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A multidisciplinary definition and evaluation of resilience: the role of social justice in defining resilience

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ABSTRACT
This paper aims to explore how insights from the philosophical and social science literature can be incorporated into the definition of resilient infrastructure so that considerations of social justice can be accounted for and addressed more adequately. Building on the view that engineering ultimately aims to promote societal well-being, this paper argues that human well-being depends on (1) the resilience of the physical infrastructure and (2) the socioeconomic context, both of which in turn affect (i) how the impact and recovery of the physical infrastructure translates into societal impact and recovery and (ii) the ability of individuals to recover/adapt independently from the recovery of the physical infrastructure. The paper suggests that a capability approach may be a suitable framework for providing content to the formal concept of resilience as a capability approach is especially suitable for expressing non-tangible damage that might be caused by natural hazards and disasters.

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Social justice; capability approach; well-being; critical infrastructures; resilience

1. Introduction

In the last decade, resilience has become a fundamental paradigm for thinking about risks and safety threats, ranging from climate change and natural hazards to threats related to economic crises, migration, and globalization. Despite its widespread and increasing use, the term is used rather differently across various disciplines. In the traditional engineering literature, for example, resilience often refers to some measure of robustness and buffering capacity of an engineered system to changing conditions (Agudelo-Vera, Leduc, Mels, & Rijnaarts, 2012, p. 3) or to the recovery of infrastructure to pre-disaster conditions (Liao, 2012) or better. The study of the social dimensions of resilience is of more recent date, emerging in the beginning the twenty-first century. These studies often focus on issues concerning governance, politics, and social justice (Adger, Dessai, Goulden, Hulme, Lorenzoni, Naess, Wolf, & Wreford, 2009). Approximately at the same time, the term resilience was also adopted by policy-makers and here the term resilience increasingly represents an ideal for society (Béné, Mehta, McGranahan, Cannon, Gupte, & Tanner, 2017; United Nations International Strategy for Disaster Reduction, 2015; United States National Research Council, 2012).

So far, a comprehensive approach to resilience that integrates the insights from the engineering literature on resilience (e.g., Sharma, Tabandeh, & Gardoni, 2018) and the social science literature on community resilience is still lacking (Koliou, van de Lindt, McAllister, Ellingwood, Dillard, & Cutler, 2018). The social science literature seems to have a rather static view on the role that engineered objects, and especially infrastructure, could play in the resilience of societies. Vice versa, some of the engineering literature does not adequately take into account the interaction of human beings with engineered objects and does not pay sufficient attention to what engineering should ultimately be aimed at (Gardoni, Murphy, C, & Rowell 2016). While there have been considerable efforts to integrate insights from mental health in the community resilience literature (Gunderson, Holling, Peterson, & Pritchard, 2001) and to understand the relation between natural resource dependency and social resilience (Marshall, Fenton, Marshall, & Sutton, 2007), little research (with exceptions such as Ellingwood, Cutler, Gardoni, Peacock, van de Lindt & Wang, 2016; Gardoni & Murphy, 2017) has been done that tries to integrate the engineering literature with the social science literature on community resilience.

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This paper aims to explore the interlinkages between resilience as it is understood in these various fields to see how insights from the policy and social science literature can be translated into the context of resilient infrastructures. Building on the view that engineering ultimately aims to promote societal well-being (where that is a function of the well-being of individuals), this paper argues that societal well-being depends on (1) the resilience of the physical infrastructure and (2) the socioeconomic context, which in turn affect (i) how the impact and recovery of the physical infrastructure translates into societal impact and recovery and (ii) the ability of individuals to recover/adapt independently from the recovery of the physical infrastructure. The social–economic context (which includes, for example, the financial resources and know-how) affects the resilience of the physical infrastructure, since physical infrastructure often requires human interventions to recover. Thus, the definition of the required level of resilience of the physical infrastructure should take into account how the infrastructure contributes to human well-being and define minimum levels of individual well-being that might be acceptable or tolerable. In doing so, the definition of acceptable and tolerable levels brings in considerations on social justice.

Following this introduction, Section 2 discusses the origins of the term resilience and the evolution of its use in different disciplines. The section concludes with the observation that resilience is a 'formal concept,' which needs further content. Section 3 elaborates how the notions of physical infrastructure resilience and well-being relate to each other. In this section, the capability approach is presented as a suitable approach for providing the requisite content. In Section 4, we discuss how to address social justice, and ethical considerations more generally, in the operationalization of physical infrastructure resilience.

2. Origins of the term resilience and evolution of its definitions across disciplines

2.1. Origins of the use of the term resilience in scholarly literature

Much of the scholarly literature on resilience refers to the work of the theoretical ecologist Crawford Stanley Holling, who introduced the term resilience in the context of ecosystems (Holling, 1973). However, the history of the term goes back further. The word resilience comes from Latin to refer to the ability to come back or rebound. The first use in an engineering context was at the beginning of the nineteenth century, when the term resilience was used to describe the property of certain types of wood that were able to accommodate sudden and severe loads without breaking (McAslan, 2010). In the middle of the nineteenth century, a report to the British Admiralty used the term *modulus of resilience* as a measure for assessing the ability of materials to withstand severe conditions (Hollnagel, 2017).

Although not the first use of the term resilience, Holling's paper is probably one of the first to attempt to provide a more formal description of resilience. Holling developed his view in the context of ecology, that had until then primarily been concerned with the presence or absence of particular species or populations. For Holling, this narrow focus on presence or absence of particular species was too static and implicitly assumed that there is only one stable equilibrium state for an ecosystem. Holling called this ability of a system to return to its equilibrium state after a temporary disturbance 'stability,' which he later changed to 'engineering resilience' (hereafter 'narrow resilience') to emphasize the similarities with how in his view engineering focuses on maintaining efficiency of function, constancy of the system, and a predictable world near a single steady state.[1] Holling's paper should be seen in light of the rise of systems thinking (Davoudi, 2012). Crucial for systems thinking is that the performance of a complex system is more than the performance of the parts or components that make up the system. Analysis of these systems should therefore not focus on the stable performance of the different components, but rather on the relations between these components and how new performance may emerge from interactions among these components.

Holling also linked his insights to ecosystem management strategies. One such strategy starts from the narrow resilience view that an ecosystem has one static equilibrium and to conserve the existing situation will aim at resisting disturbance and change. For some contexts, this may be a useful focus if we are, for example, examining the performance of an engineered device specifically designed to perform well-formulated tasks under a rather narrow range of predictable external conditions. However, for more complex systems, and ecosystems are considered complex by Holling, a management approach that aims at stability may not suffice; indeed, if the system is not near an equilibrium and in extreme situations, aiming at stability may even lead to loss of the integrity of the system's structure. Instead of trying to control change, we should focus on the system's ability to cope with, adapt to, and shape change. This may mean that the system will reach a different equilibrium state. Such a management approach would emphasize flexibility and the need to adapt to the evolving environment. A system would be better equipped to deal with unexpected future events as 'it does not require a precise capacity to predict the future, but only a qualitative capacity to devise systems that can absorb and accommodate future events in whatever unexpected form they may take' (Holling, 1973, p. 21).

The impact of Holling's work on resilience thinking can hardly be overstated. His emphasis on examining systems rather than individual components and his distinction between resisting change versus adapting to and absorbing change have influenced conceptions of resilience beyond the context of ecosystems. We next provide an overview of how different aspects of Holling's description have found their way in different definitions of resilience.

2.2. Different definitions of resilience across disciplines

After its introduction in ecology in the 1960 and 1970s, the term resilience became popular in other domains as well. The term resilience entered the field of safety engineering (Bruneau, Chang, Eguchi, Lee, O'Rourke, Reinhorn, Shinozuka, Tierney, Wallace, & von Winterfeldt, 2003; Woods & Wreathall, 2003), psychology (Connor & Davidson, 2003; Southwick, Vythilingam, & Charney, 2005), disaster management (Adger, 2000; Paton & Fohnston, 2001; Walker, Holling, Carpenter, & Kinzig, 2004), and business (Hamel & Valikangas, 2003). Unsurprisingly, with the use of the same term in different domains, different conceptions of the term emerged. In the last decade, several studies have identified the varying conceptions of the term resilience (e.g., Béné, Mehta, McGranahan, Cannon, Gupte, & Tanner, 2017; Doorn, 2017; Folke, 2006; Sharma, Tabandeh, & Gardoni, 2018). A commonly used taxonomy is the one provided by Folke (2006), who distinguishes between three conceptions of resilience: narrow resilience; ecological/ecosystem and social resilience; and ultimately a broader social–ecological interpretation of resilience (see Table 1). These different conceptions implicitly and explicitly emphasize different aspects of Holling's basic framework as we show below.

As noted above, the first, narrow conception conceives of *resilience as the ability to the return to a stable equilibrium*, and focuses on recovery and constancy. There is a return to the state or condition prior to the disruption. This is similar to what Holling referred to as 'stability,' as discussed in the previous section. The second conception of resilience is close to Holling's idea of resilience as capacity to absorb change. Although Holling derived this conception of resilience from the context of ecology, it can also be applied to social systems and it refers to a system's buffer capacity and ability to withstand shocks and maintain its functions. This view on resilience recognizes that there is not just one equilibrium to which a system returns after disruption, but that *resilience is essentially the capacity of a system to absorb disturbance and re-organize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks* (Walker Holling, Carpenter, & Kinzig, 2004). Hence, resilience does not require that a system goes back to an equilibrium state, where that entails a return to a status quo ante condition. Adger (2000), for example, defined social resilience as the ability of human communities to withstand external shocks to their social infrastructure, such as environmental variability or social, economic, and political upheaval. Since this view explicitly allows for change, withstanding or absorbing shocks is taken not to require societies to be exactly as they were prior to the shock.

The third conception, lastly, refers to *the capacity for adaptation, learning, and self-organization*, in addition to the general ability to recover from a disturbance. This notion goes beyond the notions of resilience developed by Holling. In the literature, this concept is often termed 'social-ecological resilience.' In this view, resilience goes further than being persistent or robust to disturbance, but also includes opportunities that disturbance opens up in terms of recombination of evolved structures and processes, renewal of the system and emergence of new trajectories (Folke, 2006). Carpenter, Walker, Anderies, & Abel (2001) characterize social-ecological resilience as

(1) The amount of change the system can undergo and still retain the same controls on function and structure;
(2) The degree to which the system is capable of self-(re)organization to accommodate external changes; and
(3) The ability to build and increase the capacity for learning and adaptation.

Table 1. A sequence of resilience concepts, from the more narrow interpretation to the broader social–ecological context (In revised form taken from: Folke, 2006)

Resilience conceptions	Characteristics	Focus on	Context
Narrow resilience	• Return time • Efficiency	• Recovery • Constancy	• Vicinity of a stable equilibrium
Ecological/ecosystem resilience, and social resilience	• Buffer capacity • Withstand shock • Maintain function	• Persistence • Robustness	• Multiple equilibria • Stability landscapes
Social–ecological resilience	• Interplay disturbance and reorganization • Sustaining and developing	• Adaptive capacity Transformability • Learning • Innovation	• Integrated system feedback • Cross-scale dynamic interactions

In the literature on disaster management and climate adaptation, the third conception of resilience as the capacity for adaptation, learning, and self-organization now seems the most widely supported definition of the term (Doorn, 2017). Thus, disaster management has moved beyond the idea of equilibrium and allowing for change through adaptation and learning to ensure that a system's functions persist (Murphy, Gardoni & McKim, in press; Olshansky, in press; Prior & Hagmann, 2014; Wardekker, de Jong, Knoop, & van der Sluijs, 2010). This conception of resilience as adaptive capacity has also been taken up in the economics literature, in which 'economic resilience' is recognized as an important ability to recover from shocks in the aftermath of disasters (Rose, 2004). There seems to be a general consensus that in the context of disasters, resilience should not be interpreted as stability or simple recovery to the state before disaster struck, because only the additional capacity for adaptation and learning will enable the system to cope with uncertainty and deal with new system requirements (Barnett, 2001; Norris, Stevens, Pfefferbauam, Wyche, & Pfefferbaum, 2008; Rose, 2017). In the economics literature on resilience, for example, a distinction is made between static economic resilience, which refers to the ability of a system to maintain function when shocked, and dynamic economic resilience, which refers to the ability to hasten the speed of recovery from a shock. Where static resilience pertains to making the best of the existing capital stock (productive capacity), dynamic resilience is about enhancing capacity and it has a time-related aspect to it (Rose, 2017). While the focus had been primarily on single systems, more recently Guidotti Chmielewski, Unnikrishnan, Gardoni, McAllister, & van de Lindt (2016) pointed out and described the role of dependencies among different systems in modeling and promoting resilience. Sharma Tabandeh & Gardoni (2018) started the process of mathematically quantifying resilience as well as describing the recovery process.

We can also make a moral case for the importance of adaptation and learning. From a justice point of view, simply recovering to pre-disaster conditions is considered undesirable as this will reproduce existing vulnerabilities (e.g., Bahadur & Tanner, 2014; Béné, Godfrey-Wood, Newsham, & Davies, 2012; Leach, 2008) and as such might not be the most minded allocation of resources. More generally, recent literature (e.g., Meerow, Newell, & Stults, 2016) suggests that resilience is increasingly becoming a contested idea, because it often ignores how benefits and burdens under different resilience regimes are distributed. A growing number of scholars now recognize that, for policy to draw on and benefit in practical ways from a resilience approach, the appropriation and use of resilience to justify policy measures should be critically scrutinized, as they contain particular normative choices that are often not made explicit (Cote & Nightingale, 2011; McEvoy, Fünfgeld, & Bosomworth, 2013; Porter & Davoudi, 2012). Finally, as Gardoni & Murphy (2008) noted, considerations of sustainability imply 'that recovery efforts should aim to (re-)build, maintain, and, if possible, enhance the quality of life of members of the disaster-stricken community in the short and long term.' To account for these moral considerations, Gardoni & Murphy (2008, 2017) proposed a concept of resilience that is intimately linked and designed to address sustainability requirements like promoting social equity (intragenerational justice), promoting intergenerational justice, addressing environmental concerns.

2.3. Resilience as a formal concept

The focus in many engineering disciplines that emphasize resilience is on *socio-technical systems*, which can be seen as heterogeneous engineering systems that not only consists of technical infrastructure but also of people and institutions (Kroes, Franssen, Van De Poel, & Ottens, 2006). A flood defense system, for example, is composed of both material objects (storm surge barriers, closeable gates, dykes, and levees), people operating the system, and rules or 'institutions' which tell under which conditions a barrier or gate needs to be closed. Those nodes are essential for the performance of the flood defense system as a whole.

This attention to socio-technical systems also led to a new focus on how to think about the desirable performance. Resilience in engineering no longer simply refers to recovery to some stable equilibrium as it did for Holling, but rather provides a new way to look at how complex socio-technical systems operate (Hollnagel, 2014). Resilience is a measure for the potential of a socio-technical system to perform in a certain way (Hollnagel, 2017). Such performance for a *socio*-technical system is not restricted to the performance of physical artifacts but also to how humans function and make decisions within that system. The resilience of an operation room, for example, depends on the performance of the medical equipment but also by how well humans use this equipment and how well they monitor their environment and adapt if needed. We expand on the interaction with humans in the next part, for it is this interaction that leads us to consider resilience to be a formal concept.

The view of resilience as the potential of a socio-technical system to perform in a certain way suggests that resilience itself is not the ultimate aim, but that a system's resilience is instrumental to achieving what is considered desirable performance (Doorn, in press). This desirable performance in the context of engineering is ultimately linked to the goals of engineering. Such goals are often described in terms of contributions to specific values, for example, human well-being or safety (Doorn & Hansson, 2011, 2015; Gardoni & Murphy, 2008, 2017; NSPE, 2007; Royal Academy of Engineering, 2014; Smith, Gardoni, & Murphy, 2014), or, more broadly, to the promotion of human flourishing (Bowen, 2014). Unsurprisingly, there are approaches that focus on engineering for health (Amorosi, 2009; Graschew, Roelofs, Rakowsky, & Schlag, 2009; Siebes, Viceconti, Maglaveras, & Kirkpatrick, 2007) or patient safety (Guédon, Spruit, Wauben, van der Elst, Doorn, Dankelman, van den Dobbelsteen, & Klein 2017), or simply engineering for human well-being (Farrer, Goulev, Watt, Parr, Bowyer, & Allan, 2016; Gardoni & Murphy, 2008, 2017; Harris, 2015; Larsson & Larsson, 2008). This 'functional interpretation' of resilience is consistent with the three resilience concepts that Folke described: each of these concepts focused on a system's ability to maintain its functions, be it via recovery to the same equilibrium (narrow resilience), via reorganization (ecological or social resilience), or via adaptation and transformation (socio-ecological resilience).

The above description of resilience also suggests that resilience is a 'formal' concept: it does not prescribe *what* the functions are that a system should be able to maintain but rather that resilient performance is the ability to keep or enhance certain – still to be described – functions. In the next section, we turn to resilience in the context of natural hazards and describe how the substantive content of these functions can be related to a specific ethical approach.

3. Resilience to natural and anthropogenic hazards

With resilience seen as the ability of a socio-technical system to keep or enhance desirable performances and with the view that engineering is ultimately aimed at contributing to human well-being, the question arises: how can we apply and operationalize resilience.

Carpenter, Walker, Anderies, & Abel (2001) suggest that any discussion on operationalization of resilience should be guided by the question: resilience *of* what *to* what? Based on an observation that operational indicators have received little attention in the literature, Carpenter et al. argue that in order to assess 'a system's resilience, one must specify which system configuration and which disturbances are of interest' (Carpenter, Walker, Anderies, & Abel 2001, p. 765). Without further explication, the term resilience remains little more than a metaphor that may have rhetoric value but that does not provide concrete insight if and how specific measures contribute resilience. Also, resilience of one system or in one time period or at a particular scale can be achieved at the expense of another system's resilience or the system's resilience in a later period or at another scale (Carpenter, Walker, Anderies, & Abel 2001, p. 779).

In this paper, we focus on both natural and anthropogenic hazards[2] and the answer to the 'to what' question is therefore relatively straightforward. Typical natural hazards in the context of engineering include earthquakes, hurricanes, tornados, floods, and volcanic eruptions. Typical anthropogenic threats are security attacks and accidents, or demographic trends like urbanization and aging (Doorn, in press; Stewart & Mueller, in press). These processes may put pressure on a system in various ways.

In disaster and risk management, resilience is conceived as a concept that applies to socio-technical systems: it is often not the individual person that is able to do something, but it is the joint action of individual people, private parties, local and central government that together provide basic services, prevent harmful events, etc. In the context of flood risk management, for example, the implementation of evacuation plans is a typical strategy that can be used to reduce the impact of the flood on individuals: some people are not able to evacuate without the help of others, so for evacuation measures to be successful, healthy people should probably support elderly and people with reduced mobility. But the physical infrastructure may also come to fulfill a different function than it had fulfilled previously. In this context, the locus of resilience is mostly some society, where the specific society may be a city ('urban resilience') or some other collection of people (e.g., 'neighborhood resilience' or 'community resilience'). It is society, and society's ability to perform in a certain way in the face of a hazard, that is of interest and that is often addressed in the various policy appeals.

It is critical to recognize that *societal resilience* is a function of *physical infrastructure resilience* as well as of the individuals' capacity to deal with adverse conditions. *Physical infrastructure resilience* concentrates on the performance of the built environment that includes various critical infrastructure networks (e.g., water, transportation, communication, electricity) but also residential buildings, commercial buildings as well as hospitals and schools, accounting for their dependencies and interdependencies (Guidotti, Gardoni, & Chen, 2017). In addition to the recovery of the physical infrastructure, individuals also have the ability to adapt and invent new ways to improve their well-being separately from the recovery of the built environment (Olshansky, in press). When quantifying the resilience of a socio-technical system, this transformative capacity should be taken into account as well.

When talking about recovery of well-being and the individual person's ability to deal with threat and adverse conditions we need to ask the following fundamental question: what do we want individuals to be able to maintain, recover or improve in the aftermath of a hazard (Gardoni & Murphy, 2008)? A natural and conceptually appealing way of answering this question is in terms of *capability*. Capability refers to the genuine opportunity of an individual to do and become things of valued (Nussbaum, 2001; Sen, 1989). The things of value individuals may do or become are called *functionings*. The fundamental definition of the concept of capabilities was proposed in the text of development economics. Murphy & Gardoni (2006, 2007, 2008, 2010, 2011a, 2011b, 2012) and Gardoni & Murphy (2008, 2009, 2010, 2013, 2014, 2017) proposed a capability approach to conceptualize, quantify, and evaluate the societal impact of natural and anthropogenic hazards on the well-being of individuals as well as disaster recovery and resilience. As an application of the capability approach for natural and anthropogenic hazards, Van Ootegem & Verhofstadt (2015, 2016) looked at the flood distasters. In this project, the authors used the capability approach to better account for intangible, indirect types of damage, such as psychological or (mental) health problems and political, societal, or environmental consequences in the aftermath of flooding.

Examples of *functioning*s include being nourished, being mobile, being sheltered, and being socially connected (as opposed to socially isolated). In a capability approach, whether or not an individual has a genuine opportunity to achieve a given *functioning* depends on two general factors: what an individual has and what an individual can do with what s/he has (Wolff & de-Shalit, 2007). To illustrate this, consider mobility. Whether an individual has a genuine opportunity for mobility requires looking into the resources an individual has (e.g., a bike, a car, cash for public transformation) as well as his or her knowledge (e.g., of how to use a bike or car or of how to access and use public transformation). The characteristics of the built infrastructure matter as well in shaping, for example, whether there are paved roads or paths suitable for whatever tool for mobility will be adopted by an individual. Beyond the built infrastructure, legal norms dictate who has legal permission to use tools for mobility of different kinds and social as well as gender norms shape for whom it is socially acceptable to use tools for mobility without risk negative consequences (e.g., ostracism, shame, informal punishment, or vulnerability to physical harm).

4. Operationalizing physical infrastructure resilience and the role of social justice

So far, we have sketched a picture of community resilience that is dependent on the resilience of its infrastructure and the individual person's ability to deal with threat and adverse conditions. We also mentioned the general criticism that policy aimed at strengthening resilience should address issues of social justice to prevent that the resilience narrative becomes just a justification of existing vulnerabilities (Section 2.2). How could we bring these different aspects together? Or formulated differently, where in the operationalization of societal resilience through the promotion of both infrastructure resilience and human well-being can and should considerations related to social justice be addressed?

4.1. Operationalizing physical infrastructure resilience

In recent years, the following three questions have emerged in the engineering literature on resilience as central for defining and operationalizing physical infrastructure resilience:

(1) What kind of functionality do we want to be able to maintain or recover in the aftermath of a given hazard (Guidotti, Chmielewski, Unnikrishnan, Gardoni, McAllister, & van de Lindt 2016)? Functionality of a system is intended in this paper as the ability of a system to contribute to a certain output or state.
(2) What are the appropriate metrics to quantify/characterize the resilience (Sharma, Tabandeh & Gardoni 2018)?
(3) What are the roles of the individual components within each network and of the dependencies/interdependencies toward the overall resilience of the physical infrastructure (Guidotti, Gardoni, & Chen 2017)?

In Section 2, we described resilience as essentially a formal concept that refers to the ability of a system to maintain or improve its functions, but that did in itself not say which functions are or should be considered important. The answer to this first question brings in this content and it is therefore also an ethical question, as it relates to the ultimate goal of our infrastructures.

In Section 3, we introduced the capability approach, which focuses on human *functionings*. An especially important difference between human *functionings* in the capability approach and functions in physical infrastructure resilience is in the source of the value the functions and *functionings* have. The source of the value of infrastructure resilience is instrumental; we do not care about it or value it for its own sake but rather for the sake of the goods it makes possible. By contrast, individual *functionings* are valuable for their own sake. They are the manifestation of human well-being. Resilience allows individuals to maintain the genuine ability to do or become things that are valuable in themselves and constituent dimensions of individual well-being. The underlying question here is therefore one about the functionality that is required for human beings being able to live a minimally decent live.

There are two important implications of this difference in the value of infrastructure resilience versus individual well-being. The first implication is that resilience in infrastructure is instrumentally valuable, valuable only insofar as infrastructure is necessary for individual capabilities. To the extent that infrastructure is not necessary, the reason to ensure its resilience diminishes. The second implication is that human *functionings* are intrinsically important. These *functionings* matter for their own sake, insofar as they are a constitutive element necessary to protect what we ultimately care about, namely human well-being.

The different nature of the value of infrastructure versus individual resilience should inform specifications of resilience of each kind. In particular, the definition of an acceptable or target level of resilience for infrastructure cannot be done in isolation; that is, without considering the role that particular infrastructure plays in fostering intrinsically valuable capabilities and resilience when hazards negatively impact such capabilities. This approach contrasts with many examinations of resilience of the built infrastructure which consider infrastructure as the subject of interest, with little attention to the relationship between infrastructure resilience and individual well-being. The latter must be based on an understanding of what level of capabilities it is intrinsically important and acceptable to maintain, and the resilience that is necessary to restore this level quickly in the face of a hazard. This is essential in the definition of acceptable and tolerable levels of resilience (Tabandeh, Gardoni, Murphy, & Myers, 2017).

This brings us to the second question: what are the appropriate metrics to quantify/characterize the resilience and to decide on the acceptable risk levels accordingly. Many risk scholars recognize the importance of including ethical considerations in management and in the context of natural and anthropogenic hazards and the ethical question on acceptable risks seems basically one of distributive justice (Doorn, 2015; Gardoni & Murphy, 2014, 2017; Murphy & Gardoni, 2008). In the context of risks, distributive justice requires protection of individual people up to some threshold level because further protection would often come at the expense of other values (Doorn, 2018). Hence, justice requires us to take into account the levels of capabilities that individual people are able to maintain and make sure that all people are placed above some acceptable threshold level. It requires us to focus not on the average but to ensure that all individuals have an acceptable level of resilience and capabilities as average values can mask important variations among a population. The same average may reflect a case in which all individuals had roughly the same impact, or a case in which some individuals were not impacted but a portion of the population was severely impacted (Gardoni & Murphy, 2014, 2017; Murphy & Gardoni, 2012).

Lastly, the question as to the interdependencies is basically one that needs to be investigated in concrete situations and cannot be assessed outside a real-life context. Although human functionings are intrinsically valuable, human also function within a given socio-technical system and they are, in that sense, also instrumental to the performance of the infrastructure as a whole. Though different in many ways, individuals' *functionings* and the performance of infrastructures are therefore importantly interdependent. As many of the examples above illustrate, the genuine opportunities open to individuals depend on infrastructure (and some people even argue that the people themselves are to be considered infrastructure; Simone, 2004). Educational opportunity increasingly depends on the quality of the communication and information technology infrastructure. Mobility depends on the transportation and structural infrastructure, including that of roads and bridges. Health depends on the character of the infrastructure used to provide clean and remove or sanitize wastewater. A necessary (but not sufficient) condition for many genuine opportunities is one or more of the infrastructure listed above.

The dependence goes the other direction as well (i.e. as such it is an interdependency). Building, using and maintaining infrastructure depend on the functionings of the individuals responsible for its construction, maintenance, and functionality. Infrastructure cannot be built, used and maintained absent the physical strength, knowledge and skills, and personal (or public) resources necessary to construct infrastructure. If users lack the knowledge or resources needed to effectively operate physical infrastructure (along with all of their components) then the physical infrastructure will not be used or used properly. Similarly, the long-term functionality of infrastructure depends on many factors, including, importantly, knowledgeable individuals who are able to identify when maintenance are repairs are needed and perform the appropriate operations required. Also the functionality of an infrastructure often depend on the number and needs of individuals using such infrastructure (Guidotti, Gardoni, & Rosenheim, 2018; Rosenheim, Guidotti, & Gardoni, 2018).

The interdependence among physical infrastructure and human capabilities is not static. It can evolve over time and in the face of shocks like a natural hazard. When infrastructure is down and functionality not recovered, then individuals may find ways to bypass the need to use that infrastructure in order to achieve certain doings and beings (e.g., mobility or shelter), either temporarily or permanently. The capacity of individuals to improvise in the face of sudden disruptions or reductions in the functionality of infrastructure must be factored into any analysis or prediction of human *functionings* and well-being (Olshansky, in press).

4.2. Social justice in physical infrastructure resilience

Discussion of the three questions on operationalizing the resilience of physical infrastructures suggests that there are quite a few 'value-laden' choices to be made, which in turn provide opportunities for addressing social justice. The first is in the identification of the required functionality the physical infrastructure. Since resilience is a 'formal concept,' in the sense that the concept in itself does not contain content, content can be provided through the specific choice of the functionality. Take the example of a transportation network, if we define the functionality of this network in terms of accessibility it may contribute better to social justice than when we define it in terms of the maximum attainable speeds at which one can drive on particular roads.

Also the choice of the metrics is a value-laden one. Metrics that can only be assessed on a community level are less able to provide detailed insight in how individual people are affected by certain natural and anthropogenic hazards. Social justice requires that acceptable and tolerable capabilities are not only assessed on the collective level but also on the individual level.

When assessing the overall impact on a community, a process of disaggregation may be used to examine whether members of specific subgroups are differentially affected (Murphy & Gardoni, 2007). Disaggregating the impact on different sub-groups is one way to confirm that no portion of a population suffers unacceptable or intolerable levels of capabilities. A different strategy is to directly measure or predict the capabilities of each individual in a community, assessing whether each individual's capabilities are acceptable and tolerable (Tabandeh, Gardoni & Murphy, 2018) When assessing individual's capabilities a choice must be made between examining individual indictors or constructing a composite indicator or indices, in which individual indicators are compiled into a single index on the basis of an underlying model (Nardo, Saisana, Saltelli, & Tarantola, 2008; Tabandeh, Gardoni & Murphy, 2018, Doorn, 2017). For measuring the effectiveness of specific interventions, it is required that the effect of the intervention on an individual capability can be evaluated. Drawing on reliability analysis, Tabandeh, Gardoni & Murphy (2018) developed a probabilistic predictive model that relates the value of each functioning to a set of easily predictable or measurable quantities in the aftermath of a hazard, thereby using the predictive models of functionings to determine the probability that the state of well-being is acceptable, tolerable, or intolerable.

The assessment of the interdependencies is not necessarily a value-laden question, but rather a question of assessing what interdependencies exist as a matter of fact. However, as indicated by Gardoni & Murphy (2017), any study of the interdependencies should be linked to 'societal needs' and here, again, the way these societal needs are defined and operationalized is value-laden. For example, in studying loss of functionality, there will be choices made concerning what temporal period of loss following a disruption is acceptable and tolerable. This will in turn be influenced by the impact of loss of functionality, given consideration of interdependencies, on well-being. If 'meeting the basic requirements of social justice' is recognized as a societal need, this step also provides opportunities for addressing considerations of social justice.

5. Conclusions

This paper explored how insights from the philosophical and social science literature can be translated to the context of resilient infrastructures so that considerations of social justice can be addressed more adequately. Based on a critical discussion of the engineering literature on resilient infrastructures and the social science literature, we draw the following conclusions.

First, with a reference to Carpenter et al.'s observation that the operationalization of resilience should be informed by the question 'resilience of what to what?', we would like to add an equally important question. In the current paper, we have shown that that any use of the term of resilience should be complemented with a fitting view on what the required functions are. In the social science literature on community resilience, there is surprisingly little attention for the need to further specify the goals for resilience when appeals to community resilience are made. We suggest that the capability approach may be a suitable framework for providing this content as the capability approach also looks at the *functionings* of people instead of the distribution of primary goods, but also because the capability approach is especially suitable for expressing non-tangible damage caused by natural hazards and disasters.

Second, more insight in the performance of infrastructures is needed for assessing the extent to which individual humans can recover after disruptions, such as natural hazards or major disasters. The engineering literature is indispensable for assessing how the infrastructures can contribute to individual humans' capabilities: nowadays, infrastructures are essential for human flourishing and it is not without reason that we talk about *critical* infrastructures.

Third, when it comes to modeling and assessing the resilience of typical socio-technical systems, there is currently little insight in the interdependencies between different infrastructures but also in the interdependencies between human behavior and infrastructures, including adapted use of infrastructures. A major challenge is to develop models that can account for both the resilience of the socio-technical system, but also the well-being of individual humans. This also requires the definition of the appropriate community resilience metrics to account for the interplay of all aspects involved.

Notes

1. We think the term 'engineering resilience' is misleading, since this 'narrow resilience' is not the same as the definition of resilience that is common in the field of engineering. For that reason, we will use the term 'narrow resilience' to refer to this interpretation of resilience in the remainder of this paper.
2. The 1755 Lisbon earthquake marked a change in our thinking about natural disasters. Rather than acts of God, natural disasters started to be perceived as partly preventable. Similarly, these risks can also increase due to human activity. For this reason, these hazards are also referred to as human–natural or techno-natural hazards, which are strictly speaking more correct terms.

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