Analyzing Inverse Infrastructures using a Complex Adaptive Systems Perspective

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Abstract. The number of inverse infrastructures (Vree, 2003), that is, user-driven and self-organizing infrastructures, is rising and unsettling policies that are foremost tailored to deal with large-scale and centrally-governed infrastructures (Egyedi et al., 2012). To better understand and address this mismatch, Van den Berg (2012) has developed a complex adaptive systems (CAS) framework for analyzing inverse infrastructures. It is based on and well-fits CASs in physics, mathematics and biology. In this paper we explore the framework’s applicability to three inverse infrastructures, i.e.: Wikipedia (Davis and Nikolic, 2012), citizen-driven waste paper collection (De Jong and Mulder, 2012), and the user-driven roll-out of local glass fiber networks (Weijers, 2012; Nederkoorn, 2012). Applying it reveals that, while the framework’s most basic elements can be identified rather straightforwardly, other elements are often more difficult to identify in human CASs. Our tentative conclusion is that (i) the framework is a good starting point for analyzing inverse infrastructures, and (ii) more case studies are needed to fully understand the conditions under which self-organized emergent behavior of complex infrastructures can be observed.

Keywords. Inverse infrastructures, self-organization, user-driven, CAS, community networks, Wikipedia, waste paper collection, citizen-driven glass fiber networks

1 Introduction

In recent years the number of user-driven, self-organizing and decentralized infrastructures seems to have risen sharply. This is most evident in the domain of Information and Communication Technologies (ICT). Examples are the Internet (Vree, 2003), Wikipedia (Nikolic and Davis, 2012), social media facilitated networks (Boyd and Ellison, 2007; e.g., Myspace, Facebook and Hyves), city-wide Wi-Fi networks (Verhaegh and Van Oost, 2012; Lemstra et al., 2010), peer-to-peer networks for exchanging digital content (e.g. Napster and BitTorrent; Egyedi et al., 2007). But this infrastructure phenomenon is argued to take place in other sectors as well (e.g. energy cooperatives; Kamp, 2012; water supply and sanitation, Correlje and Schuetze, 2012).

Drawing on the word invert – to turn upside down – Vree (2003) coins them as inverse infrastructures “…because they display general patterns of emergence [emphasis by TE/JB] and development that are opposite in nature from those of large-
scale infrastructures familiar to us today” (Egyedi et al. 2012, p.3). The latter Large Technical Systems (LTSs; Hughes, 1983) are typically top-down developed and centrally controlled by governing bodies or service providers, while inverse infrastructures are typically developed bottom-up and decentrally controlled. Moreover, “[t]he inverse pattern is marked by bottom-up investments made by individuals and companies rather than top-down government funding. They are not designed according to a predefined specification or blueprint, as for example high-speed rail infrastructures, and often appear to emerge spontaneously. Although inverse initiatives are not without aim or direction, given their developmental characteristics, their outcomes are less predictable than those of their more designed counterparts.” (Egyedi et al., 2012, p.3)

What makes inverse infrastructures salient is that they emerge in a context in which, first of all, top-down developed LTSs have been dominant for decades. Current policies, regulation and other institutional arrangements have been tailored to support the operation of these dominant LTSs. As a result a mismatch is arising between inverse practices and LTS-oriented policy and regulation. This becomes manifest in, for example, (i) unsuccessful attempts to police Internet content (e.g. attempts to contain and control WikiLeaks content), (ii) hesitance towards arranging buy-back tariffs for decentralized wind energy providers, and (iii) active hindrance by incumbents, supported by government, of inverse initiatives for basic telecommunication services in developing countries (Westerveld, 2012).

Second, inverse infrastructures emerge in a context in which – developing countries excepted (Westerveld, 2012; Correlje and Schuetze, 2012) – similar services are already offered by public authorities (e.g. water supply) or private companies (e.g. energy and telecommunication). For example, volunteers initiated the freely accessible city-wide Wi-Fi network of Wireless Leiden at a time when commercial wireless Internet access was already available (Verhaegh and Van Oost, 2012).1 Such situations give rise to new questions such as: Should citizen-driven inverse infrastructures like city-wide wireless networks be subjected to the same policy as commercial companies (e.g. liability for malfunction and responsibility for monitoring)? How should policy deal with a situation in which infrastructure components are user-owned but ownership of the infrastructure is not clear? The increasing use of inverse infrastructure services in society requires new and more adaptive policies. To systematically address these challenges, however, first a better understanding is needed of this relatively new phenomenon. The latter is the aim of this paper.

To analyze inverse infrastructures, we further explore a line of reasoning developed by Van den Berg (2012). Triggered by the notion of self-organization, a key characteristic of inverse infrastructures, he interprets inverse infrastructures as Complex Adaptive Systems (CASs) that “emerge at the edge of order and chaos” (Van den Berg, 2012). CASs are thought to originate from interactions between many, relatively simple entities or agents. If the circumstances change, the system immediately adapts by spontaneously and automatically adopting a new state. Van

1 Their emergence in domains dominated by large-scale service providers distinguishes them from the early history of infrastructure LTSs, which was often also user- or community-driven (Egyedi et al., 2012).
den Berg has developed a theoretical framework to address the question under which circumstances people spontaneously self-organize such that complex inverse infrastructures emerge (Van den Berg, 2012, p.18). In this paper we examine the framework’s applicability and robustness using three inverse infrastructure cases: an inverse knowledge infrastructure (Wikipedia; Nikolic and Davis, 2012), a citizen-driven infrastructure for waste paper collection (De Jong and Mulder, 2012), and a user-driven local cable network roll-out (Weijers, 2012; Nederkoorn, 2012).

In the following we introduce the CAS framework (section 2) and apply it to the cases (section 3). We discuss our findings on framework’s applicability in section 4. Conclusions are drawn and recommendation are made in section 5.

2 Complex Adaptive System Framework

Since the mid-1980s, a rich body of multidisciplinary studies on Complex Adaptive Systems has been written on emergent – as opposed to pre-determined – systems behavior, and self-organizing and adaptive systems (e.g. Gell-Mann, 1994; Holland, 1995; Dooley, 1996). While a discussion thereof falls outside the scope of this paper, the CAS studies in the fields of physics, mathematics and biology, in particular, inspired Van den Berg’s analytic framework.

Van den Berg (2012, p.27) hypothesizes that five basic CAS elements are crucial to analyze and understand the sometimes spontaneous emergence of complex, potentially evolving, global (in contrast to local) patterns like inverse infrastructures:

1. CASs consists of many basic components (‘agents’) that all have a certain autonomy (for example, particles, ants, humans);
2. A mechanism is in place for the agents to communicate (for example, forces between particles as studied in physics, pheromone delivery by ants);
3. A driving principle or aim is present that underlies the system’s self-organization (like energy minimization in physics, or an incentive structure for people);
4. To show complex behavior, the system should be in a state of delicate balance at the edge of order and chaos (in physics: this occurs at critical temperatures where magnetic forces are in balance with entropy enhancing thermal fluctuations). This state is often the most productive one, according to Fryer (2011), but it usually does not persist permanently;
5. A changing context or changing internal interactions between system components may make the system behave differently (i.e., adapt) over time and pass through ordered (stable), periodic, chaotic and complex states. Complex states with different emergent structures can sometimes be observed at different critical balance points.

To illustrate Van den Berg’s CAS framework, we quote him on the behavior of an ant colony looking for food, one of the CASs on which he based his framework. “In ant colonies an aromatic substance, termed ‘pheromone’, is the communication mechanism: if an ant has good news (e.g. it just discovered a new food source), it delivers a large amount of the pheromone on its way home, hereby trying to seduce
other ants to choose this route during their search: this concerns global (non-local) information. However, each ant also takes local information into account, collected through its own inspection of its immediate environment. Overall, each ant makes route decisions according to a probability distribution that is calculated using both the local and the global information sources. If a few ants accidentally discover a new food source, they will deliver a lot of pheromone on the path to their nest, a signal that will be picked up by a growing number of ants. As a consequence, the collective behavior of all ants will soon end up in a short path that will be chosen by the ants that are searching for food. Since the pheromone evaporates over time, when the food source becomes exhausted and ants stop delivering new pheromone, the ants return to their behavior of a random search, resulting in the global exploration of their environment. (…) A remarkable observation is that the ‘most productive’ search state is that at the edge of order and chaos, where individual ants make search decisions such that the colony as a whole is able to discover quickly a newly available food source. (…) The crux is to find the right balance, during the search for an optimal solution, between ‘exploitation of what is already known’ (in an ordered regime) and ‘exploration of what is not yet known’ (in a chaotic/random regime).” (Van den Berg 2012, pp.25-26)

Extrapolating the framework to analyze the emergence of critical states in CASs of a human nature is shown to be more difficult than in non-human CASs due to the highly dynamic and complex interactions among humans (Van den Berg 2012, p. 33). In the following, we take up this challenge and test the applicability of Van den Berg’s framework for inverse infrastructures, the purpose for which it was designed.

3 CAS Analysis of Inverse Infrastructure Cases

In the following we analyze and describe three cases of inverse infrastructures in different sectors using the basic elements identified in Van den Berg’s CAS framework: agents, interaction mechanisms, driving principles (i.e., incentives for self-organization), the state at the edge of order and chaos, and the CAS’s dynamic context and changing internal interactions.

3.1 Wikipedia

Wikipedia is a user-driven, easily accessible Internet-based encyclopedia that offers information in an unprecedented number of areas. Its development and maintenance depends on voluntary contributions.

Nikolic and Davis (2012, p.117), from whose study we heavily draw in this section, already note that Wikipedia can be viewed as a complex adaptive system. In this CAS the primary agents are the contributing volunteers (aside from bots, the small programs that are used to help maintain the system). They communicate (read and write) via the editorial structure of the Wiki-platform. According to Nikolic and Davis, the raw material that Wikipedia consists of is the free cognitive energy of the contributors- i.e., their ‘cognitive surplus’ (Shirky, 2008). The contributors may self-organize for different reasons (Nikolic and Davis 2012, p.117), for example, because Wikipedia serves their own need for knowledge; for the satisfaction of contributing
(altruism) and the rewarding experience of learning from each other (reciprocity); because it allows one to identify with a community or increase one’s reputation (e.g., respect and appreciation); and for the feeling of being intellectually autonomous (e.g., by taking ownership of entries; Kuznetsov, 2006).

In addition, Nikolic and Davis (2012) discern mechanisms that trigger and facilitate self-organization, such as the self-reinforcing effect of participating (i.e., the more one contributes, the more others are also likely to contribute) and network effects (i.e. the increase in the infrastructural value of the wiki with every new participant); and favorable conditions for self-organization. As Vree (2003) already noted, a key condition for the emergence of inverse infrastructures is that the threshold to participate and contribute (i.e., transaction costs) is low. This is the case for Wikipedia. The required tools of Internet and wiki-software are overall easily available and accessible. Likewise possible changes in the internal editing process (e.g. reducing ease of contributing content) or reduced accessibility of Internet in the future may pose threats to its survival.

Under certain circumstances “a wiki can collect and productively harness the cognitive energy of users into an emergent knowledge structure” (Nikolic and Davis, 2012, p.117). The Wikipedia-platform together with the largely trust-based editing process channel the contributors’ cognitive surplus (Shirky, 2008). Thus, a dynamic knowledge infrastructure emerges ‘at the edge of order and chaos’ (Van den Berg, 2012). It emerges on the edge between, on the one hand, the traditional order of existing (paper-based) encyclopedia (i.e., centrally coordinated efforts that center on hierarchically structured knowledge); and the set of unrelated knowledge entities (e.g., the chaos of Internet pages), on the other. As such Wikipedia could be understood as representing the most productive state of balance between an ordered regime (hierarchically ordered knowledge) and a random regime (the chaos of unrelated, or at least badly structured, knowledge on the Internet).

### 3.2 Citizen-driven waste paper separation and collection

Citizen-driven waste paper separation and collection in the Netherlands between the end of the second world war (1945) up to the present (2010) is an inverse infrastructure of longer standing (De Jong & Mulder, 2012). Instigated by the scarcity of raw material after the war, the Dutch government called on citizens to help the country by separating waste paper from other residential waste. In a society in which sports clubs, schools and shops typically belonged to one of the three societal pillars (i.e., protestant, catholic or socialist), volunteers – mostly children - would collect the waste paper door-to-door and bring it to their sports club, school or church to sell it to tradesmen. The money earned would typically be used by the organization to organize extra activities.

Over the years the societal context changed. The motive of citizens to separate and collect waste shifted from addressing the scarcity of raw material and supporting one’s own pillar, to addressing environmental concerns. Moreover, the rising prices for waste paper on the world market triggered industrial interest in recycling. International industrialization in waste paper handling spread (e.g. technology developments in handling equipment and ink extraction) and efficiency arguments were gaining prominence. As other countries became aware of this potentially
lucrative Dutch export product and the number of providers grew internationally, the world trade prices for waste paper dropped. Low prices threatened the sustainability of local community infrastructures for waste paper handling. To help them survive and to maintain the political support of citizens, the Dutch government stepped in and guaranteed a minimum price for waste paper (De Jong and Mulder, 2012).

The ‘agents’ in this inverse infrastructure, the residential citizens and members of volunteer organizations separate their waste to contribute to society at large (e.g. national campaign for post war reconstruction) and to support local volunteer organizations. They primarily seem to be driven by a feeling of community and a wish to ‘do the right thing’ (interaction mechanism: sense of community and social relatedness). This reflects an ‘appropriate cognitive distance’ (Van den Berg 2012, p. 22) for the emergence of self-organization.

In addition, the members of volunteer organizations are motivated by the extra source of income for their organization and possibly the local rivalry between sport clubs, schools and the societal ‘pillars’ (Catholics, Protestants, Socialists). The latter form the linking pin in the waste paper value chain: the volunteers are part of different local communities (family, neighborhood, church) and play on these memberships to harvest more waste paper. For the volunteer collectors - and thus also for their residential ‘suppliers’ - the earnings for waste paper collection are a crucial incentive for triggering self-organization ‘at the edge of order and chaos’. ‘Chaos’ could in this case be equaled to the absence of waste paper collection (i.e. treating waste paper as garbage and not separating it) or to collection and trading by individuals; while centralized collection and trading by a municipality or commercial party could be seen as ‘order’. We hypothesize that, without the incentive of sales earnings and (compensating) price interventions from government, the self-organizing system would dissolve and lead to no recycling of waste paper or centralized (un)differentiated waste handling (paper, glass, plastics, etc.) by municipalities or commercial companies.

3.3 Citizen-Driven Neighborhood Broadband Network

Since 2008, the Hazenkamp neighborhood in the city of Nijmegen has its own citizen-driven and self-governed glass fiber network for broadband Internet (Weijers, 2012; Nederkoorn, 2012) - despite lack of interest from dominant telecom providers. 66% of the residents are connected (Glazenkamp, 2012). The network is leased from a commercial provider by the Glazenkamp Foundation, a resident-driven organization run by volunteers who also support residents in case of conflicts with the network provider. The contractual agreement between the foundation and the provider ensures continuity and a minimum level of maintenance by specifying that a yearly amount of the provider’s earnings is to be spent on (volunteer) work that keeps Glazenkamp running.

In the words of the CAS framework, in this case the ‘agents’ are the active residents of Hazenkamp. The initiative for Glazenkamp was taken in 2002 by two such residents, so-called ‘expert users’, who had previously been involved in organizing the roll-out of a glass fiber network between the Nijmegen university, student accommodation, the Surf foundation (a collaborative organization for breakthrough ICT innovations in higher education), and certain municipal services
such as the social service and the fire brigade. Their incentive to self-organize was to get affordable high bandwidth Internet access at home. Together with a neighbor they initiated a feasibility study (finalized in 2004) and a demonstration project with twenty-two connected homes (finalized in 2006) using seed money via the municipality from the ministry of Economic Affairs. These helped to convince other residents to participate in the project and create enough demand to make it worthwhile for a provider to invest and accept exploitation risks. The company that decided to take the risk and build the local network required that at least 40% of the residents would subscribe. The board of the Glazenkamp foundation started a ‘subscription’ campaign with help of the municipality. ‘Digeware’ parties (analogous to Tupperware parties) were held to show people what was to be gained. Residents were informed through volunteer ‘ambassadors’ for the project, meetings, posters, folders, website, local paper, radio broadcasts, etc. That is, a mix of face-to-face, electronic and paper-based media was used to communicate with other residents. Geographical and social proximity is hypothesized to have facilitated interaction.

Apart from residents strong interest in broadband access, subsequent similar initiatives in other areas of Nijmegen show, according to one of the initiators, Boudewijn Nederkoorn, that there are at least two other incentives /catalysts for self-organization, i.e. community feeling and contacts with neighbors (which appears to be less in high-rise apartment buildings than in low-rise buildings); and ownership of a house (in one’s own house such access is one’s own responsibility, while in rented apartments access is more likely to be seen as the responsibility of the house owner).

In this case the inverse infrastructure (organizing and bundling demand-side interest in local glass fiber network) emerges on the edge of (that is: ‘supply-driven glass fiber coverage’ as the ordering principle - in the Hazenkamp neighborhood this meant lack of coverage) and chaos (here: individual solutions to market demand). Erecting the Glazenkamp foundation and signing a contract with a telecom provider for multiple years institutionalize and thereby stabilize the inverse infrastructure. The contract and guaranteed money for maintenance aid in addressing two important potential sources of instability, i.e., withdrawal of the provider and of volunteer support. That is, they have a stabilizing effect on the CAS’s dynamic context.

4. Applicability of the Framework

Evaluating the applicability of the framework to the three inverse infrastructures described above, we observe that identification of the five CAS elements across the three inverse infrastructures appears to be possible but that it is not a trivial exercise. Identifying which human agents initiate and contribute to self-organization, what drives them and how they interact is a rather straightforward process. However, (i) compared to non-human CASs, in human CASs the element ‘interaction mechanism’ is often not very distinctive. A potential limitless variety of communication means are used by humans which (may) have multiple meanings. This thwarts interpretation of the communication effect: where the finding of a food source increases pheromone production of ants on their way home and results in a collective run on this food source, the precise relationship between human communication and the complex
emergent infrastructure pattern is less straightforward (e.g., in the ‘waste paper’ and ‘glass fiber’ cases) and, thus, requires in depth study.

In addition, (ii) in contrast to non-human CASs, the motives and incentives that underlie human behavior are much more divers, complex (i.e. interwoven and dynamic), and layered. Table 1 lists a number of incentives. In addition, however, the cases point to social (incentive) structures that drive the human interactions (i.e., ‘driving principle’) and seem to play a significant role in CAS emergence. Examples are: a sense of community and social relatedness in the ‘waste paper’ case, and geographical and social proximity in the ‘glass fiber’ case. This suggests that the notion of incentive structure mentioned in Van den Berg’s CAS framework deserves more elaboration in terms of ‘social (incentive) structure’.

Table 1. Basic elements of complex adaptive infrastructures systems.

<table>
<thead>
<tr>
<th>Inverse infrastructure</th>
<th>Intelligent agents</th>
<th>Interaction Mechanism</th>
<th>Driving Principle/Incentive</th>
<th>Edge of Order and Chaos</th>
<th>Dynamic Context/Internal Interactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wikipedia</td>
<td>Volunteer Contributors Bots (software)</td>
<td>Reading and writing via the editorial structure of the Wikipedia platform</td>
<td>Cognitive Surplus Self-interest in content Altruism Reciprocity Community Reputation Intellectual autonomy</td>
<td>Order: existing hierarchically structured encyclopedia Chaos: unrelated knowledge on Internet</td>
<td>Accessibility of Internet Ease of contributing content Quality of contributions</td>
</tr>
</tbody>
</table>

| Citizen-driven waste paper separation and collection | Residential Citizens (separation) Citizen volunteers (collection) | Mix of face-to-face, electronic and paper-based media | Extra source of income for own community Contribution to the post-war reconstruction effort Lessen the environmental burden | Chaos: no/individual collection Order: centralized collection | Price fluctuations in the waste paper trade De- pillarization of Dutch society |

| Community-driven glass fiber neighborhood network Glazenkamp | Neighborhood residents Business case study, pilot demonstration, ‘Digware’ parties, etc. | Affordable high bandwidth Internet access at home. | Order: supply-driven glass fiber coverage Chaos: individual demand-side solutions | Glass fiber market Involvement initiators |

Moreover, (iii) the precise formulation of the balanced state, that of ‘being at the edge of order and chaos’, is truly a difficult one. This is partly because ‘seeing order’ lies in the eye of the beholder. As a heuristic, centrally governed structures or ‘the status quo’ may well best identify the ‘ordered state’ in the context of user-driven, self-organizing infrastructures. However, possibly less obvious dimensions are more significant. This choice in interpreting human CASs needs further study.
Finally, (iv) the ‘openness’ of human CASs means that the dynamics of the context of inverse infrastructures can be quite diverse as well. Extensive research and possibly a dose of pragmatism are needed to arrive at a well-motivated CAS boundary.

A few lessons can be learned from the above-given observations. Human-activity based inverse infrastructures are even more complex than the non-human CASs studied in mathematics, physics, and biology. It is therefore important, as the starting point of analysis, to define the human inverse infrastructure under study as precisely as possible; this can be an extensive description of all kinds of aspects of the system, including, of course, a precise formulation of the emergent phenomenon. Next, the framework offers a structured means for identifying key CAS characteristics. Based on this, for each specific case, an overall picture is created describing the emergent phenomenon in its concrete context in terms of the five basic framework elements. However, to identify the necessary and sufficient conditions that explain the causes of the observed emergent phenomenon, is still a bridge too far.

To address this challenge, we think one should proceed as follows. First, a large number of inverse infrastructures should be analyzed based on the CAS framework used in our study - possibly with some elaboration of the framework like that of social (incentive) structures as drivers of human interaction. This will yield a lot of descriptions and images of emergent behavior at the edge of order and chaos. By doing a comparative study, we might then be able to induce which conditions are necessary and possibly even sufficient to observe emergent inverse infrastructures.

5. Conclusions

We tentatively conclude that the framework is a good starting point for analyzing inverse infrastructures. It offers a useful means to systematically seek understanding of emergent inverse infrastructures. To further the applicability of the CAS framework and the understanding of inverse infrastructures, we recommend that (i) the framework needs some elaboration at certain points, e.g., around social (incentive) structures as drivers of human interaction; and (ii) research should be done on the ambiguity of the role of interaction mechanisms in human CASs and dilemmas posed by the system openness of human CASs. Moreover, and most importantly, many case studies are needed to end up with a deep understanding of the conditions under which self-organized emergent behavior of complex infrastructures can be observed.

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