Complex Resilience and Entropic Risks in Urban Megaprojects

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This paper explores issues of urban resilience and risk and presents some key conceptual and analytical elements to apply the notion of entropic risk to the analysis of urban megaprojects. The paper claims that the concept of risk needs to be understood together with that of resilience, and thus the paper starts by defining both urban resilience and risk. Entropic risks are defined as the disruptive and disorderly impacts of megaprojects in urban areas. The project management literature has been concerned with risks affecting megaprojects and has neglected the many kinds of risks and negative outcomes produced by them. This is due to their modeling of megaprojects as closed systems and to their focus on providing insights to contribute to megaproject performance improvement. The purpose of the paper is to shift attention from risks affecting megaprojects to risks produced by them for a better understanding of the damage produced by megaprojects. Urban systems and megaprojects are defined as complex adaptive innovation ecosystems, or networks of people in close proximity exchanging information and opinions, creating new knowledge, and interacting, in actor-networks, with matter as well as other forms of human and non-human life. Megaprojects can be characterized as complex systems (organizationally and scale-wise) embedded in complex urban, political and socio-economic systems.

Keywords: Complex resilience, urban megaprojects, entropic risks, contestation, disruptive complexity, disorderly complexity, urban systems.

1 Introduction

In 1973 Crawford Holling first introduced the concept of resilience in the ecological literature as a way to understand nonlinear dynamics as well as the processes through which ecosystems self-maintain and persist in the face of disturbance and change. According to Holling's definition, resilience emphasizes the conditions of a complex system far from equilibrium where instabilities can transform it so that it presents another behavior regime. Thus, resilience is measured by the magnitude of disturbances that can be absorbed by the system before it is reorganized with different variables and processes. Sustainability, therefore, is the ability of a complex system to maintain itself over time despite environmental volatility fostered by learning, transformation, renewal and evolution [1].

Van Meerbeeck, Jucker & Svenning (2021) argue that resilience increases the probability of avoiding unwanted changes to "stability domains", and also provides flexibility and the opportunity for developing sustainable systems. The idea of "stability domains" refers to ecology. Ecological stability is defined as the overall ability of a system to remain in the same domain of attraction and to retain its function and structure in the face of perturbations. As it relates to current socio-global events, avoiding unwanted changes to "stability domains" will be one of the most important challenges in a world increasingly dominated by human beings in increasingly aggressive interaction with their environment. Another factor conferring resilience to ecosystems is diversity in biological communities. The reason is that diverse communities show a higher chance of including one or more species with traits that can adapt to a changing environment [2].

Resilience, then, means ability to adapt. It also entails for a system to retain its fundamental properties in spite of internal or external changes. Further, it involves systemic responses to perturbations and disturbances. Lastly, a resilient system is one that can recover quickly from such changes, disturbances, and perturbations (fires, flooding, windstorms, insect population explosions, and human activities such as deforestation, fracking of the ground for gas and oil extraction, pesticide sprayed in soil, and the introduction of exotic plant or animal species). If the ecosystem is affected by changes and disturbances to the point of reaching a threshold, then the system changes qualitatively and a different regime of processes and structures predominates. This new regime may constitute a critical transition if it is associated with "bifurcation points" [3], [4].

The concept of resilience can be seen as having three defining characteristics: (1) the amount of change or transformations that a complex system can withstand while maintaining the same functional and structural properties, (2) the grade in which the system is capable of self-organization, and (3) the ability of the complex system to develop and increase the ability to learn, innovate and adapt [5].

Jiangxi Gao, Baruch Barzel and Albert-László Barabasi (2016) have developed analytical instruments for multidimensional complex systems allowing systematically separating the role of system dynamics and thus understanding the behavior of each one of the elements of the system. They have determined the point at which a net reaches its critical point of resilience, whether it is an ecosystem (the interrelationship between plants and animals) or a technological system (the cascading collapse of servers on the Internet). This means that the resilience of the original network is predictable. Knowing the critical point of resilience allows to strengthening the resilience of the system (its networks, nodes, and flows) before little changes may provoke tipping points and damage may be irreversible – for example, total loss of biodiversity or significant population displacements due to infrastructure construction [6].

2 Methodology

This is a conceptual and interpretive paper that surveys the relevant literature and builds an analytical argument applicable to the empirical reality of urban megaprojects. The ideas of "robustness," "anti-fragility," and "panarchy" are explored in connection with urban resilience, which is connected to the notion of risk and leads to the idea of "entropic risks." The paper draws conclusions from its conceptual approach in order to analyze entropic risks as risks produced by megaprojects, an emergent property materialized in megaproject impacts. The purpose of the paper is to shift attention from risks affecting megaprojects to risks produced by them for a better understanding of the negative impacts produced by megaprojects.

The paper uses qualitative analysis of relevant sources in the field Conceptual research is conducted by analyzing already present information in the literature with the aim of selecting key, driving ideas, and develop a new interpretative framework. As is well known, the logical structure of this methodological approach is as follows: (1) selection of study topic, (2) collecting relevant literature, (3) identifying emerging variables, (4) generating the interpretive framework.

Such a logical structure develops as follows. The paper starts by considering the concept of "resilience" as applied to urban settings. As such, resilience is closely related to the notions of "robustness" and "anti-fragility".

The particular conceptualization of risk we utilize in this scenario is critical, and we need to start by briefly discussing the contributions of German sociologist Ulrich Beck. In trying to refine our approach, urban systems are defined as complex adaptive innovation ecosystems, that is, networks of people in close proximity exchanging information and opinions, creating new knowledge and interacting, in actor-networks, with matter as well as other forms of human and non-human life.

Megaprojects constitute landscapes of disruption and such disruption is often the cause of systemic disorder, or entropy increase. We characterize the entropic risks produced by megaprojects as the disruptive and disorderly impacts of megaprojects in urban areas. Given that, by and large, the benefits of megaprojects accrue to a small portion of the population in the urban areas where they are built, most resident need to come up with adaptation strategies as a consequence of the disruptions and disorder caused by large urban projects. We highlight resilience and contestation as the two most prominent adaptation strategies in urban settings.

3 Urban Resilience

Urban resilience can be an emergent property of the city-system, seen as a socio-ecological system, where it arises only through the interactions of its components. Thus, a strategy to increase urban resilience cannot rely solely on the individual resilience of its components but has to focus on the interactions. Resilience requires different approaches to explain the dynamic relationship between shocks and stressors and the outcomes of well-being. One such approach is through complex adaptive systems that exhibit historical dependency characteristics, discontinuous changes, multiple balances, and non-linearity [7].

Hopkins (2014) points out that resilience and a stronger local economy mean being more prepared for a future without waste, with greater self-sufficiency, and prioritizing what is locally produced over what is imported. They mention that there are three fundamental characteristics for a system to have the capacity to reorganize from disturbances: diversity, modularity, and feedback [8].

Along a similar line, researchers from the Santa Fe Institute (especially in the repertoire of works compiled by Erica Jen), have carried out various works related to the study and understanding of the ”robustness” mechanisms in economic, social, and ecological systems (which are properly considered complex phenomena). The researchers at the Santa Fe Institute propose robustness as the magnitude of volatility that can be compensated by the complex system before reaching the collapse of its main characteristics, processes and functions. This research aims to identify and understand the dynamics common to these systems so that they can give rise to the formation of a theory in this new field that allows the complex systems of our world today to be increasingly sustainable in the future [9].

Going beyond robustness, Taleb (2014) proposes the notion of “anti-fragility” as a characteristic and disposition whereby systems – and, presumably, people – gain from disorder and benefit from stress, volatility, and turmoil. Further, what Taleb terms “antifragile” refers not only to systemic situations that gain from chaos but that need it in order to survive and flourish. Avoiding disruption for fear of the consequences of such a disruption is an indicator of fragility, and illusion of safety actually makes systems vulnerable to shocks. In this context, robustness means standing up to shocks without compromising the essential features of the system [10].

Most research efforts study how systems can develop, learn, adapt and at the same time persist over time based on the fundamental concept of organizational resilience, which is directly associated with that of sustainability in any complex system. As a result, “resilience” can be understood as a part of a conceptual set together with the idea of sustainability, and ought to be approached from a dynamic perspective depending on variations in time and space. Further, if a system begins to ”lose” resilience, the ”potential for change” increases, that is, the possibilities of moving to a different organizational state or configuration increase, even if the system is subject to small disturbances or disturbances that were previously insignificant or did not produce any adverse effect.

The concepts of resilience and sustainability are directly related to the long-term consequences of transformations and change, and their impact on the future profile of societies, economies and the human system as a whole. Urban systems are complex adaptive innovation ecosystems and, as such, they have the potential for both resilience and sustainability. Resilience is perhaps one of the most important properties to integrate when talking about sustainability. One consequence of this is that complex system transformation is inevitable. Different transformations in different temporal and spatial scales can take infinite directions. In this way, we can say that the transformations do not follow a logical, linear course. Quite the contrary, they can happen under different conditions: continuous, inevitable, gradual, abrupt, local, global, required or not, promoted or unexpected. This leads us to the concept of panarchy.

Panarchy is a conceptual framework to account for the dual, and seemingly contradictory, characteristics of all complex systems – stability and change. It is the study of how economic growth and human development depend on ecosystems and institutions, and how they interact. The panarchy metaphor posits that socio-ecological systems operate at multiple geographic scales and that feedbacks operate both intra- and inter-scale [11]. Systems that operate on small scales can undergo changes in short periods due to the possibility that individual actors can exert great influence; while those that operate on larger scales may require long periods to experience changes considering that a greater number of interactions between a large number of actors will be required. Complexity theory suggests that properties in larger systems generally arise from interactions at lower levels [12].

In a resilient system, individual nodes (individuals, businesses, communities, and even entire countries) are able to draw support and resources from elsewhere but are also self-sufficient in meeting their essential needs in an emergency. However, in our race toward hyper-communication and the globalization of all economic and technological networks in the world, we have forgotten the second part of this postulate [13]. The great problem of a living organization, whatever it may be, is not only that of "functioning", but also that of being able to face errors, uncertainties, and dangers, that is, having strategic and evolutionary aptitudes. The important thing is not only to adapt, but to learn, invent, and create [14].

4 Resilience and Risk

The concept of resilience has turned from a purely descriptive one to one that includes a normative agenda regarding what should be done. Resilience must be seen by governments and organizations as a process, a state, and a quality. It ranges from the global, focused on food security; the national, related to critical infrastructure (energy and water) and the economic sector; and the local, in terms of climate change. Resilience sometimes focuses on individual entities and other times on the resilience of the system. This leads to the question of "resilience of what, to what, and at what scale," where geographers can contribute from their space-time perspective and society-environment systemic approach [15].

It is somewhat surprising that, despite decades of the concept of resilience being addressed in the social sciences, questions of power, governance, and social capital still do not play an important role in theoretical and practical approaches to increase resilience. Building resilience implies the opportunity to incorporate elements related to the historical and socio-political processes that create and maintains social vulnerability, as well as to develop intervention projects that guide cities and societies toward roads less vulnerable pathways [16].

An international policy effort has been undertaken to follow the Sendai Framework for Disaster Risk Reduction 2015-2030, by focusing on improving urban resilience through the planning and development of quality infrastructure. This effort goes hand in hand with the adoption of ecosystem-based approaches and integrated data-driven policies regarding disaster risk reduction and management.

The goal is to reduce vulnerability to disasters, particularly in marginal and disadvantaged neighborhoods. Obviously, the particular conceptualization of risk we utilize in this scenario is critical, and we need to start by briefly discussing the contributions of German sociologist Ulrich Beck.

In highlighting the significance of the idea of risk and the practice of risk management as fundamental components of contemporary society, Beck was ahead of his time. In his work on risk, he reflects on how the forces of globalization, individualization, the gender revolution, underemployment, and global hazards are interwoven and manifest in events like the ecological disaster and the collapse of global financial markets. Beck has examined the concept of "risk calculus," the sociology of risk (i.e., how some interest groups benefit from ”manufactured uncertainty”), and the construction of guesswork in response to crises.

In his Risk Society. Towards a New Modernity (1992) Beck states that ”risk may be defined as a systematic way of dealing with hazards and insecurities induced and introduced by modernization itself” (p. 21). Later in the book he states:

> ”In contrast to all earlier epochs (including industrial society), the risk society is characterized essentially by a lack: the impossibility of an external attribution of hazards. In other words, risks depend on decisions, they are industrially produced and in this sense politically reflexive” (p. 183).

Beck rejects the then conventional idea that risk management ought to be practiced as a merely technocratic and bureaucratic exercise where the views of civil society and citizens are treated with contempt. [17]. His analysis shows some overlap with the debate on ”the limits to growth” that the Club of Rome undertook in the 70s of the last century. The mathematical calculations and probabilistic scenario of World-3 (the computer model with which the Club of Rome analyzed the multiple global interactions between population growth, industrial production, food production, and ecosystem limits) defied cultural definitions of current and tolerable standards of living. The perceived threat then spawned an ad hoc global risk community and study and discussion groups around the world that analyzed the Club of Rome report. Likewise, World-3's simulation of ecological trends challenged many taken-for-granted rules of everyday life; it was not for less, because what the simulation offered was an unprecedented dystopian projection of global decomposition.

Beck, for his part, proposes at the edge of the 21st century a reflexive and constructivist analysis, less mechanistic and adjusted to the parameters of complexity and uncertainty of the socio-political reality, and also to its ideological constructs. Indeed, neither the notion of “limits to growth” nor that of “global risk” can be understood without taking into account the capitalist project. Today capital is presented to us as a Schumpeterian force, quasi-revolutionary, and capable of resolving the antinomies of the global risk society through its hegemony over the future. However, this ideology of power has had to face a paradigm shift in future studies, from ”forecasting” to critical analysis, since predictive and extrapolation tools were not effective in a global risk society.

Beck has defined risk analysis as ”the modern approach to anticipate and control the future consequences of human action” as unintended consequences of radicalized and accelerated modernization. The so-called ”systemic events” (geopolitical and financial crises, Exxon Valdez, the Challenger disaster, bovine spongiform encephalopathy, among many others), staged in the mass media, have paralyzed public consciousness and shown that modern societies were generating risks that they could not control and that threatened their survival.

The growing awareness of the reality of risk has also dramatically altered our perception of time. The future attack – something non-existent by definition – has been displacing the past as an obsession that has a decisive influence on the present, with the consequent distortion in the understanding of the problems of that present and their possible solutions. This change in perspective – from the historical perspective to the universe of projections – is reflected in international risk management, whose genesis lies in finance and insurance systems. The change in corporate planning models towards the construction of scenarios is today practically omnipresent. The popularity of Michael Porter's ”Five Forces” and McKinsey's ”7S” models are a reflection of these altered perceptions.

A risk society is a dappled world, to use Nancy Cartwright's expression [18]. No single elegant theory can account for a world that is not completely ordered: some features are precisely ordered, others are given to rough regularity and still others behave in their own diverse ways. This patchwork makes sense when we realize that laws are very special productions of nature, requiring very special arrangements for their generation. In this context, risk perceptions and materializations contribute to disorder and, on the other hand, warrant a transdisciplinary approach to the dappled world. In this paradigm, there is no longer any trace of the Newtonian universe of order and determinism of the Western modernist project.

The notion of risk and that of resilience are best understood as part of a conceptual set. As Davis has argued, the notion of risk permeates resilience strategies in a fundamental and unavoidable way, since it is essential to design any constructive action that mitigates or minimizes adaptive vulnerabilities instead of exacerbating them [19]. Risk is the essential and foundational element of human and non-human adaptive processes and, therefore, also of complex societies, as Ilya Prigogine persuasively explained [20].

However, the risk does not lie only in the realm of science and the ”factual.” Risk as a readable phenomenon or concern is informed by power and social issues, including who has the right or authority to define risk, how risk is distributed, and who pays for and who benefits from it.

> It is therefore important to avoid the ”tyranny of risk” as a defining principle of action, and understand that risk discourses can be abused to justify oppression, controls on citizenship, the appropriation of the right to territory and other forms of exclusion. This challenges the principles of fairness and justice that should guide civic and professional behavior, both individually and collectively [19].

Similarly, the notion of “resilience” can be misleading and can easily drift towards the ideological, either because the concept can offer an excuse to leave citizens to fend for themselves while governments and markets help each other, or because resilience refers to a desire to return to normality that has been and is the cause of the planetary problems we face, according to Davis. Focusing on resilience often means avoiding difficult questions of power, inequality, and the impact of limited resources on people.

The other way in which the notion of resilience can be ideologically misleading is that it can be conceived in terms of ”getting back to normal” after a disaster, or as a means of restoring system balance after a shock. Thus, embracing resilience can translate into having faith that, with enough attention and adaptive effort, the future can be better, an expectation that needs to be contextualized or nuanced on some way.

5 Complex Adaptive Innovation Ecosystems

Resilience and risk are present in urban systems. Urban systems can be approached as complex adaptive innovation ecosystems. A complex system is made up of various interconnected or interlocking parts whose links create additional information not visible to the observer as a result of the interactions between elements. A complex adaptive system is these parts that generate information, but in turn have the ability to change and learn from experience. Urban systems are complex adaptive innovation ecosystems, that is, networks of people in close proximity exchanging information and opinions, creating new knowledge and interacting, in actor-networks, with matter as well as other forms of human and non-human life. As shown elsewhere,

> “urban complexity can be said to emerge from the decentralized and self-organizing webs, assemblages and networks of transactions and interactions among a wide range of heterogeneous actors, agents and stakeholders that typically occur at multiple scales in dynamic, fuzzy, changing and uncertain urban settings” [21]

These transactions and interactions of cooperation and competition, informed by serendipity and randomness, highlight agents' perceptions, choices, decisions, and preferences [22],]23], [24].

Agents, actors, actants, and stakeholders can be individual, community, city and regional, involving social, economic, and political institutions. Their mutual interactions produce feedback loops that allow the adaptation of individual and group actors and the emergence of phenomena, patterns and outcomes (physical, behavioral, social, economic, ecological, environmental) that cannot be predicted by analyzing the particular webs, assemblages, networks and their constituents and components [25], [26], [27], [28].

A characteristic of life (both human and non-human) in these complex systems is that it is driven by an anti-entropic effort facilitating its adaptation and survival. Such an anti-entropic effort can be viewed as resilience or systemic energy: the ability of any urban system to maintain continuity after shocks or catastrophes while contributing positively to adaptation and transformation. As we shall see, urban resilience is one of the forces working against the entropic risks caused by urban megaprojects. Such a process of adaptation contains a transformative component of contestation against megaprojects. Some disturbances or destabilizations are critical in the transformation of complex systems.

For purposes of illustration, I would like to briefly focus attention on four essential characteristics of complex adaptive systems: emergence, uncertainty, self-organization and transdisciplinarity. Gunderson & Holling (2002) argue that the suppression of any of these factors will inevitably make the system unsustainable over time [29].

- ***Emergence*** refers to the fact that the properties of the system emerge from the interactions of the set of components without being attributable to a particular component. Emergent properties, therefore, are properties of the system and not of the individual components.
- ***Self-organization*** is a feature of complex systems also called spontaneous order; through self-organization, order arises out of the chaos of local interactions among the parts of the system. Characteristically, the process of self-organization needs not any supervision, design or control by any external agent. Self-organization uses the memory of the complex system transformations for the renewal and reorganization process. In this context, knowledge enables access to information, experience, and learning.
- ***Uncertainty*** means the range of possible values within which the true value of the measurement lies, and it is highly dependent on the degree of system complexity. This means that urban systems are undecidable [30]. The greater the degrees of freedom of the system, the greater its probability to generate variations and new interactions, that is, more possibilities. For example, diversity – which provides the sources for the adaptive responses – contributes to system resilience in human settlements and urban systems.
- ***Transdisciplinarity*** is a disposition of observers of complex systems, and an analytical consequence of complexity. It constitutes a strategy to approach and analyze complex systems that recognizes the necessity to open a breach in the territorial closures of the disciplines, multiply exchanges and communications across fields of knowledge. According to Morin (1984), the objective is to conceive not only the complexity of all reality (physical, biological, human, sociological, political), but the reality of complexity [31].

6 From Risks Affecting Megaprojects to Risks Produced by Them

In *Megaprojects and Risk,* Flyvbjerg and his colleagues identify a "megaprojects paradox": that more and more of these projects are being implemented, in spite of their dismal performance record, often with substantial cost overruns and market shortfalls. According to the authors, the reason for such poor performances is that many of the participants in the process have incentives to underestimate costs, overestimate revenues, undervalue environmental impact, and overvalue economic development effects. The authors argue that central problems are lack of accountability and inappropriate risk sharing, which can be improved by reforming the institutional arrangements of decision making and by instituting accountability at the project development and evaluation stages [32].

According to Flyvbjerg et al., innate human biases, such as 'uniqueness bias', undermine the standard assessment tools and processes utilized to evaluate megaprojects, such as Monte Carlo simulations. As an alternative, "reference class forecasting" – based on the work by Kahneman and Tversky [33] – proceeds by collecting data on past megaprojects so that future megaprojects can learn from those real-world case studies. Black swan events also affect megaprojects with devastating effects, due to the fact that megaprojects take very long to complete[1]. Further, the scale and complexity of tasks involved in megaproject planning and construction mean that there are risks originating in a lack of effective communication among stakeholders.

The literature offers many different classifications of risks in megaprojects [34], [35], [36]. At a basic level, one could consider the following:

[1]The statistics of complex systems is the statistics of power laws, where large and extreme events appear much more often than Gaussian statistics predicts.

- ***Task-dependency risks,*** whereby Task P (predecessor) must be finished before Task S (successor) can start. In these dependent situations, a delay to one task will likely impact all future tasks, thereby disrupting the entire project. Modularity has been proposed as a possible solution to isolate and control task-dependency risks.
- ***Communication-related risks.*** Two typical features of megaproject construction are (1) a multi-layered organizational structure and (2) the existence of a significant number of dependencies. Communication risks come not only from the usual human cognitive biases but also from the complex picture created by these two typical features of megaprojects. Communication failures can be due to so-called "Rashomon effect": the same event, process, task or need is described – and understood – in slightly or significantly different ways by different people who were involved.
- ***Regulatory risks.*** This refers to the threats to disrupt project progress derived from regulator requirements (including size of building, health and safety regulations or sanctions for non-compliance). Project leaders need to devise a comprehensive strategy to ensure compliance by staying ahead of regulations and paying close attention, through ther entire megaproject life-cycle, to the regulatory framework and various policies.
- ***Environmental risks.*** Risks related to the environment are acquiring increasing importance in the megaprojects literature. There is a wide range of risks to be considered here: civil society protests in pre-construction, to issues of contamination or pipe discovery during construction, to problems related to maintenance and operations, to weather impacts, to ground conditions not conducive to construction, to bureaucratic probles related to licenses.
- ***External risks.*** These risks exist outside of the project team and organization and they're often more difficult to predict and control. They include many kinds of events derived from political and socio-economic conflict situations, but also processes of policy-making and some of the other routine workings of socio-economic and political systems. External threats must both be identified and categorized before being placed within a risk breakdown structure, paying special attention to their impact on the project plan.

According to Li et al (2021), there are 22 sustainability elements and 75 risk factors in megaprojects, as shown through a survey and fuzzy set methodology. The hierarchy among those risks establishes the following order: (1) economic risks have a high probability, (2) social risks have a high loss, (3) environmental risks have an intermediate probability and loss, and (4) coordination risks have the greatest impact. The researchers found that the three most important risk factors are: construction and installation cost overruns, land acquisition and resettling cost overruns, and information sharing with the public. Let us note that these risks are still risks affecting megaproject planning, construction, and performance [37].

The project management literature has neglected the many kinds of risks and negative outcomes produced by them. This is due to their modeling of megaprojects as closed systems and to their focus on providing insights to contribute to megaproject performance improvement. The "external risks" category above works as a black box and a source of threats for projects, but it is not placed at the center of analysis.

All in all, the project management literature has been portraying an image of megaprojects as improvable and as necessary features in the process of development. In what follows, I'd like to focus on the kinds of risks and outcomes produced by megaprojects as a result of their embeddedness in the polity, economy and society. Megaprojects constitute landscapes of disruption and such disruption is often the cause of systemic disorder, or entropy increase. Let us see what this means.

7 Entropic Risks

One way to understand entropy is as the degree of disorder in a system. Put differently, entropy is a measure of the likelihood of energy and matter being arranged in a particular state. Entropy is inversely related to energy in that the higher the entropy of a system, the less energy is available in the system to do work. As we explore this idea in urban systems and megaprojects, we characterize the entropic risks produced by megaprojects as the disruptive and disorderly impacts of megaprojects in urban areas.

Entropy is a concept that links the microscopic world with macroscopic (systemic) phenomena and defines the degree of disorder in a system. It was first introduced in physics to relate the velocities of particles (microscopic world) with temperature (macroscopic property). The concept helps to describe and analyze large complex systems defined by macroscopic concerns by decision-makers related to the microscopic dynamics of individual elements in the system. In a closed system, entropy will always increase, while open systems, including all environmental and social systems, are able to manage the rate of entropy generation to some degree by maintaining a network structure [36]. Megaprojects can be seen as open systems that remain embedded – networked - in the polity, economy, and society where they are built. The entropic risks they cause can thus be managed – or contested.

Other real-life complex systems are networked systems. Food webs, for example, are networks of species feeding on one another. Supply chains are networks of firms supplying intermediate goods to each other. Urban systems are complex adaptive innovation ecosystems - networks of people in close proximity exchanging information and opinions, creating new knowledge and interacting, in actor-networks, with the matter as well as other forms of human and non-human life. A characteristic of life (both human and non-human) in these complex systems is that it is driven by an anti-entropic effort facilitating its adaptation and survival. In systems where the number of network elements is large and the connections are subject to so many factors that they can be seen as random to some degree, the concept of (information) entropy becomes applicable.

In an analysis of global commodity trade (showing a complex network structure that arises from bilateral and multilateral trade agreements) trade using information entropy, Kharrazi and colleagues found that trade agreements can make commodity trade networks more efficient and lead to more rapid growth in the volume of trade. The research showed that gains take a toll on resilience levels, particularly to economic shocks, of which a prominent example is the 2008 financial crisis. Perhaps counter-intuitively, the results also showed that networks that had greater redundancies did not have to sacrifice growth [38]. This is an example of how compensatory mechanisms are present between forms and patterns of risk and resilience. As Davis argued, adaptive strategies in some domains may actually reinforce structural problems that create risks in other domains [19].

The notion of entropy can also be applied to systems that are both networked and path-dependent, as Thurner and colleagues have done. This is an application of the concept to complex human-earth systems. In their study, the researchers focused on situations with a winner-takes-all dynamic. In these situations simple path-dependent systems can indeed be studied by means of developed generalized entropy. Winner-takes-all dynamics appear in many socioeconomic and environmental contexts, which show strong reinforcement and hence “fat tailed” distributions. This in turn implies that catastrophic events with high impacts happen more often than common sense suggests [39].

8 Disruption and Disorder by Megaprojects

Some of these features are present in the case of megaprojects. Megaprojects can be characterized as complex systems (organizationally and scale-wise) embedded in complex urban, political and socio-economic systems. They are certainly path-dependent and open systems, where entropic risks (as in fat-tailed distributions) happen often, particularly when we look at one of their emergent properties: the disruptive and disorderly impacts (materialized risks) they have in urban areas.

The question of impacts can be approached from the notion of unintended consequences, a term popularized by Robert K. Merton, as we know, and crucial to understand impacts and consequences of human action. Consider, for example, that almost all environmental problems, from chemical pollution to global warming, are the unintended consequences of the application of modern technologies. Unintended consequences are outcomes of a purposeful action that are not planned, intended, or foreseen. They can be considered emergent properties in a system.

We could classify unintended consequences into three groups: unexpected benefits (serendipity or windfall), unexpected drawbacks (detrimental to desired effects) and perverse results (contrary to intentions). However, a more relevant classification for our purposes is the duality disruptive/disorderly complexity, which can be aligned with perverse results.

Megaproject complexity triggers a substantial degree of disruptive capacity in a variety of aspects and dimensions. Thus, urban megaprojects, regardless of context, constitute landscapes of disruption and have an intrinsic potential (often realized) to elicit substantial controversy and criticism that fundamentally questions the parameters of the projects as envisioned and publicly presented by their promoters.

By highlighting the disruptive character of megaprojects, we specifically claim that megaprojects are disorderly and contentious enterprises.

> "They are disorderly enterprises in that they substantially modify the physical appearance of cities and their urban fabric, often triggering socio-economic imbalances and realignments in urban power arrangements in growth machines and civil society. Megaprojects also require substantial financial investments which, in practice, may drain out local budgets and substantially alter the priorities of local governments" [40].

Because of both their disruptive and disorderly complexity, megaprojects are contentious enterprises. As a result, one often finds in many cities a widespread perception among urbanites that these structures are harmful to their cities.

> "The complex make-up of stakeholders with conflicting interests in their planning, construction, management and governance often triggers major obstacles for megaproject implementation, the strategic misrepresentation of costs and benefits, optimism bias among planners and promoters about megaproject risks and benefits, and a myriad of negative socio-economic, spatial and environmental impacts" [40].

There is substantial evidence showing the above features of megaprojects. The causes vary from case to case: autocratic rule (e.g., Istanbul's urban megaprojects), erosion of intent (e.g., Sydney's Bangaroo) or misrepresentation of targets (e.g., Hong Kong's West Kowloon). In all cases, however, disruption and disorder are perverse results of megaprojects, contrary to intent. Disruptive and disorderly complexity are emergent properties of megaprojects, manifested in their impacts.

A better management of megaprojects, based for example on avoiding human cognitive bias among planners, developers and managers (as proposed by project management authors) could improve megaproject performance. However, it is unlikely that such a strategy cancel the disruptive and disorderly impacts that emerge after megaproject implementation. It is reasonable that any application of optimal rationality models that disregards contextual conditions as well as potential ecological, socio-economic and equity impacts would not prevent a megaproject from negatively disrupting the affected communities in major ways, particularly when communities and citizens are excluded from key stakeholder deliberations in the planning process.

9 Resilience and Contestation Against Disruptive Megaprojects

A. Resilience

Given that, by and large, the benefits of megaprojects accrue to a small portion of the population in the urban areas where they are built, most resident need to come up with adaptation strategies as a consequence of the disruptions and disorder caused by large urban projects. These can be considered resilience strategies. According to Davis, to the extent that urban, social, economic and environmental ecologies are interconnected, both at the local level and through territories linking cities with regions, mega-regions and other (economic and governance) units, any resilience strategy must be based on an appreciation of the entire urban ecosystem and its properties as an integrated system in a larger ecology.

And this appreciation must start from the consideration of the systemic risks that determine the adaptive processes of the ecosystems [19].

This would lead us to examine the interrelationships and compensatory mechanisms between forms and patterns of risk and resilience as we consider megaprojects embedded in urban systems: not only between different residents or locations in the same city, but also in terms of immediate versus long-term gains in liveability, so that adaptive strategies in some domains (e.g. environment) may actually reinforce structural problems that create risks in other domains (e.g. inequality).

Davis argues that one needs to take into account the interdependencies between elements of the system and disaggregate adaptation strategies in order to understand when adaptive responses to vulnerabilities or crises will establish a path towards a better future. Put another way, under what specific conditions will adaptations, whether made voluntarily by citizens, imposed by government authorities, or crafted by planners and designers, decrease rather than increase vulnerability?

B. Contestation

Grassroots efforts in community revitalization can reshape the public processes and institutional framework involving the design and development of public space. This would need to include urban megaprojects in the planning phase. Hou & Rios suggest that the current participatory model involving professionals and users needs to be expanded to take into account three sets of factors [41]: (1) mobilization structure (people's engagement in collective action), (2) political opportunity (likelihood of access to power) and (3) cultural framing (shared meanings and definitions). Some researchers have argued that consensus building creates three types of shared capital among the participants: social, intellectual, and political [42]. Social capital facilitates discussions; intellectual capital enables the transformation of information into actions; political capital makes it possible to transform urban reality.

Successful grassroots-based political action can modify the intent and plans of urban growth machines. These routinely favor megaproject construction as an allegedly beneficial strategy for urban prosperity while megaprojects instead trigger processes of gentrification, displacement, exclusion, and expulsion [43]. Besides grassroots political action, growth machines need to be ideologically confronted in a forceful manner with notions of degrowth, based on ideas from ecological economics, political ecology, and environmental justice. By questioning development – and megaprojects as privileged particles in the development process – degrowth theories emphasize the need to reduce production and consumption globally. The intellectual predecessor of this movement is the "limits to growth" argument put forward in the 1970s by the Club of Rome, which questioned the possibility of unlimited or infinite growth in a planet of limited resources and a growing population.

10 Conclusion: Towards Sustainable Megaprojects

This paper has defined urban systems and megaprojects as complex adaptive innovation ecosystems, that is, networks of people in close proximity exchanging information and opinions, creating new knowledge and interacting, in actor-networks, with matter as well as other forms of human and non-human life. Megaprojects can be characterized as complex systems (organizationally and scale-wise) embedded in complex urban, political and socio-economic systems.

They are path-dependent and open systems, where entropic risks (as in fat tailed distributions) happen often, particularly when we look at one of their emergent properties: the disruptive and disorderly impacts (materialized risks) they have in urban areas. A characteristic of life (both human and non-human) in these complex systems is that it is driven by an anti-entropic effort facilitating its adaptation and survival. Such an anti-entropic effort can be viewed as resilience or systemic energy: the ability of any urban system to maintain continuity after shocks or catastrophes while contributing positively to adaptation and transformation. Urban resilience is tied to sustainability in that it is one of the forces working against the entropic risks caused by urban megaprojects.

Similarly, contesting urban megaprojects would work towards a sustainability goal by integrating communities into the megaprojects' planning process. Vojnovic (2014) argues that the three pillars of sustainable development, namely society, economy, and environment can be equally promoted through the concepts of inter-generational and intra-generational equity [44]. The first is concerned with maintaining the quality of natural ecological systems and their services over time, while the second is based on promoting the equitable access to resources within current generations, providing human populations with basic needs.

Human settlements can be defined as sustainable if they are planned and executed to take into account the capacity, suitability, resistance, diversity and balance of their surrounding ecosystem. We consider sustainability as an organic process that includes the environment, the economy and the community: form and efficiency – environmental factors in design, architecture, engineering and construction– as well as policies – urban plans and practices that explicitly aim to maintain and improve the economic well-being of citizens.

Even if environmentalism is receiving significant attention, also from the perspective of urbanism, it is just one of the components of any comprehensive strategy for sustainability. As an illustration of this argument, let us consider the fact that green and high tech capitalism claim to contribute to environmental sustainability, while neglecting sustainability's socio-economic dimension. In order to plan and build sustainable megaprojects we need a multidimensional systems approach, based on transdisciplinarity, and a new knowledge generation agenda vis-à-vis the urgency to understand the challenges and opportunities in a rapidly urbanizing world. This effort would need to factor in the idea that both "cities" and "nature" belong to the realm of organized complexity and thus the notion of an "urban ecology" would deal with the emergence and self-organizing power of complex adaptive systems. This, in turn, would entail developing a non-anthropocentric notion of sustainability, a task that goes beyond the objectives of this paper.

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