A tool for the analysis of the behaviour of building components: the cellular automaton

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An implementation of a cellular automaton is presented that allows the simulation of the behaviour of building components under diverse environment conditions. The tool has a wide range of applications because of the generality of its structure. The object on which it operates is represented as a set of cells each of which is defined, besides its geometrical dimension and position, by a set of variables and parameters. The work it performs consists in computing transitions from a state to another, i.e. the values variables and parameters take in each cell under the action of external agents and of internal laws of interaction between self. As an example of its use an application is shown analysing the thermal behaviour of the connection of a curtain wall to a concrete floor.

1. Introduction

The quality control is becoming a more and more crucial part of the design process to the extent of changing the very structure of it. The main characteristics of this change seem to be at present the following:

a) performance controls both of parts and of the whole building are required in earlier stages of the design process;
b) the controls regard the effects of ever more complex phenomena with the intervention of many external agents.

On the other hand the problem of the controls is complicated by the fact that actually the technology of building is acquiring techniques and methods up till now proper of mechanical engineering. This also has produced the need of acquiring the capability of controlling and mastering materials and solutions to which the building designers were not accustomed.

From all those requirements and characteristics of the building process two needs emerge:
- to understand qualitatively the behaviour of parts of the building made of unusual materials or of imported technology;
- to evaluate quantitatively the performances of building parts of which the attainment of a standard has to be assessed.

This last requirement can be satisfied in the design phase either through conventional calculations or through simulation of the behaviour of the building part under the assigned conditions. As always, there are advantages and disadvantages in both ways. Standard calculations need certainly less time than simulations. These last, on the contrary can be more flexible, cover a broader field of phenomena if the laws ruling them are known, have a better precision. Furthermore, simulation can be local, i.e. it can imitate the examined phenomenon in all the parts. For both ways the main difficulty lies in the fact that the complete set of detailed choices - materials, technical solutions, types of parts to be employed - has not yet been done in the earlier phases of the design process, in which, on the contrary, those choices ought to be known in order not to compromise the following steps.

When the building object has been completely constructed the best way of controlling the reaching of the wanted performances is experimentation. Simulation has much in common with experimentation. It is a sort of virtual experimentation inasmuch as it produces the

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virtual occurrence of the phenomenon while experimentation produces the real occurrence of it. The positive characters of simulation clearly appear from this comparison. It is possible to do many simulations at a relatively low cost and so to test many alternatives before realizing the eventually chosen one. The quality of the results depends of course on the validity of the tool that performs the simulation. The object of this paper is just to present a particular type of simulation tool having an high degree of elasticity and generality, able to cope with complex phenomena with a relatively simple machinery: the cellular quasi automaton.

Before describing the implementation of the specific tool in the following section a short description of the cellular automaton will be given.

2. The cellular automaton

We shall not summarize the yet fascinating history of the cellular automaton whose father is John Von Neumann.

A cellular automaton, \textit{stricto sensu} is a dynamic collection of cells having the following properties:

\begin{itemize}
  \item [a)] in each cell some variables are defined (usually one), having integer values; the set of the values of the variables constitutes a state of the automaton;
  \item [b)] the state of the automaton changes through \textit{transitions} that involve all the cells; this implies that the time is represented in a discrete way through a set of transitions;
  \item [c)] in a generic cell the value of a variable after a transition is a function of the values before the transition of the same variable not only in the cell but also in the cells of a direct neighbourhood;
  \item [d)] the rules of transition are the same throughout the automaton;
  \item [e)] the set of the cells is closed, i.e. no action is applied to the cells of the border of the set.
\end{itemize}

A somewhat connotative definition of the cellular automaton can be drawn from the work of T. Toffoli and N. Margolus (1986), authoritative scholars of the argument: \textit{“Cellular automata are discrete dynamic systems whose behaviour is completely specified in terms of local relation, much as is the case for a large class of continuous dynamic systems defined by partial differential equations: In this sense, cellular automata are the computer scientist’s counterpart to the physicist’s concept of field”}. As it can easily be seen the definition of cellular automata is conceptually broad, but its structure is rather restrictive. In its purest form it lends itself to the simulation only of phenomena in which internal evolution is important while external action is not. This is not the case of building design. In order to have a tool to model any interesting physical phenomenon the structure of the cellular automaton must be transformed by relaxing some of its constraints while maintaining its most useful characteristic: the local nature of the laws of transition through the involvement of the cells of a neighbourhood in the state transition of each of them.

The constraints to be relaxed are:

\begin{itemize}
  \item [a)] the closeness of the automaton. As every simulation deals with the behaviour of a technical part (or the entire building) under the effect of the actions the environment applies on it, it is necessary to include in the model of the automaton the representation of an environment from which some agents act;
  \item [b)] the integer nature of the variables. If they are to represent physical quantities, they must be continuous variables and then real numbers (we omit for brevity sake the Boltzmann method that can cope with continuous variables through the statistical management of the values of blocks of cells);
  \item [c)] if the automaton is to be a model of a real part of a building, it is very likely that this last is
made of many layers of different materials; it is not certain that the laws ruling the interaction between the physical agents and the various present materials shall be the same; this can imply different behaviour laws in the different materials. The implementation of the aforesaid changes transforms a cellular automaton in a cellular quasi automaton.

3. The cellular quasi automaton

The cellular quasi automaton is to be a tool able to:

a) model geometrically the architectural object the behaviour of which is to be simulated; the object geometry shall be approximated as a set of cubic cells;
b) model the nature of each cell assigning it a material, with all the related physical properties;
c) model the environment surrounding the object inasmuch as it is the spatial region from which the external agents act on the object;
d) model the agents and the actions they apply to the object;
e) model an initial state defining:
   e.1) a certain number of variables, significant for the simulation to be done,
   e.2) the value of each variable in each cell;
f) model the laws of transitions, that is the formulae tying the value of each variable in each cell after the transition to the values of this and other variables in a given neighbourhood before the transition and, if it is the case, to the external actions;
g) modelling time, assigning to each transition a time value.

4. The AuToMa

The program, thought jointly by the authors and developed by Tonino Martelli is a first implementation of a quasi cellular automaton able to perform simulations of a wide set of phenomena. A short description of the ways in which the modelling listed in the preceding section is done follows. The figures are referred to the example of section 6.

Fig. 1. The object of the simulation. A curtain wall corner fastening to a concrete floor.
4.1. Geometric modelling of the object

The modelling begins with the definition of a parallelepiped made up of cubical cells the dimension and the number of which along each axis can be fixed. 
All around this parallelepiped there is another layer of cells representing the environment. 
Furthermore blocks of cells can be defined to which a constituting material is assigned. 
The parallelepiped may be carved assigning to blocks of cells the nature of environment. By this sort of carving any form of a solid object can be approximated.

Fig. 2. Geometric modelling of the object. 
The space is modelled as a parallelepiped made up of cubic cells. A material is assigned to blocks of cells; inside a block of cells it is possible to assign a random distribution of an inclusions of another material; all around the object the environment is the place from which the agents act. An environment is assigned to an external face of the object. Blocks of cells can be defined as cavities from which agents can act on the border faces of cells. If no environment is defined on a side of the model the object is to be considered as continuous in that direction.

4.2. Modelling the material of the cells

As already said it is possible to assign a constituting material to blocks of cells and then if needed to each single cell. The assignment of a material involves the heritage of all the physical qualities and quantities previously attributed to it. In such a way it is possible to spare much memory as the assignment of a material is but a pointer to a set of characteristics. The first two (the assignment of which is compulsory) are the name and the colour with which the material is represented. It is worthy noting that a material can change its characteristics according the state in which it is. For instance, water can be present as vapour, liquid or ice. To cope with this it is possible to fix thresholds of parameters provoking a change of state and then of characteristics and behaviour.
4.3. Modelling the environment

As aforesaid it is possible to assign the nature of environment not only to the layers of cells wrapping the parallelepiped but also to blocks of cells in order to define the volume of the object. It is important to note that it is possible to define internal spaces on the borders of which agents can act like on the borders of the environment. A different behaviour is hypothesised between the environment i.e. the external spaces and the internal ones: while the state variables of the latter can change under the interaction with the cells of material, the former cannot. This difference of behaviour depends on the assumption that external environment has a mass so bigger than the one of the object that the action this last can apply on the environment can be neglected. Of course the environment may have different characteristics on different sides of the object: hence it is necessary to specify for each type of environment which side (orientation) of the cells it is acting upon.

4.4. Modelling the external agents

Each external agent can be a vector (as a wind, or a rain or a mechanical action) or a scalar (like temperature or humidity). In the first case, besides the obvious belonging to an environment, the quantity, the azimuth and the zenith related to a local axes system parallel to the general one are given as functions of the time. The relationship to time may be given as a formula, or as a diagram a table of values which can be either recursive or defined for each transition, if the number of these is fixed.
4.5. Modelling the initial state

The initial state is modelled by defining the variables whose evolution is the object of the simulation and giving them a numerical value in each cell.

4.6. Modelling the laws of transition

A law of transition can be a formula whatsoever provided computable. The value of a variable in a cell after a transition may depend on the values of the same and of other variables in a neighbourhood comprising the cell itself. There are two types of neighbourhood: the Von Neumann neighbourhood and the Moore neighbourhood. If the automaton is plane the Von Neumann neighbourhood of a cell is comprised of the four cells having a side in common with it; the Moore neighbourhood is comprised of the eight cell having a side or a vertex in common with it. Besides, of course, the cell itself. In a three-dimensional automaton the Von Neumann neighbourhood of a cell is comprised of the six cells having a face in common with it; the Moore neighbourhood is comprised of the 26 cells having a face, or an edge or a vertex in common with it. Besides, of course, the cell itself.

The most frequent laws of transition, corresponding to the physical phenomena most likely to be taken into consideration when verifying performances of building elements, are stored in a library. Among them there are the ones that cope with the relationship of the cell with its neighbourhood.

Fig. 4. Modelling the external agents.

The model of each agent comprises: name and colour of representation; environment from which it acts; intensity (constant, variable according an analytical function of the time, given through a table or a diagram); direction (if a vectorial quantity); distribution (constant, variable according a rule, random).
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A transition can interest many interacting variables, but the order in which the new values are computed does not affect the results since any calculation is conducted on the values preceding the transition. This property allows to deal with complex phenomena involving many variables that could not be easily dealt with analytically. Each of the laws is expressed in abstract form, i.e. the variables present in the formula have no particular meaning. Therefore the assignment operation consists in choosing the law, and assigning to each variable the meaning of a physical quantity. Of course, any new formula can be added to the library.

4.7. Modelling time

As dimensions are modular (really number of cells) so is time (really number of transitions). The time value of a transition is to be assigned according the wanted subtlety of the result. On this subject a short remark can be useful. As the quasi automaton works substantially discretizing continuous phenomena, it substitutes finite differences to derivatives and sums to integrals. Hence the opportunity of reducing the time value of a transition in order to have more precise results.

As regards the duration of the simulation, it can be fixed or through the number of cycles (also in function of the possible recursivity of the agents) or stopping it when a stabilization of the values of one as more variables is reached.

5. Presentation of the results of the simulation

The presentation of the results of the simulation is made in different ways. Partial results can be obtained during the simulation which can be temporarily stopped to allow the examination of the distribution of a variable values. This can be expressed either as a diagram or visually through different colour hues of the base colour representing the material. Of course the values can be printed. After having checked one or more variables the simulation can be restarted.

6. An example

As an example the simulation shall be run of the temperature distribution in the corner connection between a curtain wall and the concrete structure that bears it (see fig.1). The simulation aim could be to check if under severe conditions a different temperature distribution in the curtain wall and in the connections can give rise to stresses generated by different elongation. Of course the example has only a demo intention in order to show how it is possible to model complex objects also.

The model is composed of five layers. The first and fifth layer represent the object immediately over and under the floor in order to model also its environment. Second and fourth layers are placed respectively under and over the curtain wall steel fastener while third layer represents curtain wall and floor at the fastener height.

The model represents half the corner since it is symmetrical around the 45° axis bisecting the corner. The materials are aluminium, steel, polystyrene, synthetic rubber, glass, concrete. The agents are the external temperature and the solar radiation. the variable to control is the temperature of the different components of the curtain wall and their fasteners. The transitions are ordered in couples. The first one computes the effects of the agents on the external surface cells. The second one evaluates the interactions between the cells and their neighbourhoods. The first transition happens under the effects of the following physical phenomena.
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Fig. 5. Checking the effects of the simulation. The state of the system can be checked both at the end of the simulation and in itinere. In this second case a stop is possible at the end of a cycle. You can choose the variable the values of which you are interested in, and the object section you want to control. After the stop the elaboration can be raised again.
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Fig. 6. The comparison with figure 5 shows the alternate effect of heating and cooling provoked by the interaction with the environment.
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1) Surface conductance between the air and the components in contact with it.
2) Solar radiation.
3) Radiation of the components.

With the following symbols:

\[ T_e(t) \] = Environment temperature at time \( t \)
\[ T(t) \] = Temperature of a cell at time \( t \)
\[ h \] = Surface conductance coefficient \( (J/m^2 \text{ sec } ^\circ C) \)
\[ \gamma \] = Volumic mass \( (Kg/m^3) \)
\[ c \] = Heat capacity \( (J/Kg \text{ sec } ^\circ C) \)
\[ k \] = Heat conductivity \( (J/m \text{ sec } ^\circ C) \)
\[ \sigma \] = Boltzmann black body constant = 5,672 \( (J/m^2 \text{ sec } K^\circ) \)
\[ E_r \] = Solar radiation \( (J/m^2 \text{ sec}) \)
\[ a \] = Scale coefficient
\[ \beta \] = Stability coefficient.

The state variable is the temperature \( T \). The transition function is the relationship tying the value of \( T_{t+1} \) at the time \( t+1 \) of each cell, to the values of the temperature \( T_t \) at the time \( t \) of the cell and of the cells of the neighbourhood as well as to the actions of the external agents.

The expressions of the single agents actions follow. Later they will gathered in an unique transition function:

surface conductance \[ \Delta' T_{t+1} = \frac{h}{\gamma \cdot c} (T_e(t) - T_t) \Delta t/\Delta x \]
radiation \[ \Delta'' T_{t+1} = -a \cdot \sigma (273 + T)^4 \Delta t/\Delta x \]
solar radiation \[ \Delta''' T_{t+1} = \frac{E_r \cdot a}{\gamma \cdot c} \Delta t/\Delta x \]

Eventually the general transition function can be written as:

\[ T_{t+1} = T_t + \Delta' + \Delta'' + \Delta''' = T_t + (1/ \gamma \cdot c) \left[ h (T_e - T_t) - a \cdot \sigma (273 + T)^4 + E_r \cdot a \right] \Delta t/\Delta x \]

where the external temperature is given through a diagram not reported here, while the solar radiation is given through the diagram in Fig. 4.

The second transition function is:

\[ \Delta T = 8 \cdot \beta \left\{ \sum_j (T_j - T) / [(\gamma_j + \gamma) (c_j + c) (1/k_j + 1/k)] \right\} \Delta t/\Delta x^2 \]

where \( j \) is extended to all the cells of the neighbourhood.

This \( \Delta T \) is furtherly added to the result of the previous transition.

7. Conclusions

The example has shown the expressive capabilities of the tool.
When beginning the implementation of the automaton we believed that it could be useful as an aid to do comparisons and choices of building components while the design process progresses. The present stage of development is proved to be too slow and not enough friendly to allow such an use. We are hardly working to improve it. At present we believe that as a didactic tool it can be somewhat useful for analyses off line better suited to examine the performance classes of technical solutions, standard or aimed to standardisation. But its main use remains, according to us, research, forecasting the behaviour of new building components made of new materials whose intrinsic characteristics taken in isolation are known, but not the behaviour of the whole component.
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References


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