Evaluating Green Smart City's Sustainability with an Integrated System Dynamics Model

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Abstract: Smart cities have evolved from their initial web forms in early '90s to their recent and preferable ubiquitous and eco-friendly approaches and various exemplars can be observed around the world. To this effect, the eco-city or green city approach has been introduced and concerns an ideal urban paradigm, in which information and communications technologies (ICT) are combined with energy consumption, waste and traffic management and other practices in order to enhance urban sustainable development. This paper utilizes system dynamics (SD), as a means to capture and evaluate the sustainability performance of a green city.

Keywords: smart city, green city, sustainability, system dynamics, eco-city

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Urbanization raises steadily and recent reports (UN-HABITAT, 2008) illustrate that half of the global population lives in urban areas, while United Nations' projections reveal that urban population will exceed 6.3 billion by 2050 (United Nations, 2012). This phenomenon generates great challenges for urban planning and yields increased requirements for city sustainability (Chao & Li, 2011). On this ground, the development of green, ecological cities has been introduced as a means to support sustainable urban development within a societal, economic, environmental and demographic context. The ecological city or "eco-city" idea was first introduced by Urban Ecology, an organization founded by Richard Register in 1975 (Roseland, 1997), which concerns a city that ensures the well-being of its citizens via a holistic urban planning and management approach with the aim of eliminating waste and emissions.

Smart cities on the other hand utilize technology in order to improve urban everyday life. Information and Communications Technologies (ICT) in urban spaces for instance, simplify inhabitants' transactions and automate information flow across the city. According to (Anthopoulos & Fitsilis, 2013) the term smart city is not used in a holistic way describing a city with certain attributes, but is used for various aspects which range from mesh metropolitan ICT environments to a city regarding the education (or smartness) of its inhabitants (Anthopoulos & Fitsilis, 2013), (Komninos, 2002). Smart city was originally introduced in the Australian cases of

Brisbane and Blacksburg. Smart city was later evolved to (a) urban spaces for business opportunities; to (b) ubiquitous technologies across the city; and later to (c) ICT solutions for ecological enhancements -such as energy consumption, waste and traffic management- named eco-city or green city. A classification and analysis of the alternative smart city approaches (Anthopoulos & Fitsilis, 2013) illustrate that eco-city/green city appears to be the preferable approach.

An eco-city is a synthesis of different complex subsystems that need to be coordinated in order to deliver the desired outcomes. Additional research difficulties appear due to the lack of analytic tools that can capture the nexus of urban ecological factors and systems, and assess their development both in terms of environmental impact and business growth.

In this order, this paper aims to answer the following question: *how can a green city be evaluated regarding its sustainability within a complicated nexus of social, economic and cultural factors?* This question is critical since smart cities appear to migrate to eco-city approach, while many cities adopt solutions that aim to enhance urban environmental capacity. However, this phenomenon has to secure its success and policy/decision makers have to adopt the appropriate solutions for monitoring and assessing the relationship between environmental impact and cities' growth.

The rest of the paper is organized as follows. Section 2 contains the respective literature review. Section 3 introduces the proposed System Dynamics (SD) model, whereas Section 4 returns the results of scenarios simulation analyses along with a short discussion, recommendations and limitations based on the results related to the environmental impact of applied policies towards green city. Finally, the last Section 5 contains conclusions and some future thoughts.

1. Background

Urban sustainability has attracted attention quite early (Table 1). Banister et al. (1997) identified significant relationships between energy consumption in transportation and the physical characteristics of the urban arrangements (i.e., city size, population density etc.). Further, Rotmans et al. (2000) proposed an integrated city planning tool that can capture the nexus of the environmental, socio-cultural and economic factors that influence the development of sustainable cities. Under this context, Evans & Marvin (2006) stressed the complexity associated to the issue of urban sustainability. At a greater extent, Kennedy & Hoornweg (2012) endorsed international initiatives towards urban sustainability and encouraged the application of a comprehensive "urban metabolism" framework (Kennedy et al., 2007) for assessing urban environmental impact.

Solid waste management in cities (Davoudi & Evans, 2005; Asase et al., 2009; Kaseva & Gupta, 1996; Baud et al., 2001; 67; Oakley & Jimenez, 2012) and of greenhouse gas (GHG) emission control (Ramaswami et al., 2012; Reiter & Marique, 2012) are also of cardinal interest. (Li et al., 2011). Furthermore, various modeling tools have been introduced (Barredo, 2004; Vancheri et al., 2008), while Bojórquez-Tapia et al. (2011) proposed a mixed GIS and multi-criteria decision making tool.

Limited studies illustrate ecological cities (Ecocity Builders, 2011) and mainly refer to (i) existing urban transformation to eco-city, or (ii) eco-cities from-scratch in China, South Korea, United Arab etc. Eco-cities initially appeared in literature with "Eco-city Berkeley" (Register, 1987), while more than 174 cities were accounted by (Joss et al., 2011). The World Bank, launched a corresponding strategy (The World Bank, 2000) and supports initiatives such as the Sino-Singapore Tianjin Eco-City (The World Bank, 2009). Moreover, the "Eco2 Cities" initiative followed, where qualitative and quantitative indicators in eco-cities assess the added value and the financial benefits (The World Bank, 2010). Additionally, Li et al. (2011) evaluated the eco-city progress paradigm in China and highlighted the prominent role of low-carbon eco-city with the strategic planning framework of the Tianjin eco-city. Furthermore, Wu et al. (2011) recommended the incorporation of carbon footprint into the least-cost planning of eco-city schemes.

On the other hand, the smart city domain recognizes a particular approach, which is named eco-city or green city (Anthopoulos & Fitsilis, 2013) and concerns the capitalization of the ICT for sustainable growth and for ecological protection. This approach has been followed by many cases New Songdo (South Korea), Tianjin (Singapore) and Masdar (Abu Dhabi), Amsterdam etc.

Forrester (1974) applied SD for sustainable urban development and showed the interdependencies among social, ecological, economic and other subsystems. Existing SD modeling approaches for eco-cities are limited and refer to independent subsystems or modules and ignore their interrelations (Struben & Sterman, 2008). Accordingly, Chen et al (2006) assessed emission policies in Taipei with an SD scenario, while Wang et al. (2008) leveraged the SD approach to examine the economic, social, and environmental sustainability of transportation systems. Other approaches examine water, transportation and emission control in the urban space ; Guan et al., 2011; Krajnc & Glavič, 2005; Zhang et al., 2008; Trappey et al., 2012; Xu & Coors, 2012).

Table 1. Brief Taxonomy of the Existing Research

	SD	Ql.	Qn.	References
Urban Growth Dynamics & Sustainability	X			Han et al (2009); Guan et al (2011); Xu and Coors (2012)
		X		Rotmans et al (2000); Evans and Marvin (2006); Ecocity Builders (2011); The World Bank (2009); World Bank (2010); Kennedy and Hoornweg (2012); Lehmann (2011); van Bueren and Heuvelhof (2005)
			X	Barredo et al (2004); Vancheri et al (2008a; b); Bojórquez-Tapia et al (2011); Li et al (2011b); Gülen and Berköz (1996); Ho et al (2002); Fung and Kennedy (2005)
Transportation	X			Wang et al (2008), Trappey et al (2012); Struben and Sterman (2008); Chen et al (2006)
		X		The World Bank (2009)
			X	Banister et al (1996)
Emissions	X			Chen et al (2006); Trappey et al (2012); Feng et al (2012)
		X		Li et al (2011b); Ramaswami et al (2012); Kennedy and Hoornweg (2012); The World Bank (2009); Cao and Li (2011)
			X	Wu et al (2012); Fung and Kennedy (2005)
Waste	X			Guan et al (2011); Zhang et al (2008)
		X		Zaman and Lehmann (2011); Baud et al (2001); Kaseva and Gupta (1996); Asase et al (2009); Davoudi and Evans (2005)
			X	Oakley and Jimenez (2012)
Energy	X			Feng et al (2012)
		X		Anthopoulos and Fitsilis (2013); Ramaswami et al (2012); Kennedy and Hoornweg (2012); The World Bank (2009)
			X	Banister et al (1996); Reiter and Marique (2012); Nijkamp and Perrels (1994)

Symbols: SD for System Dynamics, Ql. for Qualitative, Qn. for Quantitative

Table 1 presents a synopsis of the matching eco-city sub-systems with relevant research efforts and their relation to SD. SD is a simulation methodological tool which is appropriate to analyze and understand the development and the behavior of complex systems over time. Originally, the tool was used to examine the instable employment environment in General Electric (Forrester, 1961). Nevertheless, over the years the SD tool was employed to capture and simulate diverse scientific and engineering systems (Forrester, 1969) and as a decision supportive tool (Roberts, 1978).

The core elements of SD modeling are feedbacks (loops); stock and flow structures; and delays (Sterman, 2000). Feedbacks are necessary because systems rarely exhibit linear behavior due to the interactions among the physical and institutional elements of the systems. Feedback structures are fundamental because they capture the real patterns or modes of systems' behavior as they dynamically evolve in time. Additionally, the dynamic behavior of a system arises when inflows and outflows are accumulated into stocks. Stocks provide the system with memory, thus enabling the disequilibrium dynamics in systems (Sterman, 2000). Finally, delays are necessary to represent the time intervals between the desired and the actual state of a system under study and thus render it with instability (Sterman, 2000). However, further analysis of SD is beyond the purposes of this paper.

2. Research design and methodology

In an attempt to answer this paper's question, an SD model is developed, which can capture eco-city components and interrelations. The SD analysis that was followed adopted the stages described by (Sterman, 2000): (a) the model of an eco-city was conceptualized; (b) hypothesis and simulation model were formulated and the structured model was validated; (c) a scenario was simulated. The main concern was to capture the subsystems that have the greatest environmental impact on the eco-city.

The formulation of the proposed model was based on the study of (Ho & Wang, 2005) about the sustainable development of the Hsinchu Science Park in Taiwan, while data was used about the Tianjin Eco-City in China in order to conduct simulation analyses. The testing of the model was performed based on sensitivity analyses and behavior reproduction of the system. Model's assessment and performance measurement was based on simulations' execution for a fifty year prediction period.

2.1. Causal loop diagram

Figure 1 concerns the appropriate causal loop diagram and illustrates the correlation of the factors and the variables that specify the behavior of the reviewed conceptual eco-city. *Households and population density* are positively related to the population increase; the *solid waste* subsystem is loaded as the population increases. The proposed system calculates produced waste per capita. Moreover, the *industrial* subsystem contributes to energy consumption and to water pollution and a respective reinforcing loop via the *business* subsystem was considered. Additionally, *workforce* is divided between the industry and the service sector. Furthermore, *service* sector is incorporated in the overall business system. *Water consumption* is made by both the city residences and the business sector. The *environmental emissions* was added accordingly. Finally, an assumption was made that the population and the business sector consume electrical energy through the respective reinforcing loops.

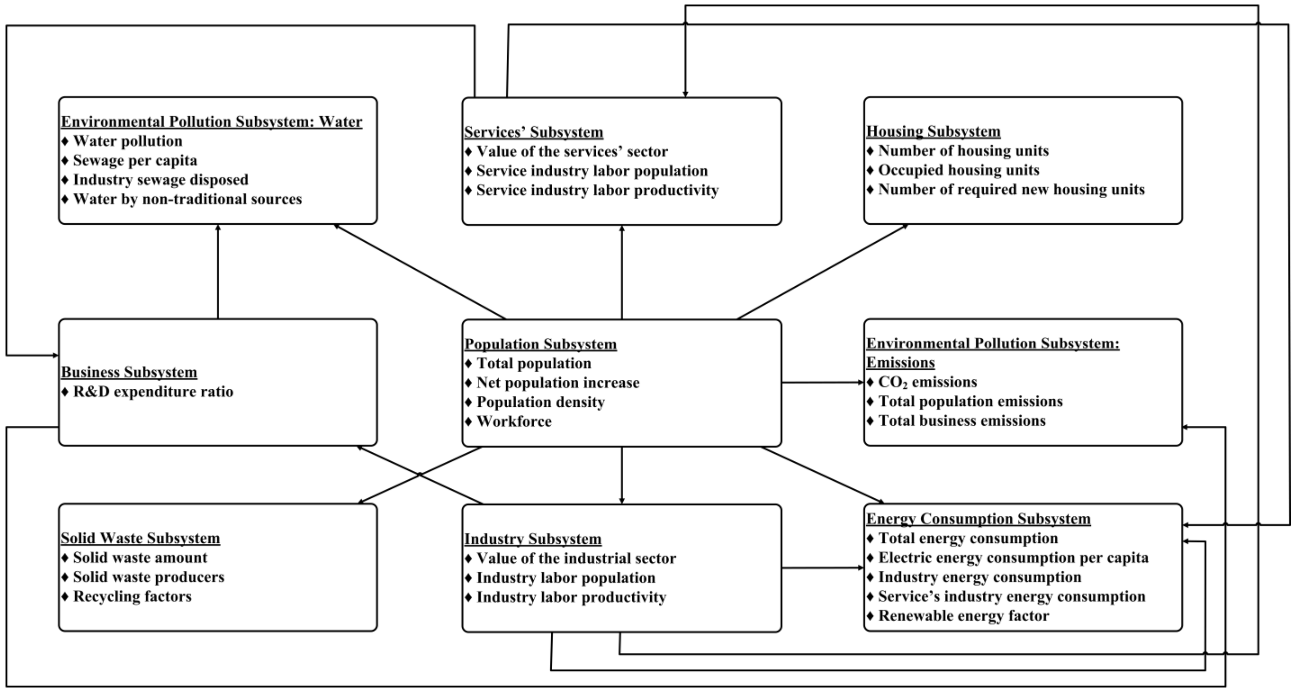

Figure 1: Causal loop diagram

The causal loop diagram indicates that the government policy can create favorable conditions, which in long run can lead to urban sustainable development and to enhanced financial benefits for inhabitants. On the other hand, inadequate government policy restricts city's sustainable growth potential.

2.2. Stock and flow diagram

The entire respective stock and flow diagram of the conceptual eco-city is exhibited in (Figure 2). The proposed SD model was developed with the simulation software Powersim 2.5c (Powersim, 1996) and contains: 76 arrays and scalars; 9 levels; 48 auxiliaries; 19 constants (control variables); 86 links; 17 flows; 9 static objects, and 1 dynamic object.

A set of subsystems comprise the proposed SD model. First, the *Population* subsystem contains a stock variable that calculates the annual population change according to (Malthus, 1978). The model describes the net global population increase and it was adopted due to the lack of any particular data through the equation $N_{t+1}-N_t=N_0\times e^{at}*(e^a-1)$, where N is the population at time t and a is a coefficient equal to 0.016888 and e equals to 2.71828. Temporary floating population living in the city was also accounted. For the purposes and size limits of this paper, only the parameters of the "Population" subsystem are illustrated analytically (Table 2), while similar factors have been utilized for the remaining subsystems.

Table 2. Parameters of the "Population" subsystem

Total_Population=+dt*(Floating_Population)+dt*(Population_Increase)–dt*(Population_Decrease)
Total_Population = 1000
Population_Increase= IF(Population_Density<Population_Density_Cap,Total_Population*(EXP(0.016888*TIME))*(EXP(0.016888)-1),0)

Population_Decrease = DELAYINF(Floating_Population,3)
Floating_Population = INT(Total_Population*Floating_Population_Modulus)
Land_Area = 85
Population_Density = Total_Population/Land_Area
Annual_Population = INT(Total_Population)
Population_Density_Cap = 65
Net_Population_Increase = Floating_Population+Population_Increase
Workforce = Total_Population*0.53
Floating_Population_Modulus = 0.05

dt concerns date change: values of ¼ years and ⅛ years were tested

Next, the housing subsystem (Figure 1) calculates household growth. The number of unoccupied houses was accounted as the construction activity aggravates the environment (Cheng et al., 2006). The economic activity subsystem calculates the overall business value (Ho & Wang, 2005) and to this end, both an industrial subsystem and a service sector subsystem were included.

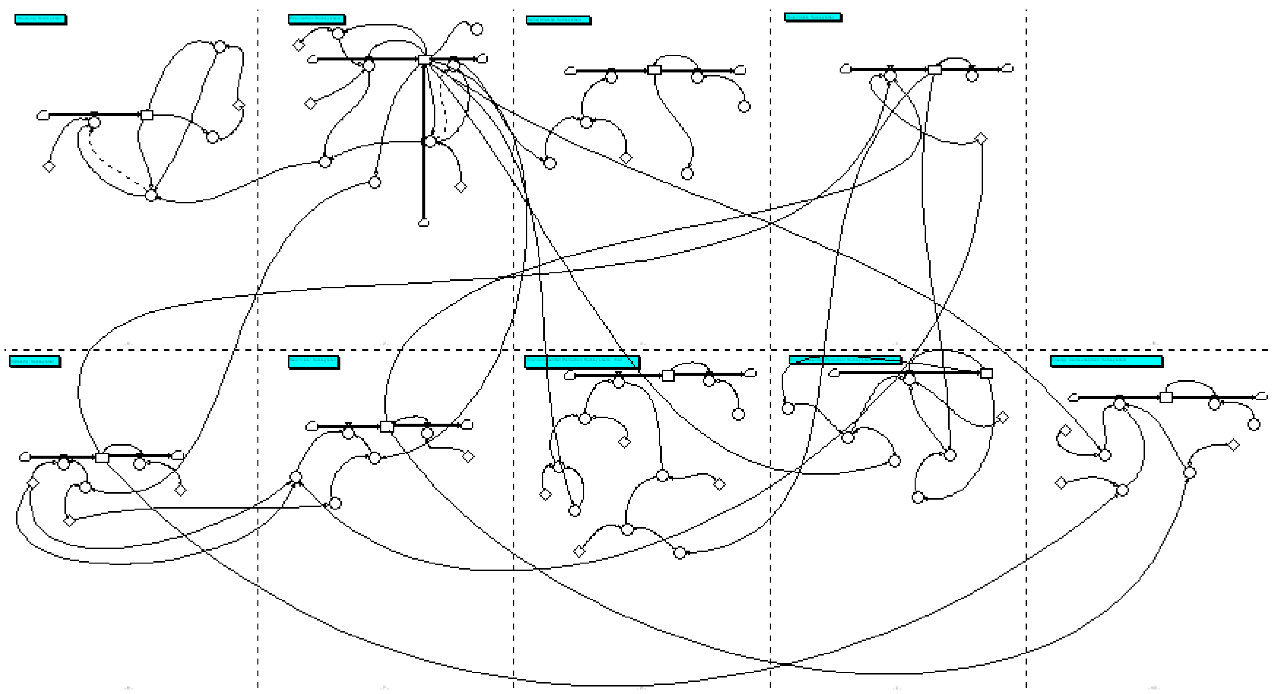

Figure 2: The integrated conceptual eco-city model diagram

Furthermore, the "Energy Consumption" subsystem illustrates corresponding carbon emissions (Golove & Schipper, 1997). For the purposes of this study, data regarding the Tianjin city were leveraged. First of all, the annual energy consumption per capita in Tianjin was 2790 kWh (Department of Industry and Transport Statistics, 2002). Additionally, the electrical power use per GDP in industry is projected to be 1.2 kWh per US dollar, whereas in services' industry it is 0.8 kWh per US dollar (USAID Asia, 2011).

Next, the *environmental pollution* subsystem measures the total impact on the environment, it concerns the core of eco-city subsystems and consists of the *water pollution* subsystem; the *emissions* subsystem; and the *solid waste* subsystem. The produced sewage is considered an integral part of an urban socio-economic-environmental system. According to Zhang et al. (2008), the water consumption per capita in Tianjin city is estimated to be 160 m3/year. They also found that the water pollution index ranges between 0.8 and 1.3.

Regarding emissions, the proposed modeling approach includes only the carbon dioxide (CO2) (Pugsley et al., 1994). According to Geng et al. (2011), in 2007 the CO2 emissions in Tianjin were 20.82 ton/capita. The estimation of the total carbon dioxide emissions from the business sector was calculated with the means proposed by (Price et al., 2013) to be 1.40 kg CO2 per US dollar. Finally, the proposed model measures solid waste per day in Tianjin about 4500 tons (Zhao et al., 2008).

2.3. Scenarios analyses

Simulation analyses were performed for the corresponding SD model's evaluation. Findings reveal that the environmental impact of an eco-city is highly correlated to the population of the city and after 50 years, a newly constructed green city exhibits signs of great increase in population growth and environmental pollution, which raise concerns about eco-city's effectiveness.

2.3.1. Scenario 1 - Research and Development Intensity

Eco-cities must secure socio-economic prosperity. Therefore, investments in research and development (R&D) can drive economic growth, while there is a clear trend of smart cities towards transforming into eco-cities (Anthopoulos & Fitsilis, 2013; Kim et al., 2012). In addition, labor productivity is pivotal regarding the overall value of the business sector in the city.

The first scenario assumes that R&D expenditure in an eco-city increases from 0% to 7% and labor productivity from 50% to 80% respectively. This change affects the monetary output of the city and shows that economic prosperity aggravates environmental pollution. As it is expected, the increase in R&D investments and labor productivity enhance the total value of the overall business sector in simulated conceptual city. The simulation results demonstrate that the R&D and productivity focus results in an annual business growth rate of 8.66%.

Notably, abrupt increase in urban solid waste production is observed, which follows quite linear growth with an increase rate of 2.97%; water pollution follows the same growth pattern with an average growth rate of 8.76%; CO2 emissions present the most interesting evolution trend, caused by the regulations inserted in the system. Policy interventions take place whenever there is recorded a sharp increase in the GHG emissions. The intensification of R&D normally increase the CO2 emissions but they have a lower effect in contrast to the water pollution. The observed annual increase rate in gas emissions is 5.34%. Finally, energy consumption follows the same growth pattern and it is estimated to an annual rate of 7.38%.

2.3.2. Scenario 2 - Environmental Management Strategy

Several eco-friendly policies and regulations are considered and to this end, the proposed model contains some quantitative key performance indicators (KPIs) (for example the CO2 emissions surpass a certain threshold then a strict environmental strategy is implemented to keep the system within the pollution boundaries). Such a strategy is in line with the KPIs for the planning and development of the Tianjin eco-city (Tianjin Eco-city, 2012) and envisions: (i) water supply of the city to be 50% provided by non-traditional sources such as desalination and recycled water; (ii) proportion of renewable energy will be at least 20%; (iii) solid waste recycling at 60%; and (iv) CO2 emission cap of 100,000 tons. The second scenario stresses the role of the environmental institutional regulations. First of all, there is no effect to the total business value, which increases 8.66% annually. On the contrary, the applied measures result to an annual decrease of solid waste by 9.26%. On the other hand, after a decade water pollution stops (annual decline growth of 5.77%), but in a 30-year period water pollution reaches the same levels before the applied policy. Policy interventions highly impact CO2 emissions, since they result to an annual reduction rate of 79.51%. Finally, the investigated policies do not appear to have any significant impact on energy consumption as the annual reduction rate is calculated to be 3.47%.

3. Results and discussion

Structural validity of the proposed SD model in terms of dimensional consistency was tested (Sterman, 2000). Based on real data, preliminary values of the model's variables were examined and their rationality was ascertained. Afterwards, extreme-condition tests were performed in order to investigate the realistic behavior of the proposed model, even under extreme policy-making decisions. For instance, no pollution was generated when coefficients were set to zero. In addition, sensitivity tests were conducted and positive and negative value sets of the effect of each external factor were interchangeably examined. To this effect, corresponding system responses regarding the total pollution were observed.

Furthermore, integration error test methods were elaborated. Euler integration method was followed, as the Runge-Kutta method is not suggested for systems that include random disturbances (Sterman, 2000). Also, the shortest time constant in the proposed model is set to 1 year. As the standard SD practice suggests that the integrating time step (DT) cannot exceed the ¼ of the shortest time constant, an initial DT of ¼ years and ⅛ years was examined and the model did not yield any diverse results.

The proposed model is an effort to capture comprehensively the complex nexus of the factors which involve in a eco-city. Nevertheless, the subsystems are not analyzed in detail since each can be considered an individual research field. For example, an assumption was made that the population and business subsystems consume only electric power, whilst excluding other forms of energy sources. Additionally, the effect of other key subsystems -such as transportation- were not accounted.

Moreover, only firms that either belong to the services' or the heavy industry sector were considered, whereas a more detailed model should cluster the business environment according to more sectors. Moreover than not, there are no considerations about the agricultural and food industry in the city, since green city should be self-sustained (Waggoner, 2006). Further, educational institutions and research centres were not considered herein. Finally, financial elements like inflation rates and operational costs or any political/institutional instability factors were not accounted.

4. Conclusions

This paper recognizes the recent smart city's trend to evolve to eco-friendly approaches named green or eco-cities. In this order, it aims to evaluate the sustainability of an eco-city with regard to a set of social, economic and cultural parameters that coexist in urban spaces. A conceptual eco-city that was based on particular systems was identified and quite a simple but generic SD model was composed, which can establish such an evaluation.

The proposed SD model was tested with two scenarios regarding policy intervention strategies that affect economic output and environmental pollution in terms of water pollution, CO2 emissions and solid waste production. Results indicate that population and business sector increase in an eco-city and the environmental pollution increases accordingly. On the other hand, policy interventions with regard to environmental protection only achieve in limiting the increasing pollution rate. The only environmental aspect that interventions seem effective is the reduction of CO2 emissions. A major observation is that after a 30-year period, the population increases in eco-city expands. The most prominent policy intervention is to set a limit on the population that an envisaged eco-city can accommodate.

Future research aims to focus on specific real or under development eco-cities, in order to accurately identify and appropriately select the key variables and parameters so as the proposed model to be rendered with robustness. Finally, economic parameters (i.e., tax incentives, funding etc.) could yield insightful managerial insights and have to be considered.

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