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Embedding the Dimensions of Sustainability into City Information Modelling

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Abstract**—**The purpose of this paper is to address the functions of sustainability dimensions in city information modelling and to present the required sustainability criteria that support establishing a sustainable planning framework for enhancing existing cities and developing future smart cities. The paper is divided into two sections. The first section is based on the examination of a wide and extensive array of cross-disciplinary literature in the last decade and a half to conceptualize the terms 'sustainable' and 'smart city', and map their associated criteria to city information modelling. The second section is based on analyzing two approaches relating to city information modelling, namely statistical and dynamic approaches, and their suitability in the development of cities' action plans. The paper argues that the use of statistical approaches to embed sustainability dimensions in city information modelling have limited value. Despite the popularity of such approaches in addressing other dimensions like utility and service management in development and action plans of the world cities, these approaches are unable to address the dynamics across various city sectors with regards to economic, environmental and social criteria. The paper suggests an integrative dynamic and cross-disciplinary planning approach to embedding sustainability dimensions in city information modelling frameworks. Such an approach will pave the way towards optimal planning and implementation of priority actions of projects and investments. The approach can be used to achieve three main goals: (1) better development and action plans for world cities (2) serve the development of an integrative dynamic and cross-disciplinary framework that incorporates economic, environmental and social sustainability criteria and (3) address areas that require further attention in the development of future sustainable and smart cities. The paper presents an innovative approach for city information modelling and a well-argued, balanced hierarchy of sustainability criteria that can contribute to an area of research which is still in its infancy in terms of development and management.

Keywords**—**Information modelling, smart city, sustainable city, sustainability dimensions, sustainability criteria, city development planning.

I. Introduction

INFORMATION Systems have been applied to almost all fields, disciplines, human activities and societies. In the field of city planning and development, the concept of Information Systems refers to a set of urban technologies, infrastructures, applications, services, and computational analysis capabilities employed for sensing, collecting, analyzing, synthesizing, manipulating, mining, modelling, managing, networking, exchanging, and sharing urban data. Developing and applying of such systems are usually driven by the purpose of monitoring, understanding, guiding, and planning smart and sustainable cities to achieve particular goals [1].

The literature shows [2]-[4] that the links between information systems and sustainability in the field of city planning and development are not well developed in theory or practice. Despite this, during the last few years, there have been some research efforts to develop new tools and address a range of sustainability concerns using building information modelling. These efforts have covered specific sustainability aspects or dimensions, including the economic dimension of sustainability [5] the social dimension [1], [6] and the environmental dimension [7], [8].

This paper aims to address the relationship between sustainability and smartness and their respective roles in city information modelling. Furthermore, the paper intends to identify and present the required sets of sustainability criteria which can serve the establishment of a sustainable planning framework for developing existing and future smart cities.

Towards establishing this aim, the paper is intended to address the following objectives:

1. Conceptualizing the term 'sustainable city'.
2. Conceptualizing the term 'smart city'.
3. Addressing the economic, social and environmental sustainability criteria at the city level.
4. Mapping the sustainability criteria to city information modelling.
5. Addressing the requirement for dynamic approaches to city information modelling.

II. The Importance of Sustainability at the City Level

In the last five decades or so, sustainability has become a more important and popular research field. According to the Google TM search engine statistics of the year 2017, the term 'sustainability' can be tracked in the title of over 187 million pages, and has been the core for thousands of books, international conferences and journal articles. The popularity of sustainability is related mainly to the great applications of the concept in various contexts [9]. This includes applications in the context of built environment, specifically knowledge of urban sustainability and related technology to the planning, design and development of sustainable cities.

Dealing with sustainability concerns at city and district levels has gained considerable attention and momentum in the last two decades, and this can be attributed to many reasons. The first reason is related to the UN population statistics, which pointed that more than half of the world's population currently lives in cities and the number is estimated to rise up

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to 75% by 2055. This huge number of people occupies just 2% of the Earth's land, but cause the main economic, social and environmental sustainability concerns. An example of these concerns is the UN statistics, which show that the urban areas account for about 71 –76% of energy-related CO2 emissions and the world's cities produce almost half of all global green-house-gas emissions [10].

The second reason is related to the optimal size, in terms of scale, provided through the city level [11]. It is possible and easier in dealing with the scale of city or district level to maintain a successful implementation of sustainability practices and accommodate the direct interests of various stakeholders, granting considerable change through collective action and creative solutions.

The third reason is related to the favorable environment provided at this level. The city or district community normally share common principles and behaviors; the people tend to acquire insider knowledge about the region and its sustainability challenges. Such environments make cooperative work possible where participation and empowerment are key elements for the success of sustainability practices [12].

Despite the efforts in promoting sustainability practices at the city level, the scale of implementing such initiatives is still limited. Moreover, the integration between the national and city sustainability policies are not well developed. National policies and strategies for sustainability are not strong enough and have only a limited capacity to guide sustainability practices at city level. This is the case in the most of countries around the world including European countries [13].

III. Conceptualizing the Term 'Sustainable City'

The term 'sustainable city' has inspired and motivated many scholars and practitioners in the field of urban and city development. The inspiration is driven by the potential impact of sustainability practices in the three dimensions: Economic, social and environmental. This includes lowering resource consumption such as energy use, reducing environmental impact such as lessening pollution and waste levels, as well as enhancing human life quality. The literature [1], [14]-[19] has provided many definitions, showing broad aspects of what a sustainable city should be or look like. Based on the examination of a wide and extensive array of cross-disciplinary literature in the last decade and a half, Table I will provides the criteria for the main aspects of sustainable cities as understood and approached by the scholars and practitioners in the field.

TABLE I
Overview of the Sustainable City Criteria

The Criteria	The Criteria Descriptions	References
Improve the Quality of Life	1. Adopting sustainable land use and urban design 2. Make urban places more attractive and pleasant 3. Providing social interactions and easier access to a wide range of services 4. Adopting green building design technologies 5. Preventing urban sprawl as well as restoring park and greenway systems	[20] Coplak and Raksanyi, 2003 [17] Jabareen, 2006 [19] Wheeler, 2013 [21] Williams et al., 2000
Sustainable Transportation	1. Improving and maintaining pedestrian ways and their Connectivity 2. Decreasing transport needs, and encouraging walking and cycling through providing and maintaining bike paths and lanes. 3. Providing efficient transportation and easier access to public amenities 4. Reducing traffic road usage demand	[20] Coplak and Raksanyi, 2003 [22] Drumheller et al., 2001 [17] Jabareen, 2006 [19] Wheeler, 2013
Environmental Protection and Restoration	1. Bringing nature into city life 2. Minimizing the environment negative impacts of urban development 3. Adopting renewable approach to resources and maximizing efficiency of energy and material resources	[20] Coplak and Raksanyi, 2003 [17] Jabareen, 2006 [14] Convery et al., 2008 [23] Wackernagel et al., 2006
Waste Management	1. Providing reachable recycling facilities. 2. Reuse the waste produced by human activity. 3. Reduce the use of non-renewable resources and the waste impact on the environment.	[15] Davidson, 2011 [24] Harris 2000 [19] Wheeler, 2013 [25] Mavropoulos, 2010
Social Equity, Safety and Stability	1. Increasing affordable housing 2. Maintaining quality and protection for life standards 3. Improving the participation of community stakeholders into decision-making processes.	[26] Agyeman and Evans, 2003 [19] Wheeler, 2013 [27] Spinak and Casalegno. 2012
Green Development	1. Increasing the use of clean and green technologies. 2. Supporting green business and job opportunities initiatives 3. Developing sustainable infrastructure. 4. Encouraging walkable, mixed-use and transit-oriented real estate developments	[28] Ecimovic et al., 2007 [29] Nixon, 2009 [30] Quendler and Schuh, 2002

IV. Conceptualizing the Term 'Smart City'

The term 'smart city' is linked mainly to the use of information and communication technology innovations in different urban systems and domains for developing integrated, efficient and smart systems, which serve designing, planning, developing and managing of various activities and practices for environmental and economic regeneration and enhanced public and social services.

Similar to the term 'sustainable city', the literature [31]-[36] has provided many definitions, showing broad aspects and many faces, depending on the context, as well as why, how and in what ways ICTs are used, applied and managed. Based on the examination of a wide and extensive array of cross-disciplinary literature, Table II will provides the criteria for the main aspects of smart cities as perceived and approached by the scholars and practitioners in the field.

TABLE II
OVERVIEW OF THE SMART CITY CRITERIA

The Criteria	The Criteria Descriptions	References
Built Infrastructure	1. Merging ICT with traditional infrastructures, coordinated and integrated using new digital technologies. 2. Monitoring and integrating conditions of the city critical infrastructures including complex buildings, communications, and transport infrastructure such as roads, bridges, tunnels, rails, subways, airports, sea-ports, as well as utility infrastructure such as water, power to optimize resources use and plan preventive maintenance activities. 3. Connecting the physical infrastructure, the technology infrastructure, the social infrastructure, and the business infrastructure to leverage the collective intelligence of the city. 4. Developing urban environment through combining ICTs with infrastructure, architecture, everyday objects, and people to address social, economic and environmental problems.	[37] Batty et al., 2012 [31] Chourabi et al., 2012 [32] Hall et al., 2009 [35] Schaffers et al. 2012 [38] Townsend, 2013
Management and Organization	1. Using ICT in deploying and managing the existing capacities and resources in a wise way. 2. Improving efficiencies, optimizing the use of natural resources, and becoming better places to live and make business.	[39] Azkuna, 2012 [40] Craren et al., 2012 [41] Dixon, 2012
Smart Governance	1. Building advanced relations between city government and citizens with a strong reference to the use of modern technology in everyday urban life. 2. Adapting city services to the user needs and to provide customized interfaces. 3. Managing information to create value by applying advanced technologies to search, access, transfer, and process information. A smart city covers e-home, e-office, e-government, e-health, e-learning and e-traffic.	[42] Huawei, 2014 [43] Lombardi, 2011 [33] Nam and Pardo, 2011 [34] Piro et al., 2014
Policy Context	1. Merging advanced digital technologies and urban planning approaches to find innovative solutions that contribute to improving livability and enhancing sustainability. 2. Developing a high-tech intensive and advanced city that connects people, information and city elements to create a sustainable greener city, a competitive and innovative commerce and an increase in the quality of life. 3. Delivering a set of new generation services, based on information and communication technologies. Such services should be easy to use, efficient, responsive, open and sustainable. 4. Using innovative technology and the willingness to change behavior related to energy consumption in order to tackle climate goals. 5. Using information and communication technologies in order to contribute to self-sustaining city development in ordinary times, while it functions for disaster prevention and mitigation in times of disaster.	[44] González et al., 2011 [45] Japan Ministry of Internal Affairs and Communications, 2013 [5] Lee et al., 2012 [35] Schaffers et al., 2012 [36] Toppeta, 2010
People and Communities	1. Driving collaboration between citizens, community leaders and local stakeholders. 2. Engaging and interacting with the citizen that makes use of city services	[46] Giffinger et al. 2007 [44] González et al., 2011 [47] Kirby, 2013 [48] Munier, 2007

V. SUSTAINABILITY AND SMARTNESS CRITERIA AT THE CITY LEVEL

As concluded earlier, the term 'smart city' is associated mainly with the use of technological innovations, specifically the ICTs, in the field of city planning, development and management. The links between technology and their positive and negative impact on the economic, social and environmental dimensions of sustainability have fueled many arguments between the scholars in this field. The central issue of these debates is reflected by Ashford's argument [49] that the industrial age technologies, which construct part of the driving forces that have sent the world in the wrong direction, could be replaced by new sustainability technologies to reverse course and improve the state of the world.

In analyzing Table II which has presented the criteria for the main aspects of smart cities as perceived and approached by the scholars and practitioners in the field, it was found that most authors placed sustainability as a key concept in at least one of their dimensions of smart cities; generally, multiple dimensions have an aspect of sustainability within them. Most descriptions of smart cities likewise incorporate some aspect of sustainability within them. Few examples exist of well-defined criteria to assess smart cities. With authors' liberal use of the term, sustainability is generally always a common theme, yet there is no consensus on the description of a smart city as the meaning tends to follow the research direction.

The lack of consistency makes it necessary to define a set of criteria that are more relevant to the aims of this research project. Considering this paper as the first phase in a research project, which is aiming to develop Cross-Disciplinary City Information Modelling Framework for Sustainable and Smart City, the selected set of criteria will be based on all of the aspects of sustainability that this research will address. The framework and the criteria must have the following characteristics:

1. The development process of the framework has to be carried out adopting an integrated and systemic approach. Integration means embedding technology innovations with the sustainability dimensions and their associated criteria: The social, economic and environmental dimensions.
2. The framework has to enable comprehensive application of ICTs to economic, social, and environmental dimensions of sustainability, and the contribution of each dimension to others in the city context.
3. The proposed criteria for city information modelling framework should be readily measurable for existing and future cities.
4. The proposed criteria have to be adaptable to the dynamic nature of modelling approaches, and obtainable through use of the variety of available quantitative and qualitative methods.
5. The criteria have to consider the methods used in modern tools. These tools generally serve a set of either statistical or physical methods.

VI. Between Statistical and Dynamic Approaches for City Information Modelling

Capturing, analyzing and modelling cities' information is a very challenging process. There are many techniques and technologies available for collecting and capturing such information such as EDM, GPS, photogrammetric applications, and other building surveying applications.

The limitations of using one of these technologies include their restricted capabilities in terms of serving a single narrow objective; moreover, they have not been practical and efficient with regard to time, cost and accuracy. The broad sets of criteria for developing conclusive sustainable city plan, as shown in Fig. 1, require a cross-disciplinary knowledge base, created from quantitative and qualitative data for historical, architectural, environmental, social, and economic criteria.

Looking specifically at statistical approaches, the BREEAM tool was identified as one of the most widely used in City Information Modelling. BREEAM is an evaluation tool with assessment for management, health and wellbeing, energy, water and land-use/ecology. Points are rewarded based on performance in these fields whilst certain scores are mandatory requirements in certain fields. The versatility of this tool is arguably its most powerful feature; its interdisciplinary assessment of a range of fields has allowed this tool to enjoy a great deal of popularity across multiple fields in academia and industry. BREEAM is in essence an assessment tool and while it would suit part of these research objectives, it lacks the ability to make accurate physical future projections. Future projections based on physical models that are validated are a valuable base of evidence and can be instrumental in policy change. The aims of this research greater align with a physical model capable of dealing with possible future scenarios and capable of measuring the possible long-term effects of policy. These features are shared across models incorporating statistical modelling approaches. These approaches are validated using past data and are thus only as effective as their inputs. Often referred to as black-box methods, these methods relate a set of inputs to outputs while the user knows nothing of this relationship. For black-box methods to be effective, they thus require a large amount of data; the model is also sensitive to the quality of the data. The model produced is also very contextual to the data used to produce it; it is only effective in the same setting used to obtain the input data. Black-box modelling is nonetheless widely used, whether through regression based techniques or more powerful advanced neural networks, these models can produce very accurate models in a wide range of scenarios given appropriate inputs. In comparison to dynamic physical models, it is considerably easier to develop an advanced neural network and the process also tends to be less computationally intensive.

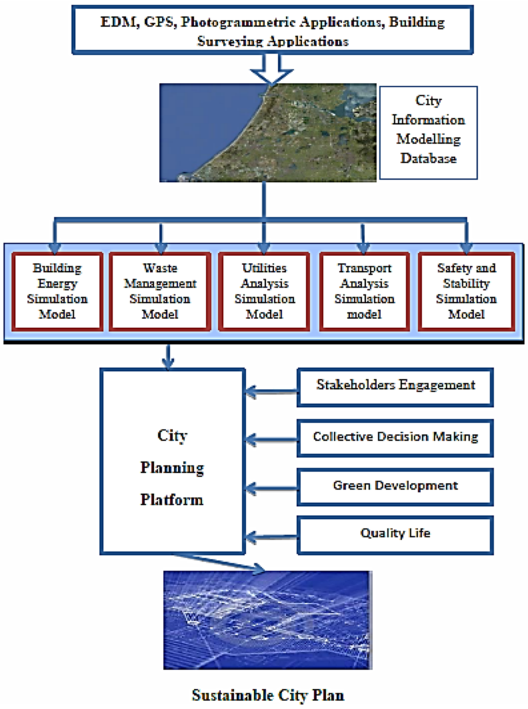

Fig. 1 The Data Sets Required in a City Information Modelling Scenario

The cross-disciplinary nature of this research makes black-box modelling based on neural networks a promising approach for certain aspects of City Information Modelling. As it is not always possible to produce a dynamic physical model for all aspects of the city's model, black-box approaches can be adequate alternatives for these cases.

Advanced neural networks are a group of black-box modelling techniques that go a step further than linear statistical regression and multiple regression [50], [51]. These methods are widely used in multiple fields and have seen success in some applications of City Information Modelling. Neural networks are non-linear models; as we do not necessarily know the relationship between model inputs and outputs, this non-linearity is rather important. They rely on multiple layers, an input layer of model inputs, an output layer of one or more model outputs, and hidden layers in between the two. The hidden layers carry out a number of transformations on the variables in order to arrive at the output. The transformations are based on a mathematical model of human neuronal behavior, hence the name of the modelling technique. Multiple hidden layers are the key feature of neural networks allowing them to deal with more complex relationships where multiple regression techniques just weight variables based on a linear relationship between them and the output.

Dynamic physical models take considerably more time to develop. Even if an already present model is used, implementation would be more difficult and computationally intensive relative to other methods. Bourdic and Salat [52] comment on dynamic agent based models citing their superior reliability and technical robustness. The authors go on to say that such dynamic models are very difficult to use due to the data requirements; similar to statistical methods, dynamic models have very specific data requirements relating to the modelling subject.

The superior reliability and technical robustness of dynamic models are not the only advantages. Physical dynamic models are more far more widely applicable, as they have physical basis, and since the user knows the exact relationship between model inputs and outputs, they can be used wherever there is available data. Future projections are also far more reliable; the physical basis means that future scenarios can be modelled just as accurately. This is a key advantage of dynamic models: As they simulate in real-time, their outputs are a valuable evidence base for planning scenarios.

While an approach utilizing dynamic physical models would be ideal in City Information Modelling, the cross-disciplinary nature of CIM lends itself more to an approach incorporating a variety of different modelling methods. In certain aspects of city and built environment planning, it will be possible to take advantage of the robustness of dynamic physical models. The BIM part of CIM is one such field where there exists a number of dynamic models which are readily usable, for example EnergyPlus. Where there do not exist dynamic models, it will be necessary to use advanced neural networks with a set of relevant inputs, in order to model the city. This alternative is a strong one which will offer excellent results given adequate input training data.

VII. Conclusions

The concept of a sustainable smart city is referring to an urban development designed and managed with the aid of Information and Communication Technologies, directed by the objectives of contributing to improved environmental quality and social wellbeing over the long run. These objectives can be attained through adopting sustainable urban development strategies to foster advancement and innovation in urban infrastructure, urban management, ecosystem service provision, and public service delivery, while continuously improving efficiency gains.

Analysis of the criteria associated with the concept of smart cities as perceived and approached by the scholars and practitioners has shown that most authors placed sustainability as a key concept in at least one of their dimensions of smart cities. Generally, multiple dimensions have an aspect of sustainability within them and most descriptions of smart cities likewise incorporate some aspect of sustainability.

Although the use of statistical approaches are very popular in addressing specific dimensions (like utility and service management) of development and action plans of the world cities, the analysis has shown that the use of such approaches for embedding sustainability dimensions in city information modelling has a limited value. These approaches have restricted capabilities in terms of serving single narrow objectives. Moreover, they have not been practical and efficient with regard to time, cost and accuracy, and they are incapable to deal with the complexity and dynamics of sustainability criteria across various city sectors.

The cross-disciplinary nature of City Information Modelling lends itself to an approach incorporating a variety of different modelling methods rather than the use of dynamic physical models. Therefore, the suggested approach to embedding sustainability dimensions in city information modelling frameworks has to be an integrative dynamic, and cross-disciplinary. Nonetheless, certain aspects of city and built environment modelling, including the BIM aspect of CIM, already have a number of readily usable dynamic models and so can take advantage of their robustness.

The dynamic models have been criticized as their data requirements make them very difficult to use. They require cross-disciplinary knowledge base created from quantitative and qualitative data for historical, architectural, environmental, social, and economic criteria. Moreover, dynamic physical models take considerably more time to develop, even if an already present model is used, implementation will still be more difficult and computationally intensive relative to other methods.

The superior reliability and technical robustness of dynamic models is not the only advantage, physical dynamic models are more far more widely applicable, as they have physical basis and the user knows the exact relationship between model inputs and outputs they can be used wherever there is available data. Future projections are also far more reliable; the physical basis means that future scenarios can be modelled just as accurately.

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