Thermodynamic Dissipative Systems and Information Theory to Study the Social Component of a Smart City

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Abstract. In this article, we discuss the application of information theory and the theory of thermodynamic dissipative systems to smart cities. Specifically, we study how to model the interaction between a society and a smart city, under an information-theoretic approach. Because the smart city comprises both a social and a technological component, it then becomes possible to use information theory to study them both. In this paper, we discuss a model that applies the constraints from thermodynamic dissipative systems theory in order to study smart cities, and their associated social system, in their information processing capacity and in their evolution over time. Within the context of our model, we are allowed to study under what conditions a smart city would expand or contract, or to state that the smart city shrinks if its output greatly exceeds its input.

Keywords: Smart cities, socio-technical systems, information theory, dissipative systems.

1 Smart cities as an open thermodynamic systems

Social systems are non-equilibrium, open thermodynamic systems that exchange energy, matter, and information, with the rest of the environment [1]. They inherit this property from the set of biological organisms that comprise them; i.e. the humans, whose interaction with one another constitutes the social system [2]. Because it is possible to frame social systems as thermodynamic systems, it is therefore also possible, in principle, to apply information theory for their analysis. This implies, for example, the possibility to apply entropic methods from statistical thermodynamics and information theory, in order to study the trajectory of the dynamic evolution of a social system in its environment [3]. In using this approach, however, the problem that we face is that the description of the state of a social system implies the arbitrary definition of a finite and small set of variables, as it is common in the application of agent-based modeling to social systems [4]. This, in turn, draws the most complex system in the universe, the social system, in a rather cartoonish form that grossly trivialize most of its aspects and characteristics, and therefore reduces the complexity that is studied. Another possible research direction is to apply not entropic methods, but dissipative systems theory [5], which has already been applied to study cities and their growth [6]. This is promising but does not directly allow the researchers to model the internal mechanisms of the social system, which is best treated as a problem of entropy and its variation. This inability by traditional thermodynamic approaches to represent social systems sufficiently well is, however, typically not a characteristic of purely technological systems such as computers or information networks [7].

Social sciences provide a useful frame to study hybrid systems comprising a social and a technical component, under the theory of socio-technical systems [8]. This type of approach is useful, for example, to delimit and analyze the system that we call a smart city. A smart city is, in this context, a cyber-physical system for the intelligent management of space and agents in an urban environment [9]. Because it is a technical system, a smart city can be studied under thermodynamic and information-theoretic approaches, insofar as we study its computational or information-network components. Because it is a social system, it is also possible, in principle, to study a smart city under a thermodynamic or information-theoretic approach. In this paper, we propose to use the consideration that a smart city is a hybrid socio-technical system that operates in non-equilibrium as an open thermodynamic system, to extend the information-theoretic approach for the study of its technological component to the study of the social system in which the latter is embedded.

2 Modeling of the system

We argue that, if the social system can be considered as a dissipative system, then a smart city that comprises that social system also can. This means that a smart city can be modeled as a system with a state $X(t)$ at time t, that receives a thermodynamic or information input $u(t)$ from the environment and responds with an output $y(t)$. If the supply rate for that smart city is $w\big(u(t), y(t)\big)$, then the following inequality holds:

$$\dot{S}\big(X(t)\big) \leq w\big(u(t), y(t)\big) \tag{1}$$

In here, $S\big(X(t)\big)$ is a storage function that indicates the energy held by the system at time t, with $S(0) = 0$ and $\forall t\colon S\big(X(t)\big) \geq 0$, which is the condition required for the system to exist. We also assume S to be continuously differentiable. Further, we also assume that, even though this is not so obvious for real world systems, the input, and the output $u(t), y(t)$ to the system consist of known measurables. This means that there is a finite-dimensionality vector comprising all the variables that describe the input from the environment into the smart city, and another one comprising the output.

In this model, we can apply information theory to describe $X(t)$, the state of the system, and its variation over time. If X comprised only of computers and networks, we could then describe it as we do for those systems, and the theoretical problem we indicated earlier would not exist. The state X however comprises also the state of the n individuals that populate the social system, and we call these states x_i with $1 \leq i \leq n$. For simplicity, we imagine that the state of the technological component x_{sc} of the smart city comprises a single computing system, that represents the multitude of computers and IoT devices that, in a real-world smart city, characterize the latter's technological component [10]. If we do that, then the set of states of the elements of the system is the state of the system:

$$X = \{x_{sc}, x_1, x_2, \dots, x_n\} \tag{2}$$

This, however, does not take into account the existing relationships between the humans in the social system with one another, and all humans individually with the technological component of the smart city. The rest of the modeling can then be conducted by constructing a directed graph $G = \{V, E\}$, where V and E can be described as:

$$V = \{sc, 1, 2, \dots, n\},\ E = \{e_{sc}, e_1, e_2, \dots, e_n\} \tag{3}$$

All human elements of this graph connect to a finite and small subset of V. The vertex sc, corresponding to the technological component of the smart city, possesses undirected edges with all elements of V other than itself. In other words,

$$e_{sc} = \{(x_{sc}, x_1), (x_{sc}, x_2), \dots, (x_{sc}, x_n)\} \tag{4}$$

The smart city also distinguishes itself from a standard computing system because its technological component makes decisions by considering the decisions that its human components would make. This means that there exists some kind of decision function f such that:

$$x_{sc}(t+1) = f\big((x_1(t), e_1), (x_2(t), e_2), \dots, (x_n(t), e_n)\big) \tag{5}$$

Whereas all humans make decisions according to their decision functions g_i:

$$x_i(t+1) = g_i\big(x_i(t), e_i(t)\big) \tag{6}$$

This gives us a skeleton model on which we can apply entropic methods to study the variation in complexity of the system, as the supply or the decision functions change.

3 The measurement of the input and the output, and why does all of this matter

We can measure the input $u(t)$ from the environment by measuring the bits that enter the smart city system or its database at any given time. The measurement of the output $y(t)$ can also be analogously conducted. This is because, in order not to clutter any information system, information must be deleted from it. Deletion of information, according to Landauer's principle, generates heat [11]. The information deleted from a smart city, or its corresponding heat, therefore comprise the thermodynamic output from the system. This consideration allows us to treat smart cities as dissipative systems, and supports the validity of the abstract model we propose. If we are allowed to frame smart cities as dissipative systems, we are also allowed to ask additional questions that pertain the latter, in its application to the former. We can, for example, study under what conditions would a smart city expand or contract, under the constraint indicated in (1), above. For instance, a simple consideration would be to state that the smart city shrinks if its output greatly exceeds its input, such that the supply rate $w(u(t), y(t))$ is very low. If we assume that most of the input of the smart city comprises data concerning the human population, this brings us to ask questions such as "how does the variation in the human population affect the growth of a smart city?". We can, in fact, imagine a smart city that keeps growing its database even in absence of a human population, as a consequence of input from IoT devices. Albeit undesirable, this is in principle possible. If, instead, we have a way to relate the information originating from the social component of the smart city to the one originating from IoT, this gives us a language for studying trade-offs between the increase or reduction in the two, and the growth of the smart city as a whole.

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