A Systemic Approach for the Optimization of Urban Surfaces Usage

S Croce¹,², D Vettorato¹ and R Paparella²

¹ Institute for Renewable Energy, Eurac Research, Bolzano, Italy
² Department of Civil, Environmental and Architectural Engineering, University of Padova, Padova, Italy

silvia.croce@eurac.edu

Abstract. This paper proposes a method to support the sustainable development of existing cities through the optimization of the usage of their urban surfaces (i.e. roofs, facades, streets, public spaces, etc.). Adaptation and mitigation strategies aimed at improving resiliency and sustainability of urban areas are highly related to the utilization of these surfaces. The current trends demonstrate the lack of a systemic approach able to integrate multiple possible functions and avoid sub-optimal solutions by considering the physical and morphological characteristics of the urban environment. For example, in cities, conflicts are arising between the surface uses for renewable energy production, urban agriculture, and green solutions.

This study aims at systematizing the existing approaches and proposing a novel method to support the effective application of these solutions. In particular, an analytical procedure is presented to support the integration of different surface uses aiming at the maximization of throughputs, while avoiding conflicts. The method has been tested in a district in Bolzano (Italy) and it is replicable in areas with different morphological characteristics and climate conditions. The final configuration, in which several solutions have been systematically applied and integrated, demonstrate the potentialities of the proposed approach. Outdoor thermal comfort in the district is improved, with a reduction of Universal Thermal Climate Index (UTCI) up to $-5.8 \, ^\circ\text{C}$, by simultaneously guaranteeing the production of renewable energy through solar active systems, and the preservation and expansion of existing green areas.

1. Introduction

In recent years, massive urbanization and fast grow of urban population worldwide are accentuating various environmental and energy issues clearly related to anthropogenic causes. Numerous studies have demonstrated the link between urban development and climate change, and the unprecedented risks faced by urban areas [1]. The impacts of these phenomena have major noticeable effects in cities, which are receiving increasing attention by the scientific community [2–5]. Many of these impacts, which are summarized in Table 1, are clearly linked to the “urban surfaces”, i.e. all the surfaces that modify the physical and morphological characteristics of the built environment from the radiative, thermal, and hydrological perspective. This includes the surfaces of the building envelopes, green areas, and public spaces (e.g. parks, streets, etc.) that can be characterised by different materials and can host several functions. Urban surfaces and their characteristics may have a key role in tackling issues related to urbanization and climate change effects. In this scenario, the present study discusses the most promising surface uses and the potential conflicts and interactions among them, aiming to systematize the existing
approaches. Based on that, a systemic approach is proposed to promote the sustainable transition of consolidated urban areas through the optimization of the usage of their surfaces.

**Table 1. Urbanization and climate change: impacts, major effects, and involved domains (D).**

| Impacts of urbanization and climate change | Major effects                                                                 | D                          |
|-------------------------------------------|-----------------------------------------------------------------------------|-----------------------------|
| • Increased concentration of greenhouse gases emissions | • Raise of temperatures and increase in frequency and duration of extreme climatic phenomena | **Urban climate**           |
| • Replacement of natural surfaces with mineral materials; increase of anthropogenic heat flux | • Urban heat island effect<br>• Reduction of outdoor comfort; negative impacts on human health |                             |
| • Extensive use of materials with low albedo | • Increment of the fraction of solar radiation absorbed and re-emitted inside urban areas |                             |
| • Loss of green spaces | • Reduction of latent heat emission and evapotranspiration<br>• Entrapment of radiation inside the urban canyons<br>• Lower wind velocities; reduced convective heat removal |                             |
| • High urban densities | • Species richness decrement<br>• Spread of exotic and invasive species, with consequent decrement of native plants diversity | **Habitat & biodiversity**   |
| • Habitat loss and fragmentation | • Decreased biodiversity and environmental degradation |                             |
| • Import of species for gardening and urban landscaping | • Loss of soil natural retention capacity and reduced surface storage capacity; decreased evapotranspiration<br>• Higher volumes of urban runoff flows<br>• Increased discharge rates and flood peaks | **Urban Hydrology**          |
| • Increase in impervious surfaces | • Storm-water management issues |                             |
| • Urban land sealing and increase in impermeable areas | • Increment of energy consumption for cooling<br>• Peak electricity demand<br>• Heating loads in cold season may be reduced | **Energy**                   |
| • Extreme rainfall events | • Intensification of urban inhabitants’ vulnerability to insecurity and shocks in the agricultural market |                             |
| • Summer heatwaves | • Challenges in freshwater provision<br>• Changes in freshwater availability and water shortages<br>• Water pollution issues | **Fresh-water**              |
| • High urban temperatures | • Modified global hydrologic cycle and precipitation patterns |                             |

2. Resiliency and sustainability objectives in cities

In the current scenario of increased urbanization and global climate change, the capability of urban areas to pursue resiliency and sustainability objectives is becoming essential. These comprise all the actions needed to limit and overcome the negative effects discussed in Table 1, and can be grouped as following.

- Resiliency objectives refer to the capacity of cities to protect inhabitants and infrastructures from extreme weather events; they include (i) urban climate regulation, (ii) habitats and biodiversity preservation, and (iii) urban hydrology and storm-water management.
- Sustainability objectives are related to the efficient use of resources and encompass (i) energy self-reliance, (ii) food security, and (iii) freshwater availability.

2.1. Urban surface uses

The use and characteristics of urban surfaces play a key role in addressing the above mentioned objectives. The most promising can be grouped into five major clusters:

1. **Green Solutions**: comprise any vegetation sited in the urban environment. They can be classified as: a) vegetation in outdoor areas, including parks, urban forests, street trees, raingardens, etc., and b) green building elements (i.e. green roofs and façades).
2. **Water Solutions**: refer to water retention measures (e.g. rain gardens, water squares, water retentive or porous pavements, etc.) and artificial water surfaces (e.g. water curtains, sprinklers, and fountains) [6].

3. **Urban Agriculture**: aimed at the production of food, urban agriculture play an essential role for environmental sustainability and food security in cities. Such solution includes: horticulture, aquaculture, agroforestry, urban beekeeping, and innovative systems such as vertical farming [7].

4. **Smart Coats**: mainly refer to cool materials, i.e. finishing materials or paintings characterized by high reflectivity to solar radiation (i.e. albedo [\( \alpha \)]) and high emissivity factor [6,8].

5. **Solar Energy Systems**: generation of renewable energy by means of active solar systems, i.e. solar thermal (ST) and photovoltaics (PV), applied on the buildings’ surfaces or other elements of the urban landscape.

Figure 1 schematizes, for each cluster of surface usage, the main processes and services that contributes to resiliency and sustainability objectives in urban areas.

![Figure 1](image)

**Figure 1.** Surface uses’ process and services contributing to the related objectives.

2.2. **Integration and conflicts**
In the existing approaches [6,8,9], the surface uses are often selected and implemented independently one from another. This results in a scattered patchwork of solutions, which limits the capability of urban areas in mitigating the consequences of climate change, and in responding and adapting to external environmental pressures. The recognition of the main conflicts and possibilities of integration of different solutions is a critical step toward the definition of a systemic approach for the optimization of urban surface uses. The matrix presented in Figure 2 schematizes the potential interactions between different usages. Based on that, this study aims to present a workflow for the integration of several urban surface uses in consolidated urban areas, and to demonstrate its relevancy in the process toward urban resiliency and sustainability.
Figure 2. Conflicts and potential integration between main (rows) and secondary (columns) uses.

3. Methodology
The proposed method implies sequential steps to address local climate, morphological aspects, and environmental features of consolidated urban areas for the definition of guidelines for the use of their surfaces.

Figure 3. Workflow of the presented methodology and parameters involved.

The process, schematized in Figure 3, starts with the characterization of the selected area in terms of urban morphology, and surfaces’ functions and materials. The objective is twofold: (i) outline the main
features of the district, and (ii) collect relevant input data for the models. Successively, the variants and invariants are defined in terms of surfaces suitability for new uses. In parallel, the local weather is analysed to (i) define the local boundary conditions, (ii) determine the input parameters for the environmental analyses, and (iii) identify typical seasonal conditions. Successively, the empirical evidences collected are used for outlining the primary assumptions, and identifying the main objectives to be pursued in the study area. Based on that, the most suitable surface uses are identified and tested through sets of environmental analyses. Analyses, aims, and tools are described in Table 2.

| Analyses             | Aims                                                                 | Tools                                               |
|----------------------|----------------------------------------------------------------------|-----------------------------------------------------|
| Solar potential      | Identify the most irradiated areas and the surfaces most affected by overshadowing | Rhinoceros, DIVA-for-Rhino, Honeybee for Grasshopper |
| Microclimate         | Define local microclimate conditions and verify impacts of specific modifications of surfaces uses | ENVImet, Ladybug tools for Grasshopper, Rhino-2-ENVI |
| Urban airflow        | Evaluate the natural ventilation and identify the prevalent winds in the district | Butterfly for Grasshopper, OpenFoam                |

Initially, the environmental analyses are conducted to test scenarios where single clusters of urban surface use are applied. Then, the results are analysed to define a final scenario integrating several uses, which are selected based on their accordance with the sustainability and resiliency criteria set. In the final step, the proposed solution is verified through another set of analyses, whose results are then used to define guidelines for the optimization of the urban surfaces use in the area.

3.1. Characterization of the case study area

The proposed methodology is tested in an existing district in Bolzano (UTM 46°29' N, 11°21' E), a city located in the north-east of Italy, at a height of 265 m above sea level. The climate in Bolzano is categorized as moist continental (“Dfb”) according to the Köppen-Geiger classification, and is characterized by strong seasonal fluctuations. Due to its location in a basin surrounded by mountain ranges, the city is often affected by high temperatures and heat waves during summer. For this reason, the analyses conducted on the case study focused on the mitigation of typical summer hot conditions.

The case study district is one of the five areas in Bolzano taking part to the Smart Cities European project SINFONIA [10]. Its morphology is characterized by five urban canyons (Figure 4a): Via Milano and Via Cagliari from north to south; Via Brescia, Garden, and Via Palermo from west to east. The current surface uses in the area are schematized in Figure 4a. Via Palermo is one of the main connection between the eastern and southern areas of Bolzano, while Via Milano and Via Cagliari are secondary roads. Due to their importance in the traffic network of the city, these three urban canyons are considered as invariants of the district; hence, the possible uses are restrained to the solely modification of the surfaces materials by keeping their original geometrical features. On the contrary, Via Brescia, which is mainly used by the residents of the nearby buildings, and Garden, the central public green area, are considered as variants.

3.1.1. Scenarios of surface usage for the environmental analyses. In this study, several different scenarios of urban surface use have been simulated. Initially, in the Baseline scenario, the environmental features of the districts have been analysed by maintaining morphological characteristics and materials unvaried from the current situation (Figure 4b). The empirical evidences emerged from this scenario have been used for selecting the main objectives to be pursued in the area and the consequent suitable surface uses. Successively, several scenarios have been simulated, each considering a single use. Finally, the results of each scenario have been analysed and, based on their outcomes, a final configuration has been outlined by systemically integrating several solutions and surface usages. For each scenario, the
microclimate simulations have been conducted utilizing input data from the local weather station for the 29th July 2017, selected as representative of typical hot summer conditions.

4. Results and discussion
In this section, the relevant outcomes of the six simulated scenarios are discussed, along with the significance of using a systematic approach to address the use of urban surfaces.

The analysis of the Baseline scenario’s result has focused on the evaluation of the main physical parameters (i.e. air temperature \([T_{air}]\), surface temperature \([T_s]\), mean radiant temperature \([T_{mrt}]\), global shortwave solar radiation \([Irr_{SW}]\), and wind speed \([W_s]\)) at 15:00, when the peak of thermal stress is reached. The maximum air temperature is registered in Via Cagliari \((T_{air} = 31.50 \, ^\circ C)\), while in the other urban canyons the average \(T_{air}\) is around 30.50 \(^\circ C\); Garden is the coolest area with average \(T_{air} = 30.00 \, ^\circ C\) (Figure 4c). The average Universal Thermal Climate Index (UTCI) value in the district is around 38.00 \(^\circ C\), corresponding to “very strong heat stress” conditions [11].

![Figure 4](image)

**Figure 4.** Baseline Scenario: a) Aerial view; b) Surface use; c) T\(_{air}\) distribution – 15:00, 29th July 2017.

Analysing the results, four main empirical evidences emerged: (i) the area is affected by summer overheating, (ii) hotspots are localized in the main urban canyons due to elevated asphalt \(T_s\), (iii) high \(T_{air}\) is mitigated in the existing green areas, and (iv) several building surfaces present suitable levels of solar potential for the integration of solar active systems.

4.1. Scenarios of surface use
Based on the current summer conditions in the district (Baseline scenario), five scenarios of surface use have been defined. Their characteristics, and main effects are synthesized in Table 3. Four scenarios (i.e. Green Solutions, Water Solutions, Smart Coats, and Solar Energy Systems) investigated the effect of single surface uses. The results have been analysed in terms of (i) physical parameters, (ii) thermal comfort (i.e. UTCI), and (iii) potential for solar energy production using the Baseline as reference for comparison. The outputs in terms of absolute \(T_{air}\) difference at 15:00, selected as representative of the mitigation effects of each scenario, are shown in Figure 5.

In the last step, the Final Integrated scenario has been defined by systemically integrating several surface uses (Figure 5f). The main criteria for defining the final uses has been the application of each solution on the surfaces where it provided the highest improvements in terms of outdoor thermal comfort conditions. Hence, green façades have been implemented in the urban canyons where they produced the highest \(T_{air}\) reduction (i.e. Via Brescia and Via Cagliari), and avoided in the eastern side of Via Milano and in Via Palermo, where they caused the reduction of \(W\), and, consequently, decreased the convective
heat removal. On the higher floors’ façades with suitable sun exposure, the vertical greening has been integrated with solar systems. PV have also been applied on roofs, since at that height they do not consistently modify the microclimatic conditions at pedestrian level and, at the same time, they consistently contribute to production of renewable energy in the district. Furthermore, cool asphalt has been implemented on the main roads, and water surfaces have been integrated in the green area next to Via Cagliari hotspot to further contribute to high temperatures mitigation.

**Figure 5.** Comparison between Baseline and surface use scenarios – 15:00, 29th July 2017.

| Scenario | Surface uses | Main results |
|----------|--------------|--------------|
| **Green Solutions** | Façades: vertical greening (leaf area density = 1.85 m²/m³) | • $T_{air}$ reduction up to $-0.95 \, ^\circ C$<br>• Due to the reduction of $W_s$ in proximity of the buildings ($\Delta W_s = -0.80 \, m/s$), $T_{air}$ increases in Via Milano and Via Palermo hotspots ($\Delta T_{air} = +0.90 \, ^\circ C$) |
| | Roofs: horizontal greening system (grass) | |
| **Water Solutions** | Water body (water depth = 2m) close to Via Cagliari hotspot | • $T_{air}$ is reduced only in proximity of the water bodies (max $\Delta T_{air} = -0.70 \, ^\circ C)$ |
| **Smart Coats** | Roads: cool asphalt ($\alpha = 0.40$) | • $T_{air}$ reduced in all canyons (max $\Delta T_{air} = -0.60 \, ^\circ C$) |
| | Roof: cool paint ($\alpha = 0.80$) | • Roads: average $\Delta T_{air} = -2.50 \, ^\circ C$ |
| **Solar Energy Systems** | Façades: PV on surfaces with suitable IrrSW | • $I_{irr}$ ≥ 950 kWh/m² on 6 500 m² of building envelope<br>• $T_{air}$ almost unvaried (max $\Delta T_{air} = -0.18 \, ^\circ C$) |
| | Roofs: PV panels | • $W_s$ generally unvaried; max $\Delta W_s = -0.20 \, m/s$ in proximity to vertical greening systems in Via Brescia |
| **Final Integrated** | Main roads: cool asphalt<br>Green areas: + 15% increment<br>Water body close to Via Cagliari | • $T_{air}$ reduction up to $-0.50 \, ^\circ C$ in Via Cagliari and Via Milano;<br>-0.40 $^\circ C$ in Via Palermo and Via Brescia<br>• $W_s$ generally unvaried; max $\Delta W_s = -0.20 \, m/s$ in proximity to vertical greening systems in Via Brescia |
| | Façades: vertical greening systems on façades (i) at south, (ii) along Via Brescia; elsewhere PV on areas with suitable IrrSW | • Average $\Delta UTCI = -1.00 \, ^\circ C$;<br>Highest reductions: $\Delta UTCI = -1.73 \, ^\circ C$, -3.80 $^\circ C$, and -5.76 $^\circ C$ in Via Palermo, Via Brescia, and Via Cagliari respectively<br>• PV: 6 500 m²; annual solar potential: 6 320 MWh/a |
| | Roofs: PV on areas with suitable IrrSW; elsewhere cool paint | |

**Table 3.** Simulation scenarios of urban surface use: characteristics and main results.
5. Conclusions
The present study aimed to develop and test a systemic approach for the optimization of the urban surfaces use in consolidated urban areas. The main strength of the methodology lies in its replicability. The environmental analyses are based on the 3D model of the urban district, and on the local weather data; hence, the workflow may be reproduced in every climate and for every morphological conditions. The results from scenarios of single surface use proved the usefulness of environmental analyses to estimate the effects of each solutions and to outline design indications. The final configuration, in which several uses have been systematically integrated, demonstrate the potentialities of the proposed approach. Outdoor thermal comfort is improved, with an average reduction of UTCI of -1.00 °C, decreasing the thermal stress from “very strong” to “strong” [11]. Simultaneously, the production of renewable energy through solar active systems is guaranteed, existing green areas are preserved, and the vegetation in the district is increased of +15%. The results from all the scenarios are relevant for the definition of guidelines, useful in the planning and design phases for outlining the most suitable solution for each surface in an urban area. Future developments of the study will address: (i) the effects of surface uses presently not considered (e.g. urban agriculture) and, (ii) the definition of quantitative indicators and thresholds to guide the optimization process. Furthermore, a co-simulations workflow may be developed for integrating several environmental analyses on a single platform, and linking their results.

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