USING SYSTEM DYNAMICS PRINCIPLES FOR CONCEPTUAL MODELLING OF SMART CITY DEVELOPMENT IN SOUTH AFRICA

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Abstract

South African cities are in the process of transition in the changing scenario and need a change in the planning perspective for their sustainable development. The concept of smart city offers opportunities for such development to many middle sized cities of South Africa. Therefore, in this paper conceptual modelling for development of smart cities in South Africa is attempted based on systems concept. The conceptual models are built by using the principles of system dynamics methodology and based on causal feedback relationships among the various factors under different smart characteristics of a city such as, smart economy, smart people, smart governance, smart mobility, smart environment and smart living. The causal feedback loops and interrelationship among various parameters illustrate the dynamicity and influence of parameters on one another, which would able to assist in evolving plausible policy interventions for developing smart cities in South Africa. It is concluded that the modelling approaches presented here could guide the policy makers and city planners to evolve robust and responsive policy interventions for developing smart cities in the changing scenario.

Keywords: Smart city; Smart growth, Smart economy; Smart environment; Smart mobility; Smart living, System dynamics modelling

1. INTRODUCTION

While globalization, market economy and technological advances have created an environment for economic, social and infrastructural developments in many regions of the world, their influence provided opportunities for higher influx of people to the cities and added pressure on the civic requirements in the wake of the scarce availability of resources making the cities face physical and environmental ailments (Moussiopoulos, Achillas, Vlachokostas, Spyridi, Nikolaou,2010; Saavedra and Budd, 2009). Many South African cities are not far away from this burgeoning phenomenon. Most of the South African cities have potentialities for both economic advancements and appropriate spatial development. Although the Governance system of the country has taken several proactive efforts for congenital developments of the cities, it is observed that most of the cities are planned and developed conventionally by use of Integrated Development Plans (IDPs). Of course, there is no reason why the IDP process should not bring about appropriate development in the cities, however, the suitability of this conventional approach in the changed scenario of globalisation, and technological advancements is quite uncertain.

In the wake of this scenario, there is a need to rethink the planning process to incorporate the fast changing current scenarios and adapt the cities to the challenges of future, which warrant a change in planning perspectives (De Swardt, Puoane, Chopra, & du Toit, 2005; McGillivray, 2005; Naude, Rossouw, Krugell, 2009; Ramutsindela, 2002; Saff, 2001) and move from the normal planning process (Kotze & Donaldson, 1998; Lotter, 2002; Nomdo & Coetzee, 2002; Prinsloo & Cloete, 2002; Turok, 2001; Visser, 2001) towards smart growth and development process based on smart city concept (Farmer, Frojmovic, Hague, Harridge, Narang, Shishido, 2006; Giffinger, Fertne, Kramar, Kalasek, Pichler Milanović, Evert, 2007; UN- Habitat, 2009).

However, the development planning process for transforming the existing cities to smart cities requires dynamic principles for evolving plausible planning policy interventions. In this context, the systems dynamic principles based on systems thinking approach perhaps could provide an avenue for future planning of the cities of South Africa. Therefore, this investigation pertains to conceptual modelling to develop policy interventions in order to transform the South African cities as smart cities by using system dynamics modelling approach based on systems thinking and make them economically, socially and environmentally sustainable. For this purpose, conceptual causal feedback relationships among the various parameters of each characteristic of a smart city have been developed to create a road map for evolving policy interventions to build smart cities and realise the intended outcomes.

In this regard the scope of the paper is limited to development of causal feedback relations among various indicators under smart characteristics of cities of South Africa by using system dynamics principles, which shall enable developing policy interventions for future development of smart cities in the country.

2. UNDERSTANDING THE PROBLEM

2.1 Smart city Concept

The smart city concept is not considered in a holistic manner rather with reference to various aspects, which range from Information and Communication Technologies (Digital) districts to smart populace in terms of educational level. Use of modern technology in everyday urban life, which includes innovative transport systems, infrastructures and logistics as well as green and efficient energy systems are often integral part of a smart city. Further, there is a strong relationship between city government and citizens in terms of good governance. Although, there is no agreement on the exact definition of a smart city, a number of important dimensions of a smart city are identified, such as, smart economy (related to competitiveness), smart mobility (related to accessibility and connectivity); smart environment (related to natural resources); smart human capital (related to people); smart living (related to the quality of life) and smart governance (related to participation) (Giffinger et al, 2007; Komminos, 2002;

Lombardi 2011; Shapiro, 2008; Van Soom, 2009). Smart economy refers to parameters around economic competitiveness such as, innovation, entrepreneurship, trademarks, productivity and flexibility of the labour market as well as integration in the national and international market. Smart people are essentially described by the level of qualification or education of the citizens as well as by the quality of social interactions and integration, participation in public life and the receptive attitude, and openness towards the outer world. Smart governance encompasses facets of political participation, services for citizens and the functioning of the administration. Local and international accessibility in the form of sustainable physical transportation system, and Information & Communication technologies refer to smart mobility. Smart environment is expressed by attractive natural conditions, i.e., climate, green open space, level of pollution, resource management and efforts towards environmental protection. Smart living includes various indicators of quality of life such as, culture, health, safety, housing, tourism, etc., (Giffinger et al, 2007).Thus, a middle-sized city is considered to be a smart city if it demonstrates forward-looking development in these six important characteristics on the basis of a combination of local circumstances and activities carried out by politics, business, and the inhabitants (Lombardi, 2011; Komminos, 2002; Giffinger et al, 2007; Shapiro, 2008; Van Soom, 2009).

Transforming or developing a city to a smart city is based on the coordinated performance of these smart characteristics of a city and it is imperative that the city planning process needs to be different from the normal urban planning processes.

2.2 Potential and challenges in South African Context

In South Africa about 47% (112 cities and towns) out of the total number of 234 cities and towns have a population, which range between 100000 and 1.0 million (Statistics SA, 2011), which can be considered as medium cities. Out of these 112 cities, about 58.93% falls in the range of population 100000 to 200000, 32.14% have population of 200000 to 500000 and only 8.93% falls in the population range of 500000-1000000. In the absence a clear cut definition of medium cities and assuming that the cities with higher population (200000 to 1000000) have potential for higher economic development and challenges for infrastructure and environment than cities with lesser population, about 41.07% of the medium towns and cities or about 19.66% (46 in numbers) of all the cities can be considered to have the potential to become smart cities based on population criteria alone in a conservative scale.

Further, some of the development authorities and municipalities responsible for city development in the country envisioned to make their cities globally safe and attractive places to live work and invest, and to improve social and economic livelihoods through public participation, effective and efficient integrated governance systems and programs.

For realization of this vision a few among the important future guiding principles stressed upon are economic growth and jobs creation, building community resilience and self-resilience, services excellence and sustainability, civic leadership, common purpose, etc. The strategies thought of to achieve the objectives are through stimulating integrated and sustainable economic development prospects, improving and sustaining financial, human resource excellence, management excellence, evolving institutional excellence through a thoroughgoing institutional re-engineering process, effective leadership and effective long range development planning (e.g. IDP, 2012 Mangaung Metropolitan municipality), etc., which in fact complement the smart city concept.

However, there are several challenges which the cities are currently facing or expected to face in future. With the gradual change in the economic scenario, most cities are increasingly embracing multifunctional economic activities divorcing from earlier unitary economic activities, for example with the closing of mining operations in predominantly mining cities, they are either languishing or striving to keep up with incorporation of other industrial and / or service activities. It is also natural that the cities will embrace more and more diverse economic activities in future. Besides, the opening of economic opportunities will attract higher influx of people to cities increasing pressure on the existing infrastructure, which will require building of more infrastructures and in turn demand for higher investments. On the other hand, the economic development in the cities will strengthen the existing phenomenon of predominantly individually driven cars for movement in the cities leading to environmental as well as spatial development concerns. In the absence of adequate public transportation system, the problem is already felt in many cities through congestion, increase in travel time, long queue length at intersections, high carbon emission, etc., and consequent environmental pollutions. Thus, in the changed scenario large scale influence on the spatial development, as well as infrastructure and environmental consequences are also expected in the future. Based on this premise the clusters of main issues extracted are:

- How cities will cope with the challenge of changing economic scenarios in the wake of globalisation as well as expected local change in their economic functions?
- What will be the consequent spatial, infrastructural and environmental problems the cities will face in the wake of higher economic opportunities and influx of people to them?
- What are the improvements needed in the social capital and general local governance issues to face the challenges?

Therefore, the concern arises in such scenarios is that will the strategies outlined in the IDPs based on which cities are developed be adequate and competent to stand to the challenges of the future or what kind of policy interventions are needed to cope with the future development and transform the cities to smart cities.

3. METHODOLOGY

This investigation was carried by employing survey research methodology - discussion with people involved in the urban planning process and experts, review of the IDPs and literature review for understanding the problems, factors and characteristics, which contribute to the development of smart cities followed by application of system dynamics principles based on systems thinking for conceptual modelling.

3.1 Epigrammatic Outline of Systems Thinking and System Dynamics

According to Von Bertalanffy, (1974), a system constitutes a set of subsystems or in other words components, which are interlinked and interdependent on each other to perform a function as a whole. The subsystems of the system can be systems themselves. In a system, if a subsystem performs at a higher efficiency than others or becomes defunct then the effect is felt on the whole system. As a result the whole system may perform at a lesser efficiency or even may become paralysed. In order to the system to perform at a higher efficiency all the subsystems of the system are to work in a coordinated manner. While planning, a city as a whole can be considered as a system with its various components, such as people, economy, social aspects, movement and communication, other infrastructures, governance, environment, etc., as its subsystems. All these components are inter-linked and interdependent as the case may be and work in a coordinated manner for the sustainable development of the city.

Scholars like Wolstenholme, (1992) and Robinson, (2008) outlined a conceptual model as a consistent and unifying theory of behaviour taken from bits of information about the real world. The rigorous structural framework provided by system dynamics assists in eliciting and displaying information used to build a conceptual model (Forrester, 1994; Lane and Oliva, 1998). Essentially, system dynamics methodology amalgamates ideas developed in various systems theories and is a result of cross-fertilisation of ideas from traditional management, cybernetics, and computer simulation (Shen et al 2009: 15-25) and is especially designed for large-scale, complex socio-economic systems to understand how and why the dynamics of concern are generated and to search for managerial and development policies to improve the situation. It is a theory of structure and behaviour of system (Forrester, 1968, 1969) and is characterised by the concepts of causal feedback loops and time delays, which represent the dynamic complexity of a system (Sterman, 2000). Causal loop maps are usually employed to describe the elements (Montibeller and Belton, 2006) of the system. The use of system dynamics in solving real world urban development related problems are rising since its early application by Forrester in 1969. It has been applied to develop policy interventions for alleviating urban problems or understanding the dynamics that flows in the urban areas (Chadwick 1971: 36-37; Checkland 1981; Lee, Choi and Park, 2005).

4. CONCEPTUAL MODELLING, KEY CAUSAL RELATIONS AND BROAD POLICY INTERVENTIONS

The six major components or characteristics such as, economy, people, mobility, governance, environment and living conditions of a city, which are critical for development of a smart city are analysed by the help of conceptual causal loop and feedback relationships augmented by system dynamics principles. It is hypothesized that each characteristic creates a positive causal feedback loop with the smart city and the influence of each characteristic is felt on the other characteristics directly or indirectly (figure 1). Each characteristic is analysed by considering its endogenous parameters and their causal relationships and their influence on the city as a whole as well as on other characteristics to understand and develop policy interventions based on their positive and negative influences. For the purpose of this analysis the various smart factors and parameters under smart characteristics developed by (Etzkowitz and Zhou, 2006; Giffinger et al, 2007; Lombardi et al 2011) have been adopted and modified to suit the local conditions. The various conceptual models are discussed in the following subsections.

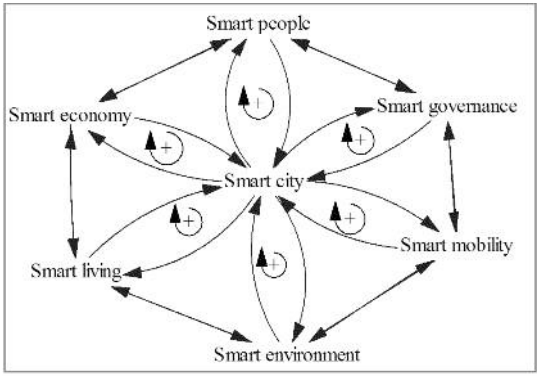

Fig 1 Causal feedback relationships among the characteristics of a smart city

4.1 Economy

The smart economic conditions of the city are characterised by factors such as, level of entrepreneurship, innovative spirit, international embeddedness, economic image and trade mark, and importance as decision making centres. Figure 2 presents a system dynamics causal feedback loop structure of the economic characteristics of a smart city. As envisaged earlier economy of a city has a positive feedback relationship with the smart city, which means if the economy of a city is enhanced, it will reinforce the development of the city (ER1). However, amongst other factors entrepreneurship is considered as the key factor, which defines the economic characteristics of a smart city.

A higher level of enterprising activities in a city will lead to enhancement of economy, which in turn would facilitate location of corporate offices or business decision making centres. The location of corporate offices will increase inter-(national) embeddedness enhancing both communication and business relations, which will have a positive influence on the enterprises located in the city as a feedback to the system. This relationship is presented by the reinforced loop ER2 in the feedback loop diagram. Besides, entrepreneurship will bring in innovative spirit, which will positively influence productivity in the city. Higher productivity will enhance the economic image and trade mark of the city creating a congenital environment for entrepreneurship development as a feedback, which is presented by the reinforcement loop ER3 in the diagram. Thus, the causal loop ER3 reinforces the loop ER2, with entrepreneurship remaining as the key factor in smart economy of a city development. Similarly, feedback loop ER5 reinforces loop ER3 and vice versa through increase in productive and its causal relationship with Gross Domestic Product (GDP) of the city or per employed person.

Further, location of corporate offices or decision making centres in the city will enhance the importance of the city as a decision making centre (loop ER4), reinforcing the economic image of the city and trademark and as a result reinforcing the loop ER3. Thus, all the factors are reinforcing each other through dynamic feedback relations ultimately enhancing the economy of a city and transforming it to a smart economy. However, it is also observed that the each factor is influenced by certain parameters. For example entrepreneurship is dependent on self employment rate, new business registration, flexibility in labour market, etc. Similarly international embeddednes is dependent on air transportation facilities and Information communication technologies (ICTs). If these parameters are conducive, then they will reinforce the system with a positive influence and if they are of opposite nature, they will create disturbances in the system or balance the development.

Therefore, policy interventions are needed to enhance the positive parameters and alleviate the shortcomings, if any. South African cities observed to be lack in international embeddedness, innovative spirit and in turn large scale entrepreneurship. The R&D expenditure and registration of patents are insignificant and negatively influence innovative spirit, although employment in knowledge intensive sector influence positively to a certain extent. Similarly, air transport of freight and ICT limits the international embeddedness. Lack of flexibility in labour market, low number of new business registration and self employment rates drag entrepreneurship and stand in the way of development of a smart economy, which require appropriate policy interventions.

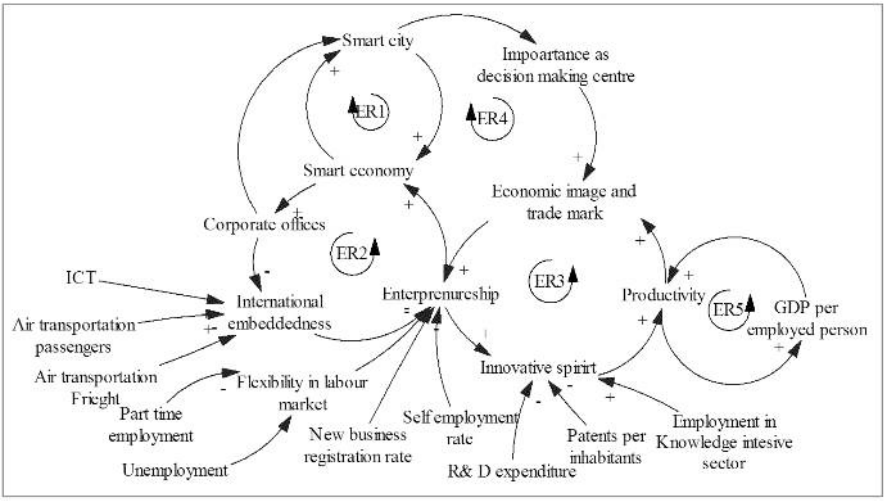

Figure 2 Casual feedback relationships for development of smart economy

4.2 People

The factors, which characterise smart people are level of qualification, creativity, affinity to lifelong learning, flexibility, social and ethnic plurality, cosmopolitanism / open mindedness, and participation in public life. Each factor is also influenced by their endogenous parameters. Figure 3 presents the causal feedback loop diagram for smart people in a smart city. It is envisaged that smart people, level of qualification and smart city are interlinked through a positive feedback loop (PR1) as each factor influence each other. This feedback relationship is reinforced by the feedback loop PR1A through participation of people in public life as observed in South African cities. However, lack of social and ethnic plurality is influencing cosmopolitanism or open mindedness negatively and in turn is discouraging people away from participating in public life, thus create a negative feedback loop (PB1) with smart people. Similarly, the scenario of inflexibility and lack of affinity for lifelong learning develop a negative feedback relationship with people (PB2), which along with the feedback loop PB1 influence development of smart people in the city negatively and either disturbs or balances the development. Simultaneously the feedback loop (PB3) based on the lack of cosmopolitanism discouraging immigration of people, and peoples' lack of interest in the knowledge about country and province act as deterrents for creation of cosmopolitanism. Although, adequate knowledge about country and province would reinforce voters turn out and is expected to reinforce public participation in a feedback relation (PR1C), yet lack of it disturbs the development of smart people.

Similarly, creativity leading to affinity to lifelong learning would result a positive feedback relation with smart people (PR1B), however, it is observed that meagre number of people working in the creative industry and lack of participation of people in lifelong learning influence the loop negatively. Therefore, the factors, such as flexibility, affinity to lifelong learning, cosmopolitanism, immigration friendly environment, development of creative industry, etc., which are currently influencing negatively need to be addressed, while the positive factors such as, level of qualification, participation in public life, etc., need to be strengthened through appropriate policy interventions.

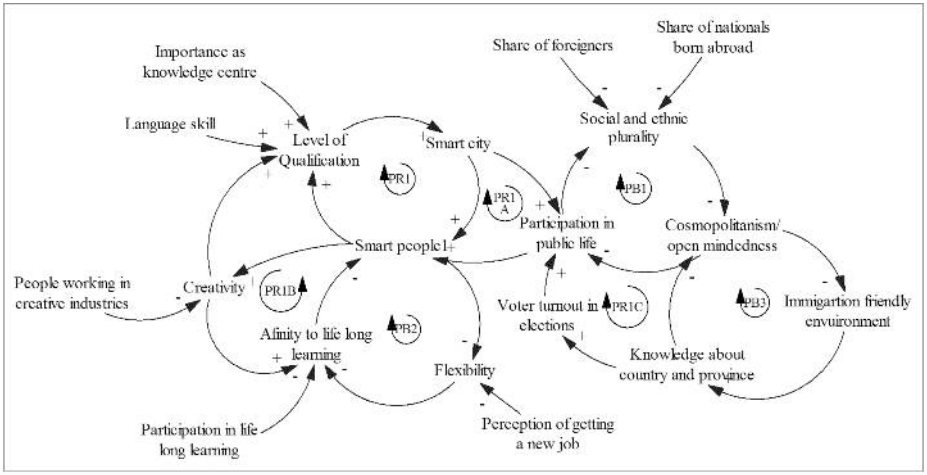

Figure 3 Casual feedback relationships for development of smart economy

4.3 Governance

The governance system of the South African cities are observed to be based on the characteristics such as, participation in decision making, transparent governance, public and social services, political activity of inhabitants, city representatives', female city representatives, and importance of politics for inhabitants. Each factor is also dependent on its indigenous parameters. The figure 4 depicts a causal feedback loop structure for smart governance of South African cities. It is visualized that smart governance will have a positive influence on people's involvement in decision making process, which will lead to transparency in governance system and as a feedback will strengthen governance system of the city (GR1). The transparency in the governance is influenced by transparency in bureaucracy and perception of fighting against corruption. Political and social services are influenced by quality of school, care for children, expenditure on residential suburban areas and participation in voluntary work. The performance of the feedback relations GR1 is dependent on the performance of these parameters.

Similarly, participation in decision making will positively influence political activities of inhabitants and provide opportunities for adequate female and city representatives in the governance system, thereby reinforcing the participation in decision making through reinforcing loop (GR2). The governance system developed through loop GR1 reinforced by the reinforcing feedback loop involving smart governance, smart city and participation of people in decision making (GRA1). Further, the importance of politics for inhabitants, participation in decision making along with political activity of people develop a feedback relation (GR2A) with the loop GR2 and reinforces loop Gr1.

Thus, all the feedback relations reinforce and strengthen the governance system and consequently are creating an environment for development of a smart city. With a democratic set up and adequate local governance system, there is an opportunity for development of a smart governance system in the cities of South Africa, if policy interventions are made to make people politically active; create an environment to involve people in social and political activities by encouraging participation in voluntary works, child care, making equitable expenditure in suburban areas and developing quality schools; allowing them to be a part of decision making process; and build transparent bureaucracy and eradicate corruption.

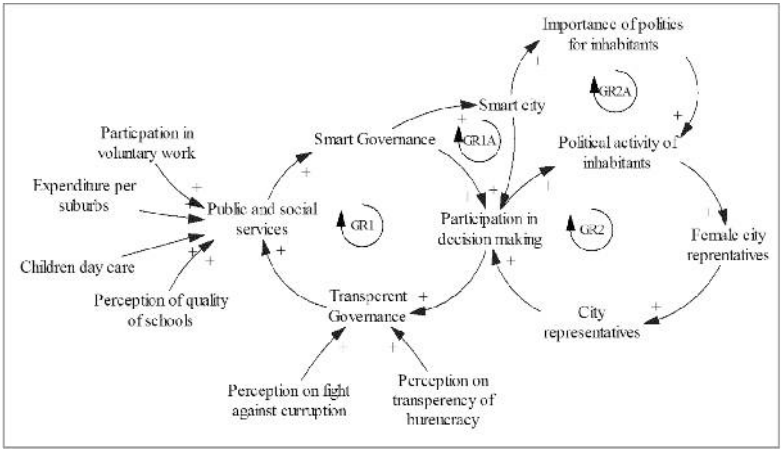

Figure 4 Casual feedback relationships for smart governance

4.4 Mobility

Smart mobility has two significant components such as, physical movement at the local level and international accessibility through information communication technological system and international transportation system. In the South African context, it is based on three major reinforcing causal feedback loops involving factors such as, (1) sustainable, innovative and transportation system, (2) availability in ICT infrastructure, and international accessibility and (3) local accessibility (figure 5).

It is envisaged that a sustainable, innovative and safe transportation system and effective local accessibility create a feedback relationship with smart mobility (MR1). The sustainable, innovative and safe transportation system is influenced by use of economical cars, green mobility share and traffic safety at local level, which need to be addressed to enhance performance of the accessibility in a city. Simultaneously, smart mobility creates a feedback relationship with ICT infrastructure, international accessibility by both air transportation and broad band system (MR2). Availability of ICT infrastructure is designated by computers in households; and international accessibility is influenced by broad band in households and international flights connecting the city. Both the loops in turn reinforce smart mobility of a city. At the same time public transportation network, quality of public transportation system and access to public transportation develop a feedback loop (MR3) with local accessibility, which reinforces feedback loop Mr1.

Further, feedback loop MR1 is reinforced by feedback loop MR1A involving smart city, smart mobility and sustainable, innovative and safe transportation system; and feedback loop MR2 is reinforced by feedback loop MR2A involving availability of ICT infrastructure, smart mobility and smart city. Therefore, augmentation of both sustainable, innovative and safe transportation system and ICT infrastructure are highly essential for creating smart mobility system and in turn a smart city. Thus, policy interventions for enhancement of sustainable innovative and safe transportation system, which can be achieved by enhancing traffic safety, use of economical cars, and increase in green mobility share are highly essential. This should be complemented by adequate quality public transportation system providing easy accessibility to people. Further, policy interventions are also needed for increasing use of computers by households; expansion of broad band, and enhancement in international flights to such cities.

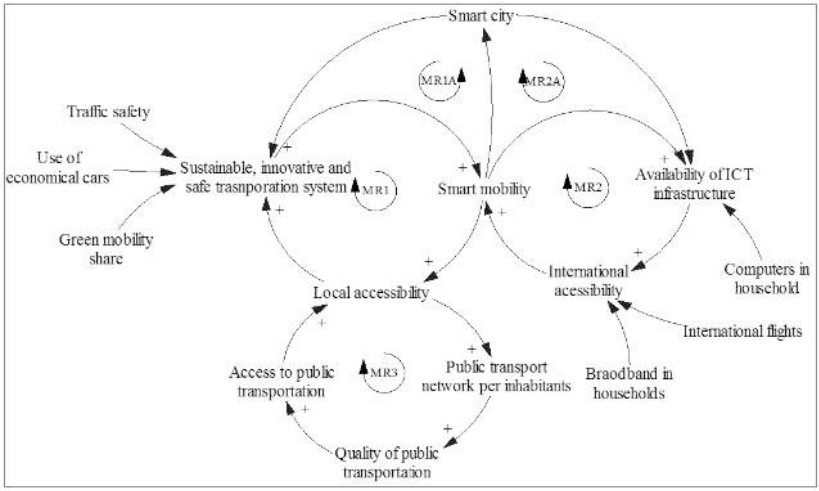

Figure 5 Casual feedback relationships for smart mobility

4.5 Environment

The environment sector is essentially characterised by sustainable resource management, environmental protection and attractive natural conditions. It is envisaged that sustainable resource management will lead to environmental protection, which will protect the attractiveness of the natural conditions of a city leading to a smart environment. Thus, in South African cities these factors are interconnected by a positive feedback relationship (ER1) enhancing each other (Figure 6). Smart environment, which would lead to development of a smart city develops a causal feedback loop ER1A connecting at sustainable resource management and reinforces loop ER1. Thus, sustainable resource management becomes highly essential for smart environment. However, on the contrary in the absence of proper environmental protection and availability of particulate matter in the city leads to pollution and consequently cause chronic diseases. Thus, these factors make a negative feedback relationship with environmental protection (EB1) and impact the smart environment negatively. Therefore, policy interventions in terms of reduction of particulate matter through sustainable resource management would reduce pollution and increase environmental protection. Further, environmental protection can be enhanced by creating public opinion and taking proactive measures for increasing individual efforts for environmental protection. Also, sustainable use of water and electricity will help sustainable resource management. Enhancement of green space and Sunshine, which measure the attractiveness of natural conditions, need careful attention.

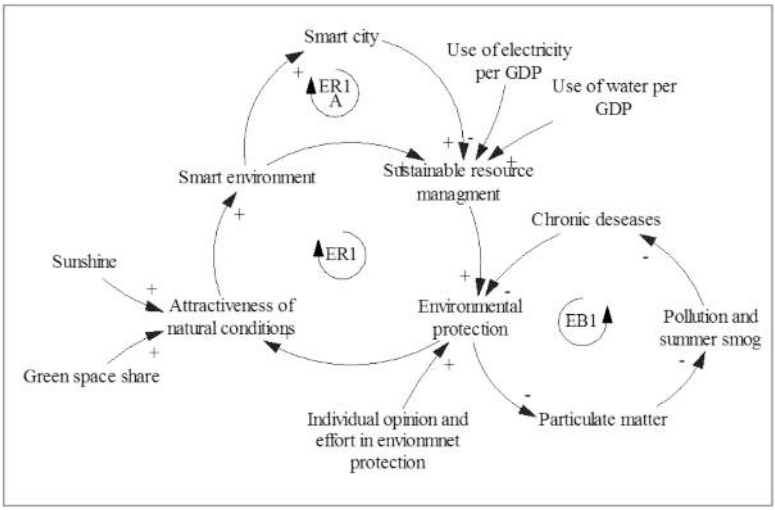

Fig 6 Causal feedback relationships for smart environment

4.6 Living

Living conditions of a smart city is influenced by six factors such as, cultural facilities, tourist attractiveness, housing quality, health conditions, educational facilities and social cohesion in South African cities. It is envisioned that each factor will develop individual causal feedback loops with living conditions and smart city development as represented by feedback loops LR1, LR2, LR3, LR4, LR5, and LR6 respectively in figure 7. However, each factor and consequent feedback loop is influenced by several parameters governing them. Cultural facilities are governed by cinema theatre attendance and museum visits, which are essentially observed to be low in South African cities. Tourist attractiveness is influenced by factors such as, importance of tourist locations and overnight stay, which vary from city to city. Housing quality is measured by share of standard quality of housing, average living area per person, and people's satisfaction with housing condition, which essentially are location specific. Health condition is characterised by hospital beds per inhabitants, doctors per inhabitant, perception of quality of health system, life expectancy, and individual safety & crime rate. In this case, although, many of the major cities have standard health facilities, the health care system is observed to be expensive.

The life expectancy is quite average and almost similar (about 55 years) all over the country. However, individual safety & crime, which is a function perception of personal safety and death rate by assault is a major concern almost in all the cities. The educational system is indicated by quality of education, students per inhabitants and access to quality of education. It is apparent the Government has a quality system in place of educational system although accessibility to quality education and number of students in particularly higher education in many cities are cause of concern. Social cohesion is characterised by poverty rate and perception of personal risk of poverty, which is essentially indicated by high unemployment rate in the country and more so in the cities. Thus, the living condition of South African cities although not highly deplorable is a cause of concern from several accounts. Therefore, policy interventions based the designed feedback loops and their influences are needed to augment almost all aspects characterising living conditions in the cities for creating smart living conditions and in turn development of smart cities.

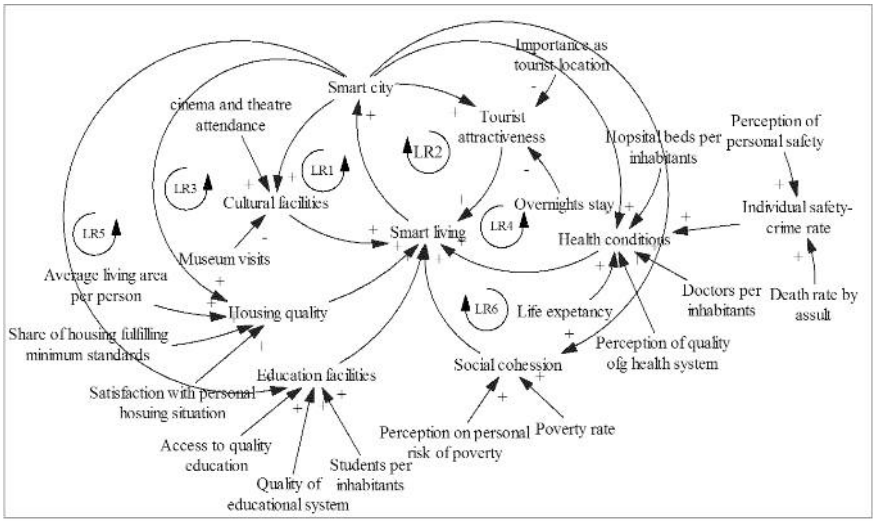

Fig 7 Causal feedback relationships for smart environment

5. CONCLUSION

A smart city is essentially regarded as a well performing city in all its characteristics and the development is based on self decisive and citizen participation. According to scholars a city becomes smart if investments in human and social capital, traditional (transport) and modern (ICT) communication infrastructure, judicious utilisation and management of scarce resources, and participatory governance stimulate sustainable economic growth and a high quality of life (Caragliu, Del Bo, and Nijkamp, 2009). There is also need for adaptability of the people in terms of their learning and innovation (Coe et al, 2001) and able to utilise the technology and benefit from them. The purpose of developing such a city is to enhance the capability of the potentials of the city and judicious resource management for optimal development of the city. This is more so important for the South African cities and this investigation provides an analysis keeping these factors in the eye for sustainable development of these cities.

However, development of smart cities pose specific modelling challenges that include interdependency, inter-linkage and causal relationships among the various parameters influencing smart city development, compounded with lack of adequate and reliable data, uncertainties, role of stakeholders, and other prominent aspects such as, people, governance, environment, living conditions, etc., which are not easily amenable to quantification. This investigation shows that system dynamics with its integrative nature is well suited to undertake such modelling challenges.

It was observed that it has provided a framework to elicit system description, which conveyed complex and dynamic inter-linkages based on which policies can be generated to augment the strengths and alleviate the weaknesses in an urban system (cities) in order to facilitate development of smart cities in South Africa. Therefore, application of system dynamics methodology in this context is particularly valuable.

The primary goal of this study was to develop conceptual models, which would show the causal relationships among the various influential parameters in each aspect of a smart city and develop a roadmap to create smart and sustainable cities in South Africa. However, there is also a need to transform these conceptual models to computer simulation models, which would reveal the gaps and inconsistencies in the conceptual models, and that is the next goal of this investigation.

Further, the process of rigorously extracting a conceptual model from apt understanding of the smart city concept brought about clarity and awareness of the interdependencies and causal feedback relationships among various influential parameters of cities and their implication on the future development. This could guide the policy makers and planners for plausible actions for developing smart cities, which is perhaps the most significant contribution of this work.

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