Programmable Cities: A new ICT approach

Mario Siller[*+] and Agnis Stibe[*]

[*]MIT Media Lab, Cambridge, MA, USA
{msiller}agnis@mit.edu
[+]Cinvestav Unidad Guadalajara

Abstract. This paper introduces a new approach for the design, deployment and operation of information and communication technology infrastructure for what we conceived as "Programmable Cities". We address how urban environments can be retrofitted and complemented with technology considering the core nature of cities being systems of systems and complex adaptive systems. We believe that this novel approach will allow city stakeholders to set the ground to transit from a *passive* to an *active* ICT infrastructure. Based on this, the emergent and aggregated complex behavior of a city, which is driven by its different layers and elements, is better matched by their digital counterparts as it evolves and adapts. The aim is to address the implications of systems of systems and complexity theory in City Science for the development of the ICT infrastructure.

Keywords: ICT Adaptive Complex Systems, Wellbeing, Quality of Experience (QoE), City QoE, ICT QoE

1 Introduction

Evolution is constant in our species in many aspects. As we do evolve the artifacts we have created are evolving too. This includes the cities we have created in which by 2050, 70% of the World's Population will live in them. The first human settlements appeared 8,000 BC and the rise of technology based societies in 600 AD. Cities and technology have been bi-directionally related since the very beginning. In fact the evolution of one wouldn´t have been possible without the other. It is estimated that most of the technological progress made by modern humans has occurred over the last 10,000 years. This occurred after humans were able to domesticate plants and animals, went from stone to metal tools, simple artifacts to the development of systems, and the initial settlements evolve into larger and permanents ones allowing civilization to take place.

Human settlements and the activities that take place in them have been studied for many years. This includes attempts to define a city, from the *classical categories* approach [1] to what has now been referred to as a new science in its own, City Science. The conceptualization of a city has been addressed by different disciplines:

economics, sociology, anthropology, ecology, systems engineering, etc. A basic and general definition is as follows – *Cities are large and permanent centers of population, commerce, and culture*-. In terms of size there is not a unique number to define it but it can be agreed that a digitalization process has been taking place in many aspects over the past years. This actually intensified as we entered the *second wave* in computing (the era of the PCs) and especially during the third wave, *ubiquitous computing* (UbiCom) as referred to as Mark Weiser in [2]. In the latter, Information and Communication Technology (ICT) systems allow information and tasks *anytime* and *everywhere*, in an intuitive way to the user. There are three types of environments identified for these systems [3]: (i) the infrastructure of other ICT systems; (ii) the physical world; and (iii) the human.

As we reduced the size of computing devices (hardware and software) we started to embed them into other specific design purpose systems, mainly mechanical and electrical systems. This derived into a new classification of integrated systems, known as *embedded systems*. The interconnection of these systems resulted in new networking paradigms, underlying technologies, systems architectures and applications, including machine-to-machine communications (M2M) and the Internet of Things (IoT). In the latter a new dimension was added to the ICTs, connectivity for *anything* [4]. This new dimension extended the previous two, "*anyplace* and *anytime* connectivity for *anyone*". Systems consisting of interconnected computing devices designed to interact with the physical world, using sensor and actuators in a feedback loop are called *cyber-physical systems*. The ICT system infrastructure is also referred to as *cyberspace*.

The ICT for Cities and technology in general is being driven mainly by 4 digital laws [5]: (*i*) Kryder´s law ("memory doubles about every 12 months"); (*ii*) Moore´s law ("power of chips doubles every 18 months"); (*iii*) Nielsen´s law ("effective bandwidth doubles every 21 months"); and (i*v*) the Caveman Law ("Whenever there is a conflict between modern technology and the desires of our primitive ancestors, these primitive desires win each time*"*).

W. Mitchell suggests in [6] that twenty-first century cities have all the sub-systems that are needed by *living organisms*. This includes structural skeletons, various layers of protective skins and artificial nervous systems. In other words, cities have evolved from physical fabrics in which the *inhabitants* (urban agents) supplied the coordinating intelligence need it to make a city to function as a *system* to entities in which now combining different technological elements intelligence emerges in a different way. According to W. Mitchel the intelligence of cities "resides in the increasingly effective combination of digital telecommunication networks (the nerves), ubiquitously embedded intelligence (the brains), sensors and tags (the sensory organs), and software (the knowledge and cognitive competence)" [7]. Further elaboration of these ideas of how cities work smarter not harder is presented in [8] [9] [10]. The first deployment of these intelligence-enabling technologies was done in the Smart City Lab (now Changing Places) of the MIT Media Lab, lead by Mitchel at that time [11].

The conceptualization of using technology related to different aspects of Cities has been termed in different ways such as "Smart Cities", "Intelligent Cities, "Digital Cities", etc. The most popular one has been "Smart Cities" over the past 20 years in many sectors and areas, and yet there is not a single agreed definition. A wide review of many of the different definitions is presented in [12]. For instance, the ITU-T Focus Group on Smart Sustainable Cities at its fifth meeting in June 2014 after reviewing many of them agreed on the following definition of a smart sustainable city [13]: "*A smart sustainable city is an innovative city that uses information and communication technologies (ICTs) and other means to improve quality of life, efficiency of urban operation and services, and competitiveness, while ensuring that it meets the needs of present and future generations with respect to economic, social and environmental aspects*". The British Standards Institution developed a different definition in 2014 (BSI PAS 180) in [14] as: "*effective integration of physical, digital and human systems in the built environment to deliver a sustainable, prosperous and inclusive future for its citizens*". The notion of considering the goal of enhancing the quality of life considering the needs of people and community (*wellbeing*) had been previously addressed in [15] by Batty et. al. A common denominator in all definitions is the use of ICT technology to enable the smartness and computation of the city.

In [16] the ISO/IEC JTC 1 presents a model on the system integration characteristic of a Smart City (Figure A.6). This is a view of the system integration property of a Smart City in which it is represented as a combination of four Internets or networks: Internet of Data, Internet of Things, Internet of People and Internet of Services. A similar integrative view is presented in [17] by Cisco in which cities are considered as microcosms of the interconnected networks that make up the Internet of Everything (people, process, data, and things). The ICT infrastructure can be modeled as a single layer of multiple ones that compose a city such as physical city, environment, applications, innovation, society, etc. A comprehensive set of layered abstractions for smart cities is presented in [16].

From Systems Engineering perspective cities can be modeled as *Systems of Systems* (SoS) and their "smartness" depicts the ability to bring together all their resources, to effectively and seamlessly achieve their goals and fulfil their purposes [16]. One focus area of city science is the study and modeling of Cities as complex systems. Besides of being *SoS* and *complex systems* cities are also *self-organizing* and *non equilibrium systems*. Following the work of Nicolis and Prigigogine (dissipative structures) from [18] in Self-Organization in Nonequilibrium systems, Perter Allen showed that towns and cities are self-organizing systems [19]. He showed that the landscape rather than following an equilibrium state, as suggested from *The Central Theory* of Christaller and Lösch, a *far-from-equilibrium* condition is observed.

A different approach and discipline to study self-organizing complex systems was proposed by Haken in [20] as *synergetic theory*. Both Progigogine and Haken works are known as the Brussels School. From the perspective of synergetics two approaches have been used to study self-organization in the cities: (i) *master-equation*; and (ii) pattern recognition approach. For the former relevant research work has been done by Weidlich while for the latter Haken and Portugali. In [1] Portugali distinguishes two main elements to model the city: *infrastructure objects* and *urban agents*. In [21][22] using theory of cognition, cognitive mapping and urban dynamics based on synergetic inter-representation nets (SIRN) showed that local behavior and interaction between urban agents give rise to the global structure of the city. He also argues that Planning Theory has not yet adopted the implications of complexity theory to city planning.

A alternative perspective, known as the Santa Fe School or the Algorithmic Approach, was developed initially by Stanislaw Ulman and John von Newman in 1940s, then followed Christopher Langton and Stuart Kauffman (1990s) and more recently Stephan Wolfram (2000s). The studies are based on computational models to understand in a general way how complex systems self-organize and adapt. The main focus is on the algorithmic logic of model systems. Further review of studies of cities as self-organization and complex systems can be found in [1][23][24][25].

We believe that a new conceptual model of the city, which considers inhabitants-wellbeing and the SoS, and complex system nature of cities still has to be developed. From this model an *active ICT infrastructure* approach for the design, deployment and operation of ICT infrastructure is required. The proposed framework is integrative and transversal to all city stakeholders. The proposed conceptual model extending Mitchel´s abstraction of cities as *living organisms* to a new one in which key properties such as openness, non-linearity, unpredictable mutations of triggers for change, feed-back (positive and negative) and feed-forward, circular causality and wellbeing are taking into account.

The rest of the paper is structure as follows. Section 2, elaborates the need of transiting from a *passive* to an *active* ICT infrastructure. In Section 3 the new ICT approach is presented. In Section 4 the wellbeing aspect in the context of the new model is addressed. Section 5 presents conclusions and further research.

2 From a *passive* to an *active* ICT infrastructure

The smart city ICT infrastructure matches the three dimensions of IoT introduced by the ITU-T in (*any place*, *anytime "*for *anyone"*, and *any thing*). Furthermore, given the systems of systems nature of a city and its integrative property viewed either as microcosms of interconnected networks or as a set of Internets, opens the ground for new three dimensions. These are *any person, any data* and *any service.* In the context of cities, the "for anyone" ITU-T expression from the original two dimensions refers to *urban agents*. Therefore, we redefine it as a new dimension, meaning people. The *any data* refers to all possible information that originates and flows across all the different layers (physical city, etc.) while the *any service* to the set of activities intended to meet the urban agents needs and ultimately their wellbeing.

The first two IoT dimensions are associated to UbiCom systems. In [3] Posland identifies five core properties for this type of systems (distributed system properties, iHCI system properties, context-aware system properties, autonomous systems properties and intelligent systems properties) and a set of 70 sub-properties for this kind of systems. Furthermore, he identifies four main types of designs for autonomous systems: (*i*) reusable and extensible component (design & interface autonomy); (*ii*) event-driven architectures (EDA) and context-aware; (*iii*) hybrid goal-based and model-based Intelligent system (IS) (distributed artificial intelligence or multi-agent system design); and (*iv*) pre-configured inbuilt local goals. However, the concepts and definitions of autonomous, automatic and autonomic systems have mature and conveyed as follows. Automatic systems are self-steering systems in which a human designer provides the control rules, for instance, a software script. The autonomous systems extend automatic systems as self-governance is achieved [26]. IETF RFC 7575 [27] refers to autonomic systems as self-managed systems, meaning, they are self-configuring, self-protecting, self-healing, and self-optimizing with a high level guidance (intent) of a central entity. These four properties are known as the four core major characteristics of autonomic systems [28] and were originally defined by Kephart and Chess in [29].

Cities are SoS and complex systems. However, not all complex systems are considered SoS from the perspective of Systems Engineering. It is the collaborative nature, neither the complexity nor the geographic distribution, of its components what makes an SoS. The definition that has been adopted by many was proposed by Maier in [30] as follows:

"*A system-of-systems is an assemblage of components which individually may be regarded as systems, and which possesses two additional properties:*

1. *Operational Independence of the Components: If the system-of-systems is disassembled into its component systems the component systems must be able to usefully operate independently. That is, the components fulfill customer-operator purposes on their own.*
2. *Managerial Independence of the Components: The component systems not only can operate independently, they do operate independently. The component systems are separately acquired and integrated but maintain a continuing operational existence independent of the system-of-systems*."

Some other characteristic of SoS are [32]: autonomy, belonging, connectivity, diversity and *emergence* (Boardman-Sauser characteristics). These characteristics interact with opposing forces [33] and they are meaningfully independent among each other [32]. We argue that *emergence* in the case of cities is driven by its *self-organizing complex system nature*. Four kinds of SoS have been defined: virtual, collaborative, acknowledge and directed [31], see Table 1. Cities, in a sense, can be mapped to *acknowledge* and *directed* SoS, depending on their organization and operational and management policies. SoS are in many cases complex systems but this is not always true [34].

There is not a rigorous and unique definition for *complexity*. In [35] Mitchell presents two definitions for complex systems:

- "*a systems in which large networks of components with no central control and simple rules of operation gives rise to complex collective behavior, sophisticated information processing, and adaptation via learning or evolution*"
- "*a system that exhibits nontrivial emergent and self-organization behaviors*"

Complex systems components are referred to as *agents*. There are two sub-fields in the studies of complexity, which focus on two kinds of emergence [36]: complex physical systems (CPS) and complex adaptive systems (CAS). In general, they present properties such as [37]: *distributed control*, *synergy*, *emergence*, *autopoises*, *dissipation* and *adaptivity*; see Table 2. Emergence (aggregated behaviors) can occur both at local and global scales. In the literature some other properties are defined and in some cases these are also referred to as behaviors and even with different names. In most cases these behaviors are counter-intuitive. These include collective behavior, hysteresis, signaling and information processing (internal and external environments), self-organization, chaotic behavior (chaotic dynamics and butterfly effect), "flat-tail" behavior, competition, cooperation, reproduction, innovation, reinforcement learning, robustness to perturbation ("stable attractor"), abrupt change from one state to a completely different ("tipping points" and systemic shift), arbitrarily large fluctuations, cascading effects (characterized by power laws), and critical fluctuations [35][36][38][39]. In some cases complex systems might present only some of these properties. For instance, some properties relevant to cities are [1], see Table 3: *no-linearity, unpredictable mutations of triggers for change, embedded system observers and predictions, existence of feed-forward and feedback loops, open future, and self-organization*. In the case of cities self-organization has been studied in detail considering different aspects of them [1][23][40][41]. Some of these aspects and urban processes include land organization, spatial structures, interactions among agents, flows, networks (physicals and socials), evolution and emergence, size, shape, scaling, etc.

The self-organization property of cities can be further expanded into the following sub-properties or characteristics:

i. No one fully controls them.

ii. Both a city and systems of cities can be characterized as *networks* following the power of law. This maps Barabasi´s mark of self-organization [42].

iii. *Circular causality* occurs between the local and the global.

iv. *Dual-self-organizing*: urban agents are complex systems themselves and planners at a certain scale.

v. *Slaving principle (*proposed by Haken*)*: the order parameters both the macroscopic structures of the system and govern and enslave the space-time behavior of the systems parts to their specific space-time motion. This defines the interplay between slow and fast processes. In the city context, fast maps the local micro level and slow to regions. This can also be scaled to cities and regions.

vi. *Captivity principle*: cities evolve stably as a whole but with the presence of instable chaotic areas being captive in the overall stability. Portugali suggests that this principle complements the Hakens slaving principle and that "*local islands of instability are needed in order to maintain the overall global stability of the city*" [1].

vii. Self-similarity and fractal dimensions: this applies to several aspects of a city such as: edge of built-up area, spatial distribution of land uses, size distribution of internal clusters, transportation networks, among others [25].

viii. Self-organized criticality: the system is stable in its global state but unstable in many of its local locations.

ix. Physical and cognitive circular causality: urban agents, according to Haken and Portugali [43], determine their location and actions in the city based on their cognitive maps. A circular causality occurs between the physical and the cognitive. The cognitive maps determine the physical structure of the city and it affects the individuals' cognitive maps of the cities.

x. Information interpretation: information that comes from the environment is interpreted with meaning assigned to it [44]. This is referred to as semantic information, which is different from Shannonian information.

xi. Low entropy: self-organization means greater order, which implies lower entropy. In other words, as order takes place entropy is exported from the system elsewhere.

Table 1. SoS Types

SoS Type	Description
Virtual	Lack of central management authority and central agreed purpose.
Collaborative	Voluntary fulfillment of agreed central purposes.
Acknowledged	Recognized objectives and defined managers and resources. Built and managed to fulfill specific purposes.
Directed	Components systems operate independent to each other but subordinated to the central manager.

Table 2. Complex Systems General Properties

Property	Description
Distributed Control	There is no central supervision of components.
Emergence	Global structures appear from local interactions. This is caused usually by *positive feedback*. This involves a state of high-level properties and relationships.
Autopoiesis	Emerged global structures are preserved by local interactions. This is caused usually by *negative feedback*.
Dissipation	Systems are *far from equilibrium* but stable. In information theory this is modeled as a *low-entropy* state.
Adaptability	Interacting agents modify their behavior or system structure based on experience or an evolutionary process.

Table 3. Cities as Complex Systems properties

Property	Description
Non-linearity	Cause-effect relationship is not linear.
Triggers mutations	The triggers that cause state transitions can change.
Embedded system observers and predictions	The observer and predictions (planners) are part or embedded in the system and its dynamics.

Feed-forward/Feedback loops	This is a key property in the context of cities. This is derived from the circular causality that occurs in different aspects of cities.
Open future	This is characteristic of opened systems.
Self-organization	Order, rules and organization emerge from the interaction of a number and variety number of agents without any full control.

The main approach for SoS management has been to address the SoS characteristics. It has also been derived from the fact that a SoS can be considered as an array or network of systems functioning together to achieve a common goal (as suggested in [45]). Based on this the Gorod et.al in [46] applied network management theory to study SoS management. Furthermore, in [32] they proposed a SoSE management framework using modified fault, configuration, accounting, performance and security (FACPS) network principles from ISO. This framework was founded from five SoSE Management areas: risk management, configuration management, business management, performance management, and policy management. It consists of four essential functions: (i) indication of current overall status of SoS (Part A); (ii) feedback process (Part B); (iii) development of policies for the SoS management, covering the five conceptual areas (Part C); and (iv) forces interaction among the SoS distinguishing characteristics (Part D). In other words, the A, C, D parts (functions) are looped by the B part. This feedback approach and part principles have been similarly used to architecture ICT infrastructure. In [47] this feedback loop is presented for autonomic systems based on four functions: collect, analyses, decide and act. These functions (autonomic system phases) have been also referred to as [48]: monitoring, analysis, planning and execution. The aim is to allow the operation of *communication devices and services* in a totally unsupervised manner (self-configure, self-adapt, self-monitor, and self-heal). In the case of computing devices, the autonomic architecture aim is to reduce intervention and perform administrative tasks according to predefined policies [49]. The building blocks of autonomic computing systems are the autonomic elements (software agents). These consist of two parts: managed elements and autonomic manager. The former implement behaviors while the latter the self-management function guided by administration policies.

The **control loop** (*feedback loop*) from autonomic systems approach has been also proposed in the context of smart cities in order to simplify the management process and reduce human intervention [50]. This proposal was made on the ground that both cities and autonomic computing activities have complexity, dynamism and heterogeneity. They also considered smart cities environments as complex, unpredictable and large scale. The authors on [50] also mapped this consideration to autonomic computing challenges such as: (i) heterogeneous functionality management; (ii) reliability; (iii) scalability; (iv) robustness; (v) adaptability; (vi) application of learning and reasoning techniques to support intelligent interaction. From these challenges they derived their framework autonomic architecture requirements as: scalability, modularity, self-stabilization, real-time requirements, and learning and reasoning. However, the framework is limited to enable autonomic properties to city management systems. In other words, their main focus is system-self management and approached as originally suggested in network management theory.

We postulate that the ICT infrastructure must reflect the SoS and complex system nature of Cities. For this we present the following arguments:

1) Beyond system management. As suggested by W. Mitchell, cities can be abstracted as living organisms, and therefore system management is just one aspect of many that should be addressed as we get a better understanding of cities. We believe that cities are the most complex systems ever created by humanity.
2) Meeting and supporting city properties. This includes the Boardman-Sauser characteristics, general complex systems properties from Table 2, the specific complexity considerations of cities from Table 3, and self-organization sub-properties of cities.
3) It should support all scales of planning and their cognitive essence [51] derived from the self-organization property of cities. Portugali in [1] suggested that there are different scales of planning: solitary, collective and professional. Furthermore, such levels of intervention are not necessarily proportional effects or consequences in cities [57].
4) ICT infrastructure should be ubiquitously provided and supported. As technology continues to evolve, according to the 4 digital laws, its use and intervention in city processes and activities happens at both scales SoS (holistic - inter-systems) and intra-system.
5) ICT infrastructure should meet and enable the proposed five dimensions: *any place*, *anytime any person, any data* and *any service.*
6) We need better and even in some cases different ICT infrastructure interfaces to support arguments 1-5. This implies other activities as those proposed for the control loop from autonomic systems (collect, analyse, decide and act).
7) Wellbeing should and ICT persuasiveness plays key property on this.
8) There is a need to study and perhaps identify tipping points of cities. In other words, to study how the city and its systems can maintain its basic functionality in the event of errors, failures and environmental changes. For instance, the network characteristics that enhance or diminish complex systems in general have been identified in [53]

From the previous discussion we define two types of ICT infrastructure: *active* and *passive*. The former refers to ICT infrastructure, which reflects the SoS and complex system nature of Cities while the latter to the traditional ICT approach. We believe that *active* ICT infrastructure will be part and enablers of future cities.

3 The Programmable City ICT Abstraction

In this section we define a basic and initial abstraction for cities in the context of *active ICT infrastructure*. We extend Mitchel notion of intelligence of cities from a holistic point of view and black box approach. Rather than defining the elements in which intelligence resides (nerves, brains, sensory organs, etc) we encapsulate all SoS components in a *single box with computational capabilities*. This box, the city, is a complex system in nature in which many different systems/components coexist and interact and yet emergence is observed. Some of these systems/components and their properties and interactions are even unknown. We call this box (abstraction) the programmable city. The a*ctive ICT infrastructure* itself is part of the universe of systems within the box. Intelligence is an emergent behavior and mainly driven by the self-organization property of the city. Any intervention is considered as a "program" being fed into the programmable city (box). Each program consists of both Shannonian and semantic information, which is received and interpreted in inside the box, respectively. According to the latter, the corresponding effects to the systemic interactions take place. Programs can be originated and fed from the outside and within the box.

The ICT city infrastructure is in its own a SoS. This is referred to as SoS_{ICT}.

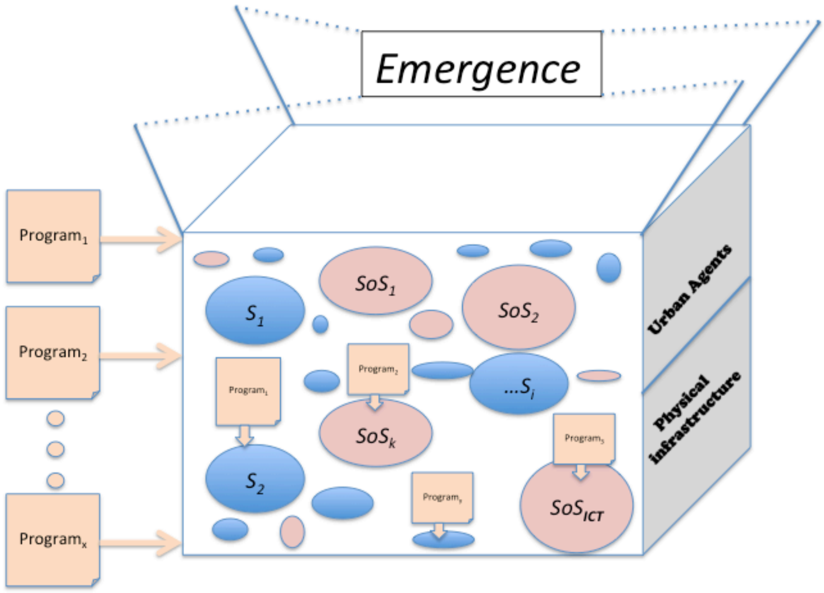

Fig. 1. The Programmable City ICT Abstraction.

We believe that this abstraction allows viewing the city in a simplistic way and the holistic complex and SoS nature of it. Based on this we can make some of many possible questions such as:

- Is there a difference in the code associated to the scale of the intervention or whether it's fed from within or outside?
- What other SoSs or Ss (systems) are inside the box?
- Is it possible to identify the tipping point between resilience and collapse for the box and the Ss and SoSs inside of it, given their interactions?
- In relation to the $SoS_{ICT:}$
  - What computing paradigm is better for the SoS_{ICT} given that it is inside the box?
  - What are the architectural and design principles that convey with the arguments from the previous section and Figure 1?

- What other tasks besides those from the autonomic computing approach model are required (monitoring, analysis, planning and execution)?
- How should Wellbeing be addressed as part of the design of the SoS_{ICT}?

From the previous discussion we propose the following basic methodology to address some of the $SoS_{ICT.}$ Questions:

I. Typify the system for which the ICT infrastructure is required within the box.
II. Interface the ICT infrastructure to the overall $SoS_{ICT.}$inside the box.
III. Design the ICT infrastructure considering interfaces and interaction with other known systems within the city.
IV. Identify the nature of all interacting systems; otherwise assume SoS and complex system nature.
V. The system interface should allow all scales of interventions (see argument 2 from previous section).
VI. Observe and measure emergence. Some relevant metrics at urban agent scales are:
    - City Quality of Experience (QoE)
    - SoS_{ICT} QoE
    - City Wellbeing

4 Conclusions

In this paper a new approach for the design, deployment and operation of information and communication technology infrastructure for what we conceived as "Programmable Cities". We presented a definition for ICT city infrastructure as *active* and *passive*. The proposed model considers inhabitants-wellbeing and the SoS, and complex system nature of cities. This includes key properties such as openness, non-linearity, unpredictable mutations of triggers for change, feedback (positive and negative) and feed-forward, circular causality and wellbeing. In the model rather than defining the elements in which intelligence resides (nerves, brains, sensory organs, etc) we encapsulated all SoS components in a *single box with computational capabilities*. We called this box (abstraction) the programmable city. The a*ctive ICT infrastructure* itself is part of the universe of systems within the box. Intelligence is an emergent behavior and mainly driven by the self-organization property of the city.

We have proposed a total of 5 dimensions for ICT infrastructure in the context of cities: *any place*, *anytime any person, any data* and *any service.* We presented a series of 8 arguments to support our postulate that the ICT infrastructure must reflect the SoS and complex system nature of Cities. Based on the proposed model we have raised a series of opened questions for further research.

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