CIVIL INFRASTRUCTURE AS A CHAOTIC SOCIO-TECHNICAL SYSTEM: HOW CAN INFORMATION SYSTEMS SUPPORT COLLABORATIVE INNOVATION

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ABSTRACT

The web is no longer just a media or communication outlet. It is morphing into a socioeconomic fact of life. The advancement of semantic web and the increased penetration of social are empowering people to harness their collective intelligence to create, collaborate and trade in knowledge. Starting from this observation, a scenario for community-based, knowledge-intensive environment for development and management of civil infrastructure is presented. The proposed scenario was inspired by similar trends in other industries and analysis of recent cases where the web influenced civil infrastructure development and planning. The proposed scenario embraces open, bottom-up decision making process where communities are empowered to develop, share and test ideas for infrastructure projects. Engineers and public officials are responsible for supporting the self-organizing emergence of these, expectedly, chaotic ideas. Putting the development process on the edge of chaos supports innovation and does not mean randomness. Consequently, it should be embraced by all. Accordingly, our analysis tools have to be geared more towards analysis of networks of people and their ideas; support autonomous evolutionary approaches that can collate chaotic ideas; providing communities with semantic-enabled analysis tools to support the generation of ideas; encourage the evolution of infrastructure Apps; and provide platforms for their dynamic linkage.

Keywords: civil infrastructure, collective intelligence, socio-technical system, networked knowledge, information system, social and semantic web.

1. INTRODUCTION

This paper presents the results of a research project which aimed at conceptualizing a vision for the future of infrastructure development and decision making in light of emerging socioeconomic and technical forces that are shaping our society—mainly the increasing desire for sustainability, globalization, e-society, and the knowledge economy. The objective of this rather hypothetical (and certainly fallible) scenario is not to predict the future. Rather, to stimulate a discussion about such future, with specific emphasis on the role of engineers in the evolving knowledge economy.

Metaphorically, in the typical mode of operation of infrastructure, the customer (the general public) delegates decision powers to public officials. Public officials retain engineers to provide professional technical services. i.e. analysis, planning, design, and project management services to realize and operate infrastructure services. Typically, the general public presents its macro-level "value" requirements during the election of public officials (by selecting left or right leaning administrations); and provides its micro-level "value" assessment of each project through the public consultation process. The public do not play a strong part in the idea generation—especially at the micro-level or the technical level.

It is argued that the chain of command (and, consequently, the business value to be presented by public officials and engineers) is poised to change. This is due to the increasing role of non-technical issues such as environmental and social issue (the hallmark of sustainability) in project development and evaluation; the prevalence of e-citizen and e-democracy trends (which empower people to participate, almost in real time, in general events); and the emergence of powerful tools to harness collective social intelligence. It is hypothesized that, like other issuers of life, the public will want to be the direct source of all ideas—technical and non-technical. They will want public officials and engineers to use their professional knowledge in technology and business to help them analyze and collate their own ideas, resolve conflicts, and professionally produce their ideas.

The fact that the public wants to be or should be the source of non-technical ideas is not strange. It has been sought by professionals and called for (or claimed) by politicians. Lately, engagement of the public in this aspect (and level) of decision making has been boosted by the social web tools. Communities firmly believe they can do everything “bottom-up”. The belief in the collective power (and intelligence) of people is extending to technical issues. As a case in point, in 2004, the Mayor of Paris announced renovation plans for the Les Halles Garden. At first the local residents' association objected due to the inadequate level of residents’ involvement, so as a counter-effort a virtual reality site named ‘Second Life’ was created. This innovative initiative encouraged locals to create avatars (virtual-doubles) of themselves; who would then compete to design their own garden. Finally, as an incentive, the winning project would receive 275,000 lindens (the e-currency of Second Life). The winning design was developed by a French group with “global” virtual help from Canada, China, and Germany (see L’association ACCOMPLIR 2010).

Given the increasing level of community activism and the new business mentality of “there is an App for that”, it is fair to expect that community involvement in technical issues will not be limited to cosmetic or graphical features (the layout of park, the route of a road, or the shape or material of a bridge). It is feasible that new software services can be developed to help communities study the impacts of their ideas of new road on traffic jams, CO2 emissions, noise levels, business activities, or housing prices. Tools for such analyses exist in the professional or academic arenas. Using service oriented architecture (SOA) or cloud computing, some engineering firms can offer such analysis as a service that shields members of the community from the technical jargon. Similar implementations have been very successful in related arenas—for example, many travel sites offer users services for route planning/selection that can incorporate traffic patterns (in some cases, in real time), mode of transportation, and route features (inclusion of scenic areas, for example).

Active involvement of communities creates a much welcomed, yet challenging, innovative and socially-savvy chaotic environment for decision making. The word chaos does not necessarily means random, unpredictable or unintelligent. To the contrary, it refers to complex systems that beneath a thin crust of randomness include and are built on an interesting (patterns of) order. Self-organizing natural systems are some of the best examples of chaotic behaviour. On the surface, ants in a colony do not portray formal order in their behaviour. Yet, the result of their work is an orderly and efficient sustainable, physical and social system.

2. THE EVOLUTION OF CIVIL INFRASTRUCTURE: A PERSPECTIVE

It is argued that, over the last century, infrastructure evolved over three phases: service, asset and industry. Traditionally infrastructure systems were viewed as public services provided by the government for its citizens to assure public health and to support economic activities. In developed countries and by the late 1970s, maintenance of existing (sometimes ailing) urban infrastructure took over construction of new ones as the main task in the AEC domain. Infrastructure was recognized as a national “asset” that needs to be managed well to preserve its function. Quickly thereafter and with the opening of global markets and the increasing acceptance of deregulation, major features of a full-fledged industry are maturing in the domain.

The evolution of infrastructure from a service to an asset and then into an industry has had significant impacts on three fundamental dimensions: engineering, management, and policy making (see Figure 1). In the “service” phase, engineering work focused on the design aspects of facilities (structural integrity, and public safety). Typically, design efforts were focused on a single project and considered only direct costs. Value engineering and later constructability analysis were issues that engineers considered, again within a single project scope. During the “asset” phase, the role of engineering evolved to study issues such as structural deterioration, rehabilitation mechanisms and life cycle analysis and costing.

The Hunter Water Board (in New South Wales) represents a sample success story for deliberate and sustainable evolution from the “service providing” to “asset management” mentality. The Board (a private-like public corporation) replaced the outdated public works department and immediately embraced very rigorous asset management practices. Consequentially, in the period between 1994 and

2004, the average charges per customer were reduced by around 30% (in real terms). Accompanying the reduced charges there were improved performance levels; surveys documented improved customer satisfaction; and 12 of 21 wastewater treatment plants achieved full compliance with all license conditions – the remaining 9 plants achieved 99.6% compliance. In the same time period their audited average operating costs per service were reduced by over 40% (in real terms) and the company went from 1500 employees to 450 (GAO 2004).

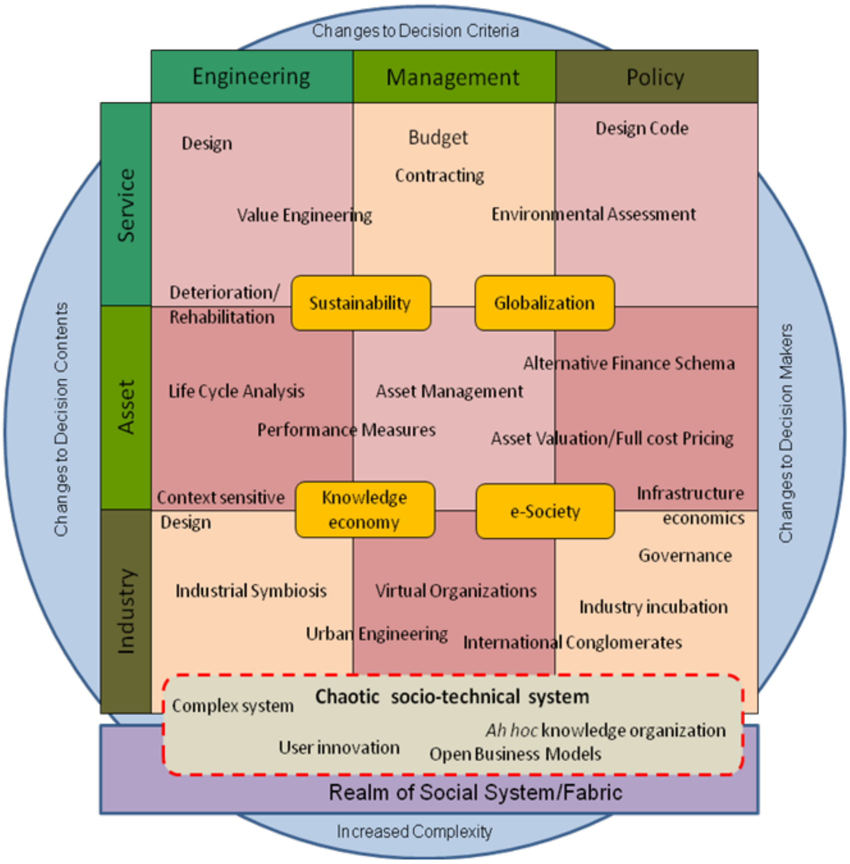

Figure 1: A Perspective on the Evolution of Infrastructure

Finally, in the "industry" phase, engineering work is starting to focus on issues such as formalizing environmental and social analysis studies; consideration of multi-project scenarios (using, for example, industrial symbiosis principals); and what can be called holistic "urban engineering" systems (such as analysis of city metabolism, urban energy usage, localized recycling systems). The City of Malmö, Sweden is a case in point. The city enacted plans to assure that by 2020 it will be climate neutral and by 2030 the whole municipality will run on 100% renewable energy. By 2015, all city buses will be fossil-free. Even more, work is ongoing to replace natural gas – which fuels the majority of today's gas buses – with biogas. This will be generated through effective recycling systems and using the industrial symbiosis principals (Malmö, 2011).

It is important to notice that many of these technical "ideas" originated from within a social context (the sustainability-savvy community). For example, the new transportation system in Malmö (with its rather cold weather) emphasis bicycling. In Toronto, where the law mandates a minimum number of parking spots for any new building, a new high-rise is being built without any because all residents committed to using public transit, bicycling and ride sharing in all their transportation

On the management dimension, during the "service" phase, the focus was on fair contracting and bidding systems; securing budgets for new construction, and cost optimization at the single project level (using value engineering, for example). In the "asset" phase, focus shifted to issues such as performance evaluation (from physical and service points of view), integrated decision making, and long-term budgeting. In the "industry" phase, the managerial dimension witnessed the emergence of global conglomerates in the management of infrastructure assets.

Adoption of global, manufacturing-like industrial patterns can be observed in the transformation of the Chinese Railway Engineering company to an international conglomerate, the spin-off of a private construction company by the Finnish road authority, and the formation of a quasi-consulting firm by Dutch municipalities–advising cities in emerging economies on sustainable planning and efficient governance. In the Hunter Water Board case, around 100 of their employees work for a subsidiary; that provides service to Hunter Water and earns external income from other utilities by providing a range of consulting and operating services. They also formed a subsidiary for telemetry service and then sold that company for revenue – which they reinvested into the base system (GAO 2004).

Public policies also evolved as the industry matured. Initially, the focus was on design codes, contracting practices, and environmental assessment. In the "asset" phase, the focus shifted to accounting and valuation of public assets along with a push for full cost pricing (through realistic user fees) and investigation of alternative finance schema (public private partnerships). This was very clear in the privatization of many water and wastewater facilities (in France and the UK, for example). Finally, in the "industry" phase, the focus shifted towards enhancing the governance model of public and privatized infrastructure systems. The evolution of the British governing bodies of water entities is a case in point. Initially, there was a limited structure. Currently, a multi-board elaborate system controls asset performance, pricing and finance, and environmental stewardship.

The Finnish road authority self-imposed reengineering is also a case in point. Fundamentally, the road authority incubated a smart, viable, knowledge-savvy industry in road construction, operation and maintenance as well as traffic management. This was done through two fundamental means: holding its own construction department to highest standards in innovation and management quality; and experimenting with advanced procurement and project delivery systems that pushed local industry to re-invent itself. This was coupled with a bold move to establish risk-based partnerships with local industry that fostered innovation and collaboration in knowledge generation and sharing. The authority then spun off its highly-competitive construction department into a separate company to propel change and compete locally and internationally. The authority, then, reinvented itself to focus on becoming a powerhouse of knowledge in planning, decision making and operations to "provide better customer services" (FINNRA 2006).

3. EDGE OF CHAOS: FROM SERVING SOCIAL SYSTEMS TO BEING PART OF IT

Fundamentally, it is argued that infrastructure is morphing into a global, wealth-making full-fledged manufacturing-like industry where the principals of knowledge economy are being exploited to achieve competitiveness and realize sustainable development. Industry here is not limited to production (design and construction of physical structures), or just maintenance or even selling services. In addition to these, new trends in the domain mimic typical "manufacturing" style industries: customer-orientation (understanding demographics); establishment of national and international marketing strategies including vertical and horizontal integration of competencies and services (as seen in the increase of local and global joint ventures and many mergers and acquisitions); increased investment and maturity of technical (and business) software/technologies (as seen in the increased use of Building information modelling and web-based technologies); diversification of investments/funding sources (with an increasing role of global sources).

In one perspective, the emerging trends in the knowledge economy expose and magnify the inefficiencies of traditional and current practices: sporadic project development; limited community engagement; and inadequate tools for quantifying sustainability. The proposed scenario suggests that active citizens are no longer settling to provide "commentary" on ideas by professionals. They want access to data and want to "lead" the idea generation on equal footings with professionals. They also want decision making rights equal to those granted to government officials and/or business-focused private owners and operators of privatized infrastructure.

Formal methods such as operation research, network analysis, or complex system theories are very good candidates to support the management or analysis of the new infrastructure morphology. For example, Ant colony optimization and swarm intelligence (and other operational research systems) can help find an artificial intelligence (optimal) solution. Attempting to use parametric analysis to find an optimal solution does not contribute to understanding the nature of the process. Essentially, the new process portray elements of complex networks behaviour (Taylor and Bernstein 2009).

It is argued that to understand and manage this new morphology of infrastructure, we need to revamp our conceptual models of infrastructure, its issues, its stakeholders and the its decision making process. Beyond searching for solution mechanisms, the true need is to understand the dynamics of innovation that will take place in such networks (Taylor and Levitt 2007). Approaches such as the stigmergy collaboration approach provides explanation about how *ad hoc* online groups work together (Elliott 2006). Understanding the way these *ad hoc* networks function will support finding an optimal solution (in this case, a consensus amongst all participant or at least a design that satisfy most of them). More importantly, it will help clarify the true needs/opinions of the community and, hence, allow public decision makers to empower community to innovate. The role of public agencies is no longer finding the best solution but to empower communities to discover it through democratizing innovation (von Hippel 2005).

With this scope, using chaotic system as a theoretical/philosophical basis for the new morphology of infrastructure decision making presents a suitable approach to address the complex and network nature of the new morphology and at the same time put the emphasis on the ad hoc, emergent nature of the collective innovation that will take place in empowered societies. Several features of chaotic systems make them very suitable as philosophical umbrella for the neo-analysis of infrastructure systems.

Non-linearity and feedback loop: chaos typically refers to a system with a kind of order without periodicity. Or formally, the qualitative study of unstable aperiodic behaviour in deterministic nonlinear dynamical system. This system has very influential feedback loops from the environment (or from within the system itself) that help in the evolution of the system itself. This can be observed in typical decision making in societies (both traditional and web-based), whether these societies are professional or not. Chaotic systems can be seen as dynamic, evolutionary networks, where nodes in the network share influence and feedback.

Divergence-Convergence and Sensitivity of Initial Conditions: Typically, the uniqueness of each community situation has been seen as a major embedment to systematic analysis of context-sensitivity. Differences in the decision making environment can have major impacts on the design exercise or the outcome of the project evaluation process. This mimics the “butterfly effect” typically associated with chaotic systems, in which a wing flap by a butterfly in one end of the world can be linked to the generation of a typhoon or hurricane somewhere else on the globe. Of course, this catchy example is meant to draw attention to the idea rather than actually asserting it. In essence, the butterfly effect is meant to emphasis the bifurcation that takes place in chaotic systems. It refers to the splitting or diversion of two almost identical or synchronous entities (processes, situations, conditions) due to sensitivities of the initial conditions of the two entities. To illustrate, the re-design of a street in two commercial areas in the same suburbia are almost identical exercises. However, the final outcome of these two exercises could be completely different. In one exercise, some initial changes in the composition of the community, the topology, the design team, the budget or the presence of a single activist at a single meeting can lead this exercise to follow different routes from an almost exactly similar situation. Such is the nature of socio-technical domains—as they progress they bifurcate (split) or move through a labyrinth of decision trees.

Self organization and innovation: irrespective of non-linearity and the constant bifurcation, chaotic systems self organize. Without an overarching order or a plan, entities within a chaotic system re-calculate, adapt and re-invent their behaviour and actions in a dynamic manner to reach equilibrium. Perturbation of chaotic systems creates order (at the macro level) from the seemingly disordered behaviour of its members (at the micro level). In nature, one can hardly document an orderly behaviour at the single ant level in an ant colony. Yet, collectively, the system is coherent, ordered and self-organizing. One can view the development of infrastructure designs in an open knowledge-enabled e-society context as an ad hoc virtual organization. Within this organization, each member would contribute ideas and interact with others in a completely independent and, possibly, un-ordered manner. Yet, this organization can “evolve” and/or “generate” a collective design after a while of bifurcation.

In fact, the imbalance (chaos) associated with the conflicting (disordered) ideas is the fundamental source of innovation in social systems. The "off-balance" created by new ideas lends itself to regrouping and re-evaluating by the adaptive chaotic system to make needed adjustments and regain equilibrium. The co-existence of chaos punctuated equilibrium and self-awareness and self-adaptation allows knowledge organizations to open the gates for innovation and, at the same time, harness that in an orderly fashion. The .com boom showed that stagnant organizations are poised to die in the knowledge economy. The .com bust, also showed that organizations that cannot self-organize their open (disorderly generated) innovations will not survive. The existence (or oscillation) between disorder and order (or what is called edge of chaos) is what sustains an organization in the knowledge economy where it, first, support idea generation and then channel that into meaningful outcomes.

4. DECISION-MAKING IN THE FUTURE: INNOVATION THROUGH COLLECTIVE SELF-ORGANIZATION

It is envisioned that infrastructure projects will be scoped and designed through open social portals, where people will participate with their ideas and wishes for any new project. As shown in Figure 2, networks of people (P) and ideas (I) will be formed. At the surface, these are social networks (S1) that link people to others or people to ideas: who is linked to which idea, who has similar ideas to who, and which ideas share supporters. To add depth to these linkages, text mining, folksonomies, and ontologies can be used to create a semantic network (S2) on top of S1. Semantic distances can be measured between ideas. Ideas will be linked not based on the people who developed it but based on their semantic contents. Consequently, ideas can be clustered and common ideas can be discovered (shown by the circular button in Figure 2). Adding semantics and meaning to the idea networks has several advantages. Ideas of similar contents form previous or other projects (shown as ovals in Figure 2) can be added to this network to inform community of related ideas. Relevant tools (applications) can be suggested. These can help in analyzing ideas or showing relevant legal and other constraints that may have impact on the ideas being considered. Semantic representation (profiling) of people can detect synergies and discover/foster the creation of advocacy groups that are not necessarily linked to each other directly (in the social network). Lead users (von Hippel 1986) of these groups can also be identified (shown with the square button in Figure 2) for possible inclusion in focus groups or negotiations.

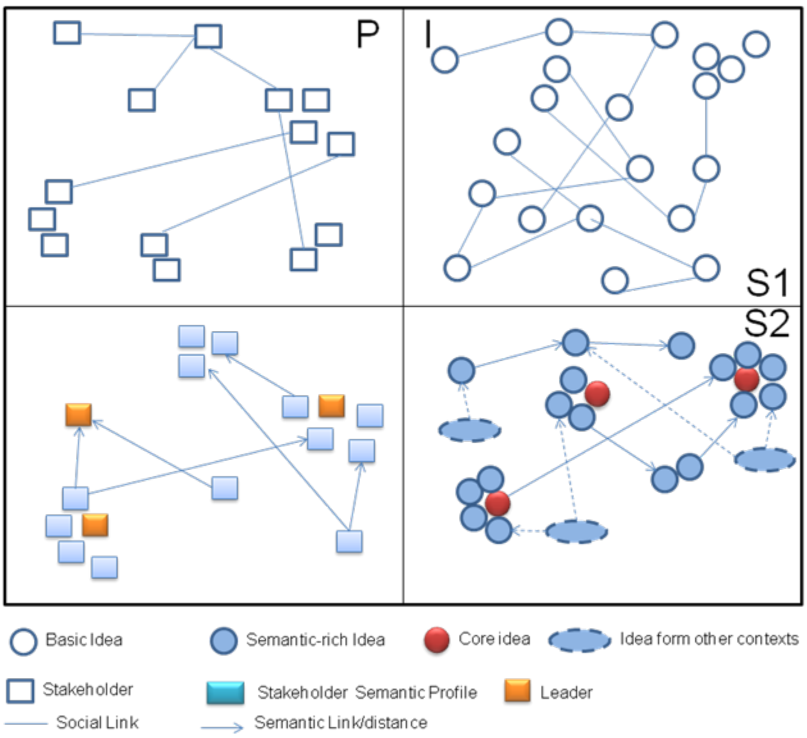

Figure 2: Social-Semantic Networks of Ideas and People

Figure 3 shows a view of how the public, "their" public officials, and engineers will interact to weave a cohesive innovative solution from chaotic input. People will be invited to access the project portal to add ideas, which are acceptably chaotic. Public agencies will retain engineering firms that can support coordinated flow and management of ideas. Public agencies will join the brainstorming with some ideas of their own. Keen on reaching a coherent "ordered" solution without hindering the evolution of innovation, at the right time, they can provide feedback on ideas, discuss impacts, and explain (not impose) and even help overcome constraints. For-profit and Non-government organization can also join the portal to advocate ideas.

The portal will provide communities with software (S3) to submit/draft ideas, change some of the attributes of existing options and study the impacts of any changes on a variety of decision attributes (CO2, average travel time, costs, project duration). The role of public agencies is not to create these "*Apps*". In fact they should avoid that. In contrast, the focus should be to create economics (market conditions) to develop these "*Apps*" based on the ingenuity of researchers, professionals, software developers, and more importantly, knowledge society at large.

What is important is to develop platforms that enable "knowledge vendors" to develop these analysis tools (the Infrastructure apps) and provide domain-specific middleware architecture to allow stakeholders to link, synchronize, and integrate these Apps to handle complex analysis tasks. To this end, we need to benchmark the successful work on BIM (Building Information Models) into the infrastructure domain. However, we should not aim for just an IIM (infrastructure information Model). Rather, learn from the lessons of BIM and move towards a Cloud-based (to shield users from programming issues), social (distributed networks of people), semantic (ontology-enabled) software platform for managing infrastructure analysis (hereinafter referred to as IIM+3).

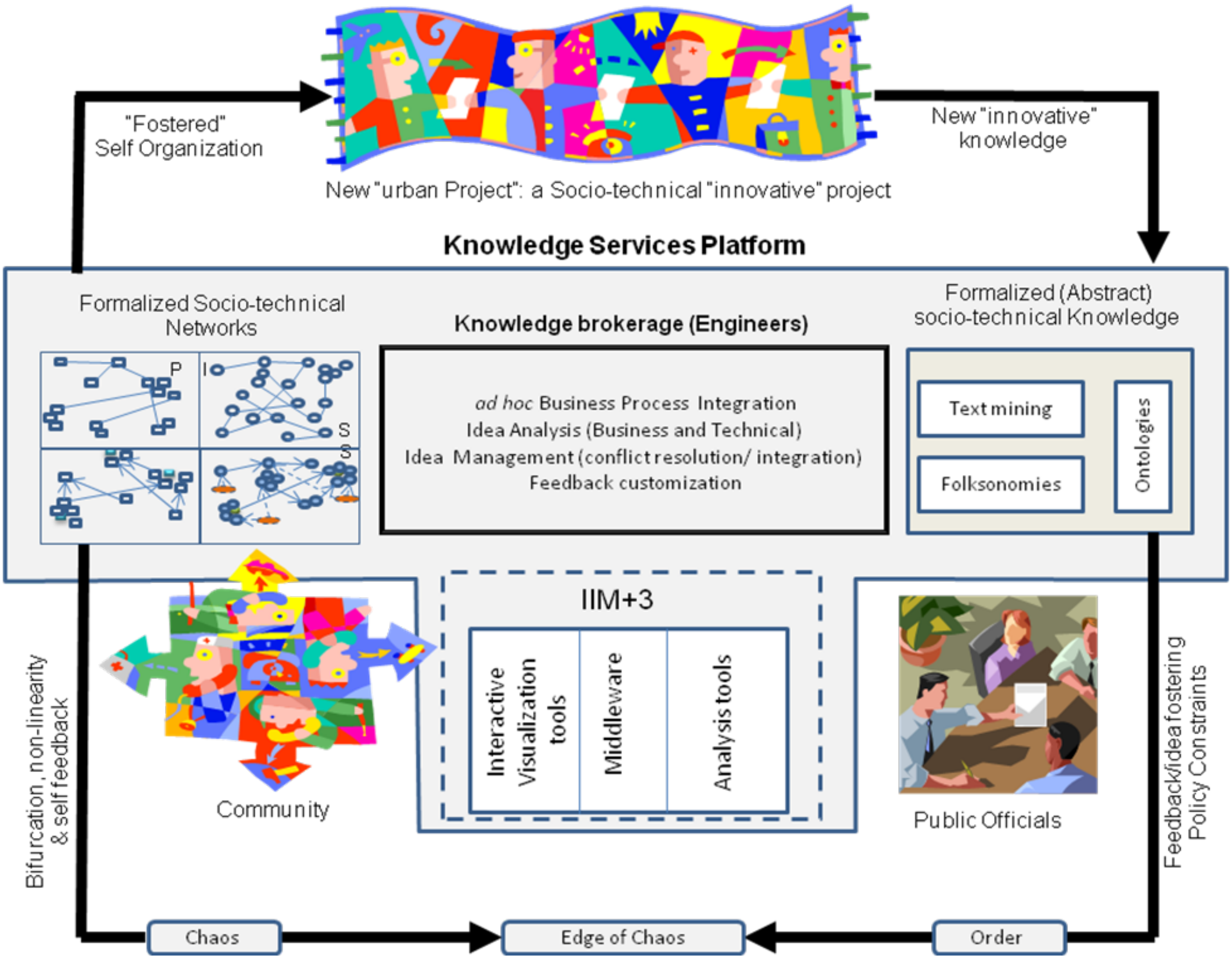

Figure 3: Knowledge "brokerage" as a service in a Chaotic System

Empowered with SOA-enabled systems, engineers will coordinate several facets of the chaotic systems:

S1: Understand and manage the inclusion of community (at the edge of chaos): the objective here is to provide real-time monitoring and support to the "social" side of the evolving networks of ideas and people. This includes tracking the profiles of people and ideas, measuring network attributes, testing and comparing the evolving networks to historical ones or similar ones in other jurisdictions, and analyzing evolving patterns (of ideas and community teams).

S2: Distil ideas and support decision making (foster self-organization): the objective here is to support the self organization of ideas by infusing meaning and some order on these ideas. Link these ideas to abstract knowledge (represented in the ontology) to help cluster ideas and people—for example, collating and/or linking similar ideas, providing feedback and educated analysis of common questions, facilitating the augmentation of ideas, distilling common themes, and benchmarking evolving ideas with similar ideas from other projects.

S3: Support the seamless operation of the IIM+3 (broker knowledge): suggesting analysis resources, customize generic (off the shelf) analysis tools to the needs of the project at hand and the existing networks, troubleshooting tool integration problems, conducting additional needed analyses (that were not addressed by the community), supporting the analysis by keeping and showing macro statistics of major indicators.

Post project analysis (Update the knowledge): the role of engineers is to work with experts to learn from project networks and update existing ontologies, and develop advanced tools for the management of "networked" ideas and (formal) means to foster community innovation.

In short, civil infrastructure projects will be managed by ad hoc virtual organizations where the customers are the key innovators, public officials are the supporters of innovation (by explaining and, when possible, breaking constraints), and engineers coordinate and manage idea networks.

5. DECISION TOOLS: THE MANAGEMENT OF NETWORKED KNOWLEDGE

In addition to their emergent nature, chaotic systems are essentially complex. Focusing on the complexity part can lead researchers to extensive use of algorithmic methods for finding the optimal solution. Tools such genetic algorithms and ant colonies are good examples in this regard given their ability to handle the optimization angle and at the same time "accommodate" the emergent nature of chaotic systems. However, it can be argued that given the extensive progress and use of complexity-oriented algorithms, the need now is for a "balancing" attention to algorithms that has stronger link to autonomous or emergent behaviour. Conceptually, agent technology has been presented as means for supporting (bottom-up) independent, autonomous and emergent behaviour. However, many have criticised the progress of agent technology. Even more, there is a substantial argument that it is impossible to realize the full claim/belief of completely autonomous, emergent and evolutionary agents.

A third approach that could have merit is the use of network theories and systems. In the proposed new decision making environment three fundamental components are networked: people (social networks), ideas (idea networks), and abstract knowledge (ontologies). Extensive research has been done in network theory since the inception of power and telecommunication grids. Lately, this field is receiving even more attention given its crucial role in social web. Research in the evolution of networks (such as cellular automata) can be of great help in the proposed new environment given the need to combine networkedness with emergent behaviour.

It is therefore argued that, in modeling and managing knowledge, attention should be given to evolutionary network analysis (of the people, ideas and abstract knowledge) at the macro level with suitable attention to complementary AI algorithms at the micro level.

Similar consideration to networkedness should be emphasised at the implementation level (i.e. software tools). While there is a need to implement BIM-like tools in the infrastructure domain, this has to be complemented with consideration of social networks (supporting distributed multidisciplinary stakeholders). It should also incorporate semantic systems as we need to handle networks of conceptual knowledge not just data models. Finally, given the diversity of stakeholders and the complexity of the information flows, SOA or cloud computing paradigms should also be emphasised. This is what has been denoted as IIM+3: Infrastructure information models that are complemented with social, semantic and service mechanisms. This is fundamentally are reflection of the evolution of BIM/IIM beyond engineering to be part of the business decision making cycles (hence the need for SOA), the progress from managing data to coordinating knowledge flows (hence the need for semantic systems), and the assumption that IIM should be accessible to innovative e-society (hence the need for social networking systems).

6. SUMMARY

For many years, the typical view was that urban infrastructure is a physical/engineering artefacts meant to provide services to the society, in particular, economic activities. Abstract arguments has been made for a more inclusive and progressive view where infrastructure is a socioeconomic artefact. In this view, infrastructure is seen as an active part of the urban social fabric.

Globalization, deregulation and the evolving knowledge economy along with the calls for sustainable systems, the push for new urbanism, and the increasing interest in context-sensitive designs are just few examples of this new view of infrastructure. It is argued that infrastructure is, finally, being transferred from a technical/business project into a socio-technical project that is part of the evolving knowledge economy and e-society. It is further argued that the challenge of designing sustainable infrastructure is, therefore, fundamentally a challenge in knowledge management in complex social systems. Infrastructure projects are interlinked and therefore so must be their sustainability analyses. The economy is embracing knowledge systems and therefore such systems must be incorporated in sustainability analyses. Communities are empowered to generate ideas and participate in decision making in many aspects of their lives, and therefore this must be adopted in the designs of their neighbourhood.

Researchers, professionals and public officials have to adopt new business models to add value in this new vision. How can we (researchers, decision makers and industrial stakeholders), support a reverse marketing system in infrastructure design and management. In other words, how can we help communities come up, evaluate and promote their own socio-technical “random” ideas, on the one hand, and then drive innovative order from these ideas on the other? How can we establish trust and open exchange of ideas and needs between community on one side and public agencies and industry on the other side? How can we brokerage knowledge and its flow between stakeholders?

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