efforts were needed to ensure that power delivery was more robust so that particular neighborhoods with large diabetic populations had more reliable refrigeration of insulin in future disasters.

APDMs also encourage new mechanisms for understanding the benefits and costs of addressing traditional or an expanded set of hazards. In CMAR or DB, early contractor involvement would allow for a feedback loop that would estimate the cost implications of different rebuilding strategies. In IPD, suppliers would provide an input on whether current materials and equipment are able to support the increased robustness targeted. In DBOM, operators would be able to provide lifecycle impacts of the decision, specifically geared toward operations and maintenance of the new facility.

5.3. Leveraging and Positioning APDMs for Resilient Infrastructure Outcomes

In translating resilience theory to practice, the Post-Disaster Resilient Infrastructure Delivery (PD-RID) Framework presented in Figure 3, provides a prioritization structure for improving the adaptive capacity of infrastructure, the services they deliver, and capacities of the communities that rely on them. APDMs have been used after disasters to rebuild infrastructure in a timely and cost-effective manner. With the addition of a third "resilience" priority, APDMs can be used to also bring about improved infrastructure resilience to future hazards.

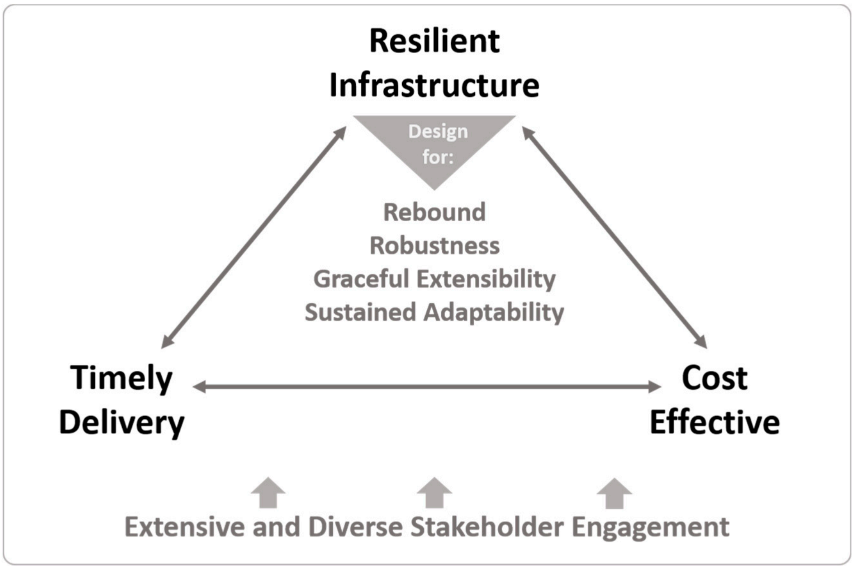

Figure 3. A Framework for Post-Disaster Resilient Infrastructure Delivery (PD-RID).

In addition to time and cost, the resilience approach selected for a given reconstruction project (out of the four regimes presented) is a critical input into the design phase. It dictates design assumptions, and therefore needs to be thoroughly investigated very early in the design process. Moreover, each of the four regimes may benefit from different project delivery methods which would allow engaging various stakeholders at different times points in the project.

The Rebound or Robustness regimes—where rebound focuses on the capabilities to return to equilibrium after a trauma, and robustness focuses on the increased ability to absorb perturbations—both rely on predefined and preplanned resources to respond to a designed (forecast) set of hazards. This is the typical approach for infrastructure design, where natural hazards are often codified through design storms or tolerances. As such, the infrastructure design process would consider how the infrastructure, supporting resources, and community capabilities offer improved protection from future hazards. In this context APDMs could provide opportunities to more meaningfully integrate community capabilities with those of the physical infrastructure systems, so that when failure occurs consequences are minimized.

Regarding Graceful Extensibility or Sustained Adaptability regimes—where graceful extensibility focuses on stretching to accommodate events that challenge boundaries, and sustained adaptability focuses on adapting to future surprises as conditions continue to evolve—both require an evolving appreciation of resources required to respond to hazards that cannot be predicted. As such, the infrastructure design processes would be providing capabilities to better anticipate bottlenecks, learn about changing disturbances, adjust to responses for the challenge, or manage resources as a system of systems. In this context APDMs could provide a mechanism that allows this type of dialogue to occur, by offering a proven contractual method to engage the right stakeholders at the right time in the project development (or redevelopment) stage. Including a more diverse set of stakeholders supports a more realistic identification of boundaries and practical adaptation mechanisms.

Within the theoretical context of Woods' regimes, delivery agencies also need the adaptive capacity to move between strategies for the four possible realities, with an adaptive capacity that is enabled by agility and flexibility [14]. APDMs appear to support agility and flexibility by offering different contracting mechanisms with a wide spectrum of team collaboration and integration [67], encouraging diverse input to design, and using inclusive processes that can be extended to broader community engagement to facilitate identifying, understanding, and protecting against future hazards.

As noted in Figure 3, APDMs must continue to prioritize stakeholder engagement, involving the community extensively in, and during, both design and construction phases of a project, enabling new ideas of what infrastructure should do, the hazards that it will face, and what impacts should be avoided if infrastructure fails. APDM can be used to integrate the impacted community in this process and request their input, their thoughts on what their local needs are, how to transition between short-term and long-term recovery, and so on. At the end of the day, the local community is the end-user, is most impacted by the disasters, has significant local knowledge, may not be biased by the traditional way of delivering infrastructure, and may provide innovative ideas that can enhance the design and construction of a more resilient new facility, with direct tangible impacts to their community.

6. Conclusions

As extreme events become more frequent and sometimes more intense, it is imperative that the infrastructure community embraces new collaborative processes for protecting people and services into the future. The specifics of how APDM can support more resilient forms of infrastructure during disaster reconstruction are important and not fully researched. However, it is clear that APDMs present opportunities to add flexibility and agility into reconstruction processes that have historically been rigid. The paper contributes to extant knowledge in the field of post-disaster infrastructure delivery, providing a pathway to embed resilience as a priority consideration alongside the existing considerations of time and cost.

Building on this conceptual study, in-depth research is needed to understand the specifics of different APDM processes in the realm of infrastructure resilience, to explore what works best under particular conditions. As the APDM literature grows, it would be interesting to undertake a systematic literature review of the field, as well as a review of the state of practice, to explore the range of theories informing APDMs around the world, towards resilience outcomes as defined by Woods.

Author Contributions: Conceptualization, M.V.C., M.E.A. and C.D.; Funding acquisition, M.V.C.; Investigation, M.E.A. and S.H.; Project administration, C.D.; Writing—original draft, M.V.C. and M.E.A.; Writing—review and editing, M.V.C., M.E.A., S.H. and C.D. All authors have read and agreed to the published version of the manuscript.

Funding: This work was in part supported by the National Science Foundation's Urban Resilience to Extremes Sustainability Research Network [grant number 1444755].

Institutional Review Board Statement: This study did not involve humans or animals.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data supporting the results are included within the paper.

Acknowledgments: The collaborative authorship builds on an Endeavour Fellowship visit by Hayes to ASU (February–August 2018), a Visiting Researcher intensive by A/Professor Chester to Griffith University (May 2019), and a resilience research project funded by ASU (Biomimicry Institute, 2019–2020). The paper builds on a shorter paper on the same topic that was presented by the third author, at the 2020 Sustainable Development of Energy, Water and Environment Systems (SDEWES) Conference (6–9 April, online).

Conflicts of Interest: The authors declare no conflict of interest.

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