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# LAND USE DYNAMICS: A CELLULAR AUTOMATA

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ABSTRACT

Usually applications of urban growth cellular automata are related to an only one town, with transition rules and constraints a priori defined. This seems to be a severe limits in applications

The paper presented is born to follow a different kind of approach, so to have rules and constraints directly from observed past data.

We consider ten European towns and for each one we have data for time series approx. 40 years long. We deduce rules and constraints directly from the data set, solving an inverse problem (in which we have input and output measures and we have to determine a system model).

The study try to define in detail the stochastic or deterministic character of transition rules (in the stochastic case evaluating transition probability).

At last the rules are applied to towns maps (by means of ad hoc cellular automaton). With this cellular automaton we try to simulate past dynamics (for a validation of the model) and also to forecast the spatial development of the towns by means of scenarios (based on the past histories).

## 1. Introduction

The main goal of this article, which is in fact a continuation of a previous paper (Rabino G. A. and Laghi A., 2002), is the identification of a cellular automaton (Cecchini A., Indovina F., Rinaldi E., Besussi E., 1999; and for further titles and articles on the subject, see  Santini L. e Pecori S., 2003), and its application on a series of European cities.  This model, previously created in the research cited above, was applied to four European cities, and is partially modified and adapted for the simulation in this study where six other European cities in addition to the four pre-existing cities are considered.   The data available for this study are in fact, land cover and land use maps of ten cities, seven of which are European cities and three of which are Italian.

The cities studied, from Northern to Southern Europe are: Helsinki, Sunderland, Prague, Vienna, Milan, the Padua-Mestre corridor, Grenoble, Bilbao, Porto and Palermo.

The data, provided by the Joint Research Centre-Space Application Institute at Ispra, are made up of three or four maps, which tend to be from the 1950s, '60s, '70s, '80s and '90s.  These maps indicate the land use of the city in a given year.  Such data come from the Moland project (Monitoring Land Use / Cover Dynamics), whose goal, as indicated in its name, is to monitor the urban changes in the cities, which have been considered here.  This research has allowed us to dispose of a set of highly detailed geographical data and is useful in understanding the evolution of a series of extremely different cities from one another when examining the historical, cultural or social aspect.  The legend is composed of four levels used for  the classification of various land uses and is an extension of the official legend introduced in the Corine program, made up of forty-four classes orgranized on three levels.

Given the vast quantity and detail of data available, we attempted to create a model of cellular automata which, based on the given data, is capable of simulating the complex interactions induced from many factors, such as economic, social, cultural and geographical causes and not only the land use of a city, in order to estimate the city's evolution as much as possible.

The elements that make up the cellular automata are the grid, the state of the individual cells, the neighbourhood, and the rules of transition taken into consideration. In our application, the grid is formed by squared elements of 100m sides.  The state of the cells is represented by the prevailing land use within it.  The neighbourhood is composed of the first two annuli around each cell, to which we assigned a different weight, that is, one for the first annulus, and one-half for the outer annulus, and whose state is represented by the prevailing state of the cells constituting it. We assumed stochastic rules, thus characterized by a certain probability of happening, directly derived from our data, as in an inverted problem (Cheney M., 1997; Groetsch, C.W., 1993; Kirsch A., 1996).

However, the legend used for the creation of the maps for the Moland project is, for this type of study, too detailed. It was considered a number of land uses reduced to the most significant twelve.

A further element, which is of extreme importance in the application of a cellular automaton, is the temporal step of the automaton itself. The lack of maps for the various cities referring to the same years induced the exploration of three different amplitudes, equal to 36, 40 and 42 months. Examining the number of months elapsed in each transition between maps of the various cities demonstrated how even in the case of new cities; the best choice was to consider the step of 36 months. This allows us to have a whole number of steps, or a difference of 1/3 of a step (over or under a whole number). Moreover, this choice allows us to remain consistent with the results obtained in above mentioned previous paper.

From the initial preparation of the data we were faced (figure 1) with a series of problems to investigate, including the problems of model specification as in particular the necessity of choosing the appropriate dimension for the grid, to specify the neighbourhood to take into consideration, and to specify the temporal step. In addition to these problems, we faced problems of model design, due to the need to specify the transition rules. The latter could have been considered deterministic or stochastic (thus, we had to consider the influence of stochasticity), space-dependent or not. We also faced the problems of calibration and validation, such as the presence of limit configurations.

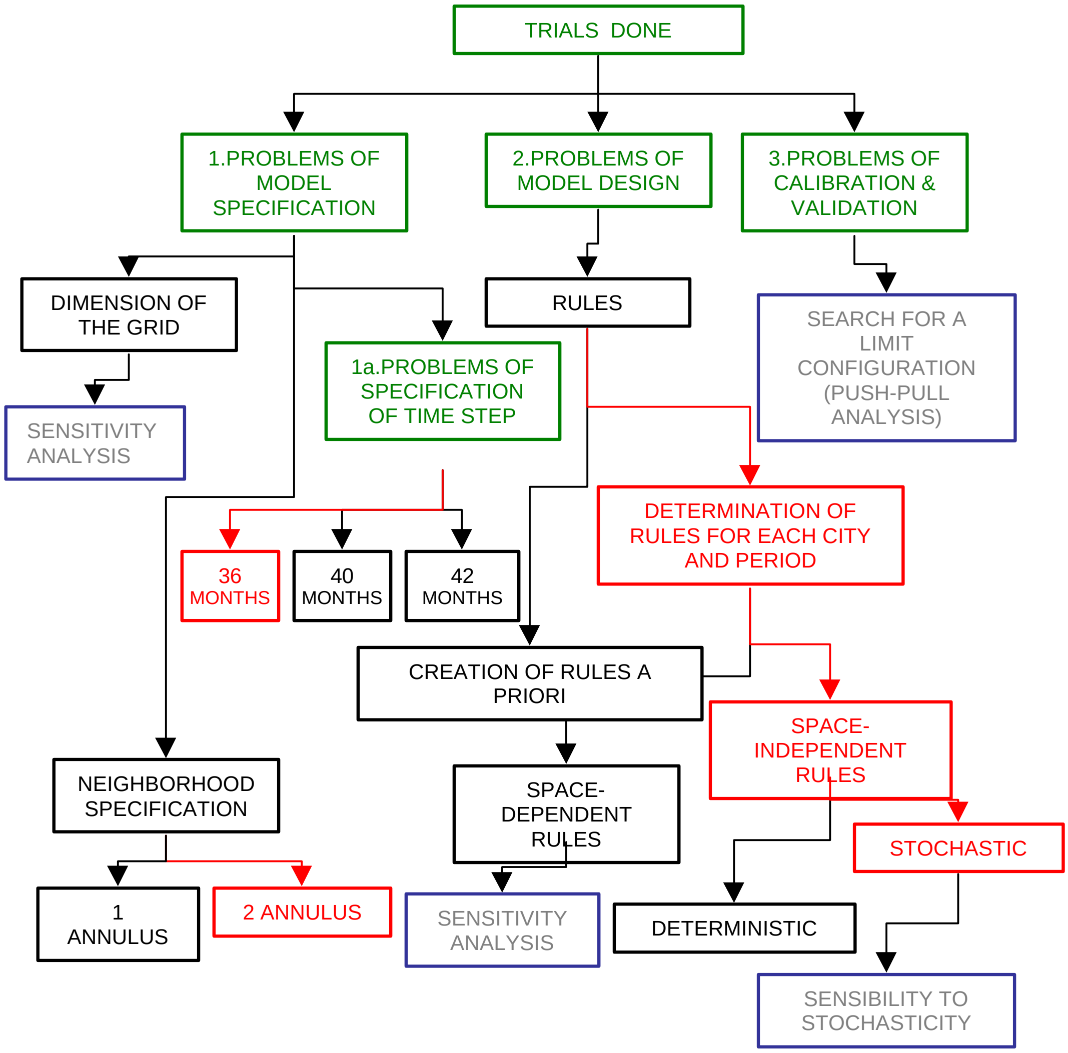


Figure 1. Scheme of the problems faced

Thanks to the ample data sets applicable to our study, in addition to the application of the model to simulation of city development, we found the need to produce a series of trials which confirmed the direction chosen and by which we could obtain a series of answers which confirmed or rejected the results obtained. For this reason, the research was developed on three different levels. A first level is composed of the trials, such as the application of space-dependent or space-independent rules, the search for a limit configuration, the study of stochasticity of the probabilities of transition etc. A second level simulates the past developments of the different cities thus producing a sort of validation of the model of simulated maps against the real maps. In the final level, we applied two scenarios, which were chosen based on the differences in evolution between the various cities and applied to the city of Milan.

Understanding which transitions actually occurred constituted the first important step achieved in this research. This step helped to determine which transition rules actually occurred in order to understand the development of each individual city, and in consequence, the past dynamics which characterized their growth. Each transition rule is composed of a triad of values: the state of the cell in the starting year, the state of its neighbourhood in the same year, and the state of the cell in the final year, which determines five different types. Firstly, we consider two types of rules in which the starting state is independently maintained from the state of the neighbourhood, these rules are called homogeneous permanence (if the neighbourhood is in the same state as the cell considered) or heterogeneous (if the neighbourhood's state differs from that of the cell considered). These two types of rules indicate that the cell maintains its own state during the transition. Secondly, three other types of rules indicate that the cells undergo a transition either adjusting their own state with respect to that of the neighbourhood, (rules of compliance), or distinguishing themselves from it. These latter rules are divided into two categories. In the distinction rules the initial states of the cell and of the neighbourhood are the same and we observe a transition towards a different state. In the multiclass rules, the initial states of the cell and of the neighbourhood are different, and the cell undergoes a transition towards a different value from the preceding two.

The analysis of the transition rules and of the past dynamics allowed us to first and foremost understand the different evolution which occurred in each single city; the changes which occurred in each, were, in fact, due to diverse factors including each individual historical-political route, and also the different socio-cultural and economic profiles typical of the wider geographical regions where they are located. Each one of these factors, both independently and when combined with the others, characterized territorial development that was at times similar, and at other times very dissimilar for each city.

Some of the cities considered appear to be very dynamic and projected towards an intense development in residential, industrial and associated functions. Other cities appear to be more static.

In the case of Vienna, Helsinki, Grenoble and to a lesser degree the case of Sunderland, we notice that the original historical city centre, composed of continuous residential areas, does not undergo remarkable variations in the course of time. The city centre remains a single compact area around which a series of discontinuous and sparsely organized residential units are born.

In contrast to this particular type of residential development, are the cases of Milan, Prague, Bilbao, and in part Padua-Mestre, even if this last case is slightly different. In these cases, the territory undergoes a different development, the discontinuous residences tend to amalgamate over the course of time and form dense homogeneous areas; these new dense residential areas are removed from the original urban centre.

In the case of Palermo, we notice between 1963 and 1989, a contraction of residential areas. This decrease and abandonment of the territory is likely due to the migration of the population towards other cities offering better employment availability.

For all the cities studied, we observed that the commercial areas and public use never exceed 3-4% of the territory on the whole. In several cities these percentages are indeed too high, as seen in the cases of Bilbao and Padua-Mestre. This deficit is seen primarily in cities with minor dimensions and in cities that underwent minor development.

Observing the real maps of the various cities we observed that between 1948 and 1960, all cities have cultivated fields which cover a large part of their territory, while in the course of time we observe a reduction of such areas. However, this process is different from city to city. In certain cities, such as Milan for example, we see a substantial change in the land use that goes from agricultural, for the most part, to residential or industrial. In other cities, such as Bilbao, Grenoble, and partially Vienna, in addition to the erosion of areas from other functions, we observe a partial abandonment of these areas that are retransformed into semi-natural areas or woodlands. On the other hand, in cities such as Padua-Mestre and Helsinki, we notice fewer cultivated areas while the city and the surrounding territory remain predominantly agricultural.

Finally, it is worth noting that for Vienna and Sunderland we only had three maps available. For Vienna, the maps are for 1950, 1960 and 1980 while for Sunderland the maps are for 1971, 1981, 1997. It is for this reason that the city of Vienna lacks information regarding evolution of the territory between 1989-90, the years closest to the present time, and for Sunderland we are missing more precise information about the state of the city prior to the 1970s, thus before recent development.

## 2. Calibration of cellular automata

The questions of great importance, as previously stated are: problems of model design, problems of model specification and problems of calibration and validation.

Several of these questions, such as the choice of neighbourhood taken into consideration, that of the temporal dimension or the determination of the transition rules, were examined and treated in the first phases of our research, more specifically, before or alongside the preparation of the data to elaborate, others were explained and studied in great detail.

In order to determine the probabilities of transition associated to each rule it is important to remember that the whole set of cells which make up the city can be divided into cells which remain in the initial state and cells which undergo a transition which induces a change of state. Thus separating the cells into two distinct classes, it is possible to determine the probability of transition in a single step of three years, to associate to each rule, under the following hypotheses:

- changes of state uniformly distributed between the various steps, which compose the time interval occurring between a real map and the following one.
- invariance of the neighbourhood, that is to say that the prevalent class of the neighbourhood calculated for each real map and theoretically only valid for that year, is maintained unaltered even for the following steps within a real transition. This is a rather restrictive hypothesis, but given the enlargement of the neighbourhood from the first annulus to the second, it is more and more valid. In fact, more cells must undergo a change in their state in order for the neighbourhood to vary.

The probabilities (see Table 1 ) that have to be associated to the different rules can thus be written in the following way:

*Cells which, in one step, have undergone a transition:*

(CONS / number of steps in an interval ) / (total number of cells with initial class x and neighbourhood y)

note: CONS indicates how many times a rule is effectively used inside a real transition. Therefore, considering the hypothesis of uniformity of transitions over an interval, the first ratio gives the number of cells that undergo a transition over a step.

*Cells that maintained the initial state in the considered step:*

((number of initial cells with class x and neighbourhood y)-(cells that change state in a step)) / (total number of cells with initial class x and neighbourhood y)

note: this ratio have to be obtained considering that the difference between cells which undergo a transition of state in the simulated step and those who undergo it in the real step, in the hypothesis of transitions uniformly distributed in time, maintain their initial state.

| **CONS** | **INITIAL STATE** | **PREVAILING NEIGHBOURHOOD** | **FINAL STATE** | **N° CELLS CLASSES WITH STATE *x* AND NEIGHBOURHOOD *y*** | **PROBABILITY ON A SINGLE STEP IN THREE YEARS** |
|---|---|---|---|---|---|
| 349 | 1 | 1 | 1 | 357 | (357-(7/5)-(1/5))/357=0,99552 |
| 7 | 1 | 1 | 5 | | 7/(5*357)=0,00392 |
| 1 | 1 | 1 | 9 | | 1/(5*357)=0,00056 |
| 5 | 1 | 2 | 1 | 5 | 5/5=1 |

Table 1. Calculation of the probability of transition (example)

The probability found is a conditional probability. In fact, it tells us which is the probability that a cell in the state x, given a certain neighbourhood y, passes into state z. This way, the if…then structure of the rules of a cellular automata is conserved.

Once the probabilities of transition are determined, we are finally ready to apply the cellular automata and to study its behaviour. In this goal, we developed a script in the Avenue language, allowing us to simulate the behaviour of cellular automata when given the initial class, the prevailing neighbourhood, and the tables indicating probabilities of transition associated in a single step of the simulation. The behaviour of the cellular automata can be resumed according to the flux diagram represented in Figure 2:

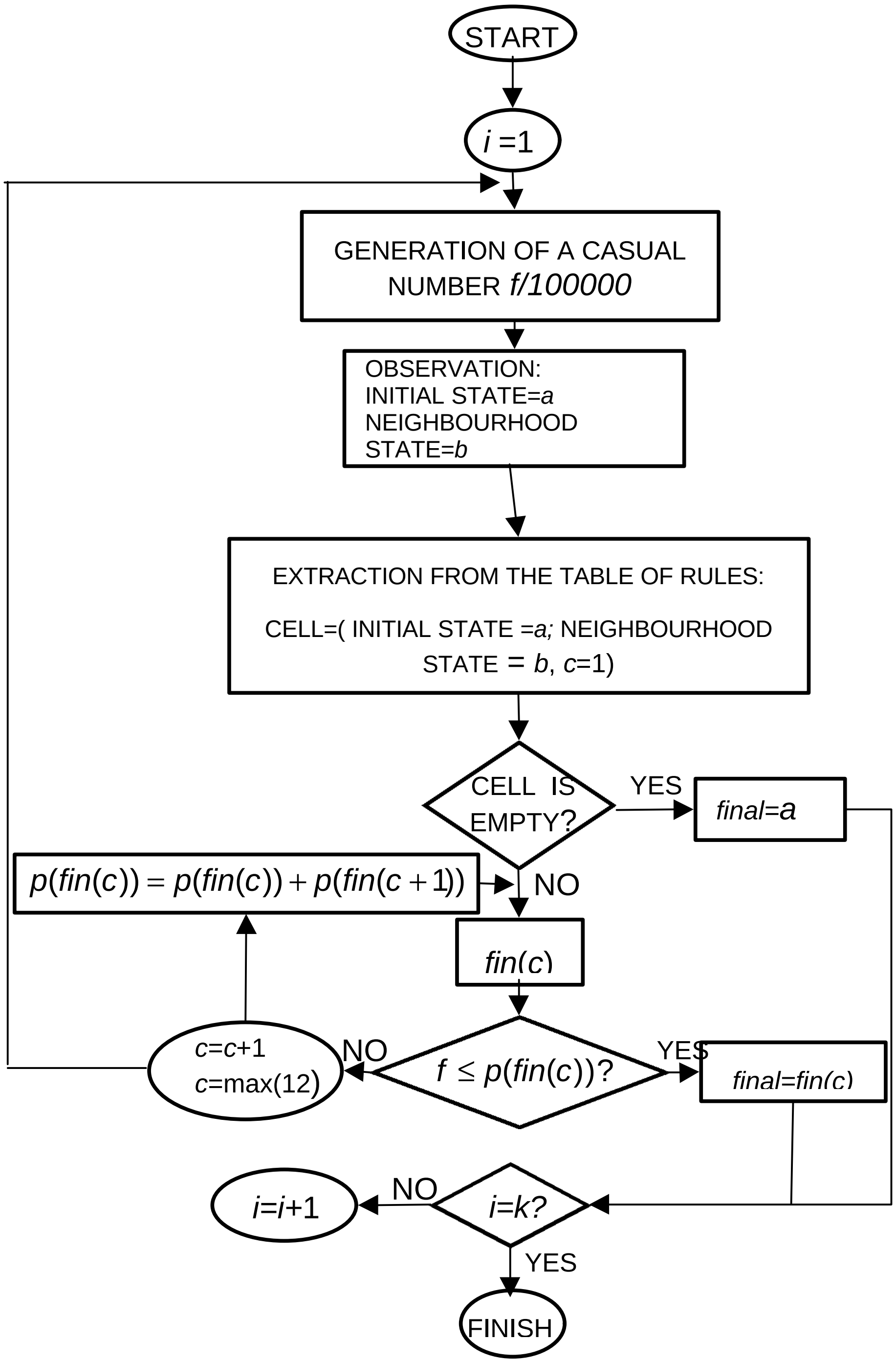


Figure 2. Flux diagram of the cellular automata

Each cell of the map is indicated with the progressive advancement of the index i of the cell, and for each one of these a causal number between 1 and 100000 is generated. In fact, we estimated the probability until the fifth decimal point in order to consider even the smallest values.

The index c, the parameter fin(c), the parameter final and the parameter k indicate respectively, the index of records selected in the table of rules, the final state corresponding to the index c, the final state assigned to the cells and the total number of the cells of the map.

In the event that the selection, obtained by query on the table of rules, is empty, that is to say that there are no records having an initial state a and neighbourhood b, we chose to assign the initial state as the final state of the cell, thus applying the rule of persistence in class. This is a further choice that is added to the previous ones in order to create our cellular automaton, due to technical constraints.

The determination of the probabilities and the successive application of the rules to maps in order to obtain the simulated maps to compare with the real maps, drew our attention to understanding the importance of stochasticity in our current research.

The study of the influence of the probabilities of transition has been conducted on Bilbao for the reduced dimensions of the city and the associated work timelines, repeating the simulations for three transitions until a sample of 10 data were available. Observing the graph in Figure 3 we can see how the majority of classes do not have values deviating from the actual value for over 20%. The less numerous and more dynamic classes present a bigger deviation from the actual value, a consideration which could have been done a priori.

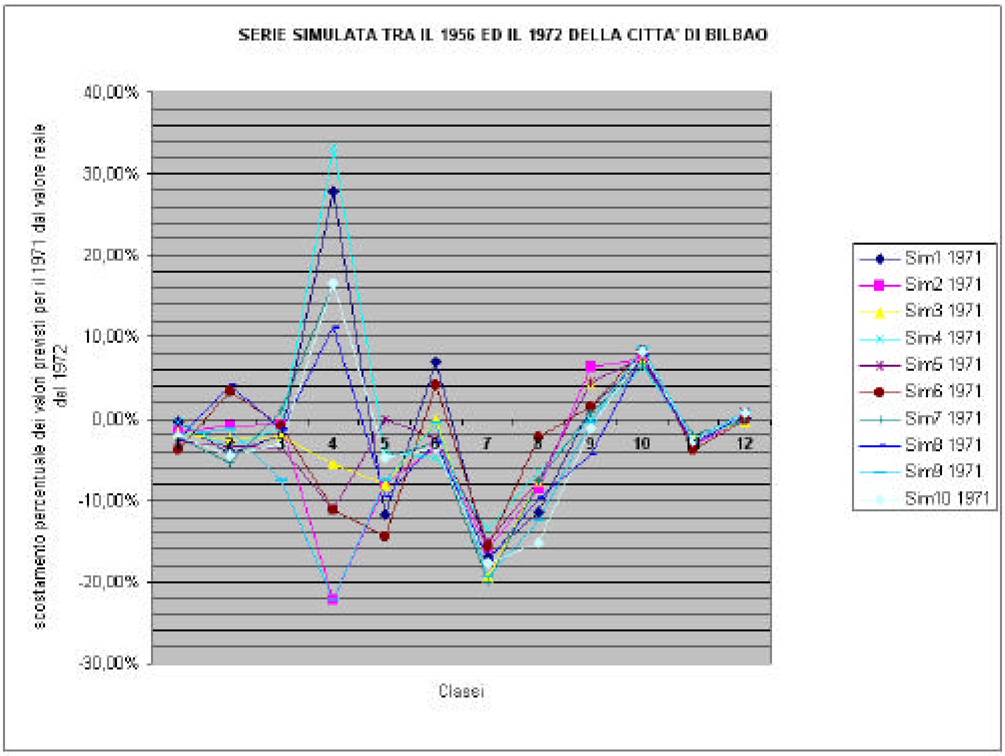


Figure 3. Series of simulations for Bilbao

In order to better understand the results obtained we calculated several indexes, with the series of data available, as seen in Table 2.

| | Mean Val. | Real Val. | Diff. % | Std. Dev. | NORMAL STD. DEV. | Diff. Max-Avg. | Abs.Diff. Min-Avg. | Abs.Diff. Max-Min |
|---|---|---|---|---|---|---|---|---|
| **1** | 1313 | 1339 | -1,927% | 14 | 0,010 | 20,80 | -25,20 | 46,00 |
| **2** | 572 | 582 | -1,804% | 19 | 0,032 | 34,50 | -20,50 | 55,00 |
| **3** | 1099 | 1123 | -2,110% | 26 | 0,023 | 34,70 | -60,30 | 95,00 |
| **4** | 19 | 18 | 3,333% | 4 | 0,203 | 5,40 | -4,60 | 10,00 |
| **5** | 173 | 187 | -7,326% | 8 | 0,041 | 13,70 | -13,30 | 27,00 |
| **6** | 169 | 171 | -0,936% | 6 | 0,038 | 13,60 | -6,40 | 20,00 |
| **7** | 590 | 712 | -17,093% | 15 | 0,021 | 25,70 | -21,30 | 47,00 |
| **8** | 168 | 184 | -8,913% | 7 | 0,036 | 12,40 | -11,60 | 24,00 |
| **9** | 271 | 267 | 1,311% | 8 | 0,032 | 13,50 | -15,50 | 29,00 |
| **10** | 5736 | 5336 | 7,489% | 40 | 0,008 | 61,40 | -65,60 | 127,00 |
| **11** | 6823 | 7017 | -2,766% | 36 | 0,005 | 57,10 | -73,90 | 131,00 |
| **12** | 1467 | 1463 | 0,260% | 6 | 0,004 | 8,20 | -8,80 | 17,00 |

Table 2. Indexes calculated with the 10 data from the 1971 sample

Observing the mean value, we can easily detect how for some classes, in particular the two residential land uses, the industrial land use and the forests, such value is inferior to the actual number of cells of the class in 1972 (value reported in the second column of the table). This implies that, on average, this class has been underestimated, and it is the automaton that produces a number of cells for this class that is inferior with respect to reality. However, in other cases, in particular for agricultural areas, the mean value is superior with respect to the actual value, with the automaton behaving inversely with respect to the preceding case. These tendencies are also confirmed from the sign of the values contained in the third column, where we reported the percentage of variation of the mean value from the actual value.

It is very important to note that the systematic errors found could be reduced by inserting appropriate corrections, for example, introducing polarizing factors, which take into account external phenomena such as human intervention.

The values of the normalized standard deviation obtained for the simulated series, confirm a precise behaviour of the automaton, in particular for classes 1, 10, 11 and 12. In fact, for all the classes, with exception of class 4, the calculated deviations are less that 0.05.

The same reasoning used for the simulation between 1956 and 1972 has been applied for the two following transitions. Also in these cases, we observe that the automaton systematically underestimates some classes while overestimating others and that it is consistent for the majority of classes, not showing excessive span and dispersion of values.

Finally this research considers the city to be a whole entity, always obeying the same rules. Nevertheless many of the cities analysed have a city core, which is older and less variable and a periphery which is quickly changing. With this goal in mind, we thought of investigating what incidence the application that space-dependent rules could have on the simulations.

This application has been conducted on Bilbao, considering a central strip of 600 metres from the river, and the remaining peripheral strip. The choice of the dimension of the inner annulus was done in order to include the oldest urbanized area, without however increasing its extension excessively.

In this case, once again, we calculated the same indexes previously presented in the study of stochasticity. The first characteristic which resulted from observing the tables reported for both space-dependent and space-independent rules, is that the average calculated based on the results obtained, using space-dependent rules, in the 10 simulations, shown in Figure 5, are much closer to the real value when compared to those determined with uniform rules the whole city as seen in Figure 4. This fact indicates the greater accuracy of the cellular automaton due to the increase in the number of parameters taken into consideration, which is found both for the simulations of the inner annulus as well as the peripheral annulus, and which can also be noticed by observing the graphs which follow.

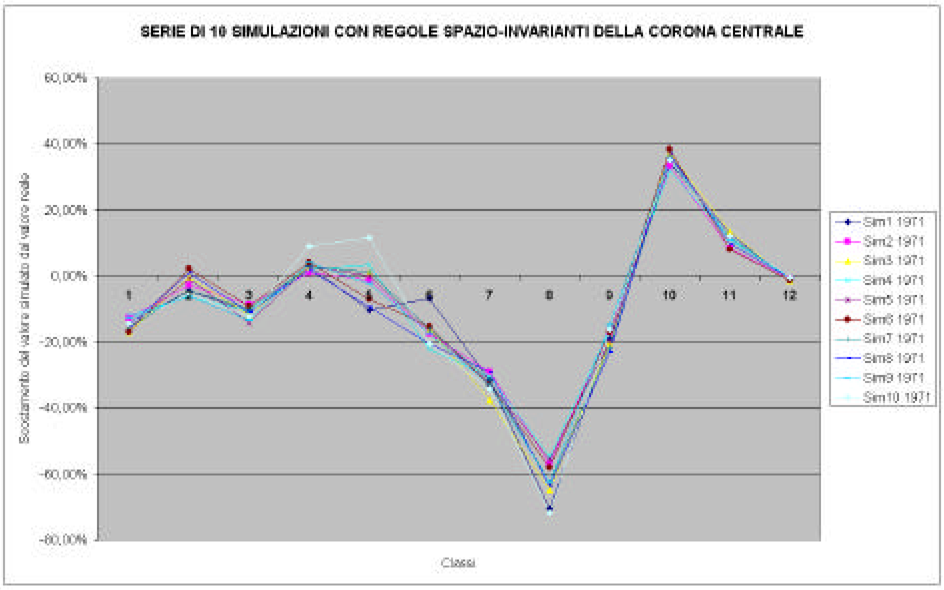


Figure 4. Series of 10 simulations with the space-independent rules for Bilbao

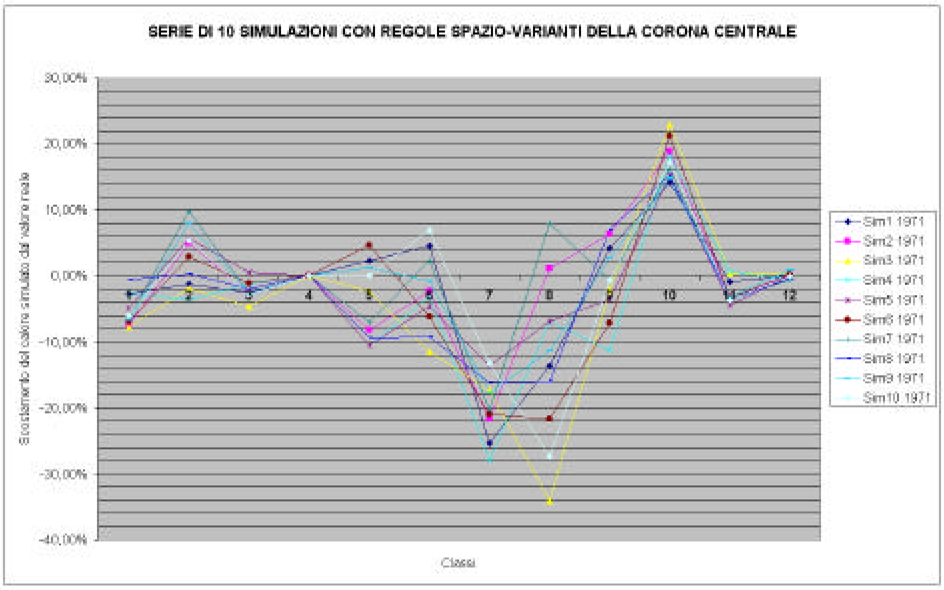


Figure 5. Series of simulations with the space-dependent rules for Bilbao

Therefore, the effect of increasing the parameters taken into consideration induces a reduction of systematic error, which was made in the simulations. Alongside this effect, we noticed however, how the value of the normalized standard deviation tends to increase, producing a dispersion of values around the average much greater in the cases using space-dependent rules compared to the cases of homogeneous rules for the whole city. This behaviour is probably due the fact that dividing the city into two annuli the central annulus composed of 5939 cells and the other of 12400, it strongly decreased the base of useful data in the determination of the transition rules and the corresponding probability.

The dimension of the grid applied to the real maps was one of the elements studied; the dimensions taken into consideration were of 100x100m, of 200x200m, of 300x300m, of 400x400m and of 500x500m.

The first effect we noticed is "crumbling" of the areas. With the increase in cell dimension, the cells lose the specificity of the contour, becoming slowly less shaped and losing their perimetrical irregularities. The status associating a single cell, which cannot be composed of several different land uses and must be composed of only one land use, is chosen based on the determined land use which prevails in the cell. It is for this reason, that when varying the dimensions of the minimum unit considered, we can induce variations in the choice of the prevalent use. For this reason there is also a loss of areas of smaller size, and in several cases, some of the land uses present in the original maps actually disappear, composed of areas which are too small to be individuated; this is the case for the big commercial areas and also the building sites.

Moreover, in the case of Bilbao we also note how the total area of some classes varies with the dimension of the grid, even if the variations are smaller percentages. For example, dense residential use continues to increase until the grid of 300m sides is applied, only to decrease in the two following cases, while the discontinuous one undergoes a continuous decrease. These two different behaviours are due to the different size of the typical areas of each of the two functions. A further study conducted on available data consists of the search of a limit configuration (Figure 6), around which the system could converge after a finite or infinite number of transitions.

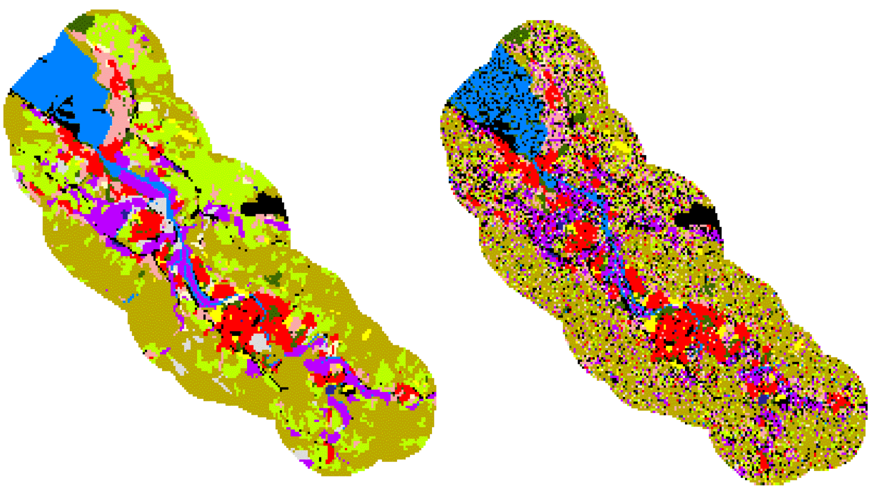

Figure 6.: Bilbao in 1997 and projection for Bilbao in 2120

This study was conducted, keeping the hypotheses of invariance of both the neighbourhood and the probabilities found in the last transition between two real maps, while continuously applying the above mentioned probabilities of transition to the real map of Bilbao 1997. This was done to obtain a projection of the evolution of land use for this city in 2120, that is, more than 120 years later.

The pretence of such an operation is not to determine a perfect projection for a city in a given year, but to search for an extreme tendency in the land use of of a given territory. The system foreseen converges to a state in which the prevalent land use is urban use at the expense of natural uses. In fact, we can observe how the agricultural and woodland areas become eroded by the strong expansion of the urban land use areas, as clearly seen in the graph represented in Figure 7.

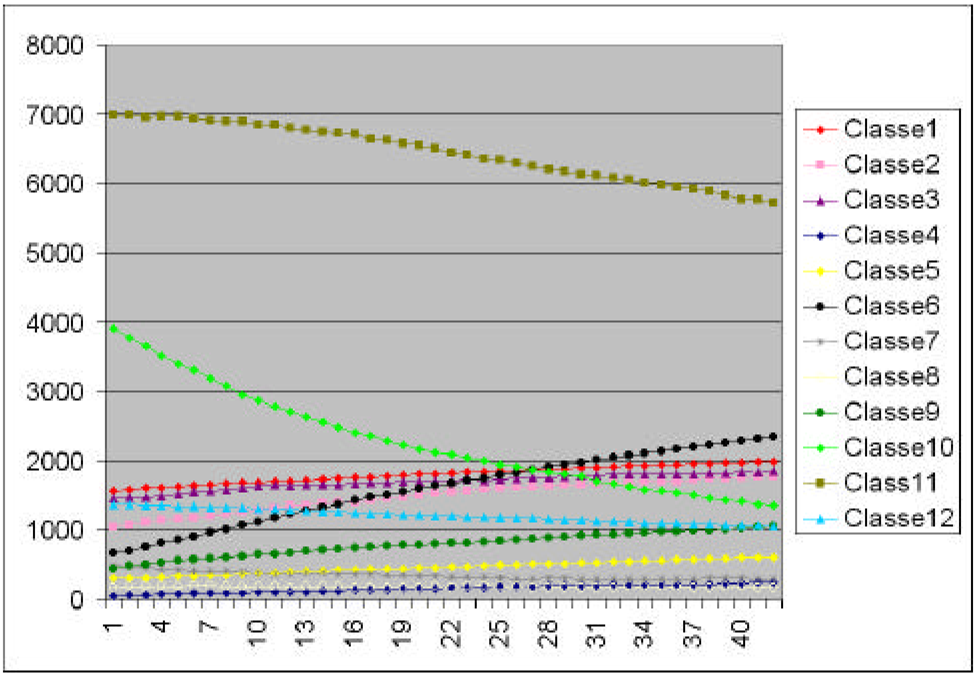


Figure 7. Search for a limit configuration

The first point in the series represents the numerosity of the cells in a given class in the initial year, that is, in 1997. The following points represent the numerosity of the following projections in 2000 and in 2120.

The observation of the trajectory of a single class is very important because the trajectory of the system in the space of states is the composition of the trajectories of the single classes in the relative space of the states, since those reported are the projections of the general trajectory on each axis. Observing the data obtained and the graph reported, we notice how several classes, including the two residential ones, the industrial class, the quarries, and the artificial green areas, following a parabolic trajectory, are close to the extreme tendency. In fact, their relative or absolute rate of change decrease progressively and do not go over 1%. However, other classes including commercial, agricultural and woodland areas, seem to be subject to a variation which has not yet stopped. Other areas, such as those used for infrastructure and public purposes have rates which are constantly positive, but oscillating in the last two transitions. Finally, to enlarge and complete the analysis presented above, we decided to conduct another study on push-pull analysis (Sonis M., 1980). This analysis, conducted under a series of hypotheses and adaptations necessary to be able to apply it to our particular case, contributes to confirm the results obtained.

This analysis demonstrated that the real situation between 1984 and 1997 was already heading toward the limit configuration, which we determined previously. Even if the results obtained seem to confirm what was previously determined, it is important to note that in order to conduct this analysis we had to use several fairly restrictive hypotheses, and that it is necessary, in order to have a clearer vision, to repeat the calculations without these hypotheses. But this, without the use of the appropriate algorithm, would result in a high increase in computing time.

## 3. Validation

The validation of the cellular automaton is understood as the assessment of how close the simulations get to reality. Simulating the real behaviour of a city is a complex and arduous task; it is necessary to keep in mind the different factors that intervene in the evolution of a territory. The most important factor is human intervention as humans model the urban-natural system "as they please" according to their own needs. It should also be noted that the cellular automaton created here does not distinguish between cells, that is, it does not know which cells will undergo a transformation from one map and the successive map. Since we did not apply spatial constraints all the cells are in the same conditions, that is, they all have the same probability of undergoing a transformation.

The results obtained demonstrate how, for the majority of cities considered, including Sunderland, Porto, Helsinki, Vienna, Prague, Padua-Mestre and Bilbao, the maps simulated are close enough to the real maps in terms of how many cells were foreseen for each class. However, for other cities, such as Milan, Palermo and Grenoble, we notice a more important deviation from reality. The reasons for this are different for each city: Milan is the most dynamic city considered in our resarch, and for this reason it is difficult to follow its evolution. On the contrary, Palermo presents important deviations both in several particularly small classes of the first transition and in the second transition. In this case, it is due to an increase in development in the area between 1963 and 1989. Finally, for the city of Grenoble the deviations from reality are due to the kind of transition rules found, which are prevalently of homogeneous or heterogeneous permanence, that is, of the 1-1-1 o 1-2-1 type, an indication of the stationariness of the system.

As we previously observed, by studying the simulated maps and comparing them with the real maps, we were able to understand if the cellular automaton which was created and used in this research was capable of reproducing the evolution of a territory.

Thus we can observe that the automaton is capable of coming close to the evolution of the cities studied from a quantitative point of view. Meanwhile, the automaton is not able to reproduce such development from qualitative perspective, as we can see from the image on the right shown in Figure 8:

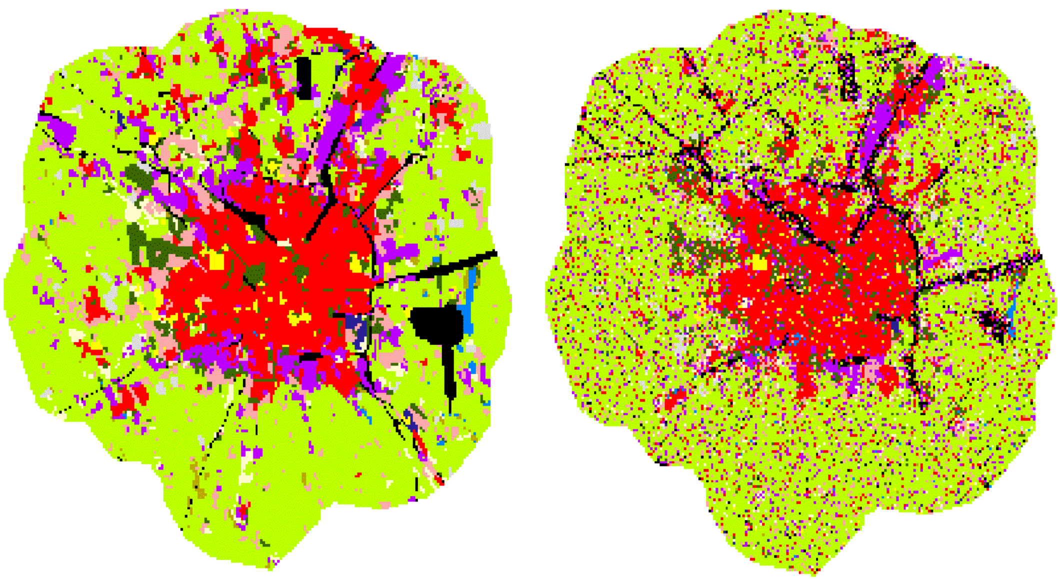

Figure 8.: Images of Milan in 1965 and of the simulation of 1964

This type of behaviour was already foreseeable, but we wanted to try to "capture" the change that occurs in a territory using the structure of cellular automata, without the imposition of external constraints. In addition to the choice of which constraints to use, and how to integrate them inside the model, we would have needed to do a preliminary study which brought us to the best solution.

In conclusion, gathering the transition rules directly from the available data is not sufficient in fully explaining the spatial mechanism of a territory's evolution. This evolution depends not only on stochastic elements, but principally on the rules of vicinity and decisional mechanisms that were not taken into consideration in this study.

In addition, this type of behaviour is also due to the limited number of classes used in this research, with respect to the initial ones. In fact, observing the maps obtained, the roads which belong to class 6, are sometimes transformed into green areas, a fact which would not easily occur in reality, but which is also due to the presence of much infrastructure in class 6, a class for which this event is possible. However, on the other hand, the high number of land uses, useful in many other projects, is too specific for this type of study, which, at the present time, makes it hardly useful.

It is necessary to add that for this preliminary analysis, it was necessary to have a quantitative estimate of the behaviour of the automaton, in a process that we can consider recursive, typical of adaptive systems. For this reason, it was important to firstly conduct the study as we did.

The work was not stopped at this stage, but we investigated two possible extensions of the model: the imposition of three thresholds to the probabilities of transition and the possibility of considering not only the two annuli of the neighbourhoods, but four.

The three thresholds taken into consideration, equal to 0.1m 0.05 and 0.01, were applied to the city of Milan to simulate the map of 1964. This was an excellent test bench for C.A., sufficiently critical for our investigation.

The results obtained demonstrate how the choice of a threshold which is too high induces the city to remain almost identical to how it was initially (a result that we already expected). The city remains very far from the real map and the automaton is not capable of reproducing the evolution of this territory in a satisfactory manner. The choice of the threshold equal to 0.01, however, gives a map which comes closer to reality, but which does not present homogeneous areas, as in the case of the simulation obtained considering all of the rules.

Even by observing the graph in Figure 9, reporting the number of cells per class of each map simulated, and of the real map of 1965, we note the remarkable difference between the simulations with the thresholds 0.1 and 0.05, and the real values, represented by a series of small red columns.

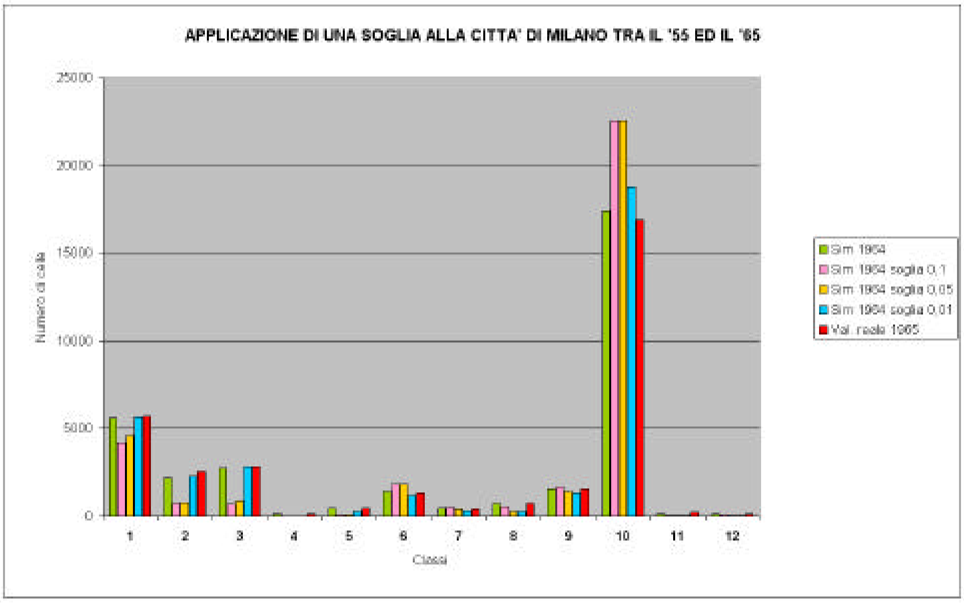


Figure 9. Effect of the application of three thresholds on the probabilities of transition

Therefore, the choice to limit the number of rules to those which have a probability superior to a prefixed value, is not sufficient in order to obtain maps that simulate the behaviour of a city in a satisfactory manner, whether qualitative or quantitative.

The second path taken consists of the enlargement of the neighbourhood to four annuli, instead of the two considered throughout the study. The last two annuli taken into consideration, as seen in the case of annulus 2, have been weighted respectively with a weight of 1/3 for the third annulus and ¼ for the fourth, thus composed of 24 and 32 cells respectively. This second trial, whose goal attained only in a small part, was to somehow choose between the transition rules to obtain the most influential ones, “filtering” the less important rules, brought us to obtain maps with areas which were less homogeneous. We must keep in mind the fact that a neighbourhood with four annuli corresponds approximately to a zone surrounding the cell with a diameter of 800m. In some cases (we think of large industrial zones, airports, fairgrounds), it is largely insufficient, given the minimum dimensions of certain areas, in others it is altogether too much, given that some classes (such as parks and road areas) vary in relation to the influence areas of a few hundred metres.

## 4. Scenario Application

The last phase of the study we conducted was concentrated on the application of two scenarios for the city of Milan. This study was conducted using the last map of 1997, the rules obtained for the last transition for Bilabo and for Prague, limited to a threshold equal to 0.05. The choice to apply one threshold to the probabilities of transition, even after what we previously stated, was adopted in order to understand how even the single application of the most influential rules of each of the two cities, would condition territories marked by different economics, history and development, without having the stochasticity render the principal trajectories of development illegible.

Before applying the two previously chosen scenarios, we calculated a projection for Milan in 2021 applying the rules found for the last transition between 1980 and 1997. The results obtained demonstrate how the territory considered tends toward a strong urbanization and industrialization, at the expense of the natural areas. The residential areas, particularly the discontinuous areas, but at a lesser percentage also the continuous ones, and the industrial areas, increase much more than the other classes. However, alongside these, also other support functions for residential and industrial areas, such as the areas of public use and the areas of infrastructure, undergo a proportional increment with respect to the previous development.

Scenario 1: urban development beside a natural development (see figure 10).

The first rules taken into consideration and applied to the map of Milan of 1997, are those from the last transition for Bilbao. The choice of this city is due to the diversity of the territory's development with respect to Milan. In fact, Bilbao has both a continuous and discontinuous residential fabric, which undergoes a certain increase over time, but, differing from the case of Milan, it does not expand in isolated spots around the principle core of the city, but integrates the areas already present forming large agglomerations.

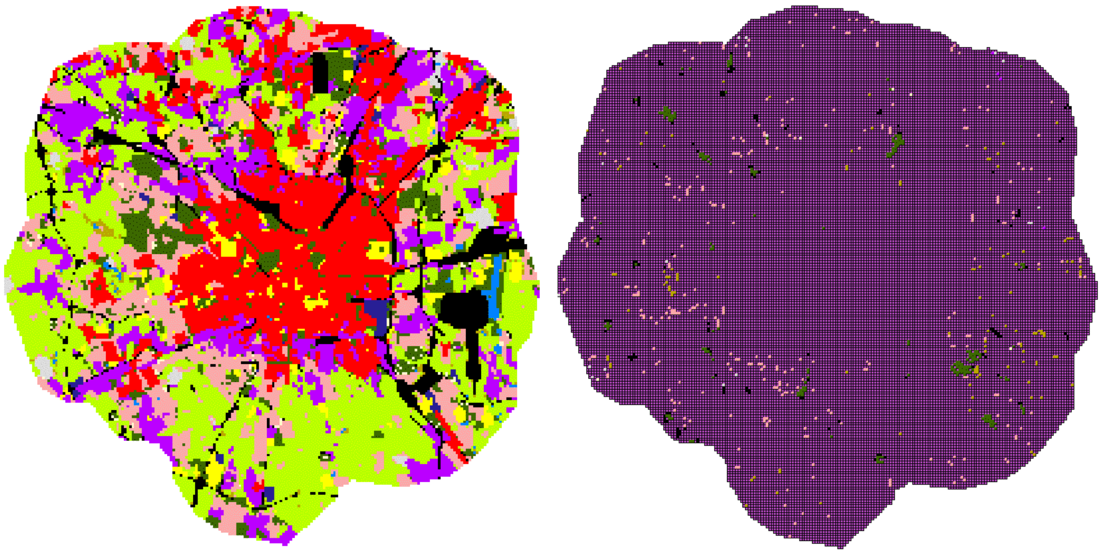

Figure 10. Projection for Milan in 2021 applying the rules of Bilbao and cells changed with respect to the initial map (1997) (colours based on the class of belonging.)

Moreover, even having a strong decrease in agricultural areas due, in part, to the industrial development, as in the case of Milan, the area around the city of Bilbao is still dominated by natural areas, occupied by many wooded or semi-natural areas.

The prevailing development of the city, with the application of a scenario based on urban development, but also on natural development, leads, in a highly urbanized city such as Milan, to an increase in the existing discontinuous urban fabric at the expense of agricultural land uses, but also to an increase in artificial green areas, woods and semi-natural areas.

Scenario 2: a city with contained development (see figure 11).

The second scenario taken into consideration and applied to the city of Milan consists of the application of the rules obtained for the last transition for Prague. With respect to the last transition, Prague underwent a minor expansion compared to other cities. In this second case, the major development favoured dense residential areas, agricultural areas and building sites. On the contrary, the development of industry and of services for residences and factories was scarce.

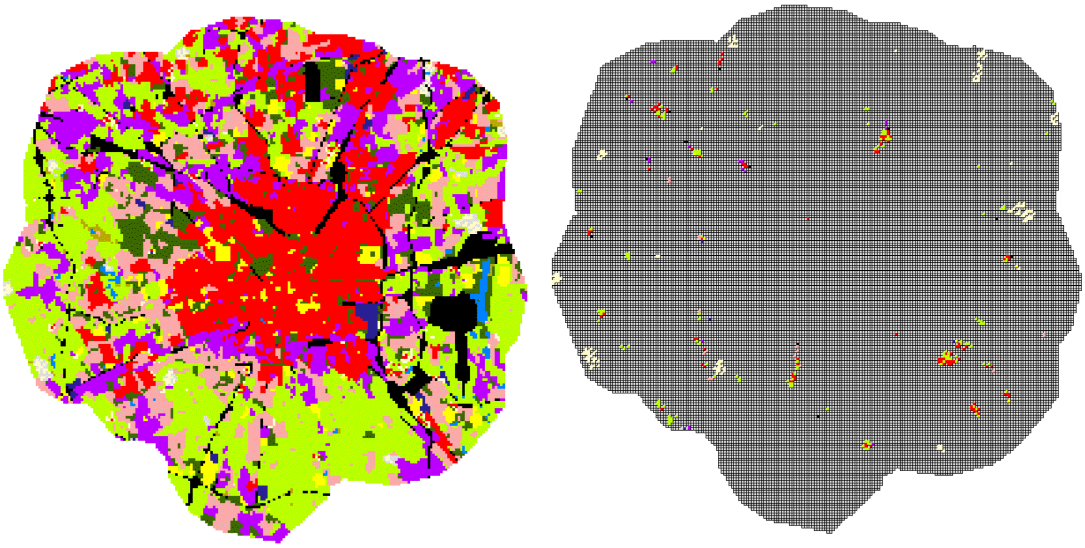

Figure 11. Projection for Milan in 2021 applying the rules of Prague and cells changed with respect to the initial map (1997) (colours based on the class of belonging).

From the application of its own rules, we noted how the natural development of Milan, maintaining constant rates of growth and the directions of evolution in the last transition studied, bring the city to an important urban and industrial increase and this is particularly true if we were to consider all the rules found.

On the contrary, from the application of the first scenario, we note how the city would undergo a remarkable "tendency inversion", increasing its urbanized areas, in particular the discontinuous ones, but not excessively at the expense of natural areas. For these areas we even notice an increase in artificial green areas and wooded areas.

The third type of scenario, as previously described, was chosen for the minor dynamism than the previous ones; in fact it implies a minor number of transformed cells, the years of transition being equal. Furthermore, it foresees a more substantial development in agricultural areas, an indicator of the fact that the city of Prague, until 1998, was still strongly agricultural and still relatively little industrialized.

The interesting part of this application was the possibility it gave us to directly compare the evolution of different cities on the same "field", in this case Milan. The direct extraction of the areas that underwent a different development between one scenario and the other clearly highlights the common aspects and the distinctive aspects that characterize the diverse evolution.

With the perspective of continuously improving the model considered, we could ideally imagine applying all the scenarios to all the cases considered. This way we could extrapolate, at a higher level of abstraction, which “external” factors of the cellular automaton (political, economic, social, etc. …) define in reality the development in one sense more than in another; but this would not be done a priori (that is, initially choosing the influence of various factors according to an arbitrary scheme) but done a posteriori, having a preliminary method of comparison available which would help us overcome, at least in part, this arbitrariness.

**5. Conclusions**

This research proposed to study the evolution of a city, whichever city, based on the maps representing land use in different years, applying the rules of a cellular automaton, stochastic and synchronous.

The objective of this research was to create a model which would simulate the development of any city, based on rules determined directly from historical series.

In fact, the available data consist of a series of maps, generally 3 or 4, of ten European cities, Helsinki, Prague, Vienna, Porto, Bilbao, Sunderland, Grenoble, Milan, Padua-Mestre and Palermo. The need to identify the best model that accomplished this task brought us to proceed by successive approximations, following different paths and conducting different research.

The main considerations that we should make on the model created, begin with the evaluation of the simulations created; in fact they highlighted two fundamental aspects. The first aspect regards the capacity of the automaton to greatly approach the real maps of the various cities quantitatively, except for a few exceptions, with respect to the number of cells foreseen for each class. The automaton, however, is not capable of capturing the spatial characteristics of the evolutionary phenomenon.

This discrepancy is due to the complexity of the city system. The city’s development is due to a mix of economic and cultural factors, decision-making mechanisms, but also proximity constraints and interaction between the cells.

Spatial patterns are therefore not reproducible using only the application of the rules of a cellular automaton, without the imposition of a series of specific constraints. However, such constraints risk bringing us to construct a model based on presumptions taken a priori, which could be good for one city, but not for another, characterized by a different type of development due to different socio-cultural contexts and due to a different geographical position.

The second aspect that the simulations highlight is that the cells that compose a city interact between themselves, reunited in sub-systems: for example centre and periphery. We observed how the separation of the macro-areas of the city helps, in part, to improve the definition of the model, and to increase the adherence to reality. However, they increase the difficulty for those developing their research based on a limited quantity of data, which are then to be subdivided into sub-systems.

There are many developments of this type of research, first of all with respect to the choice of model to apply to the data. In particular, it is important to remember how the neighbourhood taken into consideration, considered constant for all the steps in a transition, includes two adjacent annuli of the cell considered, weighted with an appropriate value. This induces two types of considerations, firstly, the possibility to examine a more ample neighbourhood, made up of more annuli that contour the cell considered and weighted in an appropriate manner. Secondly, we consider abandoning the hypothesis of neighbourhood invariance, which implies a calculation for each step of the prevailing neighbourhood, but this operation implies a remarkable increase in work time.

Moreover, as we previously observed, it is possible to apply a series of constraints, perhaps deductible from all data available in a general manner, which are good for any type of city considered.

Furthermore, the structure of a city is a consequence of decision-making mechanisms, in particular many of the big airport areas or large parks, are the result of specific investments in a determined area. These areas should be studied by attempting to insert external agents that would seize their development.

Such agents could address the city simulations in such a way that maps adhering to the real maps even from a qualitative perspective could be obtained. However, even in this manner, there is the risk of creating models a priori. Doing this would bring us closer to the application of a model in which cellular automata are placed beside multi-agent systems or fractal studies, or other different genres.

With this goal, as stated in the previous paragraph, it would be very useful to have maps which are much closer in time periods and in greater quantity, in order to be able, for example, to create scenarios, to extrapolate a model for trends of transformations which would be able to reproduce the evolution of a territory in a satisfactory manner beginning with the first real map available.

Expanding the model by adding elements at a higher level of abstraction of the cellular automaton would increase the need for an even greater quantity of data, economic, social and even cultural, in order to do the fewest assumptions a priori.

The alternative is to find a compromise between a priori assumptions and the possibility of validating and refining the model based on a recursive process, each time modifying the hypotheses and conducting new trials, in a kind of “adaptive” process. Obviously, this second path is more time consuming.

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