How Urban Resilience Can Change Cities: A System Dynamics Model Approach

Giulia Datola(✉), Marta Bottero, and Elena De Angelis

Interuniversity Department of Regional and Urban Studies and Planning, Politecnico di Torino, Turin, Italy
{giulia.datola, marta.bottero, elena.deangelis}@polito.it

Abstract. Urban resilience is an emerging approach to planning in cities. In last few decades, this concept has been also used as fundamental principle to set up urban development strategies. Urban resilience is a multi-dimensional and dynamic phenomenon and applied to urban planning it leads to cities being considered as complex socio-economic systems. The reason why few cities take appropriate action to enhance their resilience lies in the difficulty of evaluating this process in terms of time. This paper aims to overcome the difficulties which afflict the concept of urban resilience when involved in urban planning, using a System Dynamics Model (SDM) as an evaluation tool to assess how urban resilience can change cities over time, addressing their complexity. This evaluation model is applied to simulate two different urban scenarios for a real case study in the city of Turin (Italy).

Keywords: Urban resilience · Decision-making · System Dynamics Model · Resilient cities · Causality · Strategic planning

1 Introduction

Over the last two decades the concept of resilience has increasingly became recognized as having important role in urban system and more recently it is also employed as an essential principle to set upstrategies for city development [1, 2]. This attention is also due to the fact that a lot of cities across the world are more than ever exposed to a great variety of risks and hazard. These risks include all city dimensions, from the environmental, which is strictly connected to extreme events, to the social and economic [2–5].

Considering the application of this principle to developing urban strategies, urban resilience is not coincided as the return to normality [6]. It is intended as the ability to absorb, adapt and respond to changes in an urban system [7], including various contemporary urban issues, such as sustainability, governance and economic development. For these reasons urban resilience is becoming not only an objective to achieve, but also a necessity to face with the uncertainty, instability and fragility afflicting cities today [3–5, 8].

When applied in planning, urban resilience changes the procedure to define the goal of strategies. It aims to reduce the stresses and hazards which afflicts cities [2–5].

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However, few cities around the world take appropriate action to enhance their resilience. This fact is due to the difficulties concerning its concept. Indeed, urban resilience is a multi-dimensional process rather than a static concept and all urban system dimensions should be included [1, 2, 7–9]. Therefore, its definition and the measure of its implication in urban system is difficult.

Designing policies and strategies to built urban resilience underlines the necessity of understanding the dynamics and complexities of urban systems. It also encourages attempts to explain how these dynamics evolve across temporal and spatial scales [2, 10–13].

Planning with the concept of urban resilience has to consider dynamics and feedbacks across a temporal and spatial scale, so it becomes necessary to use projection techniques for anticipating potential future changes and dynamics in the urban system [2]. Considering this complexity and the aim of using urban resilience as a planning tool, it is fundamental to try to propose an evaluation approach which is able to assess the different strategies by analyzing their dynamic behavior over time and to predict how they could change cities across time and spatial scale [10–14]. The main aim is supporting decision makers in the definition and selection of development strategies [9, 12]. This research will adopt a multi-disciplinary approach to urban resilience based on the theory of evolutionary resilience [6]. From this perspective, resilience is not considered as a return to normality, but rather as the ability of socio-ecological systems to change, adapt and transform in response to stresses and strains [7]. This evolutionary understanding of resilience has been articulated using the metaphor of the famous panarchy model of Holling [15, 16]. Under these circumstances, the evaluation of urban transformation scenarios is therefore a complex decision-making problem where different aspects need to be considered simultaneously [2, 10, 12, 13, 17].

Mention has to be made of the fact that, even if the idea of urban resilience is becoming increasingly important for the assessment of urban transformation scenarios, the applications of this concept for supporting real world decision making processes are lacking or very limited [17–23].

Based on the abovementioned assumptions, the proposed paper aims to investigate the problems related to urban resilience, with particular reference to urban strategy development. It tries to elaborate the evaluation framework [17–25] and apply a System Dynamics Model to simulate changes of the city over time, due to the urban resilience scenario [9–13].

In this paper, a System Dynamics Model has been developed and in order to explore and analyze the main elements fostering or hampering resilience [12]. The model has been used to investigate the impact of actions and strategies for resilience improvement on the dynamic evolution of urban system [13, 26–29].

2 Methodology

2.1 Definition and Background

System Dynamics Models (SDMs) are a theoretical and a computer-aided approach applied to dynamic and complex systems defined by mutual interdependence and feedbacks between variables [30]. They are originated by System Dynamics approach (SD).

SD was introduced by Forrester [31–33] at the end of '50s with the aim to solve the problem of insufficient understanding of the strategic processes related to complex systems [34].

SD is considered an effective tool to analyze and describe complex and dynamic systems through the identification of the interdependent relationships between variables [9, 35]. This approach can help to understand the impacts of various factors on defined objectives in a system and provide useful information for decision makers [26, 35].

Forrester's SD methodology provides the guiding principles to develop a computer model which describes complex and dynamic system through the use of feedback loops, stocks and flows (Fig. 2).

System Dynamics Models (SDM) are useful to describe, model, simulate and analyze dynamically complex issues and/or systems in terms of processes, information, organizational boundaries and strategies [35]. It is based on feedback concepts to handle non-linearity, multi-loop and time-lag characteristics of complex dynamic systems.

SDM is an operative approach to help reveal the temporal behavior of complex systems [27] and it can be applied to model and simulate such as complex dynamic systems to understand the dynamics of systems and design management policy for sustainable development [28, 29]. In the last few decades, an increasing amount of SDM application has been recognized in literature [36]. SDMs are currently used for almost any dynamic and complex system that involves a high degree of uncertainty. Important application domains are transportation [26, 37, 38], land use [39, 40], environment management [41], waste management [41], project management [42, 43] and also sustainable urban development [10, 11, 13, 14, 42, 44].

However, there are few existing studies that have used the SDM for simulating and evaluating urban resilience [12], so this is one of the first application.

2.2 Proprieties

A System Dynamics Model is both qualitative/conceptual and quantitative/numerical (Figs. 1 and 2) [9].

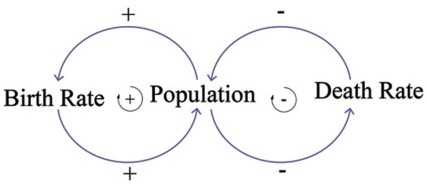

Fig. 1. Population Causal Loop diagram of a population dynamic (Source: [14])

Qualitative modeling can improve the understanding of system functioning [9]. Conceptual modeling is represented by a causal loop diagram [35]. Figure 1 shows a simple single stock model of population where the flow is only due to birth and death [35].

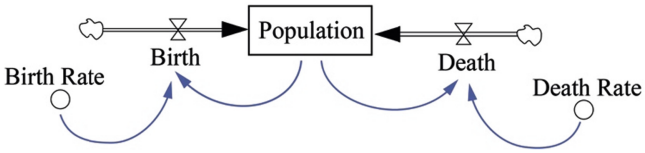

Fig. 2. Stock and flow diagram of a population dynamic (Source: [14], reworked by authors)

Causal loop is a graphic tool used to identify the variables of the system and define the causal effect relationships between them, as shown in Fig. 1. This tool diagrammatically represents the basic mechanism of the system to capture the hypothesis about the causes of its dynamic behavior over time [10, 35]. As Fig. 1 shows, the relationships between the variables can be either positive or negative [35].

Conceptual modelling also makes it possible to better understand the functioning of the system [26, 27].

Quantitative modelling describes the complex system through the stocks and flows model (Fig. 2) [9, 10, 26].

Stock is the first basic building block in SDM. Stocks represent the variables which characterize and describe the condition of the system at any particular time [9, 26, 41, 42]. The second building block in SDM is the Flow. This element tells how stocks change over time [34]. Flows can affect the stocks via inflow or outflow and also interlink the stocks within a system [35]. The third element of SDM is the conveyors, which defines the external inputs to the model. Those variable are related to either externally specified conditions, or to actions/policies [12].

Bases on differential equations, stocks and flows diagram allow the investigation and visualization the effects of different actions within the simulation model over time [10, 11, 43, 44].

3 Application

3.1 Case Study

The case study analysed in this paper aims to define urban resilience strategies for the Basse di Stura area in the city of Turin (Northern Italy). This area is very problematic and its management is complicated. Basse di Stura area is located near the Stura River. Currently, it is a brownfield area, characterized by polluted soil and abandoned buildings exposed to several hazards. Moreover, it is also characterized by complex social and economic conditions, also due to the lack of services [45]. For these reasons, the municipality aims at finding concrete answers to the economic, social, environmental and built environmental needs for this area [45]. In this paper SDM (STELLA®, ISEE Systems Inc.) has been used to investigate and simulate the impacts of two different scenarios, in order to investigate how urban resilience could affect and

change the area over time. The main aim is to investigate the role of SDM in assisting and supporting Decision Makers and planners in designing and managing resilient strategy for the Basse di Stura area.

3.2 Articulating the System Dynamics Model

According to the literature [9, 31, 35], System Dynamics Model is generally built in three general steps: (1) Articulation of the problem or conceptualization, (2) Dynamic hypothesis formulation, (3) Testing and analysis. Figure 3 shows the process followed to structure the decision problem for this specific case study, based on the review of SDM application in urban development field [9–11, 13, 29].

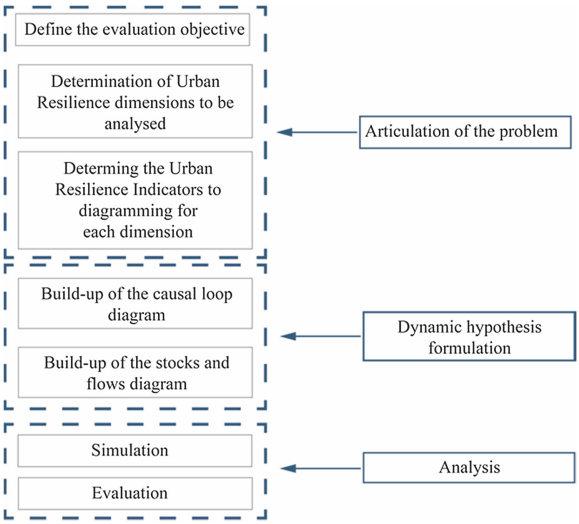

Fig. 3. Structure of decision problem process for the application of SDM (Source: Authors Processing)

3.3 Identifying the Variables of the Model

After the definition of the evaluation objective, in this paper the first step refers to the identification of the urban resilience indicators to be included in the SDM.

For this purpose, a focus group with experts and Decision Makers was organized in order to set up the multidimensional set of variables to be included in the model. As suggested by the literature [2, 17–21, 46], these variables were used both to understand the initial condition of the context and to support planners and Decision Makers in developing strategy and actions to enhance resilience.

It was proposed to the experts and Decision Makers to follow the guideline questions [47] (Table 1) to better identify the appropriate elements from the existing literature of urban resilience indicators [7, 17–21, 25].

Table 1. Questions to be considered (Source: [47])

Who?	Whose Resilience is prioritized? Who is included (and excluded) from the urban system?
What?	What perturbations should the urban system be resilient to? What networks and sectors are included in the urban system?
When?	Is the focus on rapid-onset disturbance or slow-honest changes? Is the focus on short-term resilience or long-term resilience? Is the focus on the resilience of the present or future generation?
Where?	Where are the spatial boundaries of the urban system?
Why?	What is the goal of building urban resilience? What are the underlying motivations for building urban resilience? Is the focus on process or outcome?

Table 2. Urban resilience variables for the SDM (Source: Authors processing)

Dimension	Variables	Description
Economy	New businesses	Number of new businesses created in the area
	Number of jobs	Total number of jobs: existent and news jobs created
Society	Population composition	Percentage of the population differentiation, based on age, sex and ethnicity
	Mixitè index	Index that describes the functional mix of the area
	Health and safety of inhabitants	General condition of health and safety in this area
Built environment	Regeneration	Recovered surfaces
	New construction	New construction land area
	Buildings exposed to hazards	Number of existing buildings exposed to different hazards (example: fire and collapse)
Environment	Permeable surface	Surface of permeable areas
	Soil consumption	Conversion of permeable areas into built areas
	Brownfield	Surface of brownfield area
Governance	Risk reduction	Integration of risk – based planning in the policies for the area
	Funding availability	Municipal budget spent on public services, social protection, investments
	Multi-stakeholders decision planning and decision making	Stakeholders participation in the identification of strategy objectives and actions
	Recovery and restoration	Integration of recovery and restoration in the action plan

Following the questions shown in Table 1, it was possible to identify the key issues on which to intervene (Why? What? Who?) and reasoning about the actions which could be undertaken (Where? When?).

The result of this reasoning process is a multidimensional set of 15 indicators fitted for the case study, which includes the social, economic, environmental and governance dimensions (Table 2).

3.4 Resilient Scenario

Starting from the analysis of Basse di Stura conditions [45] and the identification of the key issues with the support of the guideline questions (Table 1), a preliminary scenario based on urban resilience principle was set up.

The proposed scenario is a medium-long term plan of action (15 years) and it is mainly based on these objectives:

1. Reducing the number of existing buildings exposed to different type of hazards;
2. Reclaiming the brownfield areas;
3. Reducing soil consumption, to try to improve the permeable surface, considering the proximity of the area to the river and also its environmental potentiality;
4. Improving the socio-economic conditions, encouraging the creation of new businesses.

The founding principles of this strategy are the integration of risk reduction, multi-stakeholder decision planning and the recovery and restoration intervention into the strategic plan [23, 24].

The paper considers two different scenarios for the development of the SDM. The inertial scenario thus represents the current plan with no specific actions on the area. The second is the resilient scenario which seeks for the implementation of the transformation of the area, emphasizing the importance of integrating risk reduction, environmental attention and multi-stakeholder participation in the plan actions.

3.5 Causal Loop Diagram

When different variables were identified, it was possible to move to the SDM application. The first phase was to build up the causal loop diagram, as shown in Fig. 4.

To draw the causal loop diagram of the identified variables (Fig. 4) another expert focus group was organized, in which the basis of the cognitive mapping was recalled [48, 49]. In fact, the experts were asked to identify the reciprocal relationships between the chosen multidimensional indicators, considering their expected influence [12]. For example, Fig. 4 shows that “Soil Consumption” has a negative feedback on “Permeable Surface”.

Figure 4 represents the identification of the causal relationships between the social, economic, environmental and governance variables, which effects the urban resilience and its performance, referring to the “Basse di Stura” case study.

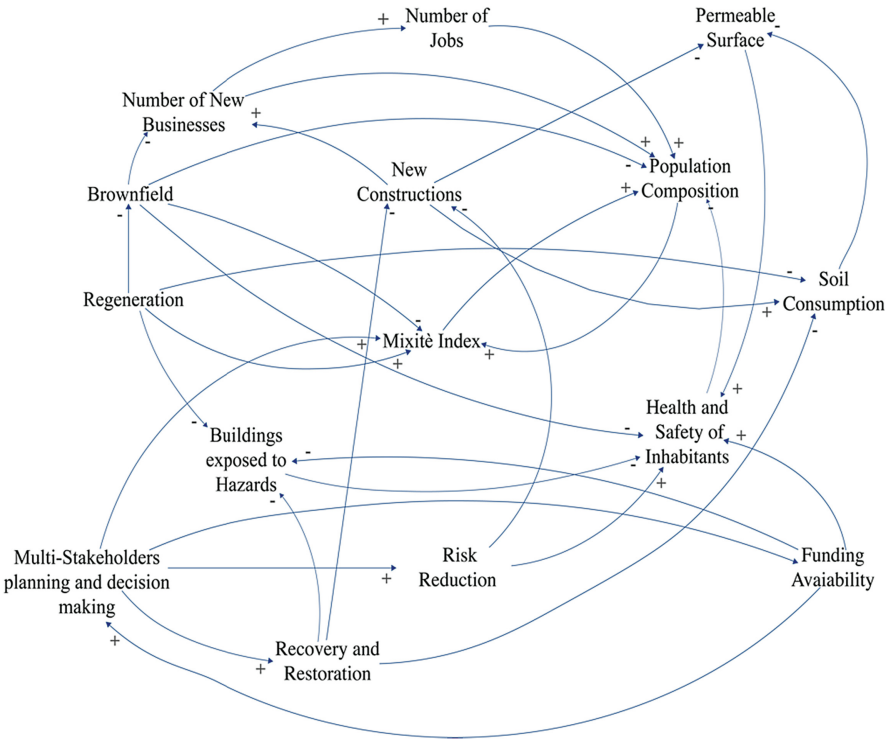

Fig. 4. Causal loop diagram of resilience variables for Basse di Stura scenarios (Source: Authors Processing)

3.6 Stock and Flow Diagram

The conceptual model was used as the basis for stock and flow diagram development. As seen in Fig. 5, some variables have been defined as stock variables and other as flows [14]. However, the strategy principles were translated into the conveyors, because these variables are related to either externally specified conditions, or to actions/policies [12, 35].

The variables identified as stocks are: (1) Brownfield, (2) Health and Safety of the Inhabitants, (3) Buildings exposed to hazards, (4) Soil consumption and (5) Number of Jobs. This choice was made both considering the mutual interdependence between the indicators and the main objectives of the resilient scenario.

Differential equations have been developed for the SDM simulation (Figs. 6, 7 and 8). As an example, we can consider the following equation:

$$\text{Soil Consumption}(t) = \text{soil consumption}(t - dt) + (\text{new construction}) * dt \quad (1)$$

According to this equation, the soil consumption simulation is given by the current soil consumption at the year 0 (Fig. 6) plus the new construction surface.

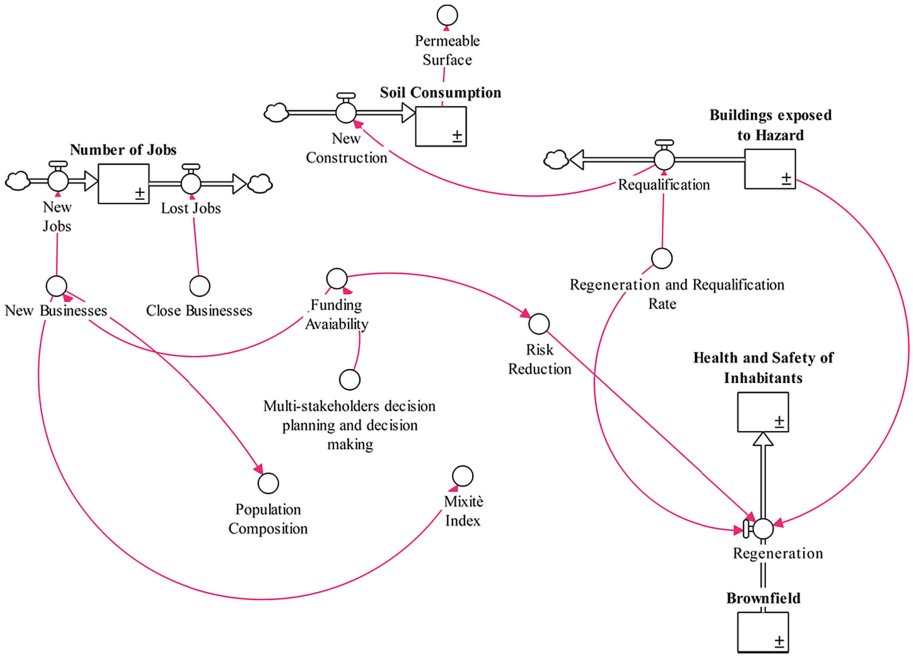

Fig. 5. Stock and flow diagram for Basse di Stura scenarios (Source: Authors processing)

Analogously, other specific equations were developed for the application of the SDM.

It is necessary to reiterate that the aim of this paper is to simulate through the SDM the possible effects over time of scenario inputs and their possible influence in enhancing urban resilience [12].

3.7 Scenarios Simulation and Analysis

The two different scenarios are simulated using SDM (STELLA®, ISEE Systems Inc.), starting from the stock and flow diagram (Fig. 5) which accounts the complexity and dynamic interactions among the multidimensional variables.

The SDM was built to analyze and compare the two different scenarios (inertial and resilient), relying on the prediction of their possible evolution and effects on urban system over time [10, 13, 14].

The main objective of this application was to experiment the use of SDM to evaluate evolution and changes of future transformation scenarios.

In this case, simulations were performed as a "what if" analysis [50] starting form a baseline conditions. The "what if" analysis supports in measuring how changes in a set of independent variables may influence depend variables in a simulation model [12, 35]. Figures 6, 7 and 8 show the results of SDM simulation.

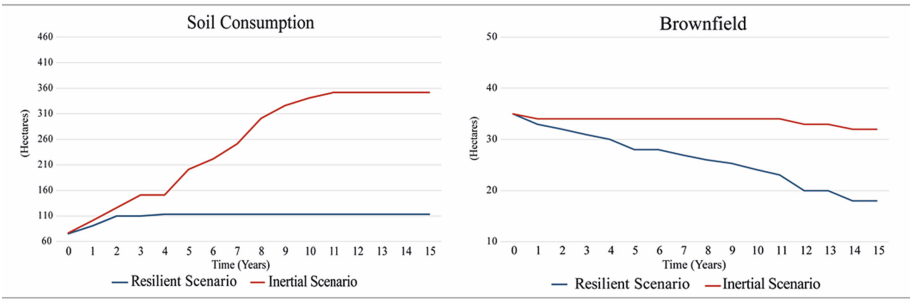

Fig. 6. SDM simulation of environmental variables, scenarios comparison (Source: Authors processing)

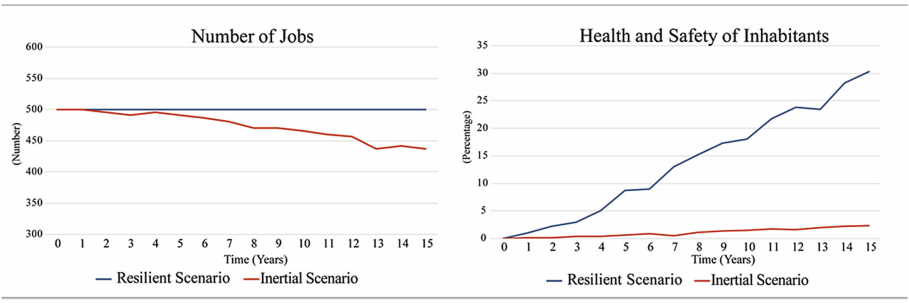

Fig. 7. SDM simulation of economic and social variables, scenarios comparison (Source: Authors processing)

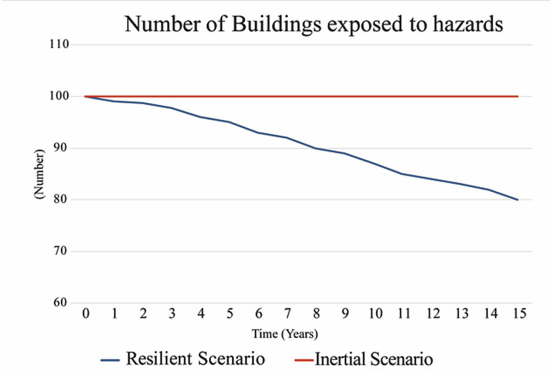

Fig. 8. SDM simulation of built environment variable, scenarios comparison (Source: Author processing)

4 Discussion of Results

The SDM development was implemented to simulate the different impacts and changes over time generated by the two scenarios [10, 12, 32].

It is important to reiterate that this SDM simulation aimed to assess how the resilience scenario could affect urban system and improve its initial condition, following the medium-long term intervention.

The simulation results are shown by Figs. 6, 7 and 8. In these figures the different developments over time (15 years) of the two scenarios have been compared.

From these figures, it is possible to see that the "Resilient Scenario" and the "Inertial Scenario" have significant differences in performance in "soil consumption" and "brownfield" (Fig. 6), "health and safety of inhabitants" (Fig. 7) and "number of buildings exposed to hazard" (Fig. 8). It seems that the resilient scenario could have a positive impact over time in these dimensions, in accordance with its initial objectives. In fact, "Resilience scenario" shows a considerable minor quantity of soil consumption and also a considerable decrease in "brownfield" (Fig. 6) and also in "building exposed to hazard" (Fig. 8). These last behaviors are also related to the improvement of the social variable "health and safety of Inhabitants" (Fig. 7), as underlined in causal loop diagram (Fig. 4).

5 Conclusion

The paper illustrates the application of the SDM to simulate two different urban scenarios, in order to assess how urban resilience applied in planning strategy could affect and change urban system over time.

This application aims to verify the effectiveness of SDM in evaluation of urban resilience strategy [12]. The main objective is to try to answer to the need of measure this multidimensional process by its effects over time [2, 9, 51]. In fact, planning with the concept of urban resilience has to consider dynamics and feedbacks across a temporal and spatial scale [51], so it becomes necessary to use projection techniques to anticipate potential future changes and dynamics in the urban system [11, 14, 17, 52–55].

This study has identified several findings. The most important can be summarized as follows. SDM represents not only a useful tool to simulate the evolutionary behavior of the system over time, considering the mutual interrelationships between its variables, it is also an appropriate instrument to integrate the opinion of different experts and Decision Makers, through its conceptual model (Fig. 4). In this way, participation should be an integral part of the planning process [6, 56–58].

The paper has also shown that SDM is a useful tool to see how the effects of the scenarios could change in relation to different inputs [12], so it should also use as participative and iterative planning process tool [9, 12, 14].

Although the strengths of these important findings, one limitation of this study is the lack of the simulation of the impacts on spatial scale, referred to urban resilience [2, 10, 12, 19]. For this reason, it will be interesting to integrate SDM with GIS to evaluate the effects of urban resilience strategies not only over time but also in spatial scale [10]. It should be an interesting research field in order to introduce and integrated tool which

could show processes and impacts in a unique map, to better understand the changes also by Decision Makers.

Taken together, the results of this application demonstrate that SDM is an effective tool for evaluating urban resilience over time, considering its multidimensionality and dynamic behavior.

The application also demonstrates that SDM can be used as tool to set up the strategy and chose the action to be undertaken [59–61], taking into account the opinion and the needs of the different stakeholders [56].

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