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Conceptualization Of Smart Cities –Making The Invisible Visible

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Abstract— **We entered the 21st century with a strong, global trend to increasing concentration of the population in relatively few, large cities. Large, dense cities can be highly productive, innovative, and per capita very green and hence desirable for our future. However the rapid influx of new citizens presents overwhelming challenges to their governments. Along with the positive benefits that accumulate from dense, diverse cities come in equal measure the negative aspects such as informal development, traffic congestion, waste management, and access to resources and crime. The demand for services is immediate, but the tax revenues to fund them come later. At the same time, globalization has connected cities on opposite sides of the planet in forms of competition previously unknown – for capital, for resources, and for the Creative Class. These challenges lead to experiments with new approaches to the planning, design, finance, construction, governance, and operation of urban infrastructure and services that are broadly called Smart Cities. Some of these approaches are related to emerging roles of information technology. A new professional community – the Urban Systems Collaborative – has formed to foster mutual learning among members of the architecture, planning, engineering, transportation, utilities, information technology, operations research, social sciences, geography and environmental science, public finance and policy, and communications profession. One of its hypotheses is a new theory of cities that makes use of new, rich sources of information about what is going on in the city. Among other things, it seeks to understand the impact that information technology can have on the urban fabric and norms of behaviour. Systems Science, in particular work on systems of systems and scaling laws, has provided new observations of urban systems at a macro -level. The Smart City provides new instrumentation that enables observation of urban systems at a micro-level. This paper describes steps towards a model that can unify the perspectives of the professions in the Urban Systems Collaborative. It begins with examples of Smart Cities and why this movement is so active. It describes how information technology plays roles in shaping new norms of behavior intended to facilitate the continuing growth of dense populations. It then explains a key hypothesis of the Urban Systems Collaborative that the increasing accessibility of information will enable us to develop Urban Systems models that are capable of helping citizens, entrepreneurs, civic organizations, and governments to see more deeply into how their cities work, how people use the city, how they feel about it, where the city faces problems, and what kinds of remediation can be applied.**

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***Index Terms*— smart city, system of systems, modeling, urban systems.**

I. INTRODUCTION

Cities are the future of humankind. In the 18th century less than 5% of the global population lived in a city and the vast majority of people were engaged in simply generating enough food to live. Today more than 50% of the population lives in a city. It is likely that by the end of this century more than 80% of the population will live in cities. Most of this urbanization is self-motivated as mechanization reduces the need for manual labour in agriculture and farm workers elect to move to cities in search of a better life. This is fortunate because this process of densification of the population is a key method for reducing energy consumption and hence CO_2 emissions [19].

This rapid transition to a highly urbanized population creates many challenges for the planning, development, and operation of cities that are stimulating new thinking in the responsible professions – architects, urban planners and designers, transportation engineers, utilities, social science, environmental science, public finance and policy, municipal government, and, most recently, information technology. Information systems in particular have many roles to play, not least in being the thread that leads to a closer integration among these communities. During 2010-2011 a professional group, the Urban Systems Collaborative , has formed to develop this inter-disciplinary collaboration.

The present work is focused on the new roles that can be played in Urban Systems by information technology. This article begins with some examples of Smart Cities and goes on to explain how they work. It then reviews related work on what is driving the current urbanization. This leads to several hypotheses on how the application of information technology can support the goals of cities in both developed and emerging economies. A number of authors have developed theories of cities rooted in Systems Science and this leads to specific hypotheses about the role that information technology can play in applying these theories to the development of cities. The article concludes with a short discussion of the goals and activities of the Urban Systems Collaborative.

A. Smart Cities

The phrase Smart Cities is not new. It may have its origins in the Smart Growth movement of the late 1990s, which advocated new policies for urban planning. Portland, Oregon, is widely recognized as an example of Smart Growth. The phrase has been adopted since 2005 by a number of technology companies for the application of complex information systems to integrate the operation of urban infrastructure and services such as buildings, transportation, electrical and water distribution, and public safety. It has since evolved to mean almost any form of technology-based innovation in the planning, development, and operation of cities, for example, the deployment of services for plug-in electric vehicles [7].

The application of information technology in Smart Cities can produce various benefits:

- Reducing resource consumption, notably energy and water, hence contributing to reductions in CO_2 emissions.
- Improving the utilization of existing infrastructure capacity, hence improving quality of life and reducing the need for traditional construction projects.
- Making new services available to citizens and commuters, such as real-time guidance on how best to exploit multiple transportation modalities.
- Improving commercial enterprises through the publication of real-time data on the operation of city services.
- Revealing how demands for energy, water and transportation peak at a city scale so that city managers can collaborate to smooth these peaks and to improve resilience.

These approaches have become feasible as a result of recent progress in technology:

- The widespread use of digital sensors and digital control systems for the control and operation of urban infrastructure. These include traffic sensors, building management systems, digital utility meters, and so forth.
- The growing penetration of fixed and wireless networks that allow such sensors and systems to be connected to distributed processing centers and for these centers in turn to exchange information among themselves.

- The development of information management techniques, specifically standardised semantic models, that allow the low-level information to be interpreted by the processing centers and that allow these processing centers to interpret each other‟s information.
- The development of both computing power and new algorithms that allow these flows of information to be analyzed in near "real-time" in order to provide operational performance improvement and other insights.

These developments allow municipal governments to coordinate the operations of their multiple agencies in somewhat the same way that medium and large-scale commercial enterprises have operated since the 1980-90s. Many governments discover that they have available free sources of information that are collected for some transactional purpose, such as road tolling, energy or water consumption billing. A road tolling system, for example, provides large amounts of precise, "real-time" information about the movement of vehicles through toll gates. Offline analysis of historical traffic data can find patterns that can be leading indicators of the risk of congestion occurring in specific city districts. When such patterns are then found in "real-time" data, they provide a warning period that enables managers to adjust the traffic management system to prevent such congestion occurring. Similar examples can be found across many of the areas for which cities are responsible.

Another kind of benefit comes simply from the ability of different agencies to coordinate their actions, for example during a crisis such as a major storm. This enables all responders to have a common view of the situation and to make better decisions about where and how to apply the available resources [18].

Such cross-sector information can uncover valuable connections. In Cardiff, Wales, a recent integration of Hospital Accident and Emergency information about the location of violent crime has not only helped the police to focus their patrolling strategy, but has also produced a 42% reduction in hospital admissions for crime-related injuries [Cardiff, 2011]. This result was achieved because the police could use all of the serious violent crime data, not just the current report, and their rapid presence on the ground prevented many tense situations from escalating.

A common feature of these systems is that the benefits they seek to produce are achieved as a result of changes in the behaviours of citizens:

- Drivers receive better information about traffic and road conditions and make decisions about which routes to follow.
- Consumers receive real-time information about their energy consumption or about the pricing of that energy and make decisions about what loads – washing, heating, cooling, electric vehicle charging – to connect.
- Emergency responders share a common view of the situation and make decisions in light of the actions other agencies are taking.

There is an assumption here of rational decision-making that requires confirmation. Some participants will understand the purpose of the system and will support its goals through their own decisions. Other participants may not understand or may misunderstand and may make decisions that neither serve them well individually nor contribute to the collective benefits. Still others may understand but oppose the system and may either ignore it or act to oppose it.

Thus although the Smart Cities approach begins as a pragmatic, engineering-based attempt to improve the operation of individual urban infrastructure and services, we can also see it as perturbing unconsciously the interactions of the many systems within a city. It may also be seen from the works cited above that it is an approach in want of a theory for dealing with these systems of systems. This article describes some of the first stirrings towards such a theory.

B. Why Smart Cities?

IBM‟s Smarter Cities [IBM, 2009] work began in late 2008 as part of the Smarter Planet initiative [IBM, 2008]. During the opening months of 2009 we were astonished at the interest that was expressed by many cities throughout the world. While we knew that there were benefits to be created by these approaches, several of which were not new, we had not anticipated such a strong response. After some investigation we concluded that the interest was only indirectly related to the benefits we had anticipated. In fact, we found that the core motivation was grounded in the cities desire for economic development.

What we came to understand was that – in the midst of the 2008-2009 economic crisis – cities realized that they are in competition with other cities in ways that they had not previously experienced. They were not only competing with their neighbours at the state or national level, but – as a result of the Internet and global supply networks – they were competing with peers on the other side of the world. And not only were they competing for investment and jobs, they were competing for the Generation Y and Generation Z people who they hope will be the developers of new economic strength.

Their interest in Smart Cities lay in fact in their own branding or image and their ability to attract these people, younger members of what Richard Florida has called the Creative Class [Florida, 2003]. Florida‟s work has emphasised that while globalization has created a „flat‟ world [Friedman, 2005], this applies to commodity industries. The high value jobs that make a city attractive are concentrated in a relatively small number of cities and regions [Florida, 2008], initially expressed in [11].

An important question, especially for developers charged with creating a new city or a new district within a city, is how to make it attractive to the target tenants. Various tangible facilities, such as public wireless networks, electric vehicle charging stations, bicycle lanes, and so forth have been fashionable in such new developments based on the premise that other, attractive cities have these facilities, but there is little understanding here of cause and effect.

Thus "Smart City" from the point of view of many elected officials has to do with creating an environment that is attractive to Generation Y and Z people. It should be a digital city to match these Internet natives‟ experience. It should offer pervasive public wireless network access. The city should interact with its citizen through instant access, digital interfaces rather than through offices with long queues and paper forms. It should also appeal to the Creative Class‟ support for sustainability, especially "greenness" in all its forms. The Smart Cities focus on resource conservation appeals here too.

At a time of economic crisis and when creative young people on the planet are increasingly mobile, this is a very realistic strategy. We see strong competition in this area - as well as others – among global cities such as New York, Paris and Singapore. Dubuque, Iowa is an example of success with this kind of strategy for a small city of 60,000 people. Dubuque was a declining city that had lost its main industry – milling logs floated down the Mississippi into furniture, doors, windows, and staircases. This industry died in the 1960s and by 2000 Dubuque decided to reinvent itself around a sustainability theme supported by Smart City methods. This has propelled Dubuque into the lists of "most liveable cities" in America [10].

C. Towards Smart Cities

As Batty observes: "In the study of cities, there are many competing paradigms." Certainly the current awareness of asymptotic urbanization has stimulated a great many conferences and debates. Yet an aphorism ascribed to Albert Einstein holds that in science, revolutions in theory are often preceded by revolutions in instrumentation. Smart Cities provide a new form of instrumentation for observing in fine detail the way that people use the city and so may enable new approaches to theories of cities. Through new sources of information cities hope to create insight, innovation, opportunity and real jobs that will increase prosperity and quality of life. Conversely, the current ad hoc approaches of Smart Cities to the improvement of cities are reminiscent of pre-scientific medicine. They may do well, but we have little detailed understanding of why. Smart Cities is a field in want of a good theoretical base [4].

Two approaches seem to be strong points of departure for such a theory. One of these is work in scaling laws going back to Zipf, but enormously enriched in recent years by theoreticians such as West and Batty to name but two. West, building on earlier work in other complex systems, notably biological systems, has demonstrated remarkable capabilities to explain the scaling behaviors of many facets of cities from average wages to crime levels. Batty] has shown that the structure of the built environment matches patterns of growth of biological systems. He refers to this as "organic order‟. West has spoken of the scaling of both biological and urban systems being governed by the structures of connecting networks. In biological systems these networks may be the nervous system or circulatory system and in urban systems we hypothesize that they may be the social and economic networks [5].

This body of work provides evidence that although many behaviors of complex systems are emergent or adaptive, nonetheless there are patterns or consistent behavior at the level of macro observation. If we consider the study of cities to be an experimental science, which is consistent with the Smart City perspective, these theories are lacking hypotheses that can be tested at the micro-level, where direct intervention is possible. On the other hand these patterns, as in biology, when combined with better instrumentation encourage us to move the level of study down to a finer granularity, in hopes, for example, of understanding the urban equivalent of a cell or nervous system. It may then be possible work upwards from the micro-level, using whole system data to reveal macro-level patterns.

The second body of work considers cities as complex systems. For example the works of Allen and Portugali among others emerged from developments in systems thinking during this period, but the notion of the city as a complex entity certainly goes back much further. This approach introduces concepts such as interconnection, feedback, adaptation, and self-organization in order to provide understanding of the almost organic growth, operation, decline, and evolution of cities. It gains support from the rich body of work around Systems Science, but in itself it appears to be more a valuable means to thinking about cities at a fairly high level rather than a means to provide detailed descriptions [3].

Deming, citied in observed that "every system is perfectly designed to produce the results that it produces" implying that there is a kind of homeostasis in which the system adapts to perturbations to return towards some normal state. Hence a desire to change the behavior of the system will require understanding and intervention at a lower level.

Implementations of this kind of thinking emerged in Urban Dynamics in which the interactions among abstract systems, such as "traffic" are composed into mathematical models based on their strengths, non-linearity, and delayed impacts. The complexity of a city becomes very apparent in these models, in which the numbers of variables can easily grow into the thousands. These models gained some notoriety in the urbanism community as they were sometimes seen or portrayed as "oracles" capable of predicting the future of a city. Today such models are seen as means for the researcher or planner to test hypotheses and to confirm his or her own thinking. The model and the modeler interact to reach a consensus [13].

The city as a complex system is, however, a valuable metaphor when linked to the evolution of information systems. The growth in complexity of both the hardware and software of information systems has generated communities of people, IT architects and software engineers, who are deeply familiar with methods to compose together vast networks of nodes, as well as tools for creating, managing, and navigating such networks. Indeed it is ironic that while Alexander's seminal book on patterns in urban architectures seems to have had little long-term effect on the development of urban planning, it became a core text in the development of pattern languages for software engineering [2].

One emerging thought is that for a city to function well as a healthy system it needs an appropriate level of complexity at all levels in its operations. This complexity is needed not just in its physical networks – its roads, its buildings and its communications, but also culturally, and economically. There are perhaps pockets in a city that are „mono-culture", which makes them very difficult places in which to thrive when the external conditions are changing. This applies both at the poor end of the spectrum in areas with a high index of multiple deprivation and rich societies [9].

Coward and Salingaros built a tentative bridge between these two worlds through thinking of the systems of systems as a network for the flow of information that "heuristically defines its own functionality by changing connections as it optimizes…". Metaphorically we may think of this as a network of software objects each of which performs some task based on the flow of information and produces new flows. Such software objects might represent individual people or institutional processes, such as banking. Coward and Salingaros, in common with many other writers, emphasize the importance of the network above the objects themselves [8].

Indeed Alexander spoke of a living city as a lattice or mesh network with very high degrees of connectivity. Recent work by McNulty builds on this by describing the city in terms of "stocks" or resources, flows (including the movements of information, money, and goods), and feedback loops.

Summarizing, we find the following:

- Innovation in instrumentation of the city and the ability to observe many individual behaviors in "real-time"
- Insights into repeatable, high-level patterns of the behavior of cities
- Conceptual models for cities as complex systems that we can map, at least metaphorically, to complex information systems
- Innovation in how to intervene in the operation of certain services in the city through flows of information coupled with analysis.
- A need to provide a theoretical foundation for Smart City interventions that can relate them to the thinking of architects, planners, developers, city managers, and so forth.

II. Making The Invisible Visible

While these approaches reveal valuable insights, they do little to help us understand at the level of individual citizens what makes a city more or less attractive. The approaches reviewed above are understandable because historically only statistical information has been available. However, one of the foundations of the Smart City approach is that today we have access to real-time information at the level of individual citizen's choices and actions. We refer to this change as "making the invisible visible".

As information systems have become pervasive in urban environments they have created opportunities to capture information that was never previously accessible. This is highly valuable in enabling the detection of patterns of behavior or anomalies in such patterns whether at an aggregate or an individual level. Thus in a water metering pilot in Dubuque, we can establish a characteristic pattern of water consumption for a given residence and then detect anomalies in consumption that may reflect a garden hose that has been left leaking. This pervasiveness also enables the city agencies or individual citizens to capture, even unintentionally, photographs of incidents on the street – such as two apparently unrelated people engaged in a brief conversation – that historically were so transient that they would never have been noticed. And these photographs may now in a matter of minutes be visible, permanently, throughout the planet. So this ability to make the invisible visible has many benefits, but also needs to address serious issues of privacy and protection of Personal Information.

III. A Theory Of Smart Cities

This is a work in progress, but the foundations are becoming clear. It begins with the concept of an Urban System, which can be understood as a generic term for a process in any of the kinds of networks of systems mentioned above. Such Urban Systems may be elementary entities or may be complex entities composed from simpler entities.

We then introduce the Urban Information Model as a means to structure and classify the many different types of information contained or flowing in these networks. From an information technology point of view, it is helpful to think of the Urban Information Model as a very large number of layers representing a common two-dimensional space, the territory of the urban environment, whether that is a single city or a metropolis. This Urban Information Model is illustrated in a highly simplified form in Figure 1. Such a model is often instantiated in a Geographic Information System (GIS), however increasingly social networking tools are taking this model in new directions.

The groups of layers are:

- The Natural Environment group including topography, flora and fauna, natural resources, geology, and so forth.
- The Infrastructure group including the Built Environment (roads, bridges, tunnels, buildings, pipelines, electrical and communication lines, and so forth) as well as Things That Move (trains, boats, buses, and so forth) that is constructed on the Natural Environment.
- The Resources group representing materials that originate in and eventually return to the Natural Environment after passing through various processes of refining and consumption in the Services group as well as capacities that are temporarily consumed, for example by the passage of a vehicle over a bridge, and are then re-generated.
- The Services group representing many kinds of services, including transportation, energy, commerce, healthcare, and so forth. Many of these services consume or transform resources from the Resource group.
- The Social Systems group, including the locations and Actions of people, such as commerce and culture, laws, regulations, governance, and so forth that exploit the Services and Resources from these respective groups. This group contains the topmost and most interesting layer in which we find the People Systems.

So the representation of an Urban Systems model takes place on these five groups of layers. The ordering of the layers is not important and the colors of the layers have no significance.

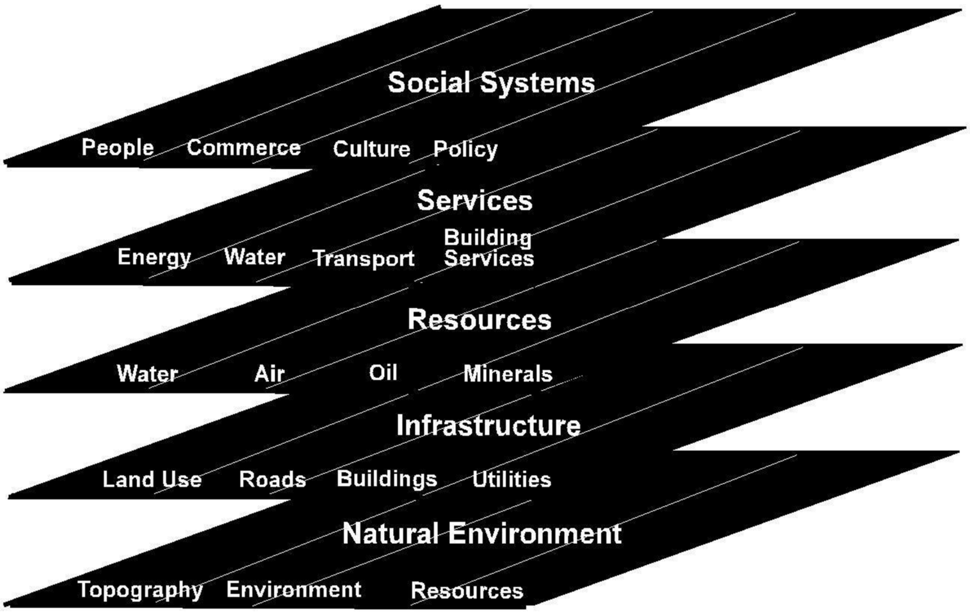

Figure 1: A simplified view of the Urban Information Model. Each plane represents a group of layers containing different, but related, types of information about the two-dimensional space

There is a sense of hierarchy in Figure 1, but there is no simple linear hierarchy in Urban Systems models; they are often recursive. The grouping of layers is also somewhat arbitrary, for example, some or all of the layers in the Resources group could well be included in the Natural Environment group. The number of layers with a group is also somewhat arbitrary in this discussion; a formal definition of the layers awaits the definition of a formal taxonomy.

Another basic concept is the Service. This is a very general concept and again may be simple or highly complex. Services are Things That People Interact With in the city, including other people or even oneself. Services often consume or transform Resources and always require some form of payment or exchange. The act of invoking a Service is called an Action, which is initiated by a person or another Service and is always either bi-lateral or multi-lateral.

For example, consider a bus ride. A bus ride is a Service and hence is represented in one of the Service layers, but is composed recursively from many other layers:

- The bus route is defined by roads that are represented in one of the Infrastructure layers.
- The roads in turn are constructed on the topography of the Natural Environment and have to reflect its terrain and bodies of water, and so forth found upon it.
- The fuel consumed by the bus has originated in the Natural Environment group, has been extracted by a production system on one of the Service layers, transported through pipelines in the Infrastructure group to a refinery and so forth.
- The bus stops are part of the Infrastructure group, but their placement is determined by the distribution of people in the Social Systems group.
- The payment for the bus journey is represented in the Social Systems group as is the Received Value of the passenger and so forth.

In the topmost layer of the Urban Information Model are the People Systems. People Systems represent Processes for Things That People Do, whether in their work or in their private lives. A People System is a composition of Actions upon high-level Services to achieve some goal, for example travelling from place of work to home. For a given person, two or more People Systems may be dynamically composed together, e.g. going home and buying groceries. This example People System might consist of:

- Walking from the place of work to a bus stop
- Taking a bus to a railway station
- Taking a train to another station
- Walking from that station to home

Some people – for example neighbors or co-workers – will share People Systems or have at least some segments of People Systems in common. It is through this sharing of People Systems that the network of systems that is constructed on the city"s Services begins to emerge. When people share a People System concurrently or sequentially, they may be competing for Resources in the Services employed or they may be collaborating to accelerate a process within a Service.

In principle the entire set of activities of a person's life can be represented by a collection of People Systems. We may suppose that this set represents to that person his or her experience of the city. Note that the model does not include the individual person himself or herself. The person is an external agent, exercising judgment and volition on a set of choices that are available at a given time and place. We do not have to assume that the person possesses complete information nor that he or she makes rational decisions.

When a person moves to a new city, he or she has to create or acquire anew much of this set of People Systems in order to function in that environment. Some of these People Systems may be discovered with, say, help from Google Maps, and some may be acquired from co-workers or neighbors. Some of the People Systems used in the previous city may also be re-used in the new city, which is part of the attraction of widely distributed Services such as McDonalds restaurant and Starbucks coffee shops – we already have the People Systems for these Services. The range of choices in what People Systems are available and how easily they can be adapted or personalized may be an important characteristic of the Attractiveness of the city.

These are some of the basic concepts in the Urban Systems model. They clearly differ from those of scaling laws and earlier complex systems thinking in the level of granularity. It is implicit here that the macro-level operations of a city are the consequences of very large numbers of decisions made by individual people in selecting and adapting their People Systems and of how the resulting Actions compete or collaborate through Services for Resources. There are assumptions here that we have the instrumentation to observe and measure at the level of the individual's Actions in People Systems, that we can aggregate these many Actions to together to observe the overall behaviors of the city, and that we can affect these behaviors through influencing the choices and construction of the People Systems employed by individual people. There is much more to be said about this evolving theory of Urban Systems and this will be reported as progress is made.

IV. The Urban Systems Collaborative

The thinking described above lead to the Urban Systems Symposium meeting that was held on 11-12 May 2011 in New York with the support of 192021, the American Planning Association, Cisco, Esri, IBM, New York University, Open Plans, Permasteelisa, the Regional Plan Association, Radical Media, the Rockefeller Foundation, and Skidmore, Owings, and Merrill. The meeting brought together around one hundred distinguished professionals across architecture, planning, engineering, construction, information technology, systems science, environmental science property development, finance, and municipal government. It consisted of a series of panels to present different professional perspectives on Urban Systems and then a set of workgroups to discuss areas for potential follow-on work. Video recordings of the panels are available on the Web site [17].

The community continues to meet through bi-weekly telephone conferences and social media since the symposium. It has adopted the name Urban Systems Collaborative and has made progress in developing a draft statement of intent, which is posted on the Web site. The opening sentence of this document reads: The Urban Systems Collaborative is an inter-disciplinary community that studies how the use of real -world information to reveal patterns of urban behavior is changing the ways that people live in cities and how these changes affect the planning, design, development, governance, and operation of cities. The Collaborative welcomes new members across the spectrum of professions listed above.

The Collaborative is also developing specific projects that will serve to improve the definition of our mission, to develop a common vocabulary among the many different professions, to develop a core body of knowledge across these professions that will result in a graduate-level curriculum, to propose a formal approach, for the management of Personal Information in Urban Systems, and a number of competitions that will invite students to illustrate the application of Urban Systems thinking [16].

Our own aspiration for the Urban Systems Collaborative is that it evolves into a formal, professional, multi-disciplinary organization that will develop Urban Systems thinking and infuse it into the study and practice of the many relevant professions.

V. Conclusion

By the end of the 21st century, it is likely that the global population will have peaked and stabilized, that the vast majority of those people will be living in cities, and that we will have ceased the present active construction and development of urban capacity. We have a unique opportunity in the coming decades to shape the future of global society through innovation in Urban Systems. How we perform that construction and development will differ from how we have pursued such works in the past, not least because of the growing presence of information technology in all aspects of our lives. The early years of Smart Cities have shown intense interest in the role of information technology in cities and encouraging initial results from its ad hoc deployment. Given the pace of construction, especially in emerging economies, it is time to develop a solid theoretical foundation for Smart Cities and to develop understanding of how these technical methods can help to achieve the pressing goals of existing and new cities. A key enabler for new theories of cities is the instrumentation of Smart Cities that “makes the invisible visible” and enables us to consider theoretical frameworks at the level of individual actions, rather than having to rely on statistical abstractions for our understanding of what is going on. This must not simply be a matter left to the information technology industry, but rather requires collaboration among these engineers and many other professionals that contribute to the architect, planning, engineering, construction, operation, and governance of cities. The Urban Systems Collaborative is one organization addressing this goal.

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