Achieving City Intelligence - A Systems Engineering Approach

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***Abstract*—Intelligent systems sense and react to their environment. They are amenable to change, heterogeneous, sustainable and secure. By their nature, cities develop due to various preconditions affirmative to local sustenance of their inhabitants. They are complex systems that encounter ranging pressures stemming from urbanization to uncontrolled socio-technical effects. To control and manage these pressures, various suggestions, frameworks and concepts have been proposed including but not limited to transitioning into Smart Cities. It is relatively accurate that most cities will aspire to be Smart merely for the perceived benefits of such a state. Nonetheless, the research on attainability and progress measurement is varied and deferring in this regard. In this paper, cities are presented as complex sociotechnical systems such that their optimization is a function of people, social systems and network-technological systems. Five incremental levels of the city's intelligence journey are proposed: Insulation, Micro-Functional, Macro-Functional, Spatial Dominance, Self-Orchestration and Astute.**

Keywords-intelligent cities; systems thinking; smat cities.

I. Introduction

Cities happen to be problems in organized complexity, like the life sciences. They present "situations in which a half-dozen or even several dozen quantities are all varying simultaneously and in subtly interconnected ways." Like the life sciences, cities do not exhibit one problem in organized complexity, which, if understood explains all. They can be analyzed into many such problems or segments which, as in the case of the life sciences, are also related with one another. The variables are many, but they are not helter-skelter; they are "interrelated into an organic whole" [1].

The city is manifestly a complicated system and only partial control can be exercised over its growth and form. It is a product of growth rather than of instantaneous creation. [2] compared the city to a biological entity. That is, a single organism covering the entire landscape surface and showing signs of a vast intelligence [3]. Cities typically evolve spontaneously and subsequently governed into desired states. Thus, more often cities are self-organizing and evolve from local-actions. This spontaneity contains elements of spatial consciousness and random unique forms commonly called *fractals*. Understanding these interacting elements have taken precedence on research on city systems since the nascent stages of the 20th Century.

As systems, cities have existed no less than over 5000 years ago and changes in their form follows a randomized process that manifest simultaneously at different spatial levels. The need for a formal control mechanism to close the gap between fur-flung anarchy and sporadic orderliness inspired the development of disciplines such as City Planning, Urban Studies et al. These specialized disciplines engaged in atomistic and mechanistic approaches to *plan* communities. Urban studies and related, have exerted a great deal of effort in theoretical and practical techniques following this pursuit.

Cities generally are taken as a composition of discrete spatial nodes that perform separate functions at different points in time. This view has been prominent and promotes a vertical hierarchical-node structure where everything is controlled from a [city's] central core. A theoretical idea extended from 19th century German economist, von Thünen whose 1826 iconoclastic treatise, *The Isolated State,* a century later led to – the mono-centric city models – one of the fundamental insights in Urban Planning. The idea of location theory, as Thünen's views are known, has since the mid-19th century inspired a revolution of economists' and geographers who have extended location theory into mainstream economic models. The latter mainly were interested in economic consideration and physical analogies as a means to explain emerging city patterns.

The vertical elaboration of the city system has been dominant therein with notable applications in research on scaling patterns and in land use planning. However, this structure is changing into a horizontal one and spatial processes are no longer mainly controlled from a central core. Thus, relational linkages tend to be horizontal rather than hierarchical/vertical. At the same time, there is the shift from competitive cities to cooperative cities. The rest of this paper is organized as follows. Section II elaborates more on the traditional view. Section III describes the core problem. Section IV discusses what an intelligent city is and Section V introduces and proposes the five stages. Section VI connects the dots.

II. The Traditional View

In Figure 1, foundational view about the city is dominated by well-defined familiar structures, a central market place or core, distinct route structures that enable people to travel rapidly to the center from outlying places, suburban locations or neighborhoods or district centers that exist within a clearly structured hierarchy of places and segregated areas where industrial activities take place [4]. This view implicitly assumes that everything in space is homogenous and works as expected.

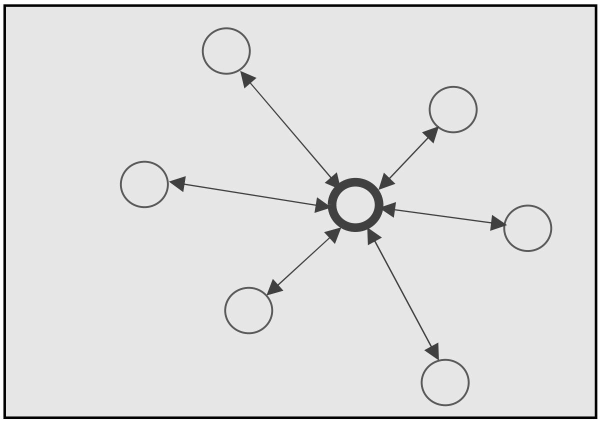

Figure. 1. Traditional view of Cities and spatial processes; akin to star networks exhibiting a one-to-one relationship

On the contrary, cities are open complex systems and exchange both mass and energy with their surroundings, and is a product many builders: Planners, Technologists, Architects, Scientists, Engineers and Policy Makers. They, [the] *builders,* constantly modify the structures of cities for reasons of their own. Regardless of the city exhibiting fundamental characteristics of open systems including the property of multiple builders, many theoretical propositions developed to explain and predict urban spatial structures typically describe the city as closed *static* system. That is, a system permitting the export of mass but not energy. Forrester [5] attempted to introduce the concept of the closed *dynamic* system in his well-received but controversial book: Urban Dynamics. By a closed dynamic system, Forrester, does not outright describe the city as a conventional open system. Instead, as a system that generates its own problems and should be capable of reinventing itself to meet internal demands given institutional, economic, governance and infrastructural structures – a common property of all-natural systems. And as an emergent property, the boundaries do not exist in isolation - in order words, cities only have imaginary boundaries. Forrester strengthened his supposition and stated that: *"it does mean cause and effect loops do not reach outside the boundary and return. For example, migration to the area [cities] has its effect by filling and thereby altering the area not by emptying the outside world".*

This position was fundamental in pioneering a complementing focus on the dynamics of urban systems as against only analyzing the current state and function of such cities. In Figure 2, we demonstrate the representation of the city as a mesh.

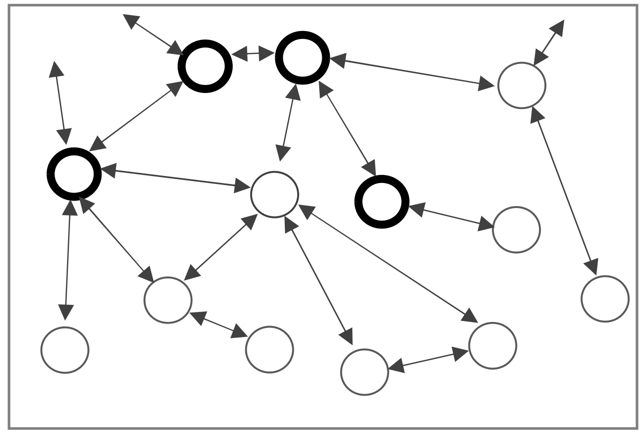

Figure. 2 The city as a mesh with many-to-many relationships

III. THE CORE PROBLEM

The governance of urban systems poses an enormous challenge to stakeholders and their community of decision makers; a challenge heighted by the increasing need for resilience, sophistication, durability and intelligence in urban instrumentation defined, embedded and utilized in cities. The city problem is getting more profound and complex. Since 2008 and for the first time in human history, the world became more urbanized than rural, with more than 50% of the human population residing in cities. Estimations predict this percentage to surpass 70% by 2050.

Attainment of this milestone ushered in a new era for which cities were opened to mega challenges and mega opportunities encapsulated in the complexities of sociotechnical systems – the fundamental goal for cities shifted. Cities seek to minimize problems and to maximize opportunities across systems and processes. Some cities by virtue of structures, processes and available infrastructure are better positioned to explore these opportunities, however, none is immune and many especially, most in the developing world are highly susceptible to the negative repercussions of urbanization. As cities continue to search for solutions in what is theoretically an infinite solution space, it is indispensable to implement and monitor systems, programs and policies that inform and enforce a set of key performance parameters. *Making-A-City-Think*; in order words, architecting an intelligent urban space has emerged as the indispensable strategy to cope with the problems generated by the changing dynamics – and there are many of such challenges. However, the success of such transformation depends on how it is done [6]

Smart or intelligent cities by definition and application imply an extended integration of new technologies, solutions, policies and decision making in the ontology of city existence comprising of mobility, living, governance, economy, environment, civic/people support [7]. It is primarily enabled by new computational power, open data availability and advanced problem synthesis and analysis.

The city system has become an experimental plot to test propositions and suppositions emanating from different academic disciplines. A new generation of city scientists and researchers employing multidisciplinary approaches to address many challenging city problems is relatively new [although actually old] and has doubled over the last decade due to rapid *urbanization*. Unlike any period in history, we observe an active desire of more and more people wanting to the move towards the cityscape in search of *city resurgence* – and not necessarily wanting to vacant the bucolic peripheries of the country side. We make this distinction, and to borrow from Forrester, such a movement is not intended to empty the country side [which will never happen] but rather to fill the cities.

It is intuitive and conceptually appropriate to describe the shift to cities – migration on bases of '*interpreted*' transaction cost theory. That is, we relate how people move as a set of transactions with the cost of the transaction split between: *perceived individual benefit(s)* and *perceived collective benefit(s)* of migrants [as agents]. That is, the decision maker(s) probabilistic outcomes of 'success' at their [intended] destination is/are larger than their origin. Assuming Occam Razor all individuals and groups – all things being equal –are greedy and rational and that tentatively, gain a cognitive [learning] ability to infer, approximate, distribute and map as a function of time their egoistic and collective goals relative to their current state. Where perceived state is greater than generated state, they seek a movement towards nearest (*Basic mobility ability, that is: distance travelled depends on distance to be travelled to reach the destination of choice*) destination for improvement, that is: ($P_s > P_g$). For instance, in developing countries, the decline of subsistence farming [favoring the masses] – the rise of mechanized large scale [favoring the few] coupled with the growing knowledge-based information centric technological age has generated a shift of form and a change in occupational dependents. When speaking with a 'Lagotian' (Somebody that has lived or preferably lives in Lagos, Nigeria – Africa's biggest megacity) recently, he remarked: "*In Lagos, you can sell anything and make money out of an*ything". In order words, whereas their *economic* choices in the bucolic regions are limited; opportunities are assumed to be abundant in cities – literally. Glaeser [8] sums this up: in reality, there is no such thing as a poor urbanized city or a rich rural region.

Succinctly, cities generate more interactions with more people than rural areas because they are central places of trade that benefit those who live there and so people moved to cities because they intuitively perceived the advantages of urban life [3]. While technically possible, the assumptions above are not intended for quantitative translations. In making the above logical constructs, we are only re-emphasizing a trait of *Homo sapiens* such that are learning creatures - we learn both voluntarily and involuntarily. And that in fact, our most valuable knowledge may be one acquired involuntarily – just like the seasoned power plant engineer who through acquired intelligent cognition can *think-ahead* of machine warnings and shut down generators before an inevitable power surge. As a pioneer, Skinner [9] was the first persuader in this direction when through a counter theory to [10] he stressed on the need to focus more on the productive behavior [of a system] itself rather than using it to make hypotheses about mental states. In Figure 3, we provide an implicit example of a pseudocode of a human agent program that may be used to explain the growth of the core problem.

The choices of many especially in the developing countries to move to urban areas underscore the high-level of attraction the city offers. In essence, people have elevated their expected value of city returns – partly economic, others technological and some cultural, others security, etc. Stereotypically, intelligence permeates our cities because we now live in a world where objects are capable of gathering, processing, displaying, transmitting or taking physical action on information all at the same time. The roles of cities are being gradually transformed into managers of these containers of intelligence - egocentric centers of innovation and cognition embedded in socio-technical complexities.

IV. WHAT IS AN INTELLIGENT CITY?

The city's problems are relatively similar everywhere, they just vary by the degree of sophistication, intensity and impact. Climate change affects all cities and megacities are not necessarily generating new kinds of problems but rather intensifying and exposing the inability of existing structures to cope with and or minimize negativities.

Due to its definitional impreciseness, numerous unspoken assumptions and a rather self-congratulatory tendency [11], a smart city can mean different things to different entities – there exist an inherent *stakeholder bias* that practitioners, civic leaders, technocrats and related must strive to. In most cases, where cities are using networked infrastructure. [sometimes mainly, 'plug and play'] solutions to gain a centralized view of information across certain city departments and agencies, they are sometimes referred as smart cities.

To the citizen, a smart city can mean automatically finding the fastest way to get to work; where smart meters control power usage and even to some [especially in developing countries], where drinking water that can be counted on, or perhaps, where they are safer streets due to increased closed circuit monitoring. To the city administrator, a smart city can mean optimization of process through the installation of city management systems, etc. To the environmentalist on the other hand, a smart city may mean a city that produces few carbon emissions or one whose citizens have a smaller ecological footprint.

Figure 4 is a *Systemigram*. Systemigrams are used to bring context to the meaning of *togetherness* that is, to unravel ambiguity in methodical system descriptions, parts and relationships. Through this approach Systemigrams are able to gather and clearly present the structure and behavior of systems diagrammatically as an emergent whole.

The mainstay [the diagonal, from left to right] is the principal stakeholder bias; this can also be termed as the dependent variable given that it acts as a centralized governance structure that depends on the perspectives of other interests/ agents in the urban system. Such a governed interplay is for purposes of good service delivery in urban systems. For instance, in the smart growth node, consider "*walkable neighborhood*" a citizen may not necessarily consider himself safe [his community walkable] on the street because business and convenient-shops are within his reach of < 10 minutes of walking but because the city has installed real-time communications technologies to monitor streets.

From above and by extension, an intelligent city is therefore a smart connected community capable of reinventing itself through appropriate and optimal communications between local nodes enabled by the network and in addition, it engages in interconnectedness with foreign entities relevant to local sustenance and/or evolution. Getting to this point is not guaranteed by the upgrade of a sub-system – *it helps*- but to achieve or work towards achieving intelligence, a city must navigate a systematic and holistic course comprising of Insulation, Micro-Functional, Macro-Functional, Spatial Dominance, Self-Orchestration and Astute**.** Therefore, where intelligence shall be a function of:

C (*intelligence*) = *f* (C*w1*, A*w2*, A*w3*, S*w4*…)

Function parameters: weighted rate of the 5 stages

V. THE STAGES

Below are the proposed incremental stages considering a city's intelligence journey.

A. *Insulation*

The main purpose of insulation is to limit the transfer of energy between the inside and outside of a system [12]. Cities [as we know] have been complex open systems since the evolution of the first of its kind. They have acted as centers of knowledge incubation, dissemination and transfer. They are the drivers of political, structural and economic growth of the national dynamic boundaries within which they are situated.

Cities need to articulate a complex insulation mechanism in the form of predictive models on people movement in and out of cities and to control the attraction and retention of talent, local education institutions and related. The above does not call for restrictive policies to constrain the mobility of people seeking social opportunities, as misguided interventions often divert resources to locations that are not profitable for local level growth [13]. One cannot design a system without understanding the boundaries of such a system.

B. *Micro-Functional*

Effective approximation of the simple functions of a city measured against a verification and validation mechanism contributed by the actors of each individual sub-system. This approach is intended to assess the optimal operation or lack there-off of the assets in a neighborhood. This approach is akin to a focus group intended to collect perceptions of a product performance, and/or to improve features. In theory, it is possible to account for all properties of any particular urban system; for instance, the Health care delivery system or the Energy system and so on if available data allowed for a comprehensive knowledge of all the characteristics of such and the relationships existing between them. Practically however, this is infeasible because, we will never be able to know or even approximate all the properties of these systems. Few reasons are because urban systems defer from city to city with multiple socio-technical interacting relationships that are varying, unpredictable and subject to multiple subjective interpretations.

C. *Macro-Functional*

This is the extrapolation and extension of a holistic representation of the state of a city. It is the assessment how micro-functional agents are working collectively and optimally. Given the whole is greater than the sum of the parts, Macro-functional states are distinct and poses a different set of challenges in complexity. From a far, there may not be direct link between mobility and education but the nuances in-between are the containers to the solution.

As a *satisficing* [14] solution to this complexity, the properties of the complex wholes – independent systems embedded in the city's system of system ecology – remain irreducible to the characteristics of their parts. Hence, they are grouped as like terms and each group of like terms is assigned a different singular or multi-objective function identified with that particular group. Any of these groups will possess a spatial view of the urban form which stems to be a representation of an urban system from their common concerns.

D. *Spatial Dominance*

There is almost never the best system, but there is an optimal system at any given point in space. While in many real-world situations, optimal strategies are unknown or unknowable [15], the city is not one of those. Enabling urban intelligence fueled by urban technological innovations begins as a pragmatic, engineering-based attempt to improve the operation of individual urban infrastructure and services; it can also be seen as perturbing unconsciously the interactions of the many systems within a city. Urban networks consist of infrastructure systems, interconnected service delivery mechanisms and social networks.

In the context of the city, spatial dominance represents the estimation of interconnectedness of cities. Regardless of how minuscule it might be, it is important for a city to achieve a preferred status, in-other-words, be known as the go-to in an area relative to another city with which is shares relation. It's possible for multiple cities to be equally preferred in enumerated areas or metrics.

E. *Self-Orchestration*

While making a city think may be a new research domain, the study of cities as systems dates back to at least the mid-1950s. Cities were first treated formally as systems when General System Theory and Cybernetics came to be applied to the softer social sciences in the 1950s. It is worth mentioning that the structure of a digital urban space is not static, that is, with the continuous improvement of theory and practice related to urban management and operations, urban components and their systems can be dynamically optimized and adjusted so that they can better cover all areas of the city [16].

With self-orchestration, there is an end-to-end function of cities as systems within systems of cities, such that multiple areas of the city function autonomously and at the same time controlled. Example, the automatic detection of a pothole and the prevention of a pothole. It is a trusted, integrated state.

F. *Astute*

This is the final stage and a culmination of insulation, micro-functional, macro-functional, spatial dominance and self-orchestration. Thinking in systems or systems thinking can be said to hold the city in its dichotomy: it helps to show how local processes and interactions give rise to global structures considering a plethora of local views and constraints and how these global structures feedback into local interactions.

VI. CONNECTING THE DOTS

Studies on cities as socio-technical systems are recent and not well developed. Either there have been undue emphases on creating diminutive *artificial societies* – a technology lead approach or a 180 degree turn to emphasize the value of social welfare. The study of cities as socio-technical systems recognizes an eminent social part and an important technological dependency. The COVID-19 crisis made it clear that cities suffer if their citizens do, and that without the well-being of the latter, they are merely empty structures [17]. This approach reduces the evidence of social and technical polarization cited in earlier works such as [18], [19].

The ability to deal with commonsense knowledge about the world is fundamental for any intelligent system that acts in the real world and it has been early recognized as one of the central topics of Artificial Intelligence to represent and reason about commonsense knowledge. Space has always been considered to be an important part of commonsense reasoning given the physical world has a spatial dimension and all objects which are dealt with are located in space relative to other objects. Early approaches involving commonsense knowledge about the physical world were trying to solve text book physics and math problems, e.g., [19, 17]. but it soon turned out that mathematical equations were not sufficient for solving most problems.

VII. CONCLUSION

Strong linkage between the state of cities and information technology is a function of time and obligate symbiosis. In order words, technological innovation, regardless of the geography within which it occurs: be it in a basement in India, Bangladesh, Nairobi, or in well-organized centers in Silicon Valley, mostly occur in cities. Technology evolves when actors nurture and develop ideas directly impacting existing spatial dynamics of their living squatters'. Because money begets money, actors are attracted to disproportionally work towards where such technology will be needed. The law of disproportionality does not deny but delay diffusion into other areas.

By employing systems thinking and systems engineering, we think about how a set of "city events" are governed and function as a function of nested complexities. We acknowledge learning in city spaces require abilities to decrypt, analyze, synthesize, apply, predict [actions] and re-configure an integral knowledge base. Such information, where gathered can be molded into patterns of behavior, develop predictive models of likely outcomes allowing better decisions and informed actions [20]., *learning* in space require Networked Infrastructure, Information Systems and City Citizens as principal agents.

Cities are complex spatial systems with social and technical rules, structures and networks. In the most general terms, there is a network of cities or a network *in* cities. Of more interest is network in cities where the city becomes less obtrusive and reinforce a network dependency of a system among systems, rightly called a *system of systems*. By extension, it is important to realize these relationships because they serve a building blocks to understand how logical and physical networks work in cities. When we say a city is connected, more 'smartly' connected we mean it is capable of reinventing itself through appropriate and optimal communications between local nodes enabled by the network and in addition, it engages in interconnectedness with foreign entities relevant to local sustenance and/or evolution.

In this paper, we have presented the background of the problem and introduced five stages of assessment and measurement. Further research will expand on guidance and evaluation of the proposed stages.

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function IMPROVE_QUALITY_OF_ LIFE(target) returns an action
        cognition: localPercept, access local conditions, initially set to null [0, 1]
                   foreignPercept , excepted opportunities for goal attainment [0, 1]
                   Goal , access short term and long term
        DEFINE:    localState [‘current local State’ based on performance measure]
              futureState [‘perceived future State’ based on performance measure]
    if {
     localPercept approaches 1 && foreignPercept approaches 0 , then
      Goal ← foreignPercept
      VERIFY
      Problem ((futureState – currentState) < (currentState – futureState))
       execute ← MIGRATIONDIRECTION (foreignPercept)
         ELSE if
         localPercept approaches 0 then
        break thought;
      return action
           if
                SOLUTION is null [0] after ‘x LOOPS ’
                AGENT is content ← SET localPercept ( approaches 0 )
      }
    END IF
     return state
```

Figure. 3 The core problem fueled by migration

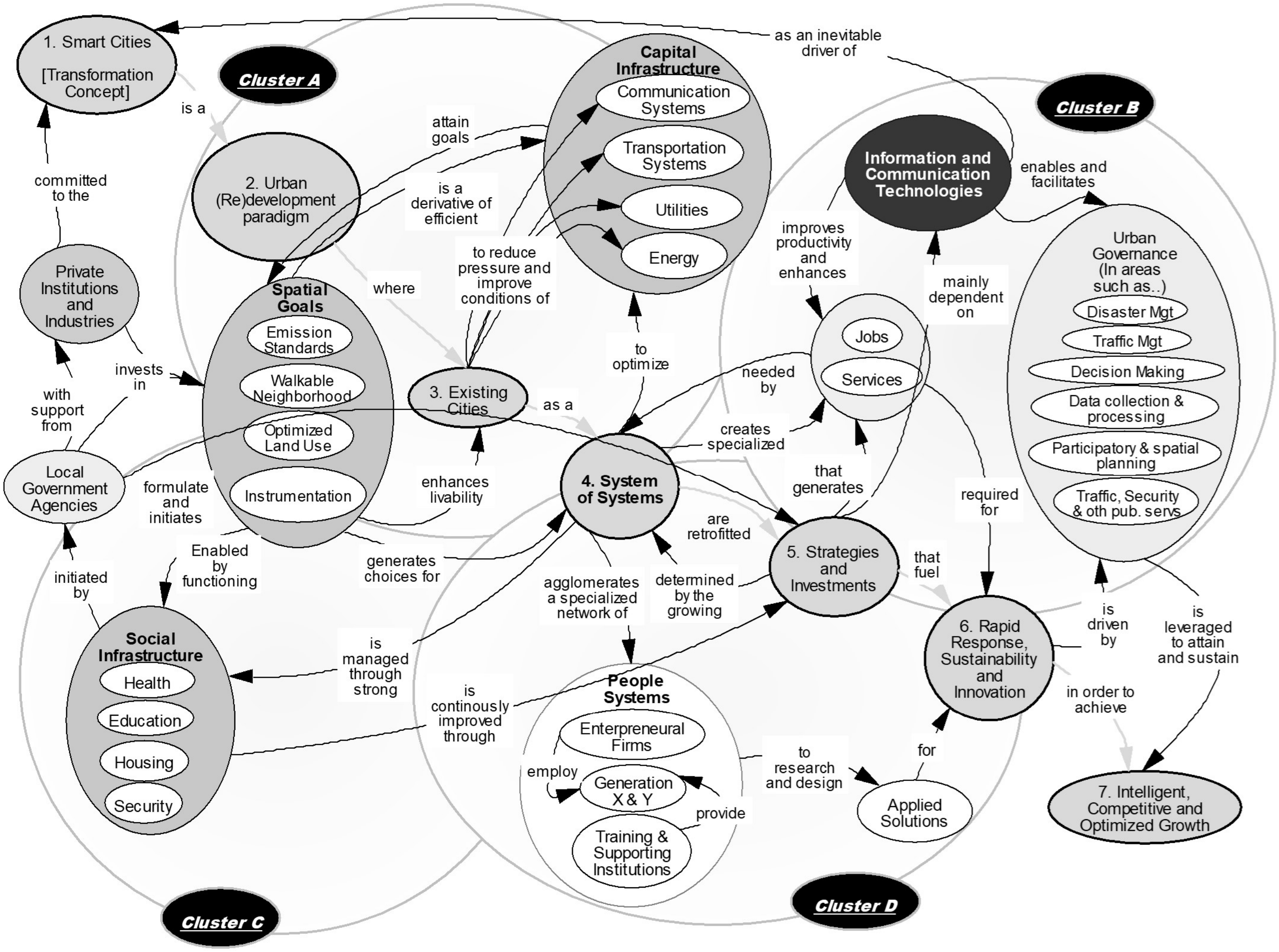

Figure. 4. The Systemigram of a Smart City