Maintenance Process Control: Cellular Automata Approach

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Abstract. In this work we consider an industrial maintenance process control problem using cellular automata approach. The problem consists on finding an optimal control for the displacement of agents in a spatial area to maintains the equipments running. The approach is based on a feedback control. Some simulation are given to illustrate our approach. The simulation software was developed under Java environment.

Keywords: Cellular Automata · Maintenance process · Feedback control

1 Introduction

From the 1980s with the development of computers, cellular automata (CA) theory has boomed in the world of science. They gradually emerged as an alternative for the microscopic realities, reflecting the macroscopic behavior of dynamic systems. They are now used as modeling tools in many sciences area.

Research in biology and chemistry were the first predisposed to exploit them. Today there are lots of applications in all areas involving the variables space and time. Indeed, by the cellular automata approach, they are taken discretely, as well as the physical quantities they describe.

Since their introduction in the 1940s as a model of self-replicative systems considered by Von Neumann and Ulam, many were the definitions around the CA, [2] (1998), [3] (2002) and [8] (2008).

Their simple conception, as well as their adaptation to strong computer architectures with respect to continuous models justify their heavy use as modeling tools in recent decades. Most recently Ouardouz et al. in [1] have proposed an CA model for the technicians allocation process in a maintenance problem in industry, to meet the needs of resources allocation under constraints of space, cost and time. The determination of the mathematical model for such phenomenon described by a distributed parameters system is the first step in the classic study

This work has been supported by the project PPR2-OGI-Env and the international network TDS, Academy Hassan II of Sciences and Techniques.

P.C. Vinh et al. (Eds.): ICTCC 2016, LNICST 168, pp. 287–296, 2016.
DOI: 10.1007/978-3-319-46909-6_26

of this kind of system (understanding the system, follow its evolution in the aim to control it). The cellular automata approach yet in this case present a huge advantage compared to its description relatively simple and for its adaptation to global realities of the problem studied.

Therefore, the need to define and characterize the concepts, long exposed in the systems theory is required for cellular automata approach. We quote for example the concepts of regional controllability, spreadability and observability [4–10]).

In this paper, we consider the controllability concept for cellular automata in order to approach the maintenance process problem. For that, we consider the model, proposed by Ouardouz et al. in [1] in the autonomous case, and we introduce a feedback control to optimize the assignments and agents displacements.

In the second section we present the problem statement and in the third section we recall some definition and the principle of cellular automata. In section four we present the methodology for the problem approach and some simulations results illustrating our approach.

2 Maintenance Process Control: Problem Statement

The maintenance problem is to assign available technicians to a set of down equipments taking into account there proximity, availability and competencies so as to maintain as long as possible all the equipments operational. The starting point is a set of operational machines falling down (not necessarily all of them) after a certain uptime.

This system is a system with spatiotemporal evolution described by the states of the machines and the interventions over time. It is a discrete system in time and space. Each machine and each agent occupies a geographic position at a given moment and the overall state of the system is a spatial configuration changing over time. That is why we opt for a cellular automaton approach.

It is proposed to develop a control based on the consideration of spatial and temporal factors in the allocation of resources allowing particularly, in the case of a manufacturing company to maintain all the machines operational.

We are interested in the control of the allocation of intervention tasks of preventive maintenance process for which allocation decisions and agent displacements are made by a simulation based on cellular automata.

The proposed control, must also apply in the case of unplanned interventions (random) due to corrective maintenance. Indeed, the application of control following the observation of the distribution of resources 'technicians' in the beggerhood of a down machine should allow to allocate maintenance tasks to the most appropriate agent, available and/or more close spatially and thus to ensure the reparation of the machine.

We consider the cellular automaton model as used in [1] but in this work we introduce the feedback control concept. We recall in the next section the definition and principle of cellular automata.

3 Cellular Automata: Generality

3.1 Cellular Automata Definition

A cellular automaton is given by a quadruplet

$$\mathcal{A} = (\mathcal{T}, \mathcal{V}, \mathcal{E}, f) \tag{1}$$

- $\mathcal{T}$ said cell space or lattice is a network which consists on a regular tiling of a domain Ω of $\mathbb{R}^n$, $n = 1, 2$ or 3. The elements of this paving denoted c are said cells and occupy the whole area.
- v said neighborhood, for a c cell is a set of cells affecting its evolution over time. Depending on the problem modeled, it can be given by

$$v(c) = \{c' \in \mathcal{T};\ d(c, c') \leq r\}, \quad \forall\, c \in \mathcal{T}. \tag{2}$$

  d is a distance on $\mathcal{T} \times \mathcal{T}$ equivalent to the norm L_∞ defined by [5]

$$d(c, c') = \min\{\ell(c, c');\ (c, c') \in J(c, c')\}, \quad \forall\, c, c' \in \mathcal{T} \tag{3}$$

  where $\ell(c, c')$ a length between c and c' and $J(c, c')$ the set of all possible joins between c and c' from their center. $v(c)$ is said radius r and size $m = \operatorname{card} v(c)$.
- $\mathcal{E}$ designates all states, which is a finite set of values representing all states that may be taken by each cell. This is generally a cyclic ring, given by

$$\mathcal{E} = \{e_1, e_2, \ldots, e_k\} \text{ with } \operatorname{card} \mathcal{E} = \mathrm{k}. \tag{4}$$

  We speak about a configuration of a CA in a given time t, the application

$$\begin{aligned} e_t : \mathcal{T} &\to \mathcal{E} \\ c &\mapsto e_t(c) \end{aligned} \tag{5}$$

  which maps each cell c from $\mathcal{T}$ a value taken in $\mathcal{E}$ which will be the state of c at t.
- f is a transition function that defines the local dynamics of the system studied. It calculates the state $e_{t+1}(c)$ of a cell at $t+1$ depending on the state $e_t(v(c)) = \{e_t(c'),\ c' \in v(c)\}$ of the neighborhood at t. We consider then the form

$$\begin{aligned} f : \quad \mathcal{E}^m \quad &\to \mathcal{E} \\ e_t(v(c)) &\mapsto e_{t+1}(c) \end{aligned}. \tag{6}$$

3.2 Controllability for Cellular Automata

First let's see how we can introduce a control in a cellular automaton as outlined in [4]. As in the case of continuous systems, a precision on the control is to give its spatial support and its values. The spatial support of the CA will be a part of the lattice $\mathcal{T}$ noted $\mathcal{T}_u$, and the values of the control will be provided by the set of real values $U = \{u_1, u_2, \ldots u_q\}$. Some U values can of course be in the set of states $\mathcal{E}$. In what follows I is a discrete time interval.

Definition 1. *Let $\mathcal{A} = (\mathcal{T}, \mathcal{V}, \mathcal{E}, f)$ be a cellular automaton and let $\mathcal{T}_u \subset \mathcal{T}$. The control over $\mathcal{A}$ is a function*

$$u : \mathcal{T}_u \times I \rightarrow U \tag{7}$$

which to each cell c from $\mathcal{T}_u$ associates a value $u_t(c)$ in U at t. In this case $\mathcal{A}$ becomes a non-autonomous or a controlled cellular automaton denoted $\mathcal{A}_u((\mathcal{T}, \mathcal{V}, \mathcal{E}, f), u)$.

The support of the control u in some cases may be reduced to a single cell, in this case we speak of punctual control. In other cases, the support may vary in time and space. This is known as scanner control. In all cases, the support may be expressed by

$$\mathcal{T}_u = supp(u) = \bigcup_i \{c \in \mathcal{T}; u_t(c) = u_i \in U\}.$$

Similarly with continuous systems, we may adopt a formulation of the transition function in the case of a controlled CA as

$$\begin{array}{c} f_u : \mathcal{E}^m \times U^m \rightarrow \mathcal{E} \\ (e_t(v(c)), u_t(v(c))) \mapsto e_{t+1} \end{array} \tag{8}$$

where $u_t(v(c)) = \{u(c', t) \in U; c' \in v(c)\}$. Acts on the control cells only in $\mathcal{T}_u$. Another much more flexible formulation, which we will use for the following, is established that

$$f_u(e_t(v(c))) = f(e_t(v(c))) \oplus u(c, t)\chi_{\mathcal{T}_u}. \tag{9}$$

It is clear that here the control is applied to a cell c when it is in the action area $\mathcal{T}_u$ of control u. The sign $\oplus$ is interpreted as a mutual action of the control and the transition function.

Definition 2. *We say that a cellular automaton $\mathcal{A} = (\mathcal{T}, \mathcal{V}, \mathcal{E}, f, u)$ is controllable during a time interval $]0, T[$ if for each initial global configuration $e_0^{\mathcal{T}}$ and each desired global configuration $e_d^{\mathcal{T}}$ there exists a control u such that*

$$e_T^{\mathcal{T}} = e_d^{\mathcal{T}} \tag{10}$$

The CA $\mathcal{A}$ is said to be weakly controllable with a tolerance ε during a time interval $]0, T[$ if for each initial configuration $e_0^{\mathcal{T}}$ and each desired configuration $e_d^{\mathcal{T}}$ there exists a control u such that

$$\frac{card\{c \in \mathcal{T}; e_T(c) \neq e_d(c)\}}{card\mathcal{T}} \leq \varepsilon. \tag{11}$$

For more details about controllability of cellular automata we refer to [4,6,8,9] and the references therein.

4 Application to the Maintenance Process Control Problem

4.1 Presentation of the CA Model

Model principle. The CA Model $\mathcal{A} = (\mathcal{T}, \mathcal{V}, \mathcal{E}, f)$ for the studied case is constructed on a bi-dimensional lattice $\mathcal{T} \subset Z^2$ where the cells in $\mathcal{T}$ noted c_{ij} has as neighborhood the entire lattice ($v(c_{ij}) = \{c_{kl} \in \mathcal{T}; d(c_{ij}, c_{kl}) \leq card\mathcal{T}\} = \mathcal{T}$). The set of states is given by

$$\mathcal{E} = \{-3, -2, -1, 0, 1, 2\} \tag{12}$$

with

$$e_t(c_{ij}) = \begin{cases} -3 & \text{if the cell contains a down equipment} \\ -2 & \text{if the cell contains an equipment under reparation} \\ -1 & \text{if the cell contains an operationnal equipment} \\ 0 & \text{if the cell is empty} \\ 1 & \text{if the cell contains an available technician} \\ 2 & \text{if the cell contains an occupied technician} \end{cases} .$$

We denote that $e_t(c_{ij}) < 0$ corresponding to a presence of an equipment in the cell, whereas a presence of a technician is indicated by $e_t(c_{ij}) > 0$. To each equipment we associate characteristic parameters determined from previous operating statistics

- $mtbf_{ij}$: the mean time between failures,
- $mttr_{ij}$: the mean time to repairs,
- zr_{ij}: an area of intervention which corresponds to a cell where the technician should stand up to repair the machine.

In this situation the equipment does not fail randomly, but after $MTBF$. The technicians likewise have the following properties

- zt_{ij}: a buffer zone where the technician returns at the end of the intervention.
- cc_{ij}: said target cell is the final destination of the technician.
- d_{ij}: is a couple $(d_1, d_2) \in \{-1, 0, 1\}^2$ with $|d_1| + |d_2| \leq 1$ reflecting a direction taken by the technician in the next moment. It is negotiated for the cell c_{ij} as a local destination $c_{i+d1,j+d2}$. $d = (0, 0) \equiv 0$ is a null direction, the technician is stationary. For cc_{ij} corresponding to the index cell c_{kl}, it is calculated as

$$d_{ij} = \begin{cases} (0,0) & \text{if } k = i \text{ and } l = j & (\cdot) \\ (1,0) & \text{if } |k-i| \geq |l-j| \text{ and } k \geq i & (\rightarrow) \\ (-1,0) & \text{if } |k-i| \geq |l-j| \text{ and } k \leq i & (\leftarrow) \\ (0,1) & \text{if } |k-i| \leq |l-j| \text{ and } l \geq j & (\uparrow) \\ (0,-1) & \text{if } |k-i| \leq |l-j| \text{ and } l \leq j & (\downarrow) \end{cases} . \tag{13}$$

- α_{ij}: a rotation angle of $\{\pm\frac{\pi}{2}, \pm\pi\}$ performed by the technician, in case of an obstacle relative to the local direction d_{ij}. The couple $[d_{ij}, \alpha_{ij}]$ indicates a direction d_{ij} followed by a rotation angle α_{ij}. For example $[(1,0), -\frac{\pi}{2}] = (0,1)$ and $[(1,0), \frac{\pi}{2}] = (0,-1)$.

Autonomous system. The transition function f can be written firstly to define the dynamics of an autonomous system. Let $e_t(c_{ij})$ the cell state $c_{ij} \in \mathcal{T}$ at t. The probable cell state at $t+1$ is fulfilled by

$$e_{t+1}(c_{ij}) = f(e_t(v(c_{ij}))) = \begin{cases} -3 & \text{if } e_t(c_{ij}) = -3 \text{ or if } e_t(c_{ij}) = -1 \text{ with } mtbf_{ij} = 0 \\ -2 & \text{if } e_t(c_{ij}) = -2 \text{ with } mttr_{ij} > 0 \\ -1 & \text{if } e_t(c_{ij}) = -1 \text{ or if } e_t(c_{ij}) = -2 \text{ with } mttr_{ij} = 0 \\ 1 & \text{if } e_t(c_{ij}) = 2 \text{ and } e_t(cc_{ij}) = -2 \text{ with } mttr_{cc} = 0 \\ dep(c_{ij}) & \text{if } e_t(c_{ij}) = 1 \text{ or if } e_t(c_{ij}) = 2 \text{ with } d_{ij} \nrightarrow cc_{ij} \end{cases} \quad (14)$$

Here $dep(c_{ij})$ is a function that is used to implement the process of moving a technician occupying the cell c_{ij}. In case of the intersection of several technicians, the priority to the right rule is performed. Displacement is thus made to avoid as much as possible blockage. The diagram in Fig. 1 describes the deplacement function where we used the following notations:

- d_{-1}: previous direction of the technician.
- c_o: obtained cell from the direction d_{ij}.
- c_{oo}: cell after c_o in the direction d_{ij}.
- c_α: obtained cell from a rotation $[d_{ij}, \alpha_{ij}]$.
- d_o, d_{oo}: direction of the technician if the cell c_o or c_{oo} contains a technician.

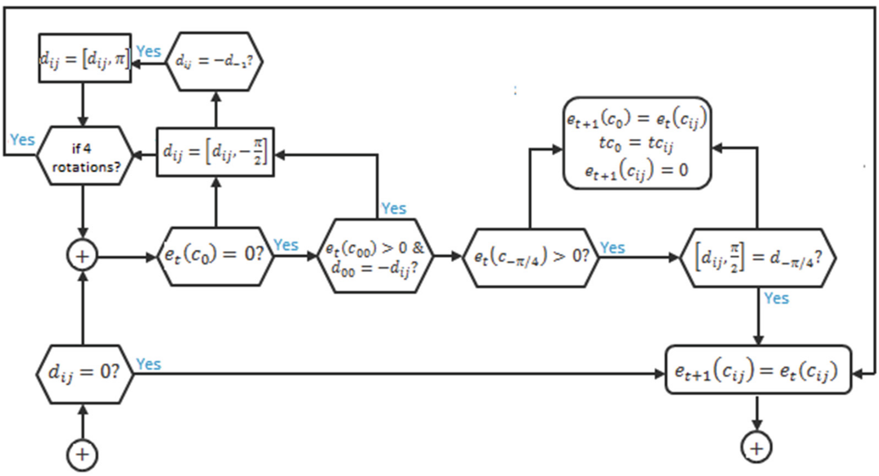

Fig. 1. Diagram of the technicians displacement function $dep(c_{ij})$.

Controlled system: Feedback control. We introduce here a feedback control on the autonomous system defined by the previous cellular automaton model. For T a given time horizon, the control will aim to keep all equipments operational. We therefore consider all down equipments

$$\omega = \{c_{ij} \in \mathcal{T}; e_t(c_{ij}) = -3\} \tag{15}$$

as a spatial distribution (or region) of the control. The support of the control, will, among other be

$$\mathcal{T}_u = \{c_{ij} \in \mathcal{T}; e_t(c_{ij}) = 1\} \tag{16}$$

the set of available technician. We choose as the control gains

$$U = \{1, 2\}. \tag{17}$$

For a desired configuration e_d of the system with

$$e_d(c_{ij}) = -1, \quad c_{ij} \in \omega, \tag{18}$$

the problem of the CA controllability we adopt is to find a control u that achieves this configuration at the time T. The one we found is a technicians assignment in $\mathcal{T}_u$ to down equipment in ω for repair, let then

$$\begin{aligned} u : \mathcal{T}_u \times I &\to U \\ (c, t) &\mapsto u(c, t) \end{aligned}. \tag{19}$$

A technician is assigned to an equipment when he is nearest the equipment than any one other (principle of Voronoi diagram [11]). Both are updated and removed in the process of assignment and the operation is repeated until that there is no more technicians available or machines in failure. For the explicit expression of the control u, we construct Voronoi diagrams [1] associated to T_u and ω:

$$\mathcal{V}or(\mathcal{T}_u) = \bigcup_{c \in \mathcal{T}_u} R_c^T \text{ with } R_c^T = \{c' \in \mathcal{T}; d(c, c') \leq d(c, c") \quad c" \in \mathcal{T}_u\}, \tag{20}$$

$$\mathcal{V}or(\omega) = \bigcup_{c \in \omega} R_c^E \text{ with } R_c^E = \{c' \in \mathcal{T}; d(c, c') \leq d(c, c") \quad c" \in \omega\}. \tag{21}$$

Then the control u is expressed by

$$c \in \mathcal{T}_u, \; u(c, t) = \begin{cases} 2 \text{ if } \exists c' \in \omega / R_c^T \cap R_{c'}^E \neq \emptyset \\ 1 \text{ else} \end{cases}. \tag{22}$$

However, it is noted that $\mathcal{T}_u$ changes in time because a busy technician may become available upon control. It is the same with ω, a machine in good operating conditions could breakdown. And since the control is performed for a definite time horizon, then the control u can be seen in a loop farm with return on observation of the state of the system.

The transition function of the controlled CA

$$\mathcal{A}_u = ((\mathcal{T}, \mathcal{V}, \mathcal{E}, f), u) \tag{23}$$

shall be defined so that all updating operations are made between the instants t, $t + 1/2$ and $t + 1$.

– Between t and $t + 1/2$, observations are performed on the state of the cells to notify the equipment failed and available technicians (ω et $\mathcal{T}_u$) according to the function

$$\begin{aligned} y : \mathcal{E}^{\mathcal{T}} &\rightarrow \mathcal{T} \times \mathcal{T} \\ e_t &\mapsto (\mathcal{T}_u, \omega) \end{aligned}. \tag{24}$$

– Between $t + 1/2$ and $t + 1$, we perform the control

$$u(c, t + 1/2), \quad c \in \mathcal{T}_u. \tag{25}$$

– At $t+1$, we update the state of each cell. And all technicians can move except those engaged before $t + 1/2$.

The transition function f_u of the controlled CA $\mathcal{A}_u$ is then written

$$e_{t+1}(c_{ij}) = f_u(e_t(v(c_{ij})) = f(e_t(v(c_{ij})) \oplus u(c_{ij}, t + 1/2)\chi_{\mathcal{T}_u}; \quad c_{ij} \in \mathcal{T} \tag{26}$$

where f and u are explained respectively by the Eqs. 14 and 22 and $\oplus$ refers to the mutual action. The principle of closed loop control on our CA for maintenance problem is summarized in Fig. 2. Some examples of Computer simulations after implementation of the CA are provided in the next section.

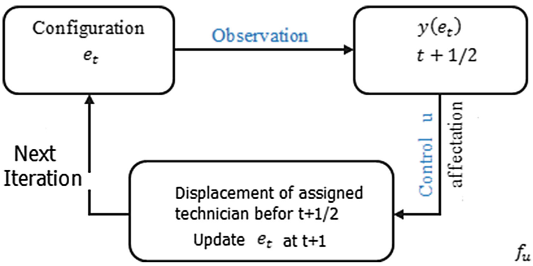

Fig. 2. Principle of feedback control for maintenance process

4.2 Simulation Results

The set of algorithms for cellular automaton built above was implemented in Java object oriented programming [12] using the architecture of Model View Controller design pattern in order to meet the simulation needs while ensuring flexibility and re-use of source code. A GUI is produced to facilitate the monitoring of maintenance process. To see some examples of simulations in accordance with the concepts of controls mentioned above, we adopt the following color connotation with respect to the state of the cells.

 Equipment down

 Cellule vide

 Equipment under reparation

 Technician available

 Equipment operationnal

 Technician occupied

A boundary condition, fixed type is considered. We maintained empty, the cells involved in each iteration. The repair area of each equipment is assumed to be the cell above the container. Of course a free choice of the latter may be performed by the user from the user interface. We associate to each technician a buffer zone (a cell to which he returns after an intervention) it is the technicians initial position. The mean time to repair and the mean time between failure are considered constant for all the equipments, with respective values 3 and 15. In the simulation (Fig. 3), the inial configuration is given at $t = 0$.

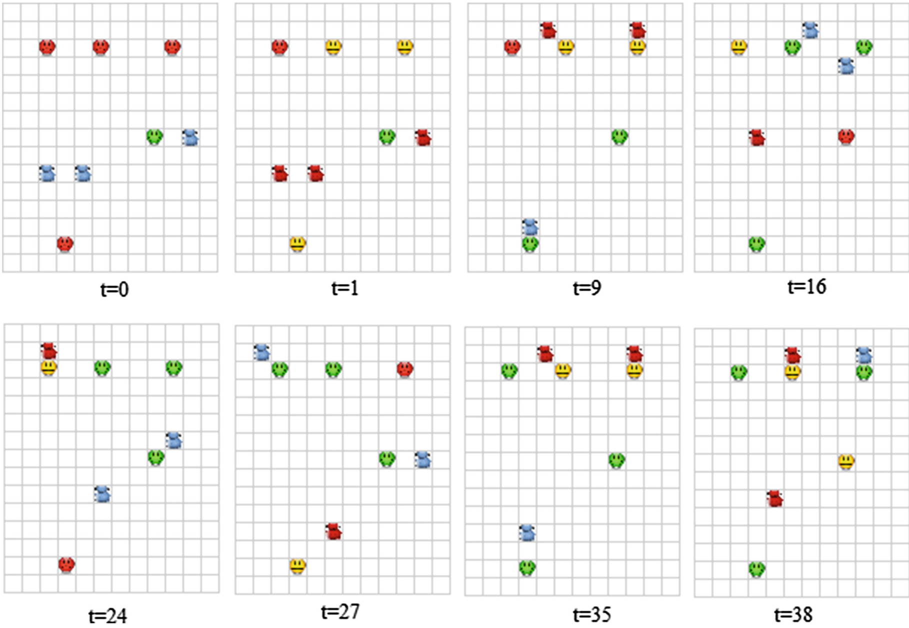

Fig. 3. Simulation results with a feedback control (Color figure online)

After the first assignment $t = 9$ a machine was repaired. An assignment is performed at $t = 10$. Between $t = 12$ and 14 four machines are operational. But at $t = 15$ an other machine fall down and the control is applied at $t = 16$. At $t = 24$ another failure is reported, and control is still established. This follows and during the time horizon, we set. The configuration at $t = 16$ returns at $t = 41$. A periodic succession of configurations, presenting three Operational equipment is then observed. And there are at least two equipments operational at each iteration, after $t = 8$. We remark in this case that the system is weakly controllable with respect to $\epsilon = 3/180$.

5 Conclusion and Perspectives

In this work we have considered the maintenance control problem with application in an industrial process using a cellular Automaton approach. The approach is based on the determination of a feedback control for the agent affectations through the observation of the state. The affectation is performed by Voronoi diagram based on the “nearest neighborhood” principle. In this work we have considered the case of 2D dimension cellular automata and it is will be very interesting to extend this results to the 3D dimension as for example the case of displacement in a building with different floors. Also it will be interesting to consider a stochastic cellular automaton model for such problem. Those problems are under investigation.

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