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Sustainable urban morphology emergence via complex adaptive system analysis: sustainable design in existing context

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Abstract

How to plan and design new elements in the city context in a way that the new elements improve the entire neighborhood energy performance and its sustainability is the main question to be discussed in this paper. In order to achieve this goal, different urban morphological factors, which have great influence on energy consumption of the city as a single entity, are investigated as based on complexity analysis. In this analysis, the urban morphology is considered as the microscopic emergence of the city element's transformation in time. Much research has been carried out regarding sustainable buildings and the energy performance of single edifices; however, there are few studies which have been carried out with consideration of the cities as a single unit. Ultimately, the aim of this paper is to elucidate a novel method to design a new urban element, architectural project for instance, towards achieving a sustainable urban form.

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Keywords: urban morphology; sustainable urban design; complex adaptive system

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1. Introduction

How best to design and introduce new elements into an existing context, in one hand, and achieve an energy sustainable pattern for planning new cities, in the other hand, are rising concerns of planners and designers nowadays. Numerous researches have been carried out with focus on these two fields separately. The ability to bridge these two issues and answer them both regarding energy aspect of the sustainability

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is the core investigation of this article. Much research has been done in different urban sciences with the consideration of the city as a complex system (CS) but there is little research on the energy aspect of the cities considered as a complex system and a single entity. CS is a system composed of many heterogeneous agents, which are nonlinearly interconnected, while the final emergence of the system is completely different than the individual element`s performance. The CS can be an economic system, social structure, computer or automobiles, for instances. Here, the energy aspect of city forms and the effect of urban morphology on energy consumption are under discussion with consideration of the cities as a complex system, and within the context of this paper, particularly a complex adaptive system. The complex Adaptive System (CAS) is a specific type of complex system with some key differing features. CAS has the ability to learn and adapt from past conditions that it has encountered. Thanks to this feature, CAS evolution is more advanced with respect to the CS. Due to its capacity to learn from the past experiences, CAS continuously adapts itself to new constraints and circumstances, resulting in a better performance therefore, the effect of urban form on the energy performance of the city as single entity via complex system analysis has been investigated. This paper aims to elucidate an approach to design a new element in to an existing context in an energy sustainable way.

Three main divisions of this paper	
Part A	City as a Complex Adaptive System
Part B	Energy performances of the city as a single complex entity
Part C	Example for Exiample

1.1. Methodology

This paper is comprised of three different parts, followed by a conclusion at the end of each part. These conclusions assist for better comprehension of each part, whilst they also bond these three main parts of the article together.

In the first division, the City as a Complex Adaptive System (Part A), is introduced through its main characteristic features. How to consider cities as a complex adaptive system and how they form their morphology via complex adaptation is discussed afterwards. The main CAS features under discussion in the first part include the Agents, Subsystems, Algorithmic Relation, Dynamic and Adaptive feature from Exogenous Constraints and finally Transformation.

The second division, Energy performance of the city as a single complex entity (Part B), depicts energy performance of the city as a single unit, comprised of different heterogeneous elements, and how these single agents affect the final energy balance of the entire city. Thereafter, new energy performance of the city due to new morphological changes in the city is investigated. Urban morphology effects on solar gaining, thermodynamic performance, density, wind effect and ventilation are the main keywords investigated in the second part.

The third division, Example for Exiample (Part C), is a simplified case study, carried out on the Exiample blocks in Barcelona, Spain. This case study represents how a single building can improve the energy performance of other buildings in one neighborhood block, as well as the entire neighborhood on a larger scale.

2. City as a Complex Adaptive System (Part A)

The Complex Adaptive System (CAS) is a particular case of the complex system with the ability to learn from prior experiences. System's agents adapt themselves to improve their performance, in a response to new internal and external constraints. According to J.Brownlee, "Macroscopic patterns emerge from the dynamic and nonlinear interactions of the systems low-level (microscopic) adaptive agents. The emergent patterns are more than the sum of their parts, thus the traditional reductionist methodology fails to describe how the macroscopic patterns emerge"[1]. As result, "Complex Adaptive Systems (CAS) refers to a field of study and resultant conceptual framework for natural and artificial systems that defy reductionist (top-down) investigation. Such systems are generally defined as being composed of populations of adaptive agents whose interactions result in complex non-linear dynamics, the results of which are emergent system phenomena" [1]. Using this approach, it is possible to characterise the distinct feature of the urban morphology.

2.1. Agents

As mentioned before, the CAS consists of different heterogeneous members, or agents, which are connected to each other in non-linear ways. An agent within the context of the city can be a building, open space, people, etc. which comprise the city. Behavioral changes of individual agent do not affect the final emergence or performance of the system directly, while a single system emergence forms by combination of all agents' performances as a whole. "Due to variation of agents and differential actions and reactions, system performance is difficult to be anticipated" [2]. Each CAS could have several agents working together in an adaptive way. According to the Holistic approach [3], the members boost and improve or even debilitate each other's performances, and due to this fact, aggregation effect of the agents' interactions is not the sum of all interactions of each agent.

"Macroscopic patterns emerge from the dynamic and nonlinear interactions of the systems low-level (microscopic) adaptive agents. The emergent patterns are more than the sum of their parts, thus the traditional reductionist methodology fails to describe how the macroscopic patterns emerge" [1].

Agents pursue their own interest while respecting certain system`s laws. For example, no individual car contributes solely to the formation of traffic, but rather a traffic jam is comprised of numbers of cars as agents, each pursuing their own interest [2]. In regards to architectural elements, as an agent, designers project different solutions for building designs whilst they must respect regulatory governmental codes, which ultimately shape the city morphology.

The potential to study urban issues while considering the city as a CAS provides an ability to deal with many urban questions such as energy consumption issues, social aspects, transportation problems, sustainability difficulties, etc. In this manner, the morphological aspects of cities are able to elucidate some main energy questions.

2.2. Subsystems and networks

Due to the presence of different types of agents and different nonlinear relations between them, complex systems also need many different subsystems in order to link these agents. These subsystems and networks, such as transportation networks, social networks and economical networks, make cities alive. "As well as the large number of distinct agents typically found in these systems, the multiple subsystems add infinitely more layers of complexity as they influence one another" [2].

Each subsystem affects other agents and subsystems either directly or indirectly and this feature is one of the most important characteristics of complex adaptive systems. Effects of transportation network on economic network, and then economic impacts on social networks, and finally individual's quality of life could be an example of subsystem and networks interactions. The role of economy and transportation in the urban scenario is one aspect transparent to all engineers and planners, and therefore of important consideration within the CAS approach.

2.3. Algorithmic Relation

There are many rules that bond the agents and systems together; while every agent follows its own interest, the relationship between agents are defined by these norms. Members constantly adapt and change their functions, behavior and performances to stay under these fundamental laws. These are known as flocking laws. Final system product emerges through these relations and interactions. For example, a flock of small fish adapts and changes the group shape to confuse sharks and larger predators. System shape adaptation emerges from every single fish when they move with respect to movement of a neighboring fish. As a simple rule between agents, in a group of fish, each fish keeps the same distance from the fish next to themselves. According to C.W.Raynold, "Basic flocking systems define a set of desired relationships between elements in a flock such as ideal distance between elements and preferred position relative to other elements and keeping that rule and distance by readjusting their proximity continuously" [4].

2.4. Dynamic and Adaptive features from Exogenous Constraints

CAS experiences two different types of constraints, internal and external forces. Adaptive reactions are the CAS response to these actions and constraints. In other words, the CAS has to adapt its reactions due to changing constraints in time. "Cities operate under changing conditions. Populations, number of businesses, weather, pollution, the physical environment, immigration and traffic all fluctuate drastically over very short spaces of times. Cities however are robust"[2].

Exogenous morphological controls, such as a river or mountains, could be seen as geographical constraints. Presence of many nonlinear algorithmic relations and subsystems, as well as dynamic reactions to constraints, has created two important aspects of complex adaptive systems. The first aspect caused by the nonlinear algorithmic relation in convolution of investigation; in other words, it is complicated to anticipate the final emergence of the CAS due to the presence of the many layers and interactions. The second aspect, caused by nonlinear algorithmic relations, as discussed in next step, is transformation.

2.5. Transformation

The CAS transforms due to adaptive and dynamic behavior of agents in response to internal and external constraints under certain laws and frameworks. This evolution occurs in two different sequential scales, microscopic and macroscopic levels. Microscopic scale could also be seen in two different phases, which are increasing the number of agents and likewise transforming each agent individually during time. "Cities will essentially evolve from state to state as a result of changing behavior patterns of agents. Cities as a whole evolve by changing in size and prosperity, and clear cycles in wealth and condition of cities can be observed over many years". [2]

Cities have been morphed and formed due to their agent's transformation throughout centuries. The city of Rome, Italy, was not built in a day, and has gone through constant transformation since the roman times. Cities transformations, like other CAS, are accruing in two mentioned phases: external and internal transformation. Increasing the size of cities could be cited as an external transformation by increasing the number of built space and open spaces, while building shape and typology progression are the examples of internal transformation. Another example which could assist to clear this point is land use policy. The construction of new spaces in urban peripheries and increasing city size is considered as an external transformation, while reusing abundant lands inside the city, urban densification, or old buildings refurbishment are considered internal evolution. The presence of different building styles in a city also shows this internal transform progression.

2.6. Conclusion (Part A)

The first part, which was more theoretical, has attempted to establish the idea that cities are complex adaptive systems. With this approach, one might clarify unsolved urban problems in different fields. As the main focus of the following research is the relationship between urban morphology and energy sustainability, city form and its relation to energy consumption is discussed further while now regarding the city as a single complex adaptive entity.

3. Energy performances of the city as a single complex entity (Part B)

In regards to the energy performances of city as a single complex entity and the impact of urban morphological changes on city energy performances, buildings play the agent role while the neighborhood is seen as complex adaptive system. Through this view point, the impacts of urban morphology on building`s solar gaining, thermo-behavior and natural ventilation can be analyzed.

3.1. Electrical Energy Consumption

In the valuable research performed by E. Morello [5], electrical energy consumption has been investigated in an imaginary neighborhood comprised of nine blocks based in Milan, Italy. According to his theory, the urban morphology impact on heat loss is negligible and this loss is almost independent of urban morphology, while lighting and solar gaining have a direct correlation with urban morphology. Solar gaining has an inverse relation with electrical energy consumption and furthermore with urban density. Specifically, electrical energy consumption rate is higher in more dense areas rather than less dense zones.

This mathematically achieved statement could provoke controversial debates between him and compact city idea supporters. Solely under the assumption that electrical energy is used for illumination purposes would the prior statement have been acceptable as a sensible conclusion.

Due to complexity of urban morphology impacts on energy consumption and numerous parameters involvement, engineers and designers must simplify the problem through consideration of many various parameters as constant values. This simplification paves the way to analyze the system in a simple way, but over simplification can lead to inaccurate results. It can be observed, due to CAS complexity that the final system emergence is difficult to anticipate. In addition, heat loss is dependent upon the city form, and urban morphology has a magnitude of impact on heat loss of single buildings as well as electrical energy consumption. In order to further clarify the subject, in the following section, urban morphology impacts on heat loss are investigated.

This research has been cited here for two reasons. First, it proves urban morphological impacts on overall city energy consumption rate, and dislike majority of researches, it considers the neighbourhood as a single entity for its energy consumption calculation. Secondly, it shows that the city is a complex system and must be studied with inclusion of its complexity if more accurate results are to be obtained.

3.2. Heat loss

In separate research performed by the SENSEable lab of MIT, Carlo Ratti et al. [6] investigated energy consumption relations to urban morphology via comparing three different urban fabrics: London, Toulouse, and Berlin. Ratti's research emphasizes the lighting results of Morello; nevertheless, his outcome shows the urban form impact on heat loss. This result is more accurate due to the involvement of more parameters within the hypothesis. As mentioned before, in the CAS, the involvement of more parameters provides a more complex and difficult analysis to deal with but the results are more accurate and realistic.

According to these case studies performed by Ratti [6], saving energy by gaining solar radiation during the summer will cause greater heat loss in winter time. The question is which one, summer solar gaining or winter heat losing, is privilege in urban energy balance? Does saving energy cost in summer time compensate heat loss cost in winter time? And according to Ratti, "Which of the two phenomena prevails in the global budget of buildings? The above question is not likely to have an absolute answer. At very high latitudes, where solar gains are scarce and temperatures harsh all year long, heat conservation strategies might well be prevalent over the collection of daylight and natural ventilation. In these cases energy efficient buildings should probably minimize the external envelope, while at low latitudes they might try to maximize them." [6] Ultimately it is highlighted that the relative importance of heat loss and solar gain is climate and locally dependent. In the other words, due to the dynamic and adaptive nature of agents in order to reach sustainable morphology, there are no certain rules to implement in all cases. The sustainable form of each city would be different due to variation of climate, location, energy prices, availability of energy recourses and even cultures, as different cultures invoke different people behavior and different energy life styles.

3.3. Natural Ventilation

Urban morphology has great impact on air flow, or wind, through the city. Natural ventilation of a single building, apart from building typology and design, is highly related to the wind speed and wind flow in the city. In other words, a single building as an agent in a CAS can save energy by using natural ventilation when each building has a role in wind flow of the city on a bigger scale; this is the exact definition of CAS. Specifically, like all complex adaptive systems, in order to optimize natural ventilation benefits one must deal with this matter on a micro scale (building typology) and macro scale (urban morphology). Luc Adolphe [7] carried out a research about the urban morphology impact of airflow through cities. In the research, the city was considered as a single porous volume, while single agents' role (buildings) emerges from three main indicators. These indicators are Rogusity, which is the wind speed alteration indicator in the city volume, Sinusity, as city volume resistance to wind flow indicator, and finally Porosity, ratio between open space volume and build-up volume.

Wind flow analysis in city of Toulouse, before and after the Haussmannian cut through the medieval city fabric, is the case study under investigation, shown in Fig.1 [7]. After the Haussmannian operation, which was the creation of the boulevard through the urban fabric, city density had reduced by about 10 percent, while rugosity had dropped 8%; meanwhile porosity increased as a consequence of density reduction. In simple words, this operation led more air flow through the city in certain directions. In this case a less dense urban fabric has more air flow than a more dense urban tissue. It is wise to sensitize the hypothesis of E.Morello, which stated that city density has a direct impact on electrical energy consumption. In other words, less density helps to save more electrical energy.

To reiterate, lighting, heat loss, people behavior, and wind flow within a less dense city shows an increase in efficiency in comparison to the dense city context. A great contrast is presented between these results and what compact European cities are performing. A number of European cities are energy efficient and sustainable due to their compactness. Therefore the newly risen question will be why there is such a great difference between these results and some European cities. The answer could be found in the nature of complex adaptive system. As mentioned before, within CAS, behavioral anticipation is delicate and difficult to anticipate.

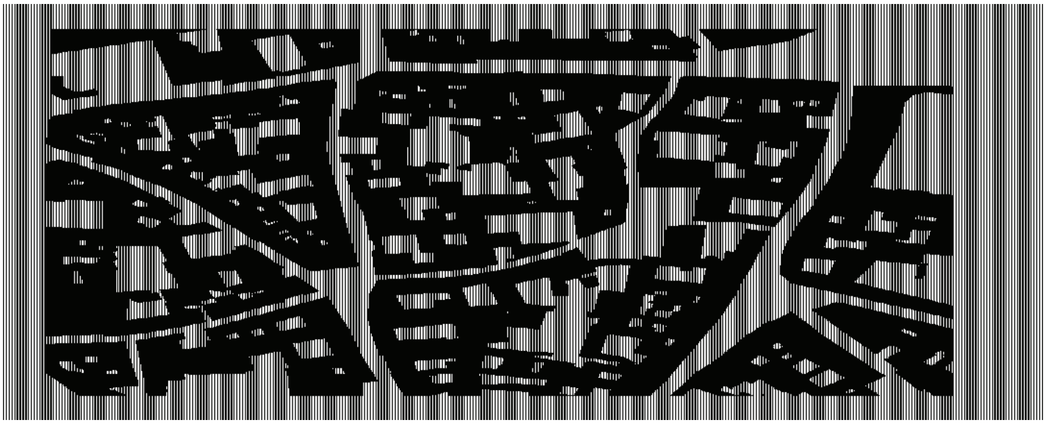

Fig. 1. (a) Mediaeval Toulouse before Haussmannian operation; (b) Toulouse after Haussmannian operation[7]

In addition to this fact, simplification of the problem could lead to unrealistic results. In order to clarify the point, the mentioned examples about energy consumption of cities are focusing just on one aspect of urban energy performance such as solar gaining, heat loss or ventilation, while the energy problem of cities is more complicated. In the examples, there are more neglected elements which play the role in the cities' energy consumption rate. In other words, over-simplification could lead to inaccurate results; therefore, simulation of complexity is recommended rather than simplification of it.

The city as CAS is comprised of many subsystems and links. Despite the prior cited researches, some European compact cities have better performances due to the interaction of the otherr subsystem within the CAS which haven't been seen in these examples. In European cases, another subsystem namely the efficient transportation network compensates other energy losses.

3.4. Conclusion (Part B)

First, it can be observed that energy consumption of the city is no the sum of all its building`s consumption, and urban energy efficiency is not confined in a single building scale for energy performance [3]. Second, any minor changes in the existing urban fabric will emerge in the entire final system performance due to CAS behavior of the city. As seen (Fig.1), the simple addition of a street can cause great impact in natural ventilation of the buildings in the city. The next question is how to design a single element in to the city context in order to help the sustainability of its neighborhood as well as the entire system.

4. Example for Exiample (Part C)

The following is a simplified case study based on an urban design workshop[a] held in Barcelona, Spain. This design workshop's main concern was devoted to quality enhancement of space and energy performances within two residential blocks of the Barcelona Exiample. It consisted of refurbishing

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[a] Recycling Urban Landscapes workshop, *Universitat Autonoma de Barcelona, Politecnico di Milano*, Barcelon, Spain, April 2011

courtyard spaces and connecting them to the urban green open space network (open space subsystem).

Additionally, enhancing energy performances of the entire blocks was on request along with a project demand to design new residential flats. The superficial energy performances of a building in the Exiample block was revealed through investigations carried out during the study phase. Usage of poor constructional technology and location, which had caused building exposure to unwelcomed west solar radiation, had soared energy demands of old building, particularly in summer time (Fig. 2a). To deal with this problem, in the most sustainable way, a new residential building location was proposed to be placed right next to the old existing building (Fig. 2b). The presence of a new building adjacent to the old building prevented the unwelcomed solar radiation incident from the west side without future costly isolation treatment. In the other words, not only had requested residential spaces been provided, but also the new residential building helped the old one to consume less energy for cooling systems in summer time.

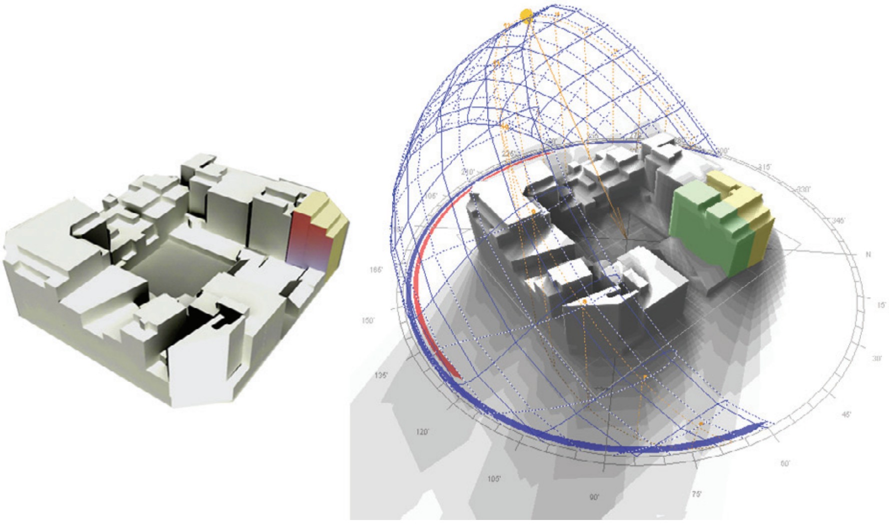

Fig. 2. (a) old residential building with maximum heat gain on lateral side, indicated in red. (b) new residential building highlighted in green, attached to the old yellow block

On the microscopic scale of CAS, one new agent, the new residential building, assists the other existing agent to reach better performances and energy demands, while in the macroscopic scale, installing a new photovoltaic panel on the lateral side of the new agent generates electrical energy for the entire block. These panels also intercept unpleasant solar radiation imposed on the new block as well.

The effect of the new proposed building on the old building is not the entire story. In order to work in a complex system, it is useful to remember other agent`s effects on new buildings as well. However, for the prior case study, due to the presence of shadow from an existing building on the other side of the block, photovoltaic panels had to be placed just on the upper half of the lateral wall. In other word, in the economical point of view, covering the entire lateral wall by solar panels is not a sustainable treatment.

5. Conclusion (Part C and final conclusion)

Trying to find a single sustainable pattern for urban development is not the right way to deal with the energy sustainability problem. Being prejudiced against either the urban sprawl theory or the compactness pattern will not lead to the correct solution. The solution is concealed elsewhere. Sustainable morphological patterns of the cities are derived from the agent's transformation in time. This transformation occurs on two different scales, micro and macro scale, due to agents non-linear interactions. In order to reach sustainable morphological transformation, one must first elucidate sustainable concerns of the building and neighborhood (microscopic) scale. Designing every single building in a way in which each one helps the other one to improve energy performances, is the first step. If this treatment expands to neighborhood scales then sustainable neighborhoods would be emerged in time. The urban morphological sustainable pattern, macroscopic results emerges through microscopic transformation over decades.

This research requires investigation of the effect of the peoples' energy consumption behavior role on urban morphology and urban energy balance. Considering the city as a complex adaptive system is the central premise, and the necessary tool for further research. As mentioned, in the urban field, the complex system must be studied with inclusion of its adaptive complexity if more accurate results are to be obtained; hence, simulation is far preferable to simplification of the complex adaptive system in further researches.

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References

[1] Brownlee J. *Complex Adaptive Systems*. 2007(070302A): p. 6.

[2] Wootton B. *Cities as Complex Adaptive Systems*. Available from: http://www.benjaminwootton.co.uk/.

[3] Morin E. *Introduzione al pensiero complesso.* Milano: Sperling & Kupfer;1993.

[4] Clarke C, Anzalone P. *Architectural Applications of Complex Adaptive Systems.* p.19.

[5] Morello E, Gori V, Balacco C, Ratti C. Sustainable Urban Block Design through Passive Architecture. *26th Conference on Passive and Low Energy Architecture*; 2009, p. 6.

[6] Ratti C, Baker N, Steemers K. *Energy consumption and urban texture*. ELSEVIER;2004,p.16.

[7] Lue A. Modelling the Link Between Built Environmnt and Urban Climate: Toward Simplified Indicators of the City Environment. *Seventh International IBPSA Confrence*; 2001,p.6.