TeMA

Journal of
Land Use, Mobility and Environment

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THE RESILIENCE CITY/THE FRAGILE CITY. METHODS, TOOLS AND BEST PRACTICES

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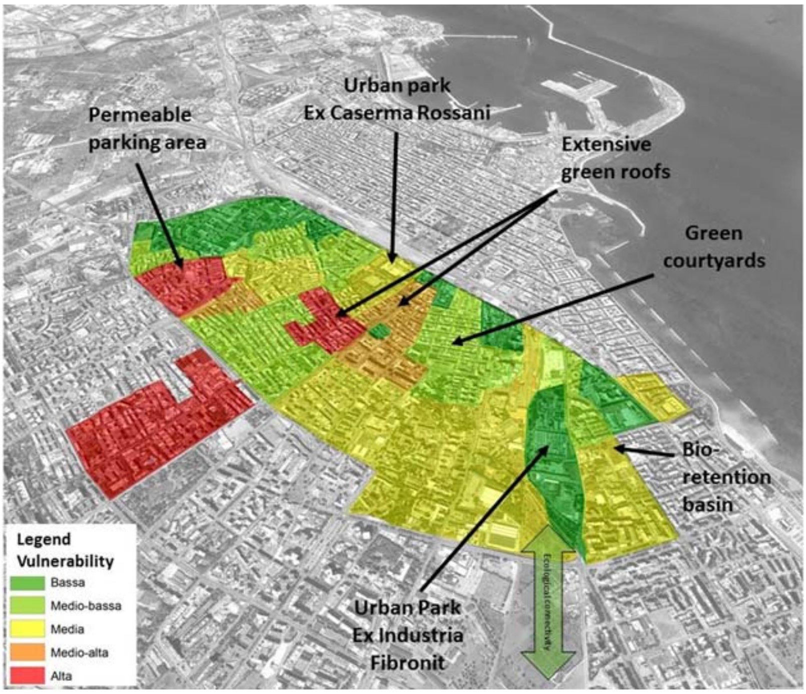

SECOND LAW OF THERMODYNAMICS AND URBAN GREEN INFRASTRUCTURE

A KNOWLEDGE SYNTHESIS TO ADDRESS SPATIAL PLANNING STRATEGIES

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ABSTRACT

Planning strategies driven by the second law of thermodynamics (SLT) are innovative approaches to sustainability but they are still in seminal phase. In this article, a coupled review of SLT within spatial planning is accomplished looking at the main applications in urban green infrastructure (UGI) planning. In particular, a systemic review of UGI planning and thermodynamics has been carried out to identify all the occurrences to date in the scientific literature. Secondly, a scoping review of SLT-related concepts of exergy, entropy and urban metabolism is presented in order to investigate the main applications of, and gaps in, urban spatial planning. Results indicate that UGI and ecosystem service planning based on SLT is a relatively new field of research. Moreover, some general indications are derived for the development of spatial UGI planning strategies based on SLT. The work then aims to contribute to the improvement and/or development of even more solid planning strategies supporting a SLT-conscious green transition of cities.

KEYWORDS:
Entropy; exergy; urban metabolism; urban planning; low-entropy city; ecosystem services

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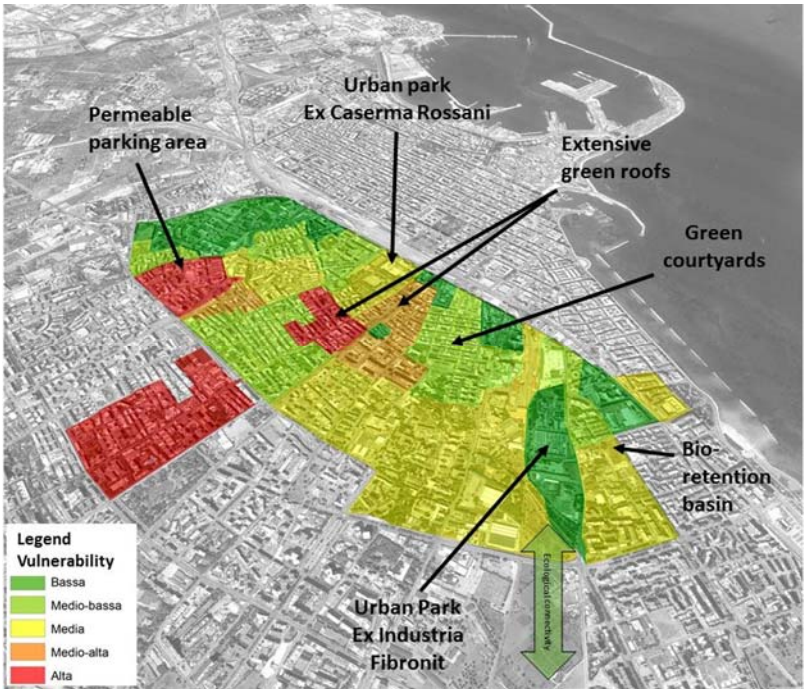

热力学第二定律和城市绿色基础设施

解决空间规划策略的知识综述

摘要

受热力学第二定律（SLT）启发的计划策略，是实现可持续发展的一种创新方法，尽管目前仍处于开创阶段。在本文中，对空间规划中的 SLT 进行了一次综合评估，并着眼于在城市绿色基础设施（UGI）规划中的主要应用。特别是对 UGI 规划和热力学进行了系统评估，旨在确定科学文献中的所有情况。其次，为了调查城市空间规划的主要应用和差距，对炯、熵和城市代谢的 SLT 相关概念范围进行了梳理。结果表明，基于 SLT 的 UGI 和生态系统服务规划是一个相对较新的研究领域。此外，基于 SLT 的空间 UGI 规划策略发展取得了一些进展。该工作旨在帮助改善和/或制定更加稳固的规划战略，为城市的 SLT 意识到的绿色过渡提供支持。

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关键词:
熵、炯、城市代谢、城市规划、低熵城市、生态系统服务

1 INTRODUCTION

City sustainability is a multifaceted task that entails non-linear processes and system complexity on different spatial scales and with a long-term view. Moreover looking at sustainable development, the evaluations should involve transdisciplinary research dealing with the interactions between natural and social systems in order to meet the needs of present and future generations while substantially reducing poverty and conserving the planet's life support systems in changing climatic conditions (Kates et al., 2012). Several urban planning and governance strategies have been developed to reach sustainability objectives giving social, economic and environmental aspects different weight. Moreover, designers and architects have embraced different sustainability criteria in their urban projects. The current approaches to sustainable urban development are therefore multiple and complex while the relevant issues are intertwined (Hassan & Lee, 2015). Thus, we should select the proper direction for future city development, but also define strong grounds on which to base our moves to avoid expensive and/or late re-thinking. The thermodynamics of open systems, with the Second Law of Thermodynamics (SLT) in particular, is one of the most solid disciplines for the study of complex systems and several applications of it have emerged in social, ecological and economic disciplines (see Pelorosso, Gobattoni, and Leone 2017).

Following the SLT, cities are metabolic far-from equilibrium systems, which utilize energy and matter flows to maintain levels of complexity, organization, and functionality releasing entropy (disorder or waste) into the environment (Fath, 2017). In pursuit of diverse objectives, humans modify land use and the socio-ecological and technical infrastructures which regulate urban energy and matter metabolisms. In a sustainable and systemic SLT view of the urban metabolism processes, exergy (or work capacity) should be maximised and entropy discharges reduced (Pelorosso, Gobattoni, & Leone, 2017). The concepts of entropy, exergy and urban metabolism (UM) are therefore strictly linked to the SLT and several applications of them are present in scientific literature as well as in sustainable urban planning and design (Bristow & Kennedy, 2015; Leone, Gobattoni, & Pelorosso, 2016).

Urban sustainability can be augmented integrating Nature and ecosystems with the urban metabolism and the socio-economic activities. The fundamental functions of natural systems that support citizen life are mainly provided by the Urban Green Infrastructure (UGI). Indeed, UGI is defined as an interconnected network of natural systems and Nature-Based Solutions (NBSs), localised at landscape scale and fully integrated with the built environment, which provides a diversified array of Urban Ecosystem Services (UESs) to the urban socio-ecological system, thus increasing its resilience. NBSs are engineered green/ecological systems inspired or supported by, or copied from, Nature (EU, 2015). UESs are benefits that people derive directly or indirectly from natural and managed ecosystems (Pelorosso, Gobattoni, & Leone, 2017). Thus, UGI planning aims to enhance the sustainability and resilience of urban systems. Recently, Pelorosso, Gobattoni, and Leone (2017) have presented a seminal low-entropy UGI strategy which incorporates social and ecological aspects and new operational entropy indicators into an adaptive SLT planning framework (see fig. 1). The low-entropy city concept at the basis of the UGI planning strategy calls for innovation and more efficient urban systems, from compacted to sprawled, with a stronger nature integration, able to use local and renewable resources, to reuse wastes and to institute closed productive cycles. These new urban socio-ecological systems, by maximizing cyclic, non-dissipative flows while minimizing dissipative flows, would release less entropy out of the system and, like a complex living organism that tends to minimum entropy production (e.g. the more healthy, mature forests at later stages of succession), they would persist and even grow in an even more sustainable manner. The low-entropy city concept represents a first contribute to the development of a new systemic urban planning paradigm in which nature of, for and in the city converges together under a thermodynamics vision of which social domain can be considered a part (Pelorosso, Gobattoni, & Leone, 2017). In the low-entropy view, NBS will be then studied, planned and designed looking at their localisation and spatial distribution, the increased internal socio-ecological complexity (e.g. creation of a network of people, new enterprises, added biodiversity), the importation of external sources of energy (e.g. for cooling systems as well as for crime control) and exportation/creation of entropy outside the urban system by wastes (e.g. pollution, runoff), to build Nature-Based Low-Entropy cities. The general low-entropy UGI strategy needs to be translated in real study cases with its embedded SLT principles (related to the concepts of entropy, exergy and urban metabolism) adopted in urban assessment and NBS planning. It is necessary therefore to know the main applications of, and gaps in, SLT planning with particular reference to urban systems and UGI in order to make the low-entropy concept operative. Despite numerous studies on thermodynamics, very little attention has been paid to SLT planning of UGI (Pelorosso, Gobattoni, & Leone, 2017). The objective of this article is then to provide essential information for the improvement/development of sustainable UGI planning strategies based on thermodynamic concepts and the low-entropy view. We adopted a coupled and sequential revision procedure to select the most significant papers and study cases able to inform UGI planning. A first preliminary systemic review has been carried out on scientific databases to select and investigate all the literature having explicit references to UGI and SLT planning within the title, keyword and abstract fields. Secondly, a scoping review was conducted to depth the knowledge on SLT planning even to cases not directly linked to UGI and not reported in scientific database. In particular, we sought for explicit spatial analyses with real study cases, which could facilitate the task of applying the research results to guide practical decision-support within planning processes. Indeed, explicit evidence of spatial anisotropies of land uses and indicators allow scenarios and urban projects to be designed considering the complex relationships among UGI components and urban systems (Pelorosso, Gobattoni, Geri, & Leone, 2017). The paper then provides evidence about the state of art of UGI and SLT indicating the main steps for the inclusion of thermodynamic concepts into UGI planning.

2 MATERIAL AND METHODS

To point out the links between SLT and UGI planning, a preliminary systemic review based on peer-reviewed papers or book chapters on the Scopus (http://scopus.com) and ISI Web of Knowledge (WoK) databases (https://webofknowledge.com) has been performed. A combination of terms was used to capture all the possible scientific products with ongoing research within the title, keyword and abstract fields. In particular, the search engines were used to explore the use of the terms thermodynamics, green, infrastructure, urban and planning (see the queries reported in Table 1). We then verified the relevance of the selected dataset with thermodynamics and real study cases of spatial UGI planning. Additionally, a second review framework, concentrated efforts on the most relevant SLT concepts related with urban planning and the sustainability of cities and landscapes. Thus, the use of exergy, entropy and urban metabolism concepts within planning has been investigated even though UGI were not considered directly. Since the scientific literature on these three research fields is abundant and diversified, a scoping review (Arksey & O'Malley, 2005) was carried out to build a knowledge synthesis regarding the following research question: what are the main applications of, and gaps in, SLT related concepts (exergy, entropy and urban metabolism) within spatial planning with particular reference to urban systems and UGI? The scoping review was carried out by Google Scholar search engine in order to widen the sample even to literature not included in scientific databases. Google Scholar was then used to search for published papers and books following the individual terms exergy, entropy and urban metabolism in an iterative process engaging with each stage in a reflexive way, repeating search steps in order to ensure a comprehensive coverage of the literature (Arksey & O'Malley, 2005). References reported in the papers identified were also checked following the same search engine. We focused in particular on the most recent literature in order to report significant update information.

The majority of the publications found were thus filtered out, taking into account only the most recent scientific products reporting spatially explicit quantifications, prioritizing works with practical applicability for urban planning.

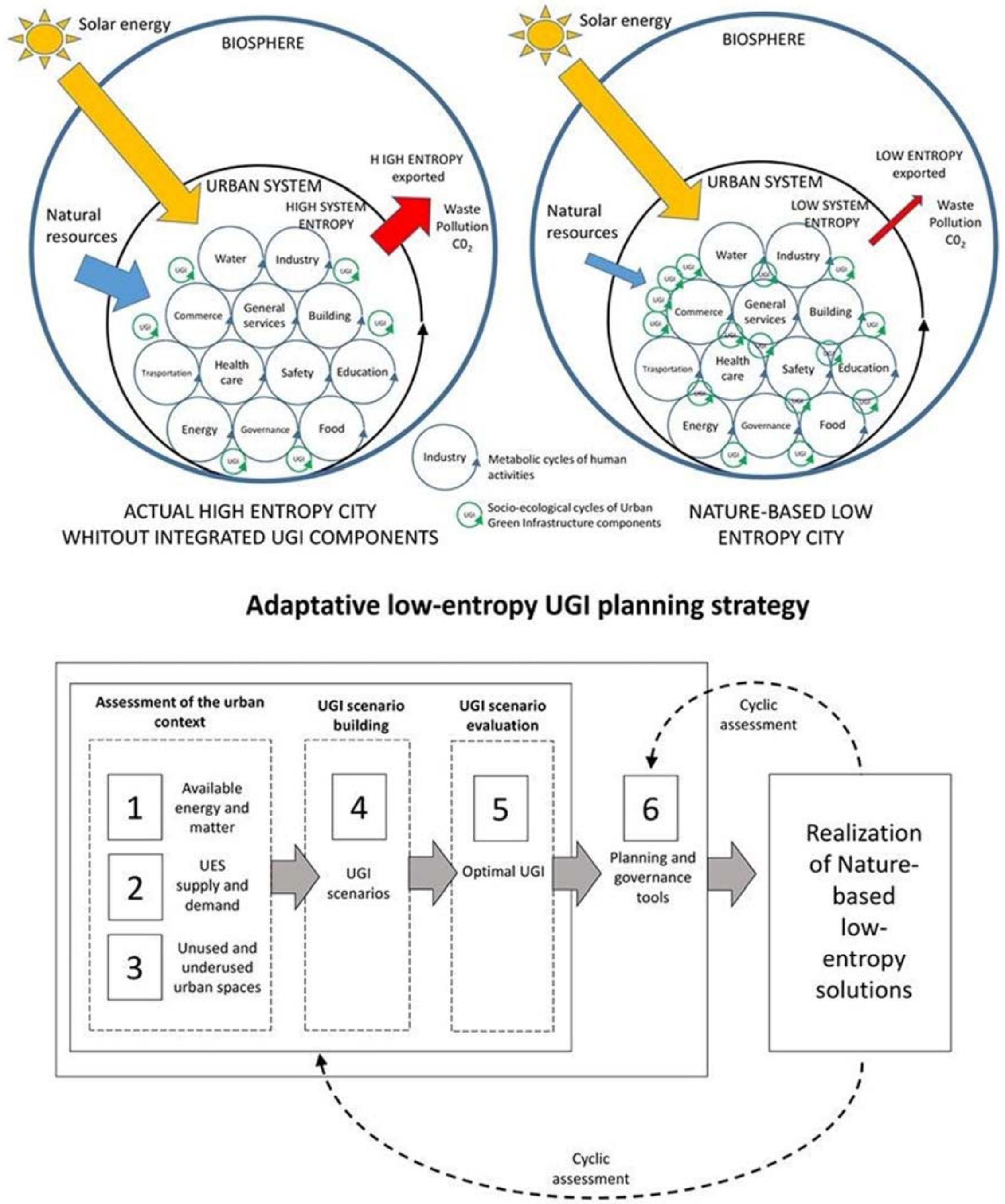

Fig. 1 Actual city without integrated UGI components compared with a theoretical nature-based low-entropy city with multifunctional UGI (top). The Conceptual framework of the adaptive low- entropy UGI planning strategy (bottom)

3 RESULTS AND DISCUSSION

3.1 THE SYSTEMIC REVIEW

The systemic review on UGI planning and SLT has brought to light few occurrences within scientific products for significant terms. In particular, no result was found considering UGI planning in urban contexts related to Thermodynamics (see queries 6 and 7, Table 1). Considering combinations of terms, the search provided a total number of 77 papers. Then, excluding overlaps between the two datasets, we kept 66 papers (see appendix A). Amongst the 66 works selected, only one paper presented an interesting application for spatial urban planning, though it does not explicitly consider SLT (He, Shen, Miao, Dou, & Zhang, 2015). The work deals with the urban climate of Beijing and proposes to use the synergy between the urban-induced heat island circulation and green-wedge planning to deliver cool/fresh air from the suburbs to downtown Beijing (He et al., 2015). In particular, the paper proposes a novel numerical-simulation-based method for detecting fresh-air ventilation paths quantitatively by taking into account both dynamic and thermodynamic aspects. The work analyses mountain-valley breezes using hourly weather station observations and puts them in relation with the built environment and the green infrastructure. Finally, a series of key planning recommendations (i.e. mitigation measures and climatic spatial planning guidelines) are presented for improving the urban climatic conditions of five planning zones proposed with reference to the Beijing city master plan. The final product of the analyses is then an urban climatic map which includes essential spatial information for planning land uses and UGI from the urban climatic perspective (Fig. 2). The final urban climatic map represents an eloquent visual tool, able to translate complex modelling studies in information useful for planners and practitioners. However, it should be noted that explicit references to ecosystem services (even climate regulation services) provided by UGI are not present in the paper, demonstrating that a full integration among urban ecology concepts and physical urban planning is still lacking. Moreover, entropy, exergy, urban metabolism and SLT are concepts not included in the study.

Although explicit references between UGI planning and SLT are not present in large part of literature, many urban ecology and design studies are founded on physically-based methods and models that rely on physical laws such as Thermodynamics (e.g. climate or energy modelling studies) (e.g. Ambrosini et al. 2014 and Fig. 3). These works deal with the simulation of green scenarios aimed at mitigating the urban heat island effect or heat waves and, in general, to enhance the thermal comfort of urban environments, reducing the energy demands of buildings and, consequently, carbon emissions. The simulations are conducted at different scales but usually they pursue design objectives while large spatial planning applications are rare and conducted at a coarse resolution. Indeed, these modelling approaches still have the drawback of high computational cost and complexity, so their use is often limited to research purposes or/and transdisciplinary collaborations among experts and planners. However, from a technical point of view, the evolution of the modelling approach is ineluctable considering also the increasing pc calculation power and availability of free (and open) software as well as digital information (i.e. big data, spatial data). The main issue appears to be the difficulty of adopting these modelling approaches within urban planning practice, considering the complexity of the model simulations (i.e. cost-effectiveness) with respect to the planning process needs (Gobattoni, Pelorosso, Galli, Ripa, & Leone, 2017).

Searched terms	Occurrences	
	Scopus	ISI
Q1:"green" AND "thermodynamic/s" AND "urban"	39	9
Q2: "green" AND "thermodynamic/s" AND "planning"	25	8
Q3: "green" AND "infrastructure/s" AND "thermodynamic/s"	7	3
Q4: "green" AND "thermodynamic/s" AND "urban" AND "planning"	9	0
Q5: "green" AND "infrastructure/s" AND "thermodynamic/s" AND "urban	3	0
Q6: "green" AND "infrastructure/s" AND "thermodynamic/s" AND "planning"	0	0
Q7: "green" AND "infrastructure/s" AND "thermodynamic/s" AND "urban" AND "planning"	0	0
Total occurrences	59	18

Tab.1 Results from queries on SCOPUS and ISI Web of Knowledge (ISI WoK) (period: up to 25/01/2017)

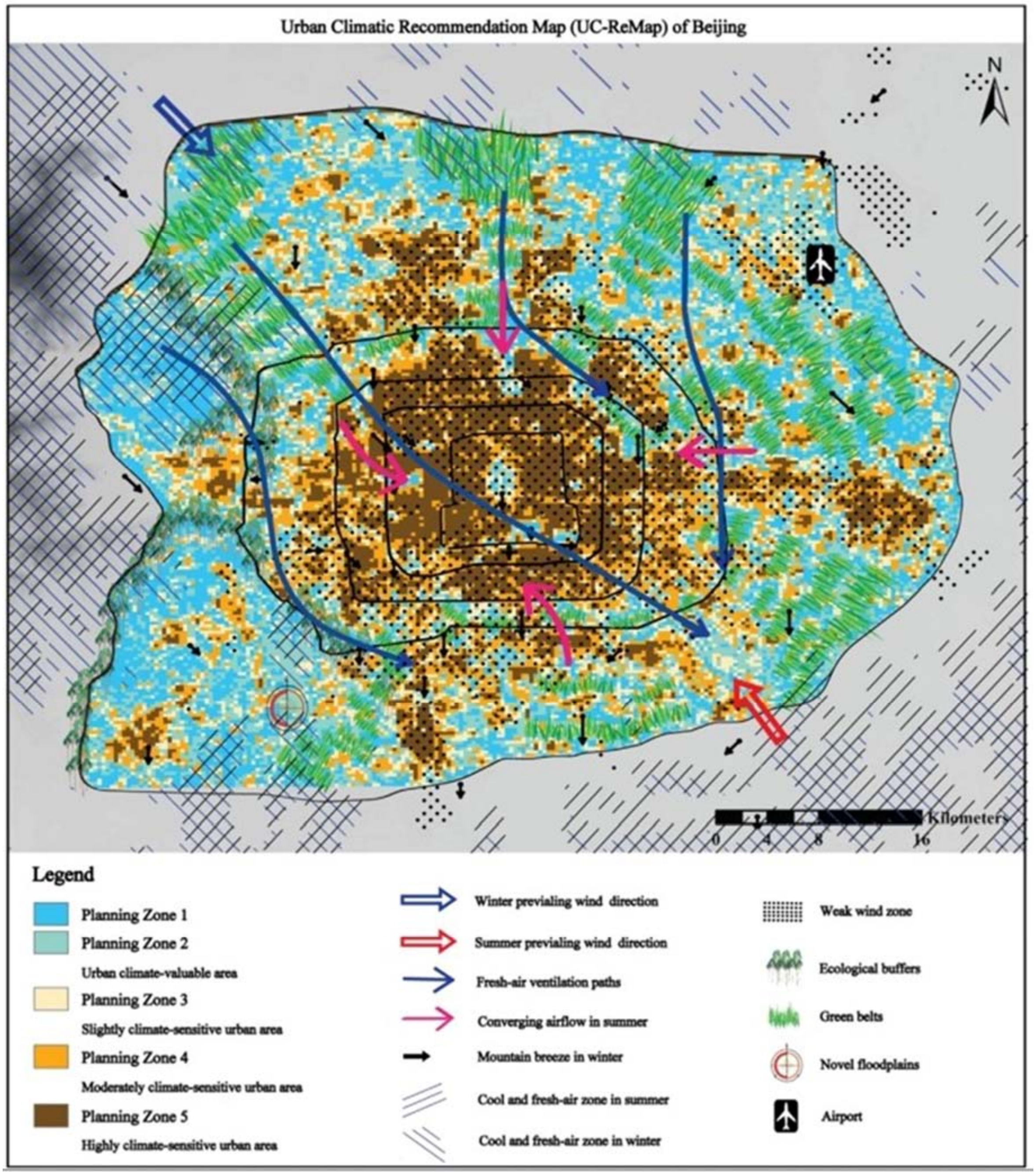

Fig. 2. Urban climatic map of Beijing

3.1 THE SCOPING REVIEW

Since few occurrences within scientific products emerged from the preliminary systemic review on UGI and SLT, a second review has been conducted in order to deep the knowledge relatively to SLT applications within spatial planning. This second review was then focused on three fundamental SLT concepts, namely exergy, entropy and urban metabolism highlighting, when possible, the planning implication for the urban systems and UGI. Table 2 reports a summary of the selected papers on SLT concepts and their field of application within spatial planning. The selected planning examples of Table 2 thus represent the state-of-art for further research developments and their applications in real case study are instances of SLT spatial planning.

	Definition	References	Field of application
Exergy	The maximum amount of work a system can perform when it is brought to the thermodynamic equilibrium with its environment. It represents the useful energy or work capacity embodied in the system (Stremke & Koh, 2011).	(Stremke & Koh, 2011; Stremke & Van den Dobbelsteen, 2013)	Renewable resources and sustainable energy landscapes. Several study cases of exergetic optimization in The Netherlands.
		(Leone, Gobattoni, & Pelorosso, 2016)	Exergetic optimization of a Mediterranean rural area. Foggia, Apulia Region, Italy.
		(Leduc & Van Kann, 2013)	Sustainable urban energy planning. Kerkrade-West neighbourhood, The Netherlands.
		(Balocco, Papeschi, Grazzini, & Basosi, 2004)	Sustainability of built up areas. Castel-nuovo Berardenga, Siena Province, Italy.
Entropy	A measure of the state of disorder of a system (Stremke & Koh, 2011). It is related to the dissipated energy (waste) during natural irreversible processes that trasform energy, move mass and drive the global biogeo-chemical cycles (Kleidon, 2009).	(Balocco & Grazzini, 2000)	Sustainability of urban areas in terms of energy. Florence, Italy.
		(Fistola & La Rocca, 2014)	Urban entropy assessment. Benevento, Italy.
Urban metabolism	The sum total of the technical and socio-economic processes that occur in cities, resulting in growth, production of energy, and elimination of waste (Kennedy, Cuddihy, & Engel-yan, 2007)	(Chrysoulakis et al., 2013)	Sustainability of urban planning interventions. Helsinki, Athens, London, Florence and Gliwice.
		(Codoban & Kennedy, 2008)	Design of sustainable neighbourhoods. Toronto, Canada.
		(Pincetl et al., 2014)	Urban environmental sustainability. Los Angeles, California

Tab.2 Spatial planning and second law of Thermodynamics: relevant applications of SLT concepts and study cases from scoping review

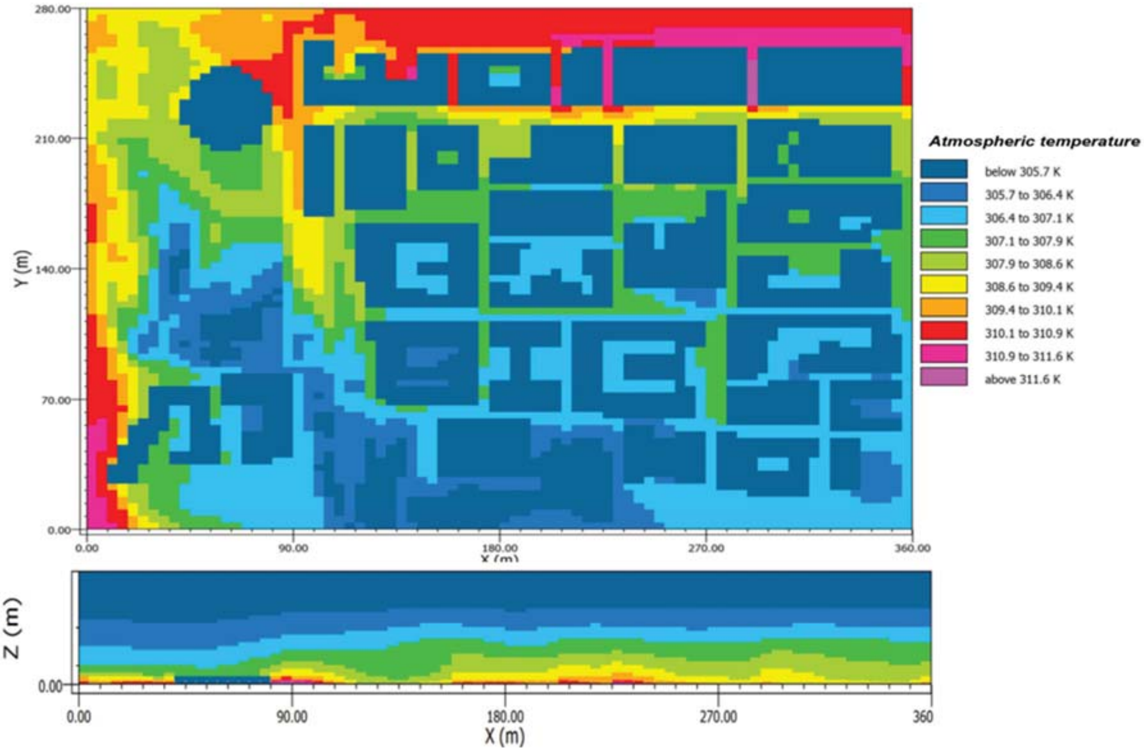

Fig. 3. Atmospheric temperature in a green scenario simulated with ENVI-met model, historical city center of Teramo, Italy

Exergy and urban spatial planning

From the consulted literature it emerged that exergy studies analyse mainly the energy aspect of cities and landscapes without specific interest in UGI spatial planning. The exergy assessment and SLT planning approach have been presented in the context of renewable resources and sustainable energy landscapes (Stremke & Koh, 2011; Stremke & Van den Dobbelsteen, 2013; Stremke, Van den Dobbelsteen, & Koh, 2011). The SLT planning approach aims to increase the exergy component of any process and, consequently, to reduce the production of pollutants (entropy) responsible for the alteration of ecosystem ecological functionality (e.g. climate change, freshwater degradation etc.). In general, the study cases on SLT planning based on exergy evaluations demonstrate how it is possible to evaluate the energy incidental to each land-use, obtaining significant productions, and increasing system resilience. Indeed, a conscious spatio-temporal organisation of the landscape based on the SLT, local renewable resources and smart energy systems increases the ratio of energy self-sufficiency and the resilience of the socio-ecological system. It allows local populations to have a greater capacity to persist and develop in the territory to which they belong through the mitigation of the negative effects derived from the fluctuations of the energy availabilities external to the system both on the productive processes and on the essential vital activities. SLT landscape planning studies have been conducted mainly in North Europe where SLT was firstly developed but the approach is attracting even more international interest. Worthy of note is the exemplificative SLT application in a Mediterranean rural area of Apulia Region (Italy) aimed at respecting landscape identity integrating traditional agricultural productions with a local industrial district and a residential area (Fig. 4) (Leone, Gobattoni, & Pelorosso, 2016).

Exergy analysis is also proposed in urban contexts. Two papers have been selected as exemplificative exergy applications because they aim to evaluate the sustainability of urban areas (Balocco et al., 2004) and guide spatial urban planning (Leduc & Van Kann, 2013).

Balocco et al. (2004) report an extended exergy analysis method in a small municipality of Central Italy, taking into account the mean life time cycle of building, to evaluate the sustainability of an urban area in terms of gas emissions. Two thermodynamic indexes, η_I and η_{II} showing, respectively, the first and second law efficiency of buildings, have been proposed as thermodynamic indexes. The applied methodology provides a single thermodynamics environmental criterion for the selection of technological alternatives, strategies and designs that produce lower environmental impacts connected to higher exergy indexes η_{II} . The method appears innovative, but difficult to apply to spatial urban planning in practice, due to its high data requirements at local scale. Moreover, it needs to be further developed for other urban issues and specific green area assessments have not been considered.

The work of Leduc & Van Kann (2013) proposes using the Urban Harvest Approach (UHA) to reach a circular urban metabolism in terms of exergy. The UHA can be defined as a strategy to investigate possible options for harvesting local resources, such as materials, water, space, energy, and for transforming these resources so that they can be used efficiently and effectively, limiting waste or output both into and out of urban regions. The proposed UHA is based on the integration of different urban functions, multifunctionality, harvesting of local renewable and residual resources at regional scale (see Fig. 5). The method described in this paper combines exergy analysis with spatial planning to test the sustainability of urban areas, including industrial areas, and proposes new productive functions. The UHA method is tested in Kerkrade-West, a neighbourhood of the municipality of Kerkrade in the province of Limburg, in the south of The Netherlands. The municipality of Kerkrade is part of a region where coal mining took place for centuries. Kerkrade-West has almost 16,000 inhabitants in an area of around 1000 ha. The proposed final strategy aims to increase the multi-functionality and resilience of Kerkrade-West, by filling exergetic gaps and by creating additional energetic synergies: e.g., adding a brewery to make good use of remaining energy potentials, and to create new jobs. Thus, the proposed spatial strategy constitutes the base for successive urban design aimed at building a multifunctional urban fabric with short connections between functions to make optimal use of the remaining residual energy flows and to apply heat cascading. The UHA proposed by the authors shows interesting aspects for spatial planning, but further application to study cases considering different contexts (e.g. compact cities), green scenarios and characteristics (e.g. water and matter fluxes, ecosystem services) should be realised. Indeed, specific gaps and constrictions (also at governance level) need to be identified to make the proposed UHA fully operative in UGI spatial planning.

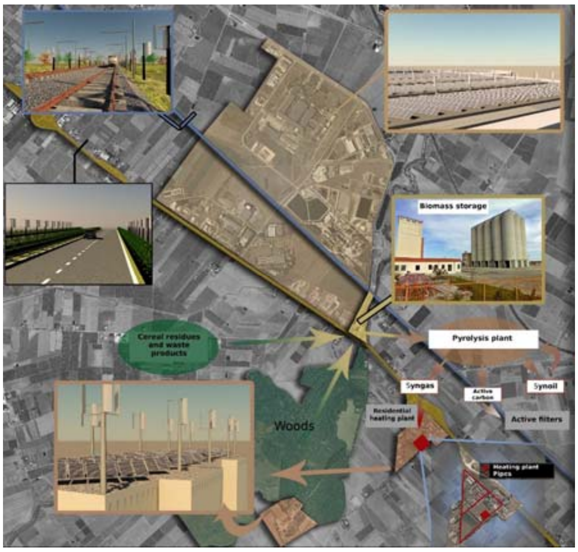

Fig.4 Scenario of exergetic landscape optimization by local renewable energies

Entropy and urban spatial planning

Despite numerous studies, only a limited number of papers present useful methods based on urban entropy aimed at supporting practical urban planning (Pelorosso, Gobattoni, & Leone, 2017). Indeed, entropy is a complex task that needs to be studied at different scales of analysis taking into consideration various urban system components such as energy, water, social aspects, waste cycles, etc. Few applications of the entropy concept have been presented in a context of spatial urban planning. The two most noteworthy ones are described below.

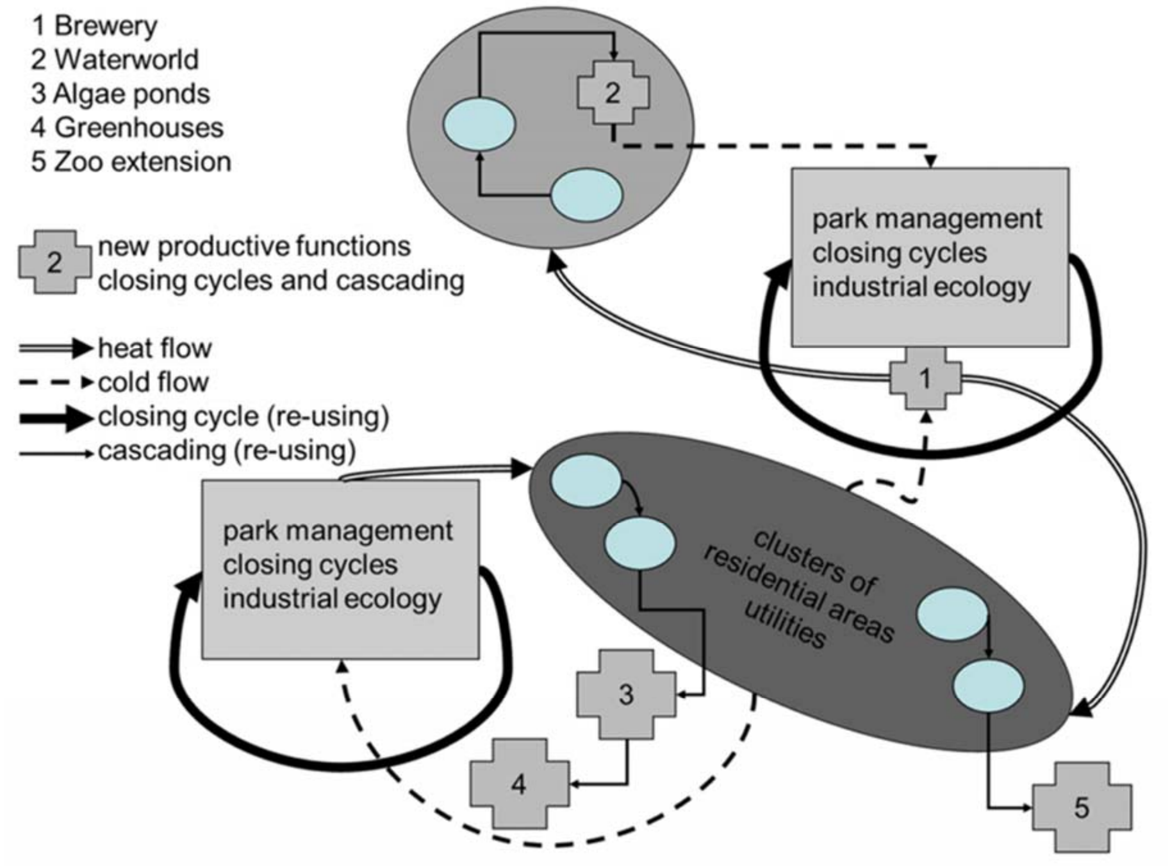

Fig. 5 Spatial energy strategy for productive urban regions

Balocco and Grazzini (2000) propose GIS and entropy indicators to study the sustainability of urban areas in terms of energy. The paper provides some indicators useful for measuring the energy sustainability of urban areas and defining planning criteria starting from an energy balance of a reference volume obtained in GIS by superimposing a grid mesh (200m x 200 m) on the built-up area under study. The work is based on the concept that real sustainability can only be obtained if total irreversible entropy is lower than the negentropy flux from the sun. A first entropy indicator is presented as the ratio between the entropy variation due to the total energy losses of buildings and the entropy variation due to the solar energy gain. The authors assert that a reduction of this indicator is necessary to reach sustainability. Moreover, another thermodynamic indicator is presented to take into account the entropy generated by building heating which considers the different sources of energy (i.e. fossil fuels or renewable sources). Even if not directly applicable to planning and evaluating the impacts and effects of green urban areas, the two thermodynamic parameters, expressed using the second law of thermodynamics, can be useful to analyse and design different sustainable urban energy scenarios. The proposed indicators are not closely connected to energy quality; nonetheless, they could be useful for analysing different energy efficiency scenarios at a defined reference scale. The definition of the assessment scale is a relevant issue for this entropy evaluation method. Indeed, urban planning requires high spatial resolution of information and reducing the mesh size of grid, the proposed entropy assessment could be not cost-effective in supporting localised interventions planning.

Fistola and La Rocca (2014) propose a different approach to urban entropy assessment within system theory and urban planning, by applying reversed sustainability indices as proxies of urban entropy. The research thesis speculates on the possibility of defining indicators of urban entropy acting in reverse: sustainability is a positive state and it is evaluated by "positive indicators" while entropy is measured by parameters describing negative states or having negative impacts on urban systems. The assessment method has been applied to the ancient part of the city of Benevento, subdivided into 59 census tracts and 572 buildings. Thematic maps and analyses were carried out by using GIS technology considering five main urban subsystems: anthropic, functional, physical, psycho-perceptive and geomorphologic sub-systems. The five sub-systems are described by a static and a dynamic component (see tab. 3) that when properly balanced indicate that a city is in a sustainable dynamic state. For each sub-system several indicators of sustainability have been identified as proxies of entropy and a composite entropy indicator has been mapped to guide urban planning (Fig. 6). The map of the composite urban entropy indicator showing the spatial distribution of critical areas was developed to support planning choices aimed at reducing specific and local sources of urban entropy. Thus the work of Fistola and La Rocca (2014), developed for urban planning aims, appears operative in the spatial planning of cities, but needs further research to confirm the usefulness of the proposed indicators in relation to thermodynamic principles which would allow a stronger theoretical foundation to be developed.

Sub-system	Static component	Dynamic component
Physical	Adapted spaces	Physical channels of communication (streets, networks, mains, etc.)
Functional	Urban activities	Communications
Anthropic	Players	Interactions
Psycho-perceptive	Images	Interpretations
Geomorphologic	Territorial areas	Connections (physical networks of interconnection)

Tab.3 Static and dynamic characters of urban sub-systems

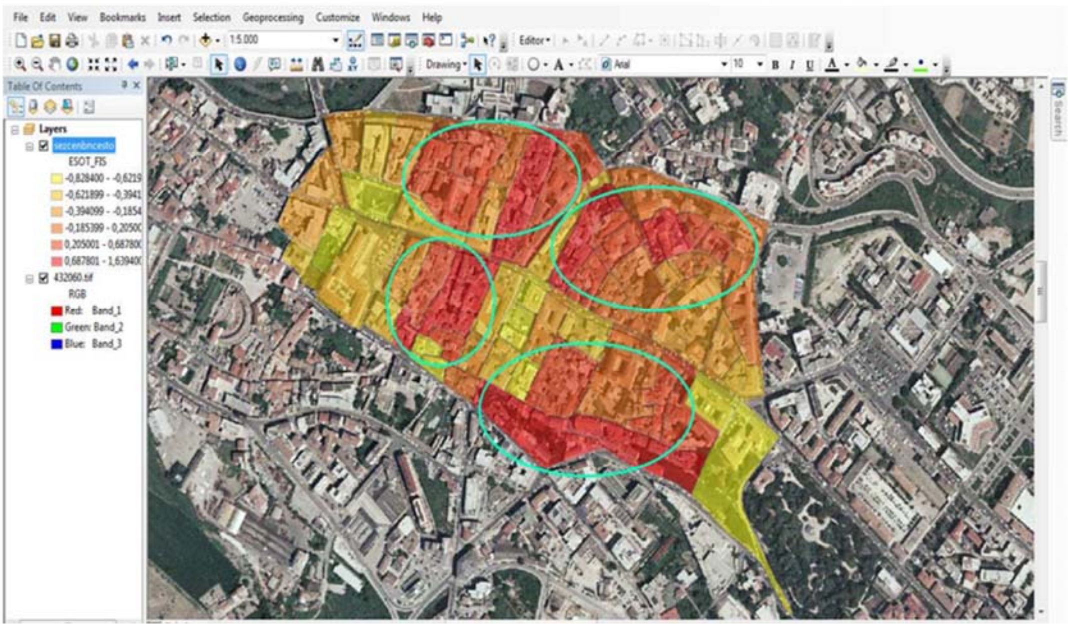

Fig. 6 Urban entropy for the physical urban sub-system

Urban metabolism and urban spatial planning

A City, like any other ecosystem, cannot be a self-sufficient system: it always requires an exchange of matter and energy to grow and evolve, and depending on its metabolism, it needs different amounts of energy, materials, water and nutrients to provide sustenance and shelter to its citizens, to produce goods and services, to grow and to eliminate waste and pollution.The regulation of the UM is therefore a priority to increase the sustainability of a city (Beloin-Saint-Pierre et al., 2017).

Two main schools of UM exist: one describes metabolism through energy equivalents (emergy), while the second studies the flows of water, materials and nutrients in terms of mass fluxes (C. Kennedy, Pincetl, & Bunje, 2011). The scoping review conducted did not reveal emergy assessment studies aimed at supporting practical spatial planning in urban contexts. In general, most UM studies use a top-down approach and coarse or highly aggregated data which cannot be correlated with specific locations, activities, or people (Chrysoulakis et al., 2013). Indeed, obtaining and managing huge amounts of data at a sufficiently downscaled level for planning purposes is often difficult (Pincetl et al., 2014). Only a few studies have presented UM as the baseline for effective designing and planning aimed at optimizing urban flows (Chrysoulakis et al., 2013; Codoban & Kennedy, 2008; Pincetl et al., 2014) and they do not specifically address UGI.

Chrysoulakis et al. (2013) report the results of the FP7 BRIDGE project aimed at defining sustainable urban planning decisions accounting for urban metabolism. The project developed a Decision Support System (DSS) based on a Multi-Criteria Analysis approach and GIS interface that aids the evaluation of the sustainability of urban planning interventions coping with the complexity of urban metabolism. Targeted end-users were involved to define planning objectives and future development scenarios were assessed in relation to the interactions between the environmental elements (fluxes of energy, water, carbon and pollutants) and socioeconomic components (investment costs, housing, employment, etc.) of urban sustainability. Five different case study cities participated in the BRIDGE project: Helsinki, Athens, London, Florence and Gliwice. For each city, several scenarios of development were defined (Fig. 7).

The evaluation of each scenario in the city study case was carried out in a participatory way in order to allow end-users to recognize the relative importance of sustainability objectives and indicators. Finally, planning alternatives in each case study were ranked in order of performance (environmental and socioeconomic components) and user preferences. Project results highlight a general positive effect of green spaces on many aspects of urban sustainability: cooling, CO_2 sequestration, water buffering and air quality. On the other hand, the develop of buildings and roads had the opposite effect. The innovation of the BRIDGE project is that these evaluations are quantified and related to urban sustainability targets and physical flows (see Fig. 8). The BRIDGE DSS thus represents a first example of a pragmatic tool for the sustainable land use decision making process at local scale based on urban metabolism. Another application of urban metabolism assessment for urban planning/design purposes is reported by Codoban & Kennedy (2008).

The study provides an analysis of the metabolism of four representative Toronto neighbourhoods, focusing specifically on the flows of energy, water, and food. Three particular metabolic processes within neighbourhoods are studied: operation of buildings, preparation and consumption of meals and beverages and transportation. The inflows to neighbourhoods include water, food, electrical, and fossil fuel energy; the outflows are solid waste and wastewater (see fig. 9). The authors report some general suggestions for the design of sustainable neighbourhoods.

These include the construction of energy-efficient buildings, development of public transit, replacement of inefficient water fixtures, the conversion of solar energy to building operational energy, the closure of waste-cycle growing urban forests and recycling grey water. The work shows a high detail of analysis, but it was not translated to specific and spatially defined actions within neighbourhoods. Thus, despite the considerable assessment efforts, the use of the information produced for practice urban planning appears is still limited to general considerations. The causes of the reduced employment of UM studies in practice urban planning have recently been investigated by Voskamp et al. (2018). The authors present an application of SIRUP tool – "Space-time Information analysis for Resource-conscious Urban Planning" in a case study of Amsterdam, focused on the investigation of energy and water flows. The purpose of SIRUP is the identification on the optimal spatiotemporal resolution of information on resource flows that stakeholders need for assessing urban interventions. In other words, the paper examined at which spatial and temporal resolution urban metabolism should be analysed to generate results that are useful for the implementation of urban planning and design interventions aiming at the optimization of resource flows.

Moreover, an investigation was performed to find out whether a lack of data currently hampers analysing resource flows at this desired level of detail. The urban planning and design measures considered were chosen among a number of interventions aimed at urban climate adaptation, climate mitigation and/or resource efficiency. The measures selected range from the conversion of cellulose in waste into power, to the realisation of PV on roofs, from parking garage as battery, to a regional smart grid. Specific water-related measures consider dike reinforcement, the concentration of sewerage flows, cooling capacity, water infrastructure improvement and the realisation of water squares.

The selected green/NBS measures are the creation of a park on a brownfield site, phytoremediation, rainwater buffering and infiltration and small scale parks. Results show that most urban planning and design interventions envisioned in Amsterdam require information on a higher spatiotemporal resolution than the resolution of current urban metabolism analyses, i.e., more detailed than the city level and at time steps smaller than a year. Energy-related measures generally require information on a higher resolution than water-related measures. Moreover, for the majority of measures, information is needed on a higher resolution than currently available. For energy, the temporal resolution of existing data proved inadequate, for water, data with both a higher spatial and temporal resolution is required.

Finally, the authors claim that for urban planning and design, the development of new types of UM analysis is necessary, rather than performing a conventional one on a finer spatiotemporal scale. The new UM analysis should thus be based on modelling and monitoring techniques that can provide a systemic understanding of urban resource flows and that are tailored to urban planning and design objectives. In particular, the use of modelling approaches, even if they are not fully accurate and simplify reality, may produce accurate enough data to inform the assessment and planning of interventions. We report the work of Pincetl et al. (2014) as the state of art in UM studies for spatial land use planning in line with the approach and issues pointed out by Voskamp et al. (2018).

The article presents an UM study using mixed methods and multiple sources of data for Los Angeles, California. In particular, electric energy use in buildings and greenhouse gas emissions from electricity are examined calculating infrastructure life cycle effects, water use and solid waste streams. The assessment is being conducted to help policy-makers better target energy conservation and efficiency programs, detect the best locations for distributed solar generation, and support environmental sustainability policies. Fig. 10 shows an example of UM spatial assessment for water use conducted at parcel level.

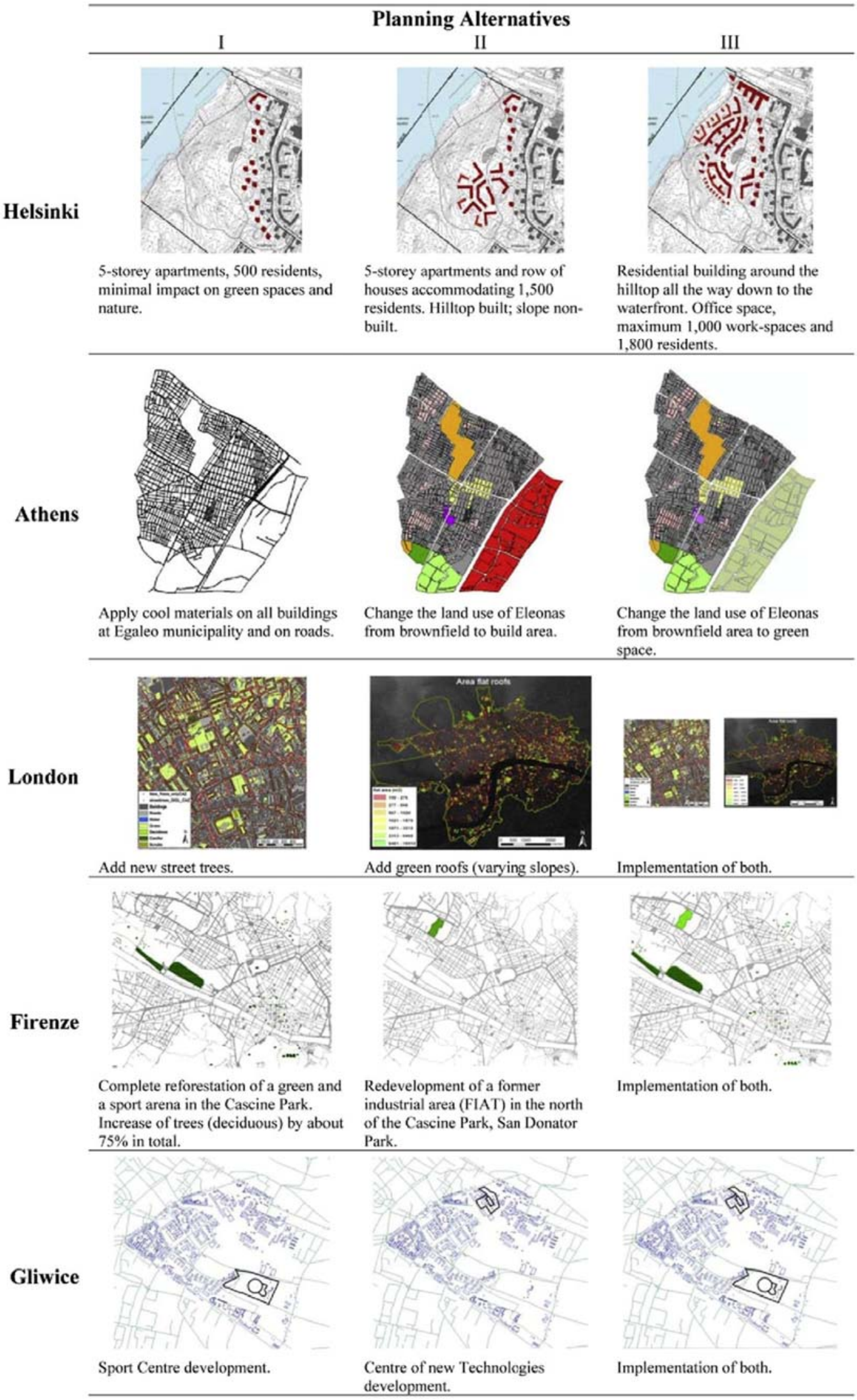

Fig. 7. The urban planning scenarios evaluated within the BRIDGE project for the five city study cases

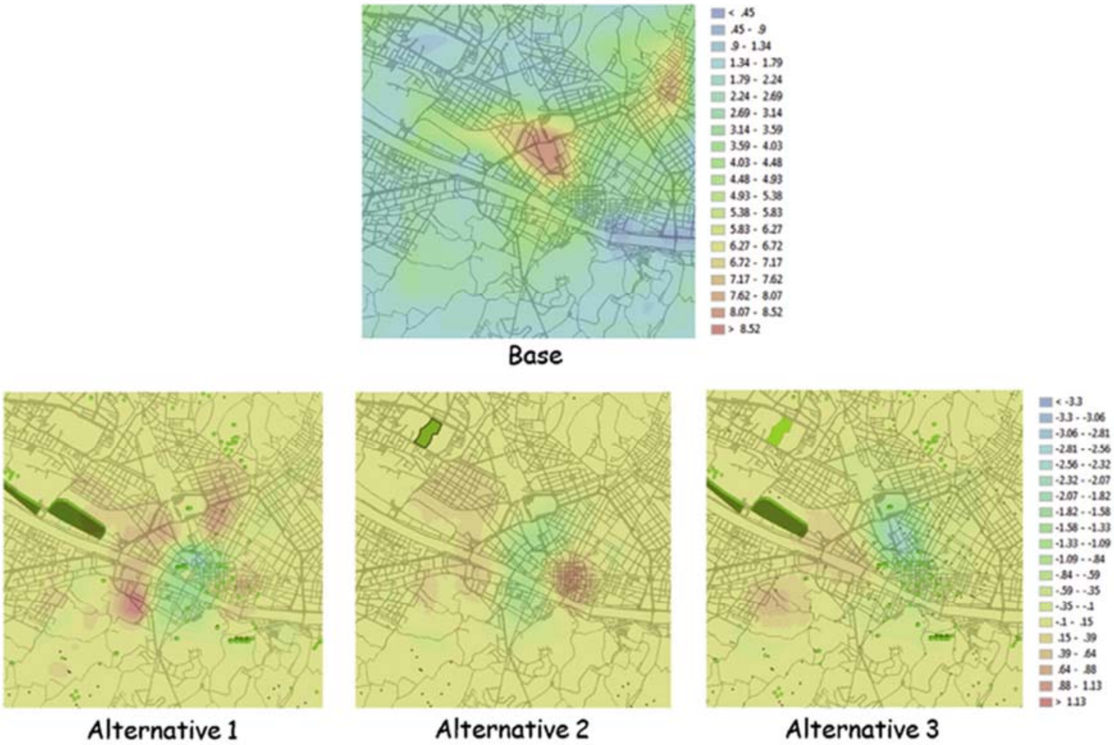

Fig. 8. Example of urban metabolism analysis conducted in the BRIDGE project. Mean surface runoff (mm h⁻¹) for summertime for the Firenze study case. The alternative scenarios (bottom) are evaluated as runoff difference with respect to the base case (top)

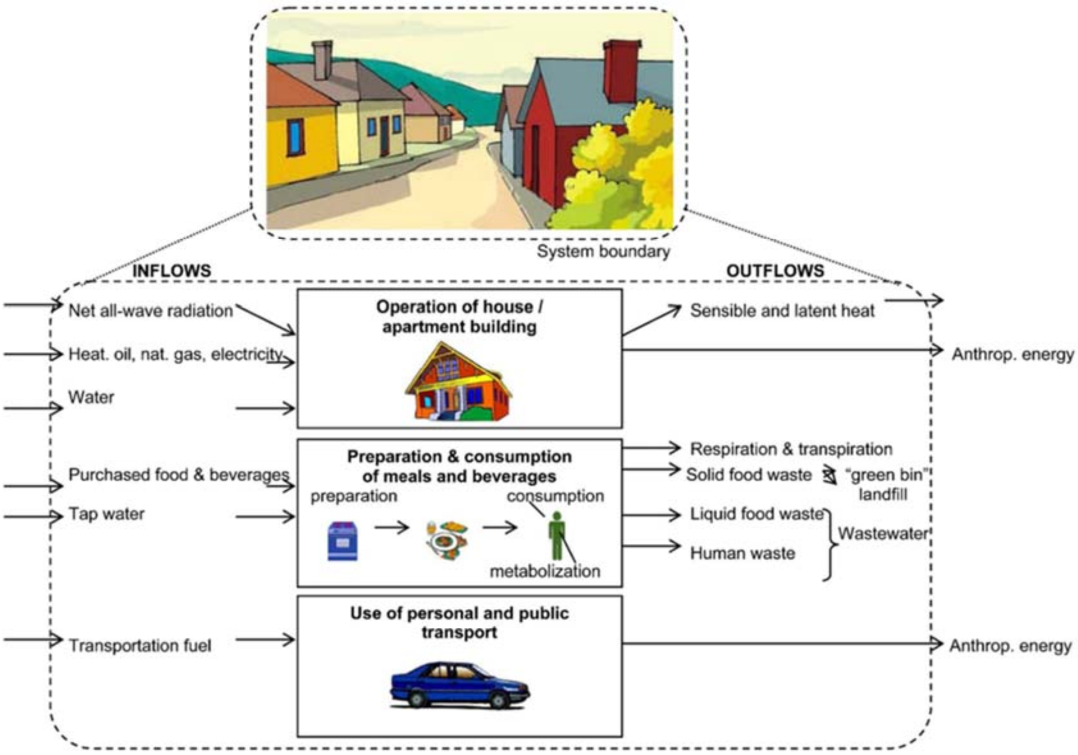

Fig. 9 Key metabolic processes analysed within the four Toronto neighbourhoods

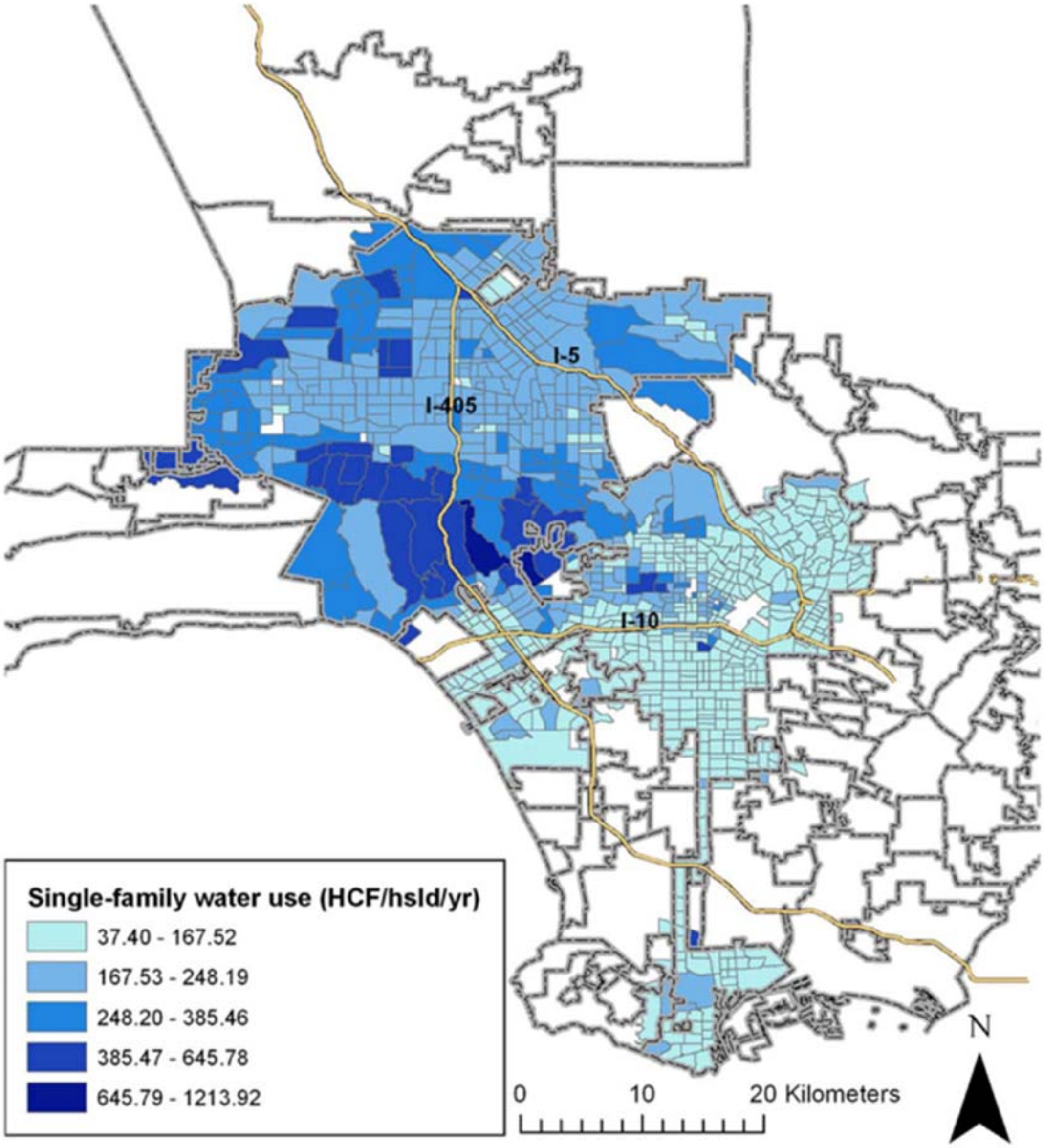

Fig. 10 Ten-year average single-family water use by census tract for Los Angeles

4 DISCLOSING SLT KNOWLEDGE FOR UGI PLANNING

From the literature review conducted, it emerges that beside technical issues, the integration of SLT into UGI planning requires a different systemic approach able to deal with different analysis scales and socio-ecological processes. As Voskamp et al. (2018) well highlighted, each UM assessment to be useful in spatial urban planning should aim to describe the urban system by linking the physical, quantitative knowledge of resource flows to its interaction with (current and historic) environmental, social and economic conditions. We think that this concept for UM can be translated for the general SLT approach. Indeed, human regulating and governing mechanisms play a critical role in urban ecosystems where policy, planning, and management decisions influence both anthropogenic and ecological processes within and beyond the city (Bai, 2016). A systemic understanding of urban resource flows must therefore be reached in order to provide insight both into the social and ecological processes affecting resource flows and into the interlinkages between processes and resource flows (Voskamp et al., 2018). Chrysoulakis et al. (2013) have shown that the choice among interventions on urban systems is not easy, even with the most accurate spatial assessments. Indeed, the dimensions of the urban sustainability are multiple, and each project has complex outcomes and trade-offs: such trade-offs are contingent to end-users' preferences and they are not fixed over time. SLT planning, especially at local scale, should then include stakeholder participation and cyclic assessment phases to adapt it to the changing socio-ecological system, allowing the best solutions (in our case NBS) to be selected and realised. Thus, two intertwined paths might be followed by researchers for the inclusion of SLT in UGI planning: a technical and a strategic path. The former consists in the further development of methodological frameworks (e.g. considering ecosystem services assessment, the integration of different SLT concepts, the proper spatiotemporal assessment scale), new applicable cost-effective indicators (in particular for entropy), the implementation of modelling approaches and the assessment of social domain related with ecological and physical processes. Among the several study cases reported, the spatial representation of the assessments has demonstrated to be a valuable support for planning. Mapping significant indicators of entropy, exergy or energy and matter fluxes at the proper scale and resolution can then represent a key aspect to facilitate SLT inclusion into UGI planning. The second path should aim to study how these technical aspects have to be considered in governing mechanisms, transforming the quantitative information produced by SLT assessment into effective and lasting urban interventions capable of increasing the quality of citizen life and the resilience of socio-ecological systems. Within this second path we should consider, for example, innovative policy and regulating approaches (e.g. compensatory measures) to encourage private owners to adopts NBS following performance-based criteria instead of conformance and prescriptivism norms (Frew, Baker, & Donehue, 2016). Finally, during recent years, several SLT planning approaches have emerged from scientific literature within different research fields such as, energy landscape planning, sustainable urbanism and urban metabolism studies. Since different field objectives, exergy, entropy and UM concepts have been applied, they have evolved separately. Even though some possible research pathways for a unifying thermodynamic-based urban planning have been suggested (Bristow & Kennedy, 2015; Filchakova, Robinson, & Scartezzini, 2007), more efforts are required to define solid spatial planning strategies able to embrace different SLT approaches above all for UGI.In this intertwined view, the low-entropy city concept and the proposed UGI planning strategy (Pelorosso, Gobattoni, & Leone, 2017) appears to be a promising cross-boundary tool which could provide a flexible integration of assessment methods taking into consideration ecosystem service frameworks, urban metabolism, social impacts and SLT-based planning. In particular, the proposed low-entropy UGI planning strategy emphasizes the role of modelling in the assessment phase and identifies several entropy indicators able to be easily applied by planners. Recently, the low-entropy approach has been applied in a exemplificative study case within the context of sustainable urban storm water management in Bari city, South Italy (Pelorosso, Gobattoni, & Leone, 2018). This research paper demonstrates the potential operativity of the low-entropy concept within the indicated technical path representing a first case of low-entropy UGI planning integrating modelling approach and entropy evaluation.

5 CONCLUSIONS

Although several scholars have investigated the role of Nature and SLT in making cities more sustainable, UGI planning based on SLT is a relatively new field of research with few real applications to urban systems. The paper, through a coupled review (scoping and systemic) of scientific literature, reports the main applications of thermodynamic concepts and approaches in urban planning. In particular, we searched for significant applications of SLT on study cases and we focussed on three key concepts related to SLT, namely exergy, entropy and urban metabolism (UM), to highlight gaps, constrictions and applicability for UGI planning. Finally, from the analysis of the selected contributions, some essential considerations have been derived with the aim of addressing and supporting future spatial planning. Exergy is an indicator of sustainability employed mainly for energy planning and several real study cases of exergetic landscape optimization exist at different planning scales. However, more efforts are required to investigate how exergy assessment can be used within specific

UGI planning, considering also the provision of ESs. Entropy appears a promising indicator of urban sustainability, but its operative application has still to be realised as well as the definition of proper and cost-effective entropy indicators able to spatially evaluate the effectiveness of green interventions at different urban scales. UM is recognised by many urban planners as the frontier for innovative land use decision making. Several issues hampering UM integration in urban planning have been highlighted by literature (e.g. demand of high resolution data) but a consolidated UM-based UGI planning is not present yet. Moreover, from the literature review, some general indications summarized in two levels of intervention (i.e. technical and strategic research paths) can be derived for the development of spatial UGI planning strategies based on SLT. From a technical point of view, practical UGI planning requires operative and integrated exergy, entropy and UM assessments with accurate descriptions of the urban socio-ecological complexity at the temporal and spatial scale at which practitioners work. In addition, modelling and mapping of SLT processes appear pivotal approaches for the inclusion of SLT in UGI planning. Strategical actions should instead look at defining adaptable governing mechanisms (e.g. compensatory measures) enabling SLT and performance-based planning criteria to be accepted and widely used among citizens in order to operationalise effective and shared interventions on UGI. The knowledge synthesis on SLT and urban planning thus confirms the innovative character of the low-entropy city concept and the proposed seminal UGI planning strategy (Pelorosso, Gobattoni, & Leone, 2017). In addition to further theoretical developments, practical implementations on exemplificative study cases or the creation of *ad hoc* urban living labs are welcomed to provide useful information to test the low-entropy strategy, and in general the SLT approach, in UGI planning. Several efforts are thus required to build theoretically sound but also operative thermodynamic-based UGI planning strategies able to integrate different approaches and to translate them into real UGI study cases. In conclusion, planning strategies driven by SLT are innovative approaches to sustainability, but they appear to be still in a seminal phase. The presented knowledge synthesis of actual SLT implementation in urban contexts and the proposed paths of action aim to address future spatial planning strategies and to support a SLT-conscious green transition of cities.

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APPENDIX A- SUPPLEMENTARY MATERIAL

List of the papers selected through ISI Web of Science and Scopus databases (period: up to 25/01/2017)

37th Joint Propulsion Conference and Exhibit 2001 (Conference Review); Salt Lake City, UT; United States; 8 July 2001 through 11 July 2001; Code 102854

Advanced Materials Research. Volume 748, 2013. 4th International Conference on Material and Manufacturing Technology, ICMMT 2013 (Conference Review); Seoul; South Korea; 11 May 2013 through 12 May 2013; Code 99779

Aleksic, S., Biljanovic, P., Butkovic, Z., Skala, K., Golubic, S., CicinSain, M., Sruk, V., Ribaric, S., Gros, S., Vrdoljak, B., Mauher, M. & Cetusic, G. (2014). Green ICT for Sustainability: A Holistic Approach. *Conference: 37th International Convention on Information and Communication Technology, Electronics and Microelectronics* (MIPRO 2014), At Opatija, Croatia. doi:ttp://doi.org/10.1109%2fMIPRO.2014.6859604

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Applied Mechanics and Materials. Volume 409-410, 2013. 2nd International Conference on Civil, Architectural and Hydraulic Engineering, ICCAHE 2013 (Conference Review); Zhuhai; China; 27 July 2013 through 28 July 2013; Code 100434

Applied Mechanics and Materials. Volume 423-426, 2013.3rd International Conference on Applied Mechanics, Materials and Manufacturing, ICAMMM 2013 (Conference Review); Dalian; China; 24 August 2013 through 25 August 2013; Code 100385

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IMAGE SOURCES

Fig. 1: Pelorosso, Gobattoni, & Leone, 2017; Fig.2: He et al., 2015; Fig.3: Ambrosini et al., 2014; Fig.4: Leone, Gobattoni, & Pelorosso, 2016; Fig.5: Leduc & Van Kann, 2013; Fig.6: Fistola and La Rocca, 2014; Fig.7: Chrysoulakis et al., 2013; Fig.8: Chrysoulakis et al., 2013; Fig.9: Codoban & Kennedy, 2008; Fig.10: Pincetl et al., 2014.

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