# Fuzzy Cognitive Maps: a dynamic approach for urban regeneration processes evaluation

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*keywords:* Fuzzy Cognitive Maps, urban regeneration, scenario simulation, scenario planning

## Abstract

*Cities are complex, dynamic and adaptive systems that are in continuous evolution. This trend is influenced by causal relationships that occur between the social, political, economic and environmental dimensions that are at the basis of the urban system. Starting from these circumstances, investigating and evaluating the city as a complex and adaptive system has become a fundamental issue in the context of urban transformation and regeneration operations. These are complex and dynamic processes both in temporal and spatial scale that are characterised by a multiplicity of variables, objectives and interests. For these characteristics, they represent particular decision problems described by an high level of uncertainty especially related to the appraisal of their possible future impacts on the social, economic and environmental dimensions.*

*Currently, in the fields of urban studies a promising approach is represented by the Fuzzy Cognitive Maps (FCMs). The peculiarity of this technique is the ability both to describe and analyse the functioning of complex systems through a cognitive map and to simulate their possible evolution, starting from the current conditions. For this reason, the technique of FCMs has been applied to study and analyse complex systems, related to those domains characterised by a high level of uncertainty, such as cities and their transformation processes.*

*This paper shows the application of an integrated evaluation approach based on the FCMs technique to two different urban regeneration processes. The article aims to underline both the strenghts of this technique, focusing on its ability to represent and manage the complexity of urban regeneration processes, and the critical aspects to identify the elements that to be developed in the future researches.*

## 1 INTRODUCTION

Cities are complex and dynamic systems (Batty, 2008; Holling, 1973) that are characterised by cause-effect relationships that occur between the social, economic, political and environmental dimensions. These relationships are the basis of both the functioning and the evolutionary trends of cities. Urban and territorial transformation operations are complex decision problems that are distinguished by a multiplicity of aspects and objectives which are introduced by the stakeholders involved (Dente, 2014; Angilella et al., 2016). Moreover, the high level of uncertainty constitutes another relevant aspect that characterises territorial transformations and urban regeneration processes (Roscelli, 2005) represented by dynamic processes that are characterised by an evolution, a diversification and instability (Mondini, 2009).

Specifically, this paper analyses two case studies related to two different urban regeneration programs.

In this specific context, it is necessary to understand the real meaning of the urban regeneration concept (Garsia, 2015). This clarification is fundamental to identify which are the suitable tools able to manage the complexity and to reduce the uncertainty that can be used to support the decision making process.

In its real meaning, urban regeneration means not only building-restoration operations, but also programs aiming at eliminating social decline, increasing the quality of life of the inhabitants, supporting the valorisation of cultural resources, protecting the environmental system, bringing economic development (Roberts, 2000). Furthermore, urban regeneration has to be considered as a dynamic, continuous and long term process that is strictly related to the context and to the necessity of citizens (Garsia, 2015). The high level of uncertainty that characterizes these decisional processes is well represented by the long term aspect. The urban regeneration process will not produce immediate effects. Indeed, the transformation process will not end with the end of the physical interventions, but it implies long term effects which occur after some years (Giuffrida et al., 2017).

For the abovementioned considerations, urban regeneration is a complex and dynamic process and its effects are distributed over time. For these reasons, it is necessary to understand and predict the possible effects of the action through an ex-ante evaluation (Mondini, 2009; Fattinnanzi, 2018; Fattinnanzi et al., 2018; Fregonara et al., 2018; Dell'Anna et al., 2019). This necessity is strictly related to mutual influence between the physical, economic, social and environmental dimension (Garsia, 2015; Roberts, 2000).

Thus, It is necessary to use tools able both to consider the multidimensionality and to predict the possible effects generated by transformations (Blecic, 2016).

This paper shows the application of an integrated evaluation approach based on the Fuzzy Cognitive Maps (FCMs) technique to two different urban regeneration programs. In these applications, the FCMs have been used as an evaluation tool to select the preferable transformation strategy considering the dynamic behaviour and long term effects. FCMs have been chosen as evaluation tool for their ability to both represent the functioning of a complex system through a cognitive network and to simulate its possible evolution over time. The purpose of these applications is to investigate the efficacy of the use of this methodology to support decision making process related to its ability of show the dynamic evolution of complex systems and analysing their possible future impacts.

## 2 METHODOLOGY

Fuzzy Cognitive Maps (FCMs) are a technique used to describe and represent the functioning and the dynamic behaviour of complex systems. They have been introduced by Bart Kosko (Kosko, 1986), who suggested their use to those knowledge domains characterised by a high degree of uncertainty. For their characteristics, the technique of Fuzzy Cognitive Maps (FCMs) represents the natural extension of cognitive maps (Axelrod, 1976).

FCMs are used to represent and describe complex systems through a "Cognitive network" (Fig.1) that is an aggregate network of concepts and weighted interconnections. This graphical representation is based on the causal reasoning and it allows to describe a complex system in a simplified way. Furthermore, the cognitive network permits also to note experts' different knowledge about the behaviour of the same system (Axerlod, 1976).

The technique of FCMs is also employed to reveal the dynamic behaviour of the system, describing how it could evolve over time, starting from the initial conditions. For this reason, this approach is considered a useful tool in the context of scenario planning and decision making. Infact, it can be applied to evaluate different alternatives using a complementary analysis. However, the main peculiarity of the FCMs is their ability to describe and analyse the dynamic behaviour of the analysed system. Infact, starting from the initial conditions and considering the mutual influences between the variables they can predict the possible future state and the stability. For these reasons, the technique of FCMs can be considered a suitable tool for the analysis of the evolution of alternative scenarios (Jetter and Kok, 2014). Infact, FCMs can support the decision process using complementary analysis (Kok, 2008) expecially in those fields that are complex and uncertain (Olazabal, 2015). FCMs are flexible tools that have been applied in different contexts (Papageorgiou, 2013), including environmental assessment (Ozemi and Ozemi, 2003; Ozemi and Ozemi, 2004; Mithos et al., 2017), engineering and technological management (Jetter, 2006) and energy planning (Jetter and Scheweinfotrt, 2010).

### 2.1 Properties

As mentioned before, the most important characteristic of the FCMs technique is their ability to describe complex systems through two different typologies of representation:

1. Graphical representation, that is composed by nodes and weighted directed edges. The cognitive network is constituted by these elements (Fig. 1);
2. Mathematical representation, that is represented by the state vector A and the adjency matrix E.

Considering these two different typologies of representation, the elements which compose FCMs in their complexity are:

- *Concepts*: $C_1, C_2, ..., C_n$. These elements represent the variables that compose the system;
- *State vector*: $A = (a_1, a_2, ..., a_n)$, where $a_i$ indicates the initial state and the value of the general concept $C_i$. The values that are assigned to the concepts are included in the range [0;1];
- *Directed edges*. That symbolize the cause – effect relationship between concepts $C_i$, $C_2$ and are visualized as arrows in the graph;
- *Adjacency matrix* $E = \{e_{ij}\}$ where $e_{ij}$ is the weight of the direct edge $C_iC_j$. The values that are assigned to each relationship are included in the range [-1;1]. The value 0 means that between the general concepts $C_i$ and $C_j$ there is not any causal relationship.

## 2.2 Mathematical representation and dynamic behaviour simulation

As mentioned before, the main characteristic of the technique of FCMs is their ability to describe and simulate the dynamic behaviour of complex systems, starting from the causal-effect reasoning.

To obtain the dynamic behaviour of the system, it is necessary to refer to the mathematical representation and to the relative mathematical method.

The simulation is the result of the iterative process between the state vector A and the adjacency matrix E.

The iteration process is performed by the following formula:

$$A_i^{(t+1)} = f\ (A_i^{(t)} \cdot E) \quad (1)$$

where:

$A_i^{(t+1)}$ is the value of concept $C_i$ at moment *t+1*;

$A_i^{(t)}$ is the value of concept $C_i$ at moment *t*;

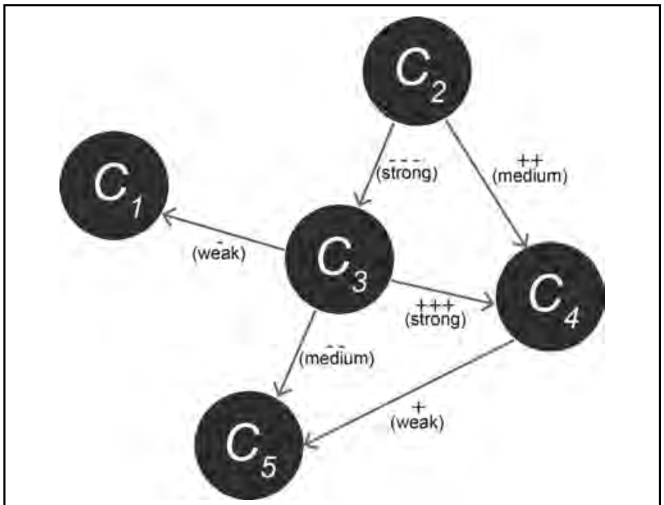


**Figure 1-** *Fuzzy Cognitive Maps, the cognitive network (Source: Bottero et al., 2017)*

The function $f$ is a threshold function (Olazabal et al., 2015; Jetter and Kok, 2014; Kok, 2008; Tsadiras, 2008), that is used to normalize the values assumed by concepts, at each iteration, in the range [-1; 1]. According to the literature (Kok, 2008; Olazabal et al., 2005; Jetter and Kok, 2014) the iterative process should be repeated at least 2xn times in order to identify effects (where n is the total number of concepts). In practice, the dynamic behaviour of the system can emerge after 20-30 iterations. It is essential to underline that the simulation is not to be intended as the exact prediction of quantitative values but rather it aims at identifying the general patterns of system's behavior.

From the iterative process, four possible behaviour can emerge (Fig. 2):

1. The concepts can implode and all values converge to zero (Fig. 2a);
2. The concepts can explode and all factors increase and decrease indefinitely (Fig. 2b);
3. There is a cyclic stabilization of the system (Fig. 2c);
4. All the concepts can stabilize at a constant value or remain the same in time (Fig. 2d).

## 3 APPLICATION

As mentioned in section 1, this paper shows the application of the FCMs as an evaluation tool for two different regeneration programs (Bottero et al., 2017; 2019). In both applications, the evaluation and the analysis of the dynamic behaviour of strategies have been made following these criteria:

1 Resilience and adaptation that indicate the capacity of the urban system to change, adapt and transform in response to stresses and strains (Desouza, 2013). Specifically, the number of oscillations, their amplitude and frequency have been considered for the evaluation of these criteria;

2 Number of iteration required by the system for reaching the equilibrium;

3 Final values of the concepts at the equilibrium considering their congruence with initial objectives.

### 3.1 Structuring the decision problem

A multi-dimensional approach has been employed to frame the decision problem in both applications, that combines (Fig. 3):

1. The **SWOT Analysis** which is a technique used to support the definition of strategies in those contexts that are characterized by high level of complexity and uncertainty, such as urban regeneration process (Storti, 2009; Mondini, 2009). Specifically, in these applications the swot analysis has been utilized to analyse and describe the urban context in order to underline the strengths, weaknesses, opportunities and threats.

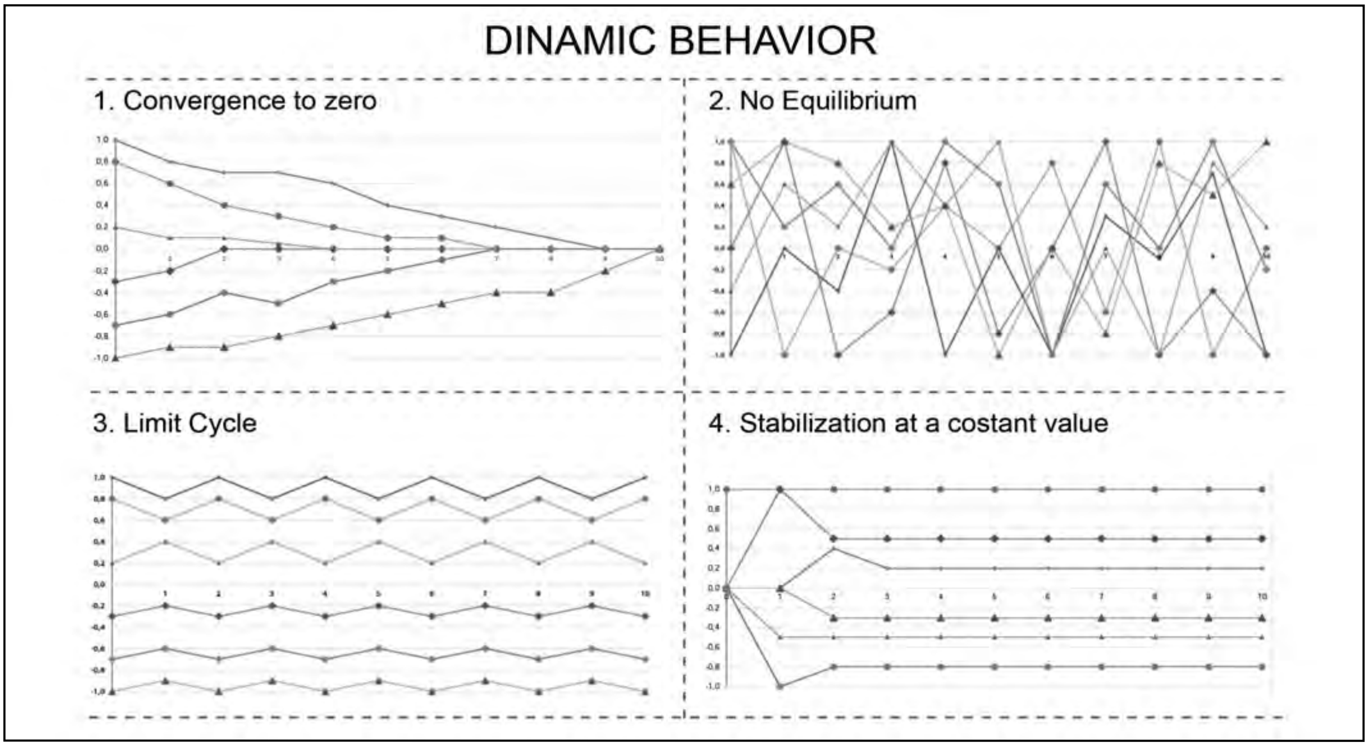


**Figure 2 -** *Possible dynamic behaviours (Source: Bottero et al., 2017)*

Therefore, this analysis has been useful to define the objectives of interventions and to formulate the transformation alternatives;

2. **The Stakeholder analysis** (Dente, 2014; Yang, 2014) that allows to identify all stakeholders involved within the transformation process, both those who can intervene in the decisional process in a tangible way and those who are only influenced by the process. In the urban transformation context, this analysis is essential because it also identifies the stakeholders' resources and objectives, showing possible conflicts;
3. **Fuzzy Cognitive Maps (FCMs)** (Kosko, 1986; Jetter and Kok, 2014) that are a technique used to study and describe the functioning of complex systems and to simulate their dynamic behaviour over time. In these applications, the FCMs have been applied to analyse the functioning of urban regeneration processes with the objective to simulate the dynamic behaviour of the different strategies.

## 4. Case studies

### 4.1 Urban regeneration program "Collegno Rigenera"

The first case study refers to the urban regeneration program developed for the city of Collegno (TO). This program has been promoted by the municipality to resolve and improve the critical conditions that afflict the social and economic sectors of the city. The municipal territory of Collegno is characterised by an irregular urban development and also by a high presence of decommissioned industrial areas.

Under this circumstance, the FCMs have been applied for the evaluation of six urban regeneration strategies (Fig. 4). These alternatives have been evaluated through the multi-methodological approach based on FCMs (Fig. 3) that allowed to consider their possible future effects. Through this approach, it was possible to chose the strategy that show a stable evolution and coherent effects with the initial objectives of the regeneration program (Bottero et al., 2017; Datola, 2017).

#### 4.1.1 Identification of criteria

After having structured the decision process, recognised the stakeholders (Bottero et al., 2017) and identified the objectives related to the program, the subsequent phase was to decompose the general aspects that distinguish the transformation. The result is a multidimensional set of criteria that refer to the social, economic, environmental, services and mobility factors. Table 1 lists these criteria that are also the nodes of the FCM (Fig. 6).

#### 4.1.2 Alternative transformation strategies

Six transformation alternatives that have been evaluat-

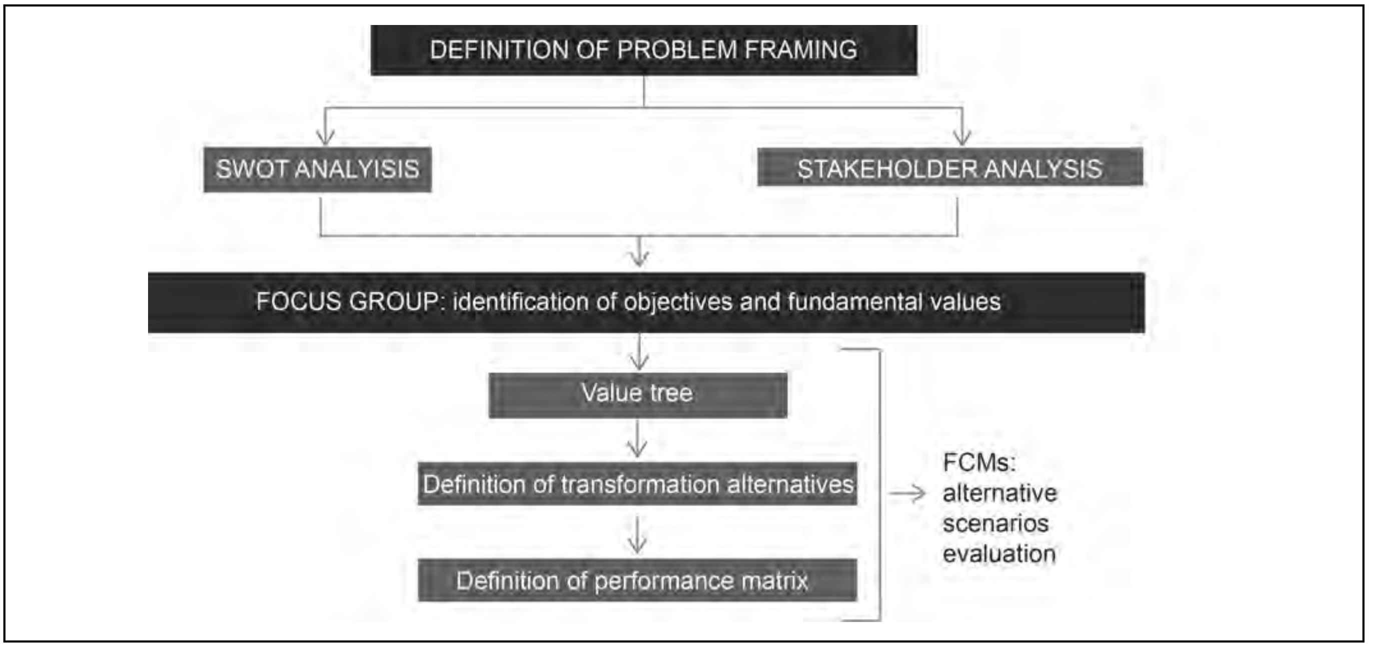


**Figure 3** - *Structuring of the decision problem (Source: Authors' processing)*

ed through the multi-methodological approach can be described as follows:

1 **Cultural District.** The objective of this strategy is creating new cultural services for the intervention area, such as a new public library and student residences;
2 **Smart City.** This plan aims to connect the area of intervention with other neighbouring. For this reason, its priority is working on infrastructures with a particular attention to slow and sustainable mobility;
3 **Start-Up.** This strategy proposes the recovery and requalification of the abandoned building to reduce the soil consumption. Its target is to create a new centrality for this area;
4 **City and Craft.** It is based on the creation of a new urban park, located at the margins of the intervention area. The main objective is to give to inhabitants a new multifunctional urban park;
5 **Sharing city.** This strategy aims to realize a people-oriented city through intervention focused on the stitching of the urban context;
6 **Green infrastructures.** The objective of this plan is to make city more liveable through the integration of those necessary services, such as green spaces and slow mobility.

## 4.2 The requalification of the Bochard military barrack

The second case study concerns the requalification project of the Bochard military barrack that is located in the city of Pinerolo (Nothern Italy). This program has been introduced with two specific targets. Firstly, it aims at giving a solution to the big urban void located in the centre of the city, which aroused from the demission of the military barrack. Secondly, it is grounded on the improvement of the social and economic conditions of the area. And in this case, the FCMs have been applied to evaluate, analyse and compare alternatives considering both their dynamic behaviour and their effects on the social, economic and environmental dimensions over time (Bottero et al., 2019).

### 4.2.1 Identification of criteria

Further for this case study, the SWOT and the stakeholder analysis have been fundamental to identify objectives, actors and interests that have been included in the decision making process. The result is a multidimensional set of criteria that refer to the social, economic, management and architectural dimension (Table 2).

### 4.2.2 Alternative transformation strategies

The five strategies developed for the requalification of the Bochard barrack can be illustrated as follows:

1 **Productive Scenario**. This strategy aims at creating spaces dedicated to co-working and workshops and also new markets for the sale of local products;
2 **Cultural Scenario.** This project is mainly focused to the construction of spaces for co-working, classrooms and a library;

**Table 1** - *Description of criteria for the Collegno Rigenera programme (Source: Bottero et al., 2017)*

| | |
|---|---|
| $C_1$: Public / private space | Ratio between public and private surfaces |
| $C_2$: Co-working spaces | Surface of the structures for workshop, meeting, training courses |
| $C_3$: Co-housing inhabitants | Number of inhabitants in new co-housing buildings |
| $C_4$: Permeable surface / territorial surface | Ratio between permeable areas and overall territorial surface of the program |
| $C_5$: Urban gardens | Total area used for community and private urban gardens |
| $C_6$: Waste production | Amount of waste produced in a year by the activities of the program |
| $C_7$: Residence | Surface for residential functions |
| $C_8$: Retail areas | Surfaces for commercial functions |
| $C_9$: Sport and leisure areas | Surfaces for sport and cultural activities |
| $C_{10}$: Mixité index | Index that describes the functional mix of the area |
| $C_{11}$: Slow mobility | Surface of the pedestrian tracks and bicycle lanes |
| $C_{12}$: New public parking | Number of new public parking lots |
| $C_{13}$: Car sharing/bike sharing | Number of car and bike sharing points |
| $C_{14}$: Total Economic Value | Estimate of the social benefits delivered by the program |
| $C_{15}$: Investment cost | Total cost of the program |
| $C_{16}$: New jobs | Number of new jobs created |
| $C_{17}$: Regeneration | Regenerated surface |
| $C_{18}$: Via De Amicis regeneration | Qualitative index showing the level of the regeneration of Via De Amicis |
| $C_{19}$: Territorial index | Ratio between the maximum buildable volume and the territorial surface |

3 **Artistic Scenario**. The main interventions of this strategy are focused on the realization of a theatre, a school music, artistic atelier and exhibits;

4 **Productive Scenario 2.0**. This plan provides for both the demolition of some parts of the barrack and the recovery of those are well conserved. The objectives is to dedicate these spaces to the sale of local product and co-working spaces;

5 **Cultural Scenario 2.0**. This strategy plans the recovery of those parts of the barrack that are well conserved, in order to create spaces dedicated to co-working and to the sale of local products.

## 5. APPLICATION OF FUZZY COGNITIVE MAPS (FCMS)

Once having structured the decision process through the SWOT and the stakeholder analysis and identified the criteria (Fig. 3), it was possible to apply the FCMs to

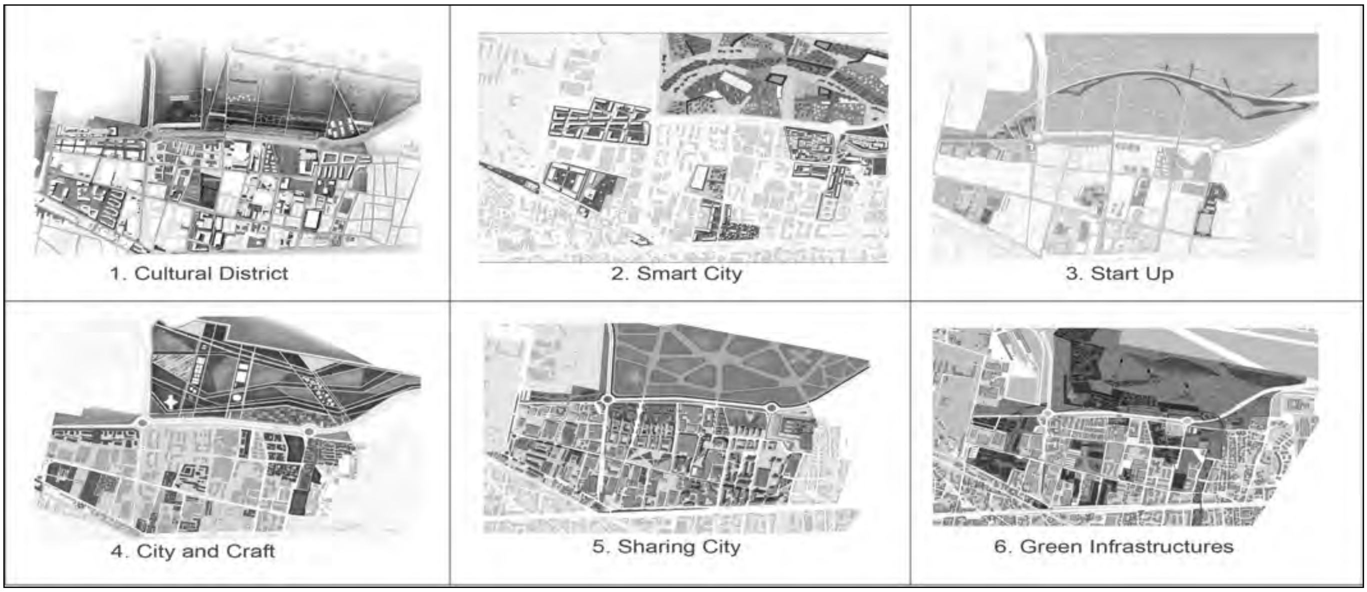


**Figure 4 -** *Six transformation alternatives for the urban regeneration program (Source: Authors' processing)*

**Table 2 -** *Description of criteria for the requalification project (Source: Authors' processing)*

| | | |
|---|---|---|
| **Socio-Environmental Aspects** | $C_1$ Cultural functions | Inclusion within the project area of functions, such as classrooms, music schools or other activities |
| | $C_2$ Mixitè Index | Index that describes the functional mix of the area |
| | $C_3$ Smart policies | Attention Presence of project elements oriented towards sustainability (e.g., use of renewable energy sources) |
| | $C_4$ Green areas | Total permeable surfaces in the project |
| **Management aspects** | $C_5$ Management cost | Operation and management costs of the structure |
| | $C_6$ Opening hours | Opening hours of the structure |
| **Economic aspects** | $C_7$ Total investment | Total cost for the requalification intervention |
| | $C_8$ New jobs | Number of new jobs created by the project |
| | $C_9$ Profitability | Income generated by the project |
| **Architectural Aspects** | $C_{10}$ Architectural quality | Quality of architectural project for the intervention |
| | $C_{11}$ Space flexibility | Possibility of space flexibility depending on the type of activities being carried out |
| | $C_{12}$ Accessibility | Facility to reach the area with several means of transport, public transport, pedestrian and cyclo-pedestrian paths |

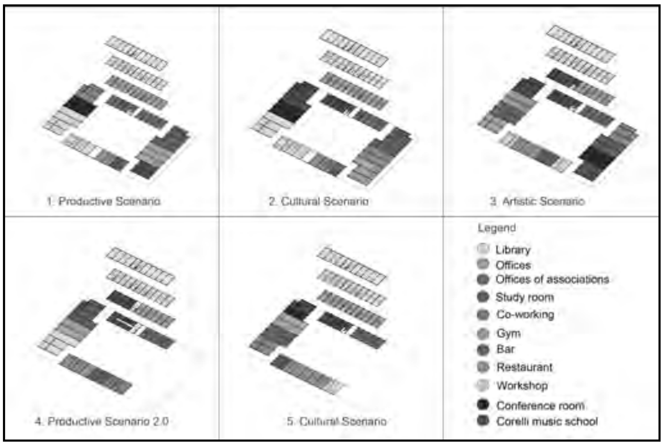


**Figure 5 -** *Transformation strategies developed for the ex military barrack*
*(Source: rielaboration by the authors of Damiano and Djarov, 2017)*

assess the transformation scenarios developed for the two regeneration programs.

The two fundamental phases that will be explained in this section are:

1. Identification of causal-effect relationships and FCMs construction;
2. Exploration of dynamic scenarios

## 5.1 Identification of causal-effect relationships and FCMs construction

The first phase of the FCMs application consists in the identification of the mutual causal relationships that occur between the concept previously identified. This passage is fundamental for the construction of the FCM.

In both applications, the maps have been elaborated by a multidisciplinary panel of experts. This panel was composed by an economic expert, an architect and a planner. In this way, through the FCMs (Fig. 6 and Fig. 7) that collect the opinion of three different expert about the same problem, it was possible to analyse the decisional problem with a multidisciplinary perspective.

Specifically, Figure 6 shows the FCMs developed for "Collegno Rigenera" program and the Figure 7 illustrates the FCMs designed for the requalification of the Bochard barrack.

These FCMs are both characterized by an aggregate network in which positive and negative relationships have been identified with their level of influence (weak, medium, strong).

Analysing the structure of these two FCMs, it is possible to notice that the two networks have a different level of complexity. Indeed, the FCM that is referred to Collegno regeneration program shows a major complexity being described by a higher number of causal relationships. In this sense, it is important to underline that this instrument is able to graphically describe the complexity of the decision problem.

## 5.2 Investigating dynamic scenarios

The subsequent step refers to the employment of the FCMs to explore dynamic behaviours of scenarios. This simulation has been obtained by the formula 1, that represents the combination of the state vector A with the adjency matrix E. It is important to underline that in these applications the state vector A has been employed to represent and describe the initial configuration of alternatives. To obtain a state vector with these characteristics, the performance matrix of the alternatives developed for Collegno and Pinerolo have been normalized. This operation has been performed to obtain values included within the interval [0;1]. The standard-

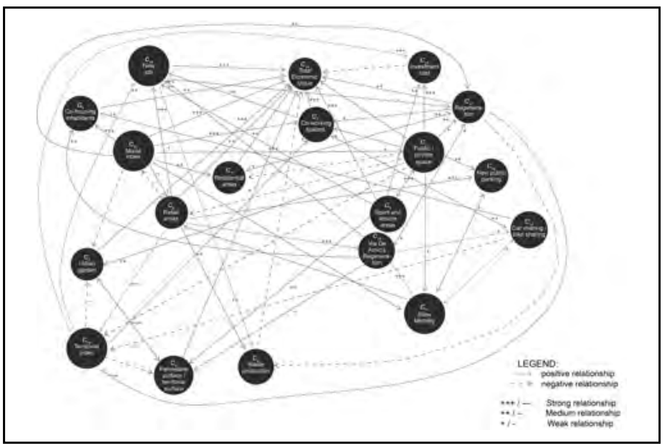


**Figure 6 -** *Fuzzy Cognitive Maps for "Collegno Rigenera" program*
*(Source: Bottero et al., 2017)*

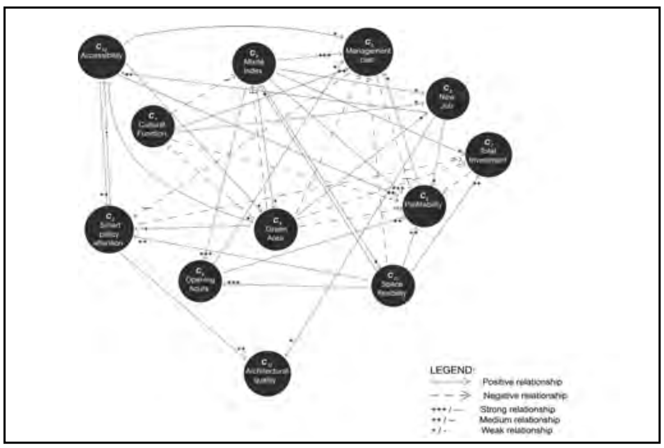


**Figure 7 -** *Fuzzy Cognitive Maps for the requalification of Bochard barrack*
*(Source: Bottero et al., 2019)*

ization has been carried out following this formula:

$$a_i = (x_i - x_{min}) / (x_{max} - x_{min}) \quad (2)$$

where:

$x_i$ is the initial value of the criterion;

$x_{min}$ e $x_{max}$ are the minimum and maximum value

Figure 8 shows the dynamic behaviours of the six alternatives developed for the “Collegno Rigenera” program. Whereas, Figure 9 illustrates the result of the scenarios simulation of the five alternatives designed for the requalification of the Bochard barrack. In detail, these graphs have on the x axis the number of iterations and on the y axis the value of different considered criteria.

In both applications, the evolution of scenarios has been analysed and evaluated through these criteria:

1. Number of iteration required by the system for reaching the equilibrium;
2. Stability of the system, frequency and amplitude of iterations;
3. Final values of the concepts at the equilibrium.

## 6. DISCUSSION OF RESULTS

Figure 8 and Figure 9 illustrate the scenario simulation that analyse the possible evolution of the considered

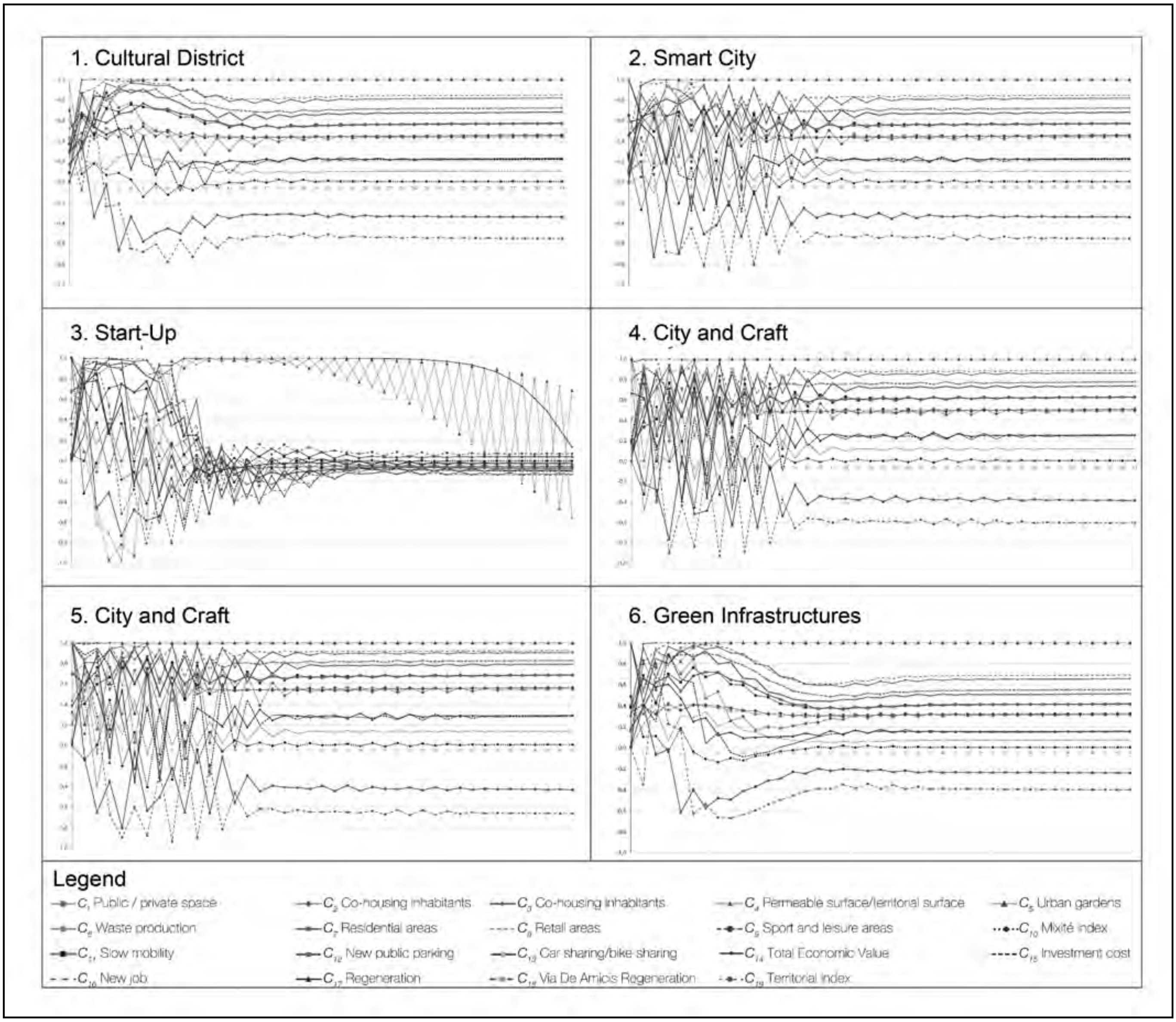


**Figure 8 -** *Scenario simulation of six transformation alternatives for Collegno Rigenera (Source: Bottero et al., 2017)*

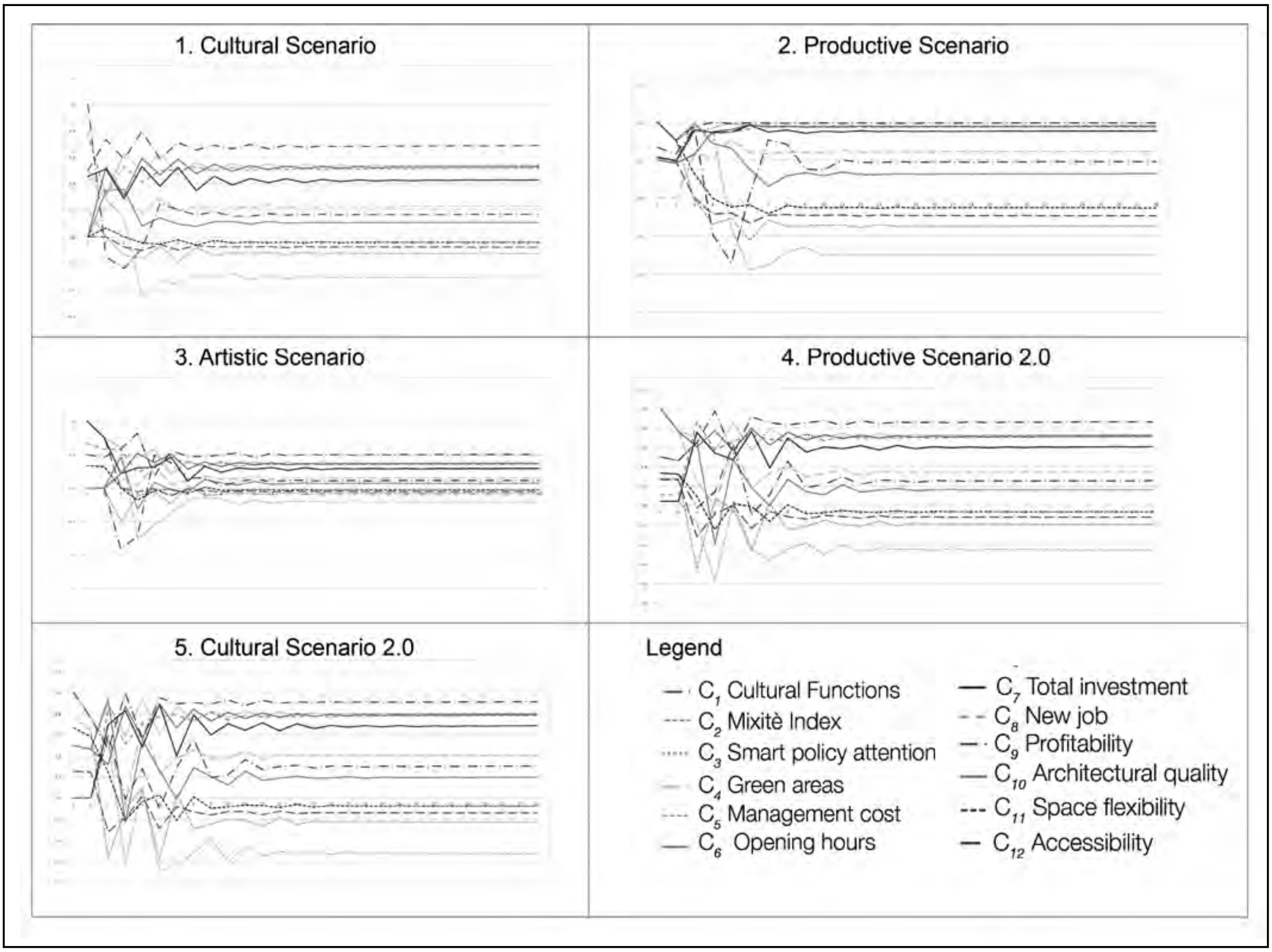


**Figure 9 -** *Scenario simulation of the five alternatives developed for the Pinerolo military barrack (Source: Bottero et al., 2019)*

transformation alternatives. According to the used criteria for the evaluation of the scenarios, the alternatives that can be considered most stable for number of iterations and amplitude of oscillation are  the "Cultural District" and the "Green Infrastructures" for Collegno Rigenera and the "Cultural Scenario" for the requalification of the military barrack are comparable. Therefore, a further assessment has been performed in both cases. This additional evaluation provided the comparison of the long term effects of these selected scenarios. The task of this assessment was to determine which impacts these scenarios may have and in which entity. This evaluation has been performed considering the coherence of the effects with the initial objectives of the regeneration programs. Two radar graphics (Fig. 10 and Fig. 11) have been produced to represent and compare the values assumed by criteria at the end of the iterative process.

Through this evaluation, it was possible to chose the "Cultural District" for the case study of Collegno and the "Cultural Scenario" for the Bochard barrack. The "Cultural District" has been selected for the program "Collegno Rigenera" for its capacity to improve the condition of the ratio between public and private space; similarly, the "Productive Scenario" has been chosen for the requalification of the Bochard barrack because it might improve the profitability reducing the management cost in the medium-long period.

## 7. CONCLUSION

This paper compares the application of the multi-methodological approach based on the FCMs for the evaluation of the transformation alternatives developed for the two regeneration programs in the Torino metropolitan area. This comparison underlines both the potentiality and the weaknesses of the proposed methodology. The main strength that emerged from these applications is the

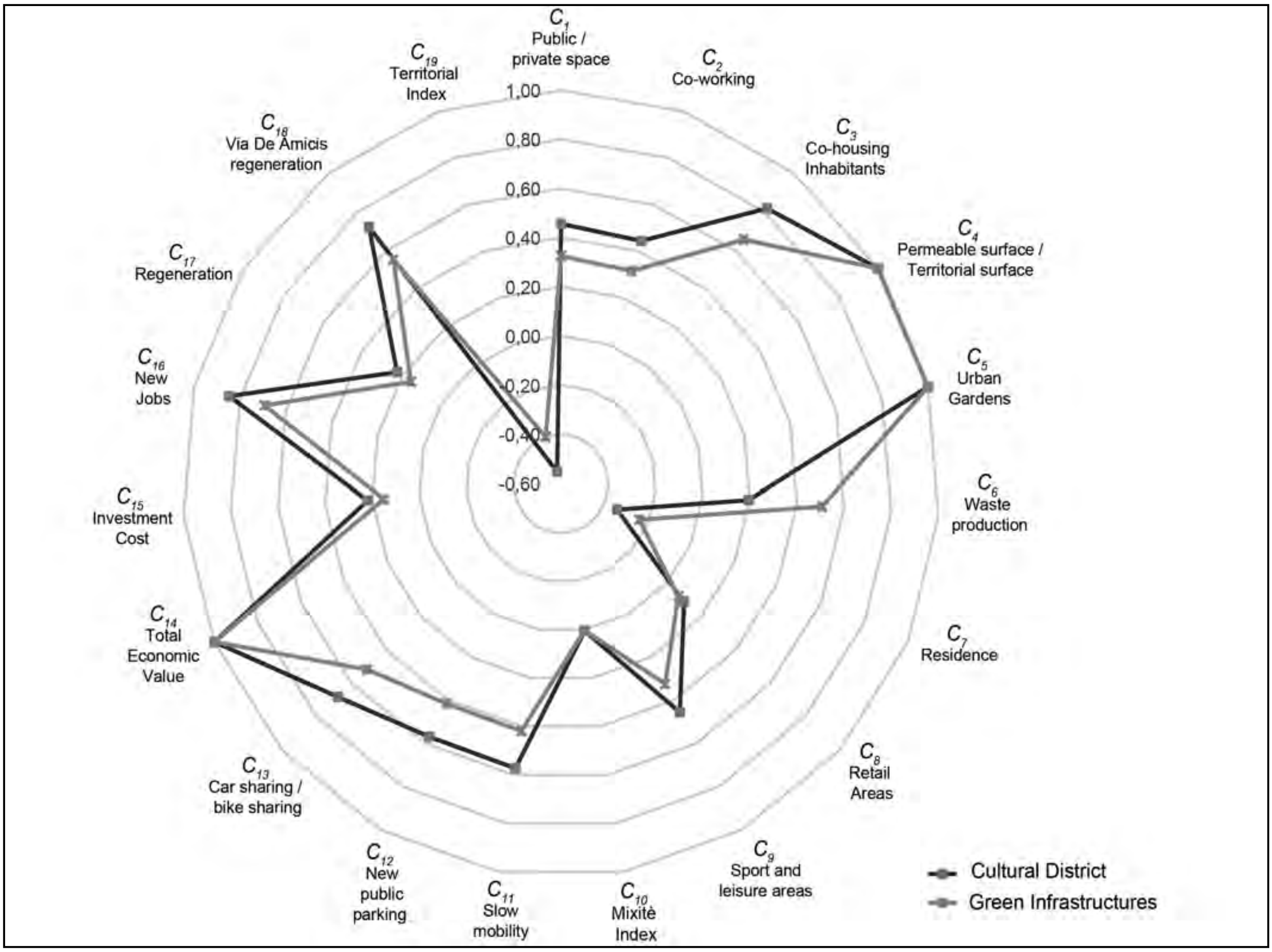


**Figure 10 -** *Radar graph to compare "Cultural District" and "Green Infrastructures" for the program "Collegno Rigenera" (Source: Bottero et al., 2017)*

repeatability of this approach to different decision processes (Bottero et al., 2018). Furthermore, these applications have demonstrated the efficiency of this approach in managing the complexity of the decision-making process related to urban regeneration programs. Indeed, the graphical representation of FCMs has been useful for two reasons. Firstly, it allowed to analyse the decision problem through a multidimensional and multidisciplinary perspective by the aggregation of different experts' opinion in a unique map. Secondly, the phase related to the identification of the causal relationships contributed to the improvement of the knowledge of the functioning of the system considered. Furthermore, the analysis of the dynamic behaviours has been helpful to explain the real nature of the regeneration process. As mentioned in previous section, it is a process inserted in an urban context with its consolidated functioning and equilibrium (Saporiti, 2012). Indeed, simulations underlined that different scenarios have comparable behaviours.

This paper underlines a number of weaknesses of the FCMs technique. Its major criticism is the impossibility to translate the iteration process in a defined temporal scale.

However, considering the several potentialities of the dynamic models employed to evaluate urban transformation process, actual researches are oriented to the application of System Dynamics Model (SDM) (Forrester, 1961; Forrester, 1968) to support the decision making process. Infact, SDM are currently used to simulate the evolution of different urban development strategies considering their evolution over time (Guan, 2011; Tan, 2018). This choice has been made because of the ability of these tools to consider both the causal relationships between different urban components and a specific temporal scale for scenario simulation. Furthermore, an other interesting research field is the integration of SDM with GIS. The objective is to assess the evolution and the impacts of urban development strategies also in spatial scales (Guan, 2011).

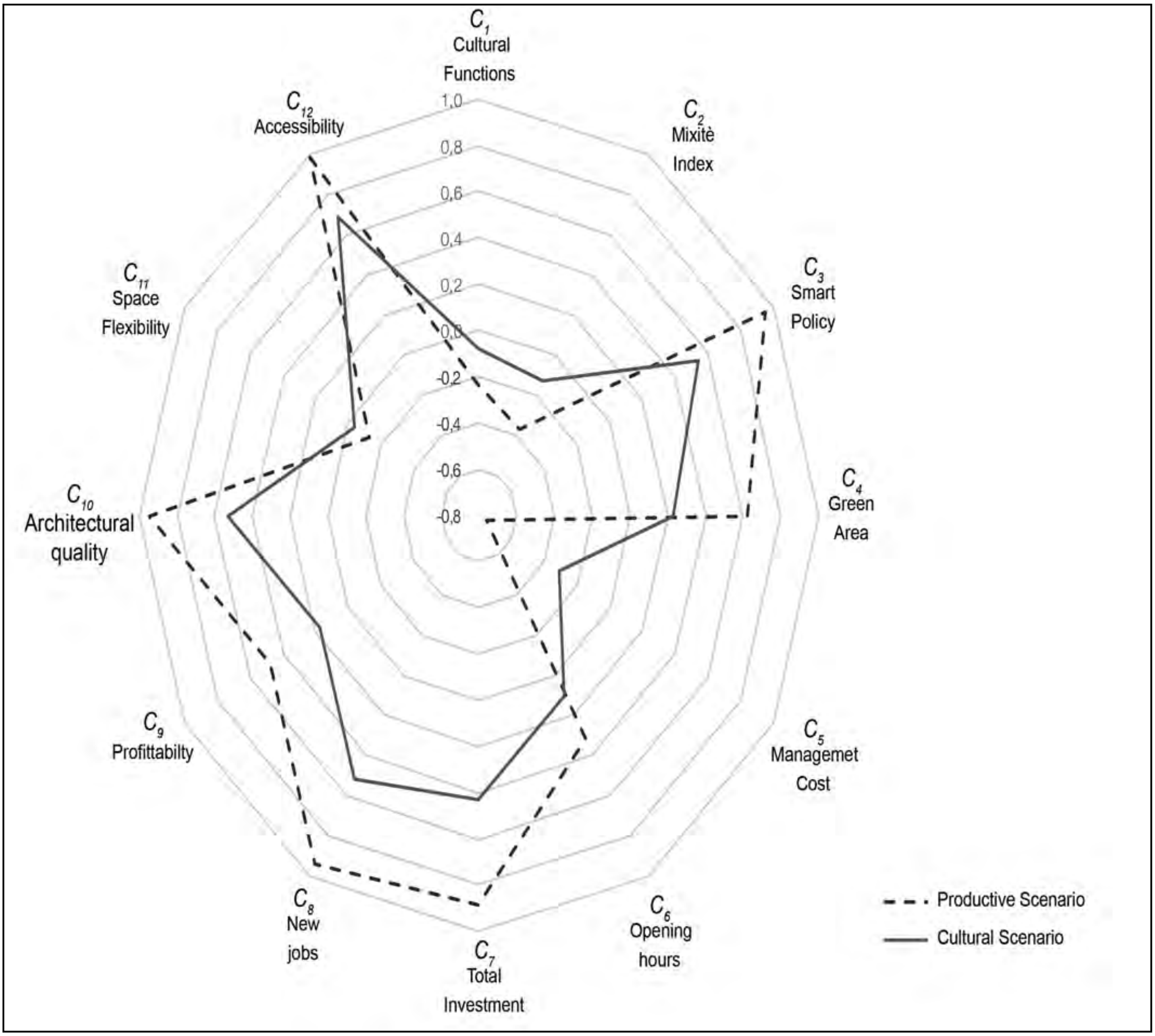


**Figure 11 -** *Radar graph to compare "Productive Scenario" and "Cultural Scenario" for the requalification of the Bochard barrack (Source: Bottero et al., 2019)*

The final objective of these research is supporting Decision-Makers in defining transformation alternatives considering their impacts both in temporal and spatial scale, focusing on the objective of "making city resilient" (Brunetta et al., 2018; Datola et al., 2019; Pagano et al., 2017; Romagnoli, 2014).


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