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Complex Urban Systems ICT Infrastructure Modeling: A Sustainable City Case Study

Adedamola Adepetu, Edin Arnautovic, Davor Svetinovic, and Olivier L. de Weck

Abstract—A modern and efficient information and communication technology (ICT) infrastructure is essential for managing the challenges in the complex urban systems development. The ICT infrastructure is a complex system consisting of many subsystems and interconnections, which makes the process of planning, designing, and maintaining a comprehensive ICT infrastructure expensive and difficult. Most approaches used for the ICT infrastructure modeling focus typically on a single ICT system, for example, a wireless network. This paper presents a systems modeling approach based on integrating different subsystems and their characteristics into a single model, applying system decomposition, establishing the logical relations between system components, and defining relevant key performance indicators. It is shown that this systems modeling approach facilitates holistic planning, design, and evaluation of the complex ICT infrastructure for a sustainable city. This is demonstrated in the form of a two-scenario Masdar city case study. The case study exhibits the practicality of the derived ICT model and the feasibility of the results.

Index Terms—Complex urban systems, information and communication technology (ICT) infrastructure, sustainable development, systems modeling.

I. INTRODUCTION

THE INFORMATION and communication technology (ICT) infrastructure is a major driver for the development of the sustainable cities. The ICT infrastructure offers different services to various urban complex system entities, most notably access to the networks, computational processing, and transmission of information. Applications are increasingly being shifted to large computing centers offering savings on space, energy, and costs. Even personal computing is shifting toward cloud computing, relying upon the use of large computing centers that provide infrastructure as a service (computing resources in the form of operating system images), platform as a service (software execution platforms), and software as a service (ready-to-use software such as word processing or customer relationship management software).

II. BACKGROUND AND RELATED WORK

These computing centers should be considered a central part of the ICT infrastructure, and should therefore be integrated into the ICT planning process. Although these computing centers provide computational services (e.g., intensive computations for weather forecasting), high-level software services (e.g., e-mail processing), and data storage services (e.g., file storage), they are typically known as datacenters. In this paper, the ICT infrastructure system is treated as a single complex system consisting of networks and datacenters.

There is an increase in the recognition of the importance of the ICT infrastructure in urban complex systems planning [1]. Due to the importance of the ICT infrastructure, it is treated with the same level of importance as the other infrastructure systems such as electricity, water, and transportation. In the case of sustainable cities, the effectiveness of energy consumption and the minimization of pollution in the ICT system are of critical importance.

Research on the city of London identified the five key aspects of the ICT system [2]: network connectivity, data center capability, electrical power supplies, security and resilience, and skills. This paper focuses on the first three aspects—networks, datacenters, and energy consumption—and models these aspects using high-level parameters, including properties of the services provided, costs, etc. Visualizing and estimating the high-level impact of the ICT system in a sustainable city is imperative, as it enables developers to forecast the ICT requirements necessary to ensure the seamless operation of the other city infrastructure systems. In turn, it is important to understand the resource requirements the ICT system places on the other systems and to evaluate the sustainability of the ICT system. Thus, the main goal of this paper is to create a model suited for ICT system planning and development in sustainable cities. This ICT model is exhibited in a two-scenario sustainable city case study.

This paper is organized as follows. Section II discusses background work and similar ICT models. Section III provides the details of the functional and spatial modeling framework used to develop the ICT model. Section IV presents the process and details of developing the ICT model. Section V presents the case study results. Section VI presents a discussion of the ICT model and results. Section VII concludes the paper.

A functional and spatial modeling framework is used for the ICT model development. This modeling framework originates...
end-to-end population communication. This network simulation is based on the multiscale integrated information and telecommunications system (MIITS), which is a part of the urban infrastructure suite (UIS). The MIITS models extensive and complex communication networks and takes infrastructure interdependencies into account. MIITS simulates the dynamics of the network behavior, real-time network loads, and the network protocol stack. In order to make the simulation realistic, the MIITS developers analyzed statistical survey data about the communication patterns and devices used. MIITS performs simulations at the level of the packets transported in the network and executes rather low-level processes such as routing. However, the MIITS has lower-level technical goals compared to the high-level modeling implemented in our ICT model. Our model places more emphasis on the services offered (including their quality) and how these services relate to costs, energy consumption, etc., taking a holistic approach and integrating computational resources.

In general, our paper is related to the area of modeling and simulation of critical infrastructures. Rigole and Deconinck [8] present several approaches for the modeling and simulation of critical infrastructures and their interdependencies. These approaches are classified as macroscopic and microscopic; the former focuses on using high-level abstractions and formulas, and the latter focuses on a small isolated part or aspect of the infrastructure. The framework used in our paper falls in the macroscopic category. In addition, Rigole and Deconinck present the Supply-Demand Graphs approach as a way to model interdependent infrastructures by representing the flow of a commodity such as electric power or communications. For example, these graphs could be used to investigate the infrastructure vulnerabilities. If the links between suppliers and consumers are weighted or quantified, some other analysis and simulations can be performed (e.g., related to investment or performance). Although the provision of services is considered in this paper (e.g., offering a computational power or network access the customers), parameters of different systems are established and linked using formulas instead of graphs.

Other approaches for modeling and simulation, for example, petri nets and agent-based simulation, deal mostly with low-level and dynamic properties of the infrastructure such as stability or reliability. Additional complex urban system models include Siemens city [9], IBM CityOne [10], and UIS [11]. However, none of these models offers the detailed level of modeling and range of possibilities necessary for integrating different systems, as required for the goals of our paper. The aim of our ICT model is to present an approach for the analysis, planning, and simulation of the ICT infrastructure using systems engineering principles. In addition, the ICT model includes computational facilities such as datacenters, potentially modeling the cloud services that datacenters provide.

III. FUNCTIONAL AND SPATIAL MODELING FRAMEWORK

A functional and spatial modeling framework [4] for city infrastructure systems is used to develop the ICT model. These two aspects of the framework—functional and spatial—work...
in parallel and complement each other in the system model development process. The functional aspect of the modeling framework comprises four processes:

1) **Conceptualization** is the process of developing the fundamental system ideas and concepts that are obtained based on the intended functionality of the system.

2) **Decomposition** is the process of systematically breaking down the system into components represented by Form Parameters (FPs), Behavior Parameters (BPs), and Key Performance Indicators (KPIs). The decomposition process is hierarchical, i.e., different parameters are placed at different levels of the system hierarchy. FPs represent the fundamental properties of the system infrastructure; BPs represent the behavior of the system based on the values of the FPs; and KPIs represent the performance of the system based on its BPs.

3) **Formulation** is the process of establishing the relationships between FPs, BPs, and KPIs, either within a single system or among different systems. Formulation involves the identification of the equations which are used to obtain the values of BPs and KPIs.

4) **Simulation** is the synthesis, analysis, and evaluation of user-defined scenarios using the developed system model.

Spatial modeling involves the synthesis and classification of the system components based on their geographical orientation and physical location. The aim of introducing the spatial orientation of the system infrastructure is to include the spatially-related parameters such as distance in the synthesis, analysis, and evaluation processes. For example, a WiFi network can be spatially synthesized based on the location of its wireless router and the range covered by the WiFi signal. The spatial modeling framework divides the system components into nodes and edges on different physical layer levels. Nodes represent system components and communicate through the edges. Using the WiFi network as an example, the nodes are the wireless routers and the end-user devices (e.g., smartphones and laptops) while the edge (edge region in this case) is the WiFi signal which connects the routers and end-user devices. This classification is similar to those used in geographic information system (GIS) environments [12]. It is important to point out that the functional and spatial aspects of the framework work in parallel rather than sequentially.

In addition, the modeling framework enables the final model to be used in the three main stages: synthesis, analysis, and evaluation. Synthesis is the definition of the values of the FPs and the physical orientation of the system components; analysis is the estimation of the values of the BPs in order to understand the system behavior based on the predefined synthesis; and evaluation is the performance assessment of the user-defined system according to the existing KPIs.

**IV. CITY.NET ICT MODEL**

**A. Conceptualization**

The concept and purpose of each ICT subsystem is explained with a focus on the system inputs and outputs.

1) **Datacenter**: A datacenter provides storage, computing, and networking services to its customers. These services can be direct such as the Internet service or indirect such as cloud services. The datacenter functions as the information hub for all the other infrastructure systems. The datacenter is evaluated with respect to its environmental and financial sustainability. This is based on factors such as servers typically having a three-year or four-year lifecycles [13], and the possibilities of disposing, recycling, or reusing datacenter equipment.

2) **Networks**: A wireless network can be a part of a wide area network (WAN) or local area network (LAN) depending on the intended service area. A wireless network is defined by its coverage area and its available bandwidth. A wired network also comprises the LAN and WAN network categories. The fundamental properties for defining a wired network include bandwidth and termination points.

Riaz et al. [14] present a comprehensive network framework which combines wired and wireless network technologies. They discuss the trend toward the combination of wired and wireless technologies in order to improve users’ networking experience. Furthermore, they point out the important parameters to be considered in networks, citing the bandwidth offered per customer as a vital parameter.

A good option for the wired WAN is the optical fiber technology. The 1000Base-LH standard has a data rate of 1000 Mbps and has a range of 70 km [15]. The other IEEE fiber optic standards are 10Base-FL, 100Base-FX, 100Base-SX, 1000Base-LX, and 1000Base-SX [15]. These standards are incorporated in the ICT model to enable different system modeling options.

Wireless technologies include WiFi and WiMAX. WiMAX is the IEEE 802.16x standard and it supersedes the WiFi technology in both bandwidth and range. The current WiMAX standard which is the 802.16e-2005 has a bandwidth of about 70 Mbps, provides mobility, and covers a range of up to 8 km [14].

3) **Resource Consumption**: The major forms of resource use in the ICT system include energy use in datacenters and communication networks, water use in datacenters for cooling purposes, and land space occupied by ICT infrastructure. Sawyer [16] provides a detailed insight into energy consumption in a datacenter, taking critical loads of ICT equipment, cooling, lighting, and Universal Power Supply (UPS) inefficiencies into consideration as these are the major energy sinks in a datacenter. The datacenter load classification in [17] is consistent with the above-mentioned classification as it also classifies datacenter loads into the computing, cooling, and power categories.

However, one of the challenges of estimating energy consumption in datacenters is the absence of energy proportional- ity. In other words, resource utilization is not necessarily the same as power utilization and this poses a datacenter modeling problem. The typical capacity range at which servers work for most of the time is 10% to 50% of the full server capacity [18] but this does not result in a range of 10% to 50% power consumption.

Vereecken et al. [19] also study power consumption in communication networks, citing instances which show that an
operator’s mobile network power consumption is about 20% of the total power consumption, while the fixed line access consumes about 50% of the total power consumption [20], [21].

The consumption of energy in the ICT system is systematically derived based on the energy consumption of individual components in the datacenter and network.

4) Energy Generation: In a sustainable city, the ICT system can also be considered to generate energy resources in the form of rooftop Photovoltaics (PVs) and rooftop solar thermal collectors to serve electrical and cooling loads respectively. The PV model [4] is applied for PV energy generation in the ICT system. These energy sources can be used to serve part of the datacenter or network hub loads, mitigating the dependence of the ICT system on the energy system.

Heat obtained from rooftop thermal collectors is made useful for cooling purposes by absorption chillers. The collector type determines the efficiency of the collector. As expected, the cost of the collector is proportional to its efficiency. Also, the chiller-effect type determines the coefficient of performance (COP) of the cooling system. A single-effect chiller has a COP of 0.7 and is used with a flat-plate collector; a double-effect chiller has a COP of 1.2 and is used with a flat-plate collector as well; a triple-effect chiller has a COP of 1.7 and is typically used with evacuated tube collectors [22].

5) Service Provision: The primary purpose of the ICT system is to provide different ICT services to its users. Each service type is characterized with different parameters. For example, parameters for network access would be the bandwidth offered and the available amount of data to be transferred per unit time. Data storage would be measured in Gigabytes or Terabytes, and the processing power is measured in GFLOATS. Platform as a Service is characterized by the properties of the virtual machines instances, where the processing power can also be measured in some form of a computer resource abstraction such as Amazon’s elastic compute unit (ECU). The ECU has a processing power equivalent to the processing power of a 1.0–1.2 GHz 2007 Intel Xeon processor [23].

6) Costs: The costs in the ICT system include capital and annual costs. Capital costs comprise equipment costs and installation costs while annual costs comprise operational costs and maintenance costs. Since the ICT system consists primarily of the datacenter, wired and wireless networks, the aforementioned costs can be identified in these three ICT infrastructure classes. For example, the capital cost for setting up a datacenter would include the costs of ICT equipment such as servers, routers, switches, firewalls, external network circuits, cooling equipment, etc. The operational and maintenance costs can be set at a certain percentage of the capital cost. Kaplan et al. [24] present a sample cost analysis for a particular application in a datacenter, highlighting ICT equipment such as servers, network, and storage equipment. Another datacenter cost analysis, which uses the datacenter critical power demand and server power as bases for estimating costs, is presented in [13] and this is the cost analysis method used in this paper.

7) Emissions: There are no direct emissions associated with the ICT infrastructure. However, indirect emissions exist in terms of the emissions resulting from the generation of energy consumed by the ICT infrastructure. These indirect emissions are incorporated in the ICT model.

B. Decomposition

The object process methodology (OPM) [25] is used to facilitate the decomposition process. OPM has objects as the core entities in a model, and processes that transform objects by creating objects, destroying objects, or somehow affecting objects. OPM represents the system structure and system behavior in the same model. This is one of the reasons why we decided to use OPM instead of a language such as unified modeling language (UML) [26].

Graphically, objects are represented by rectangles and processes by ellipses. Fig. 1 shows the OPM model of the ICT infrastructure system. There are two classes of parameters: form parameters (FP) and behavioral parameters (BP). FPs describe the systems components, attributes, and relationships. BPs describe behavior characteristics that are derived or expected from the system’s form. For example, in Fig. 1, the ICT system form is a component (FP) that contains the containment is represented by a full arrow) the Datacenter and the Network. The Datacenter has a number of parameters such as “land used” or “number of servers.” The ICT System model also comprises behaviors classified under “resource demanding” and “resource providing,” as well as the parameters defining these behaviors (e.g., “electricity generated,” or “total power required”). The behaviors are also related to some of the FPs, for example, “number of PV panels” is related to “service providing.” Table I provides a list of FPs and BPs in different sections of the ICT system and in ICT-related dependencies.

C. Formulation

The relations that define the BPs and KPIs of the ICT system are specified based on the conceptualization and decomposition of the ICT system. The symbols used to represent the parameters are listed in Table I.

1) Data Center: Energy sinks in a datacenter are typically divided into the following categories: ICT equipment, electrical equipment, and cooling. Sawyer [16] estimates the total datacenter power consumption, and some of the equations are listed below

\[ P_{ICT} = \sum N_{equipment} \times P_{equipment} \] (1)

\[ P_{UPS,loss} = 0.32 \times (P_{ICT} + P_{elec,ICT} + P_{ICT-take}) \] (2)

\[ P_{peak} = 1.05 \times (P_{ICT} + P_{elec,ICT} + P_{ICT-take}) \] (3)

\[ P_{light} = 0.0215 \times A \] (4)

\[ P_{elec} = P_{light} + P_{UPS,loss} + P_{peak} \] (5)

\[ P_{DC-Cool} = k \times P_{elec} \] (6)

\[ P_{cool} = P_{DC-Cool} + P_{elec} \] (7)

\[ P_{Gen-Cool} = 1.3 \times P_{DC-Cool} \] (8)

\[ P_{Gen} = 1.5 \times P_{elec} \] (9)

\[ P_{Gen} = P_{Gen-Cool} + P_{Gen-Cool} \] (10)
In addition, the actual energy consumed within the datacenter is dependent on the utilization of the resources (servers, network, storage) available in the datacenter. However, the power utilization of the equipment is not necessarily the same as resource utilization of the same equipment, hence, the current enterprise for energy proportionality in the ICT industry. Fig. 2 shows the utilization of servers, network equipment, and storage devices related to the power consumption [13], [30]. Barroso and Höhle [18] study energy proportionality of ICT equipment, and show a linear progression between resource utilization and power consumption. As a result, the values for the power consumption in storage and network devices have been linearly extrapolated from the power consumption during the idle states as presented in [30]. The power consumption and utilization graph of a sample server were obtained directly from [13].

\[
\text{Utilization } \mu = \frac{\text{Demand}}{\text{Maximum Capacity}}
\]

\[
E_{\text{ICT}} = 8760 \times (P_{\text{HIT}-S} + P_{\text{HIT}-S} + P_{\text{HIT}-S})
\]

2) **Network**: The required bandwidth in the network is dependent on the maximum bandwidth, utilization, and availability of each customer during different periods of the day [14]. Network energy consumption is estimated based on the energy consumed in each base station

\[
\text{BW}_{\text{req}} = Np \mu \times \text{BW}_{\text{plan}}
\]

\[
E_{\text{Network}} = E_{\text{perBS}} \times N_{\text{BS}}
\]

3) **Rooftop PV** [29]: The derivation of the energy generated by the PV panels is temperature dependent. The energy generated from PV panels is calculated based on hourly solar irradiation

\[
T_{\text{mod}} = 0.943T_{\text{amb}} + 2.869\text{DNI} - 1.528v_{\text{wind}} + 4.3
\]

\[
E = df \times \frac{\text{DNI}}{1000} \times A \times \eta \times (1 + (T_{\text{mod}} - 25) \times 0.01)
\]

4) **Rooftop Thermal** [22]: Energy generation for solar thermal cooling depends on the solar radiation and the system efficiency

\[
E_{\text{solar}} = \rho \times A \times \text{DNI}
\]

\[
P = E_{\text{solar}} \times \text{COP}
\]

5) **Land Use**: The datacenter and the network base stations occupy significant land areas, while the area occupied by the
TABLE I
FORM AND BEHAVIOR PARAMETERS

| Method | Form Parameters | Behavior Parameters |
|--------|----------------|---------------------|
| Data Center | Number of each ICT equipment (servers, routers, firewalls, switches, and storage devices) | Total ICT Power $P_{ICT}$ (kW), UPS losses and battery capacity $P_{UPS}$, Generator backup power $(P_{UPS}+P_{gen})$, Total network power rating $P_{Total}$, Generator backup capacity required $P_{Backup}$, Utility generation capacity $P_{Power}$, Power consumed by non-ICT equipment $(P_{non}$- $P_{ICT}$) |
| ICT Services | Number of each ICT equipment (servers, routers, firewalls, switches, and storage devices) $N_{ICT}$, Power rating of each equipment $P_{equipment}$ (kW), Storage capacity, Network throughput to customers, Internet bandwidth, Number of switches, Capacity of switches, Number of routers, Capacity of routers, Number of servers, Server processor speed, Server storage capacity, Storage demand, Network demand, Processing demand, Power rating of non-ICT devices (excluding lighting and cooling devices) $P_{non-ICT}$ (kW), Power rating for binary ICT devices $(P_{equipment}+P_{non-ICT})$ (kW), Datacenter floor area $A_{datacenter}$, Cooling system type multiplier $k^1$ Light utilization factor $\mu_{light}$,
| | | a) Power usage effectiveness (PUE) $[31]$:
| | | b) Datacenter lifetime $T_{datacenter}$ (years), Datacenter annual operating expenditure $T_{op}$ (US$), Datacenter capital expenditure $T_{capex}$ (US$), Server annual operating expenditure $T_{op}$ (US$), Server depreciation $T_{depr}$ (US$/year), Power rating of server $T_{server}$, and Number of servers $N_{server}$,
| | | c) Datacenter energy efficiency $E_{datacenter}$ (kWh), Energy consumed by ICT equipment $(E_{ICT})$, Energy consumed by non-ICT equipment $(E_{non}$), Energy consumed by lighting $(E_{light})$, Energy consumed by IT equipment $(E_{IT})$, Energy consumed by IT equipment and battery charging $(E_{IT+charge})$, Energy consumed for critical load $(E_{critical})$, Energy consumed by UPS inefficiency $(E_{UPS})$, and Battery charging $(E_{charge})$.
| | | d) Total cost of ownership (TCO) $[52]$ (US$/year), Storag tank capacity $T_{storage}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (kW), Collector area $T_{collect}$ (k2)
power use in a datacenter is inversely proportional to the PUE

\[ \text{PUE} = \frac{\text{Total facility power}}{\text{ICT equipment power}} \]  

Table II shows the classification for different PUE and DCiE values [32], [33].

| PUE | DCiE | Efficiency Classification |
|-----|------|---------------------------|
| 3.0 | 33%  | Very Inefficient          |
| 2.5 | 40%  | Inefficient               |
| 2.0 | 50%  | Average                   |
| 1.5 | 60%  | Efficient                 |
| 1.2 | 83%  | Very Efficient            |

b) Data Center Infrastructure Efficiency (DCiE) [31]:
This GPI has the same purpose as the PUE. The DCiE is a percentage form of the PUE inverse

\[ \text{DCiE} = \frac{\text{ICT equipment power}}{\text{Total facility power}} \times 100\% \]  

Table II shows the classification for different PUE and DCiE values [32], [33].

c) Datacenter density (DCD) [31]: This GPI represents the space efficiency of a datacenter by comparing the total energy consumed in a datacenter with the land space occupied by the datacenter

\[ \text{DCD} = \frac{\text{Energy Consumed in Datacenter}}{\text{Total Land Space Occupied}} \]  

d) Space, watts, and performance (SWaP) [31]: This GPI aids the evaluation of a datacenter’s performance with respect to the power consumed and the land space occupied

\[ \text{SWaP} = \frac{\text{Performance}}{\text{(Space \times Power Consumption)}} \]  

e) Deployed hardware utilization efficiency (DH-UE) [31]: This GPI measures the efficiency of the datacenter server capacity with respect to the service demand

\[ \text{DH-UE} = \frac{\text{Peak demand server requirement}}{\text{Number of servers in datacenter}} \]  

f) Compute power efficiency (CPE) [34], [35]: This GPI measures the power efficiency of the datacenter with respect to the server computation.

\[ \text{CPE} = \frac{\text{DCiE}}{\text{ICT Equipment Utilization}} \]  

g) IT Productivity per embedded watt (IT-PEW) [31]: This GPI refers to the actual storage, network throughput, or executed processing cycles.
\[ \text{IT-PEW} = \frac{\text{IT productivity}}{\text{Total embedded power}} \]  

h) Datacenter energy productivity (DCeP) [31]: This GPI compares the useful work done by the datacenter with the total energy energy consumed by the datacenter. Useful work done is represented by the number of bytes processed in the datacenter

\[ \text{DCeP} = \frac{\text{Total bytes processed}}{\text{Energy consumed by datacenter}} \]  

i) CO₂ Emissions: This GPI represents the carbon footprint of the ICT system. It is obtained by calculating the equivalent CO₂ emissions based on the total energy consumed by the ICT system. Although the average global CO₂ equivalent emissions per kilowatthour is about 500 gCO₂e/kWh, the actual unit emissions per kilowatthour varies by country. For example, the unit emissions per kilowatthour in Australia is about 875 gCO₂e/kWh, while it is approximately nil in Iceland [19], [31]

\[ \text{CO₂ Emissions} = \frac{\text{Energy consumed \times CO₂/kWh}}{\text{Energy Consumed}} \]  

j) MHz per Watt [35], [31]: This GPI compares the processor performance of servers with the energy consumed by the servers

\[ \text{MHz per Watt} = \frac{\text{Processor performance}}{\text{Energy Consumed}} \]  

k) Bandwidth per Watt [35], [31]: This GPI compares the network performance with the energy consumed by the network devices

\[ \text{Bandwidth per Watt} = \frac{\text{Total bandwidth utilized}}{\text{Energy Consumed}} \]  

l) Capacity per Watt [35], [31]: This GPI compares the storage performance with the energy consumed by the storage devices

\[ \text{Capacity per Watt} = \frac{\text{Storage capacity space}}{\text{Energy Consumed}} \]  

D. ICT Layers
Since the ICT system provides data storage and network services, it consists of the datacenters and the network infrastructure. As described in [4] and [36], the concept of layers, edges, and nodes is used to classify the ICT system infrastructure components. The ICT layers, nodes, and edges are as follows.

1) Layer 1:
   a) Node: Datacenter.
   b) Edge: Wired WAN (Optical fiber).

2) Layer 2:
   a) Node: Base station.
   b) Edge: Wireless WAN (WiMAX).
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V. MASDAR CITY CASE STUDY

This case study analyzes the requirements for implementing a city-scale ICT system in Masdar City and envisions the feasibility of such an infrastructure system. Masdar City is being built to be a sustainable, minimal emissions, and minimal waste community that will depend on renewable energy sources [37]. It is projected to have about 50,000 residents and 60,000 commuters. Based on this projection, the ICT service demand within the city can be estimated. The Masdar City area is geographically divided into the residential and commercial zones. Two scenarios are simulated in order to compare the range of results obtainable from different parameter values.

A. Synthesis

1) Scenario 1: Assuming an average of three residents per household results in approximately 16,667 households that require the Internet connections via the city datacenter. The datacenter acts as a central point of connection for the city network, controlling the network traffic and securing the lower layer networks. In order to reduce costs, save energy, and reduce the negative environmental impact, the residents and enterprises in Masdar City should reduce the number of typical home or office computers, and rely on the ICT services provided by specially designed and environmentally friendly datacenters. Since such datacenters are located within the city, potential issues concerning bandwidth or latency are neglected.

In addition, the case study considers 1000 offices in the Masdar City commercial district. This is based on the assumption that half of the commuters and half of the residents work within the city, and each office has an average of 55 employees. These numbers are used in the case study to highlight the flexibility in the ICT model’s range of applications.

The end users are connected via the WiMAX network, and as in [14], several base stations are required. These base stations are connected to the datacenter via optical fiber cables. Fig. 3 shows the different functional layers in Masdar City ICT system. This is based on the expectation that the users have the penetration and utilization rates listed in Table III. The variation of the utilization and penetration rates captures the expected network customer dynamics during the course of the day. Typically, each base station should have a bandwidth capacity of 70 Mbps, but due to the high population density and consequently high demand, multiple WiMAX radio cards are mounted on the base stations. In addition, customers have different service packages, and Table IV itemizes the Internet service packages devised for this case study and the corresponding number of subscribers.

Furthermore, the hourly storage and processing demand placed on the datacenter through the course of each day are displayed in Figs. 4 and 5, respectively. The data used for evaluating the system is the load estimated based on the population of the city, the average storage, and computing requirements of each home and office. This includes the variation of the loads with respect to the office hours. The data is only used to show how the ICT model can be used in practice. In order to produce real-world estimations, the actual demand data collected and obtained from datacenters should be used in the ICT model.

A 500 m² datacenter that provides storage, processing, and network services is modeled in this case study. The values of the FPs are listed in Table V. The server used in the datacenter synthesis has 12 processors with a total processor capacity of 25,088 GFLOPs. This estimation is based on the Intel Xeon X5660 2.80GHz processor which has a processor capacity of 194 GFLOPs. This processor capacity was obtained by using the QuickMark 0.4 tool [38].

Also, 90% of the rooftop area is assumed to be useful for PV panels and solar thermal collectors. This available rooftop area is equally allotted for electricity generation via PV panels and feeding the datacenter cooling demand via the solar thermal collectors.

2) Scenario 2: The second simulation scenario has a lower demand and fewer ICT facilities than Scenario 1. The expected network customers are shown in Table IV and with the same network customer dynamics as in Table III. In addition, the storage and processing service loads are shown in Figs. 4 and 5, respectively. The FP values are shown in Table V. These facilities comprise a 200 m² datacenter and nine base stations for the wireless network. However, the base stations have a lower average capacity than in the Scenario 1.
B. Simulation Results

The BPs and KPIs obtained from simulating the two scenarios are shown in Table VI. As expected, the ICT system in Scenario 1 has an ICT energy consumption of 5.35 GWh/year, and the ICT system in Scenario 2 has an ICT energy consumption of 7.76 GWh/year. In both cases, the energy generated from the PV panels and solar thermal collectors comprise a small fraction of the energy requirement of the datacenter. As a result, a larger PV or solar thermal installation would be required in order to produce a significant reduction in the datacenter’s dependence on the power grid.

In Scenario 1, the server, storage, and network utilization percentages show that the system resources are not being used to the maximum level. This implies that the ICT system in Scenario 1 could handle a growth in demand. However, the utilization percentages in Scenario 2 show that the ICT system is being used to its maximum capability. Based on the hourly demand-capacity variations in Scenario 2, there were periods during which the storage and the Internet facilities were not able to meet the demand. This implies that the storage and the Internet facilities need to be upgraded in Scenario 2.

The efficiencies of both scenarios are similar, with Scenario 1 having a PUE of 2.42 and Scenario 2 having a PUE of 2.43. However, it is important to note that these PUE values
TABLE VI
CASE STUDY BPs AND KPIs

| Parameter                                      | Scenario 1 | Scenario 2 |
|------------------------------------------------|------------|------------|
| Retrofit Thermal Energy Generation             | 1,165.59 kW| 1,165.59 kW|
| PV Energy Generation                           | 1,165.59 kW| 1,165.59 kW|
| Total Land Use                                  | 90 m²      | 90 m²      |
| Total Production Power                          | 1,927.74 kW| 1,927.74 kW|
| Total Network Power                             | 72 kW      | 72 kW      |
| Total DC Power                                  | 9.37 kW    | 9.37 kW    |
| Total Energy Use                                | 1,927.74 kW| 1,927.74 kW|
| UPS losses                                      | 1,003.00 kW| 1,003.00 kW|
| Critical Load Peak                              | 162.57 kW  | 162.57 kW  |
| Lighting Power                                  | 162.57 kW  | 162.57 kW  |
| Cooling Capacity                                | 123.95 kW  | 123.95 kW  |
| Total Electrical Power                          | 463.81 kW  | 463.81 kW  |
| Total Facility Power                            | 102.02 kW  | 102.02 kW  |
| Generator Cooling                               | 162.13 kW  | 162.13 kW  |
| Generation Critical                             | 263.61 kW  | 263.61 kW  |
| Generator Total                                 | 1,165.59 kW| 1,165.59 kW|
| Max Server Utilization                          | 59.99 %    | 59.99 %    |
| Min Server Utilization                          | 29.89 %    | 29.89 %    |
| Max Server Utilization                          | 33.23 %    | 33.23 %    |
| Min Server Utilization                          | 29.89 %    | 29.89 %    |
| Server Annual Energy Use                        | 1.12 GWH   | 0.49 GWH   |
| Max Storage Utilization                         | 100 %      | 100 %      |
| Min Storage Utilization                         | 78 %       | 78 %       |
| Storage Annual Energy Usage                     | 3.504 GWH  | 3.504 GWH  |
| Max Internet Utilization                        | 41.62 %    | 41.62 %    |
| Min Internet Utilization                        | 25.76 %    | 25.76 %    |
| Datacenter Network Annual Energy Use            | 93.131.60 kW| 93.131.60 kW|
| Total ICT Equipment Energy Use                  | 1.41 GWH   | 0.92 GWH   |
| UPS Energy Losses                               | 6.24 X 10^6 W/year | 6.24 X 10^6 W/year |
| Light Energy Use                                | 18,861.74 W/year | 18,861.74 W/year |
| Cooling Energy Use                              | 3.99 GWH   | 3.99 GWH   |
| Total Thermal Load                              | 2.98 GWH   | 2.98 GWH   |
| Electrical Energy Use                           | 3.99 GWH   | 3.99 GWH   |
| Datacenter Energy Use                           | 3.99 GWH   | 3.99 GWH   |
| Energy Use per Base Station                     | 0.96 GWH   | 0.96 GWH   |
| Network Energy Use                              | 1.44 GWH   | 0.96 GWH   |
| Total ICT Energy Use                            | 3.35 GWH   | 3.35 GWH   |

KPIs

| Parameter | Scenario 1 | Scenario 2 |
|-----------|------------|------------|
| DCD       | 1.79 X 10^8 kWh/m² | 1.79 X 10^8 kWh/m² |
| DCUE      | 0.80        | 0.80        |
| PUE       | 2.5        | 2.41        |
| DCER      | 4.13 %      | 4.13 %      |
| CPE       | 1.72        | 0.64        |
| CO₂ Emissions | 57,946.54 Tonnes | 57,946.54 Tonnes |

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TABLE VI continues...

- Based on the results shown in Table VI, the performance improvement recommendations are as follows.

1) The datacenter in Scenario 1 is underused and as a result, there is no need for making expansion plans until there is a significant growth in the city. This recommendation is drawn from its low DH-UE value. However, this datacenter should endeavor to use its land space more effectively.

2) The datacenter in Scenario 2 needs to invest in more ICT equipment in order to meet the city’s ICT demand and provide better service to the customers. This recommendation is drawn from the 100% storage and network utilization, and the CPE value.

3) In both scenarios, a larger PV station (or some other source of renewable energy) would be required in order to significantly reduce the carbon footprint of the ICT infrastructure.

VI. DISCUSSION

Modeling the ICT system without focusing on microprocesses, such as applications on each server and single network transactions, poses a challenge of adequately representing the behavior of the ICT system. However, the ICT model presented in this paper does not focus on microprocesses since the ICT model only aims to estimate the ICT system behavior and ICT-related interdependencies at the level of the city infrastructure. The ideas and concepts applied in the ICT model have been obtained from industrial and academic standards that represent datacenters, networks, and service provision.

While city communication networks are not typically controlled by a single provider as depicted in the ICT model, the model is still useful for planning and forecasting purposes. Moreover, there is a trend leading toward sustainable cities with integrated datacenters, and unified wired and wireless networks, thus making the presented ICT model potentially even more useful and applicable.

The structure of parameters presented in this paper contributes to the usability of the ICT model. The presented ICT model uses hourly variations during the day to represent the demands placed on the ICT system. Accessibility to specific user data such as the Internet bandwidth requirements, server GFLOPs requirements, storage requirements in ICT infrastructure, and the relation of these requirements to population density would improve the precision of the model. However, this specific user data is often not available at the modeling stages, and often changes even after the infrastructure system deployment.

In summary, the main contributions of this paper are as follows:

1) a hierarchical decomposition of an ICT system in order to identify the structural and behavioral parameters which adequately represent the structure and behavior of a typical city-level ICT system;
2) an ICT model comprising industry standard equations, relations, and KPIs, that can be used to forecast a planned ICT system or evaluate an existing ICT system;
3) a case study implementation of the ICT model using fiber optic, mobile WiMAX, datacenter, and renewable energy technologies; and a simulation consisting of two different scenarios demonstrating how the ICT model could contribute to the ICT system planning process of a sustainable city.

For the future versions of the model and similar developments, additional parameters could be included in order to make the model more comprehensive. Moreover, additional systems such as sensor networks which monitor weather or surveillance cameras could be introduced. Also, in order to be fully generalizable and applied in systems engineering, the ICT model has to be integrated with the models of the other city systems, such as energy, waste management, water management, etc. The integrated tool and model support would allow us to generate a large number of possible models. However, we would need to develop a systematic process for reasoning and using these models for engineering the respective systems in the future. This is a part of our future work focused on model integration within our strategic requirements engineering method [40].

VII. CONCLUSION
This paper presented a sustainable city ICT model systematically developed using a functional and spatial modeling framework. The ICT model comprises datacenter and network facilities as the two major parts of the system. This paper focused on the ability of these facilities to meet certain user-defined demands, therefore showing the capabilities of the developed ICT model. The parameters and parameter equations have been obtained from academic and industrial sources in order to ensure the relevance of the model. A case study consisting of two different scenarios was employed to show how the ICT model works and how it can be used in sustainable city planning.

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