Discovery of Crises via Agent-Based Simulation of a Transportation System*

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Abstract. The contribution deals with a class of intelligent decentralized systems that are marked by the possibility of arising critical situations. The work starts from the elaboration of an overall methodology dedicated to the discovery of crises and support of anti-crisis activities. Then the case of transportation enterprise support system is discussed in detail. A simulation study of anti-crisis management in such a system concludes the work.

1 Introduction

As it has been repeatedly discussed and confirmed, a paradigm of multi-agent systems is especially powerful when looking for the representation of existing, designed or foreseen systems of hybrid technical-human nature. Notions of autonomy and decentralization, granularity and distribution, proactiveness and environment dependency are distinctive for such systems. Acceptance of the agent-based approach opens possibility for solving many problems that until now has been tractable only with respect to tightly coupled centralized systems. Some of these problems are risk and critical situations (states) analysis [10,1].

The systems under consideration may both be designed from scratch as multi-agent ones (operating in the virtual world, e.g. network information services, virtual enterprises), as well as function in the reality as a set of cooperating autonomous subsystems of whatever origin (e.g. transportation systems, industrial complexes). Such systems (virtual as well as real) are marked by the possibility of arising critical situations that can be caused by both outer (e.g. undesirable interference or the forces of nature) and inner (e.g. resource deficit, local damages) factors. Generally, a crisis is interpreted here as a threat of loss (partial or complete) of the system functionality.

As it will be shown, crisis identification, evaluation of possible effects and application of prevention (anti-crisis) actions occur to be much more difficult tasks in the case of such (multi-agent) systems. The mentioned above features (mainly: autonomy of the agent's decisions, lack of global information and hardly predictable behaviour) stems for quite different solutions.

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The paper tries to solve, at least partially, the three specified tasks. A function schema and appropriate information structure are proposed that can serve as a basis for analysing and managing critical situations. They specify how the system can be monitored and a simulation model of its behaviour created in the face of a particular crisis. The results of simulation studies are the scenarios of the crisis progress. The investigation of the scenarios may lead to finding a strategy of avoiding the crisis or, at least, reducing its effects. The simulation model is also in the shape of a multi-agent system [8].

General considerations are illustrated and verified with the case of a real transportation enterprise, which is represented by an agent-based model. A particular organization of the enterprise including an originally proposed anti-crisis policy is modelled together with its field of operation.

The paper is organized as follows. Section 2 describes the idea of monitoring and foreseeing critical situations in multi-agent systems. Section 3 is devoted to the description of an agent-based model of a transportation enterprise together with specific solutions of monitoring and management tasks. The considered critical situations arise as traffic jams and impassable roads. At the end (section 4) the chosen results of simulation studies illustrating the applied anti-crisis policy are presented.

2 Management of Critical Situations in MAS

A critical situation is recognized as a particular state or sequence of states that violate or lead to the violation of global as well as local (the agents') goals of the system. Thus critical situations can be local (concerning a single agent) and global (involving not only all but also a group of agents). Arising of a local crisis may entail a global one in the future, but functional abilities of the system very often allow avoiding consequences at the global level. On the contrary, the threat of a global crisis usually requires especially invented mechanisms.

Two kinds of critical situations can be distinguished: *direct* and *indirect*. The direct one means the threat of loosing operability of the system in consequence of unavailability of the some agents' actions. The primary cause of an indirect critical situation is the lack of resources that, in turn, gives deficit of functionality. The detection of both kinds can be realised by a monitoring sub-system based on individual evaluations pointed out the loss of functionality, or observations of the distribution of some resources crucial to the agent's or system activity.

Let us discuss shortly the conditions for the case of local critical situations. In the obvious way an agent monitors his state as well as evaluates it on his own. Significant reduction of the set of possible strategies of further operation in a particular state can be the indication of a crisis. Analysis with respect to global critical situations is a bit harder. This is because of the problem of determining the multi-agent system state. The state can be easily defined as composition of the agents' states but its calculation is usually operationally impossible because of the following features of MAS.

- There are no strong enough synchronization mechanisms to determine the simultaneity of agents' states.

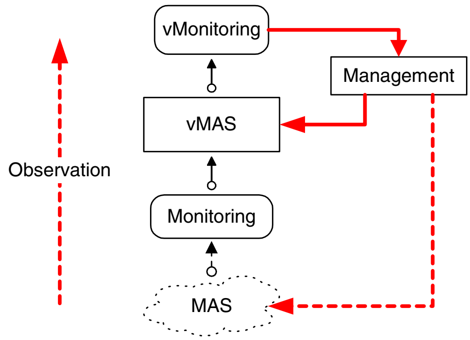

Fig. 1. Management structure for the case of *real* system

- The system state is highly multi-dimensional so that the high cost of information acquisition should be taken into account.
- Agents are autonomous. They usually intend to disclose only as much information as it is necessary for the system operation.

Putting all descriptions of the agents' states together, possibly in a single place, and regarding them as simultaneous is the only way to construct the description of the whole system state.

It seems obvious that it is hard or even pointless to search for any universal manner of management of critical situations in MAS. However, the principal assumptions of MAS operation allow for specification of an architecture, which seems to be general enough to be used as a reference one for describing crises management activities [7].

The architecture is a four-layer one as presented in figure 1. The bottom layer (MAS) constitutes the system under consideration. The directly higher layer (Monitoring) consists of agents that are assigned to gathering information about the subject system by inquiring and observing done according to the agent paradigm [4]. An agent-based model of the reality is situated as the next layer (vMAS): its agents try to reconstruct future states of the system using the monitoring data. Here scenario-based studies of the model are carried out aiming at critical situations detection and search for an anti-crisis policy. The main purpose of the upper monitoring layer is the evaluation of situations (states) arising in the course of simulations carried out using vMAS. The elaboration of a reach enough bunch of scenarios leads to finding the strategy of avoiding crises in the real system or, at least, reducing their effects. The agents of the upper layer may be equipped with the ability of decision making and, in turn, have an effect on the real system – selected strategies may be applied in the reality as a direct management or influence on mechanisms (e.g. organization) of the system. This may create a loop of semi-automatic prevention of crises in the proposed architecture.

The approach may be formally described in terms of the organizational model of a multi-agent system using some elements of M-Agent architecture [2]. Assuming that the state of MAS is observed only in certain moments of time $t_0, t_1, \ldots, t_{k-1}, t_k$ its dynamics in k-th step of operation may be illustrated by the following diagram:

$$
\begin{array}{ccccccc}
\ldots & \xrightarrow{\mathsf{org}(t_{k-2},t_{k-1})} & \mathsf{mas}(t_{k-1}) & \xrightarrow{\mathsf{org}(t_{k-1},t_k)} & \mathsf{mas}(t_k) & \xrightarrow{\mathsf{org}(t_k,t_{k+1})} & \ldots \\
 & & \downarrow \Upsilon & & \downarrow \Upsilon & & \\
\ldots & & \omega(t_{k-1}) & & \omega(t_k) & & \ldots \\
 & & \downarrow & & \downarrow & & \\
\ldots & \xrightarrow{\mathsf{vorg}(t_{k-2},t_{k-1})} & \mathsf{vmas}(t_{k-1}) & \xrightarrow{\mathsf{vorg}(t_{k-1},t_k)} & \mathsf{vmas}(t_k) & \xrightarrow{\mathsf{vorg}(t_k,t_{k+1})} & \ldots \\
 & & \downarrow \widetilde{\Upsilon} & & \downarrow \widetilde{\Upsilon} & & \\
\ldots & & \widetilde{\omega}(t_{k-1}) & & \widetilde{\omega}(t_k) & & \ldots
\end{array}
\tag{1}
$$

where:

$\mathsf{mas}(t_k)$, $\mathsf{vmas}(t_k)$ – states of MAS and vMAS respectively, encompassing the states of all agents $\mathsf{ag} \in \mathsf{Ag}$ and the environment env:

$$\mathsf{mas} \equiv \langle \mathsf{Ag}, \mathsf{env} \rangle \tag{2}$$

consecutively each agent is described in terms of actions $\mathsf{act} \in \mathsf{Act}$ it is able to perform depending on its state stat:

$$\mathsf{ag} \equiv \langle \mathsf{Act}, \mathsf{stat} \rangle \tag{3}$$

$\mathsf{org}(t_{k-1},t_k)$, $\mathsf{vorg}(t_{k-1},t_k)$ – organisations emerged in MAS and vMAS respectively, which manifests in actions performed by agents:

$$\mathsf{org}(t_{k-1},t_k) \equiv \{(\mathsf{ag}, \mathsf{act}, t) : \ \mathsf{ag} \in \mathsf{Ag}, \, \mathsf{act} \in \mathsf{Act}, \, t \in (t_{k-1},t_k)\} \tag{4}$$

$\Upsilon, \widetilde{\Upsilon}$ – observation heuristics for MAS and vMAS respectively,

$\omega, \widetilde{\omega}$ – representation of some global effects of the emerged organisations in MAS and vMAS respectively, acquired via observation heuristics:

$$\Upsilon : \ \mathsf{mas} \rightarrow \omega \tag{5}$$

For the sake of simplicity obvious variants of equations (2)-(5) for vMAS were skipped in the above definitions.

3 Crises in Transportation Systems

Plenty of various transportation system models can be found in literature (e.g. [6,9]). Their exact shape (also their complexity) depends on their general purpose or formal approach applied. Here a rather simple model is proposed oriented mainly towards the illustration of the information aspects of the proposed architecture. Solutions to the objective transportation problem introduced here are of the second importance.

It is assumed that a transportation system is modelled as a multi-agent system, so that agents represent vehicles moving around in a graph-like environment, where edges represent roads and vertices represent intersections:

$$\Gamma = (V, Y) \quad v_i \in V \quad y_{ij} \in Y \tag{6}$$

It is also assumed that the information about the cost of using a road is available for the agents in terms of *weights* of edges:

$$\lambda : Y \rightarrow \mathbb{R}^+ \tag{7}$$

This measure may represent the length, or more generally the throughput of a road. It describes the environment of MAS and thus it does not directly depend on (the states of) agents (i.e. the actual traffic).

The traffic is generated due to orders realised for the agent customer defined according to (3) as:

$$\mathsf{ag}^{\mathsf{c}} = \langle \{\xi\}, \Theta \rangle \tag{8}$$

where ξ denotes the action of negotiating and making contracts with selected vehicles, and Θ is the set of orders to be distributed among them:

$$\Theta = \{(u, v_i, v_j, \tau) : \ u \in \mathbb{N}, \ v_i, v_j \in V, \ \tau \in \mathbb{R}^+ \times \mathbb{R}^+\} \tag{9}$$

Each order is described by requested load u, route from source vertex v_i to destination vertex v_j, and finally time window τ the order has to be realised within.

A vehicle agent may be similarly defined as:

$$\mathsf{ag}^{\mathsf{v}}{}_k = \langle \{\xi, \chi\}, \langle \Theta_k, \Theta_k^*, \Gamma_k \rangle \rangle \tag{10}$$

where ξ is the action of making contract that is performed together with the agent customer, and χ encompasses all tasks that may be executed by a vehicle moving around a graph and realising orders. The state of a vehicle agent is defined in terms of allocated orders Θ_k, orders being realised Θ_k^*, and planned route Γ_k.

The action of making contract ξ means that selected orders of the customer Θ^* are allocated to a vehicle:

$$\xi : \ \Theta \rightarrow \Theta \setminus \Theta^* \ \text{ and } \ \Theta_k \rightarrow \Theta_k \cup \Theta^* \tag{11}$$

It is assumed that negotiations denoted by ξ are conducted by agents so as to maximize their *utility* (subjective measure of profit) of realising order(s). For each vehicle agent this may be defined as:

$$c_k(\Theta_k \cup \Theta^*, \Gamma_k) \tag{12}$$

and for the customer agent it is:

$$\sum_{\mathsf{ag}^{\mathsf{v}}{}_k} c(\Theta_k \cup \Theta^*, \Gamma_k) \tag{13}$$

which means that the utility in both cases depends on the set of all orders $\Theta_k \cup \Theta^*$ to be realised by vehicle $\mathsf{ag}^{\mathsf{v}}{}_k$ that takes part in the negotiations and its planned route Γ_k (e.g. how long it would take to realise the orders). Nevertheless it should be emphasised that utility functions of a vehicle c_k and of a customer c need not (in practice even *must not*) give the same values for the same orders and vehicles (the goals of a vehicle and a customer may differ).

Action χ is executed when a vehicle agent crosses a vertex and may result in starting some orders (loading) if the vertex is the source one for them, or finishing some orders (unloading) if their destination is reached, and finally updating the planned route:

$$\chi : \Theta_k \rightarrow \Theta_k \setminus \Theta^+ \text{ and } \Theta_k^* \rightarrow \Theta_k^* \cup \Theta^+ \setminus \Theta^- \text{ and } \Gamma_k \rightarrow \Gamma_k' \tag{14}$$

where Θ^+ denotes the set of orders just started (loaded), Θ^- denotes the set of just finished (unloaded) orders, and Γ_k' is the new (updated) planned route.

To recapitulate, a transportation system modelled as a multi-agent system consists of two kinds of agents and a graph-like environment, which according to (2) may be formulated as:

$$\mathsf{mas} = \langle \{\mathsf{ag^c}\} \cup \{\mathsf{ag^v}_k : k = 1,2,\ldots\}, \langle \Gamma, \lambda \rangle \rangle \tag{15}$$

The transportation system dynamics (the observed effect of the emerged organisation) is described by momentary values of vehicle flows in its edges:

$$0 \leq x_{ij} \leq x_{ij}^{max} \tag{16}$$

where $x_{ij} = x_{ij}(t_k)$ is the number of vehicles going through edge $y_{ij} \in Y$ in some time t_k and x_{ij}^{max} is the maximum flow allowed in the given edge. Also for each vertex (intersection) the balance equation for the flows coming in and out holds:

$$\sum_{y_{ij} \in Y_j^+} \delta_{ij} = \sum_{y_{ij} \in Y_j^+} x_{ij}^+ - \sum_{y_{jk} \in Y_j^-} x_{jk}^- \tag{17}$$

where $Y_j^+ = \{y_{ij} : v_j \in V\}$ and x_{ij}^+ is the number of vehicles coming into vertex v_j, similarly $Y_j^- = \{y_{ij} : v_i \in V\}$ and x_{jk}^- is the number of vehicles coming out of vertex v_j. This equation introduces a convention that allows to reflect a situation when it occurs impossible for all incoming vehicles to leave the vertex—its left side represents a queue of vehicles remaining in traffic jams (inversely, relieving the jams restores the balance). In such a situation it is possible that $x_{ij}^- \neq x_{ij}^+$ for some edge $y_{ij} \in Y$.

Having the transportation system defined, concrete tasks can be assigned to the layers of the proposed architecture. As monitoring of the transportation system is now the goal, appropriate deployment of monitoring spots can be related to the graph and parameters of the flows. Another decisive factor of the deployment comes from the higher level purpose of the monitoring. If the purpose is to supervise the whole transportation system in the sense of foreseeing its transportation capacities the spots can be located in the chosen vertices of the graph straightforwardly. Then flows coming in and out of such vertices are monitored according to the formula:

$$\omega = \{\omega_j = \sum_{y_{ij} \in Y_j^+} x_{ij} : v_j \in V\} \tag{18}$$

The goal of vMAS is to predict the future load of roads based on the observations of local vehicle flows (fig. 2), so that the monitoring data may be used for the prediction of future traffic by *i*-th vMAS agent:

$$\Omega_i^*(t) = \{\omega_{ij}^*(t_k) : t_k > t\} \tag{19}$$

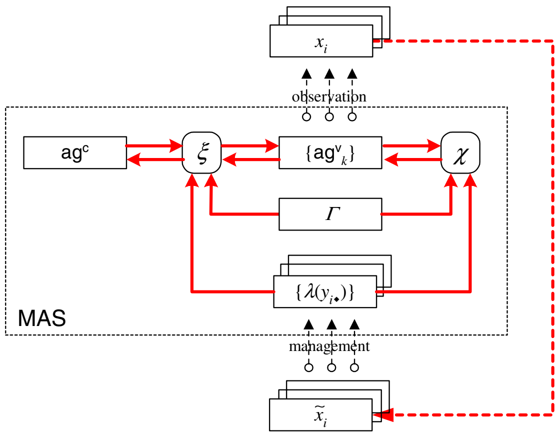

Fig. 2. Anti-crisis management in transportation MAS

And then the overall prediction may be obtained via cooperation of vMAS agents:

$$\widetilde{\omega}(t) = \{\omega_j^*(t_k) = \prod_{\mathrm{ag}_i} \omega_{ij}^*(t_k) : \; t_k > t\} \tag{20}$$

and some anti-crisis policy may be defined e.g. in terms of traffic rerouting via changing the weights of particular roads in mapping λ—see eq. (7).

4 Crises Management at Work

The aim of the experiments reported below was to show, how the consequences of the crisis situations, that are, in that case, traffic jams and impassable roads, could be minimised, using the proposed management scheme. The orders were allocated according to the dynamic PDPTW as described in [5].

The transportation network (the graph Γ) and its changes is presented in fig. 3. The numbers next to the vertices are their identifiers and the numbers next to the edges are their weights. During the experiments 80 vehicles were used. The generation of transport requests was performed as presented in [3]. In central nodes (marked on the graph as black points) the request frequency was 5 times higher than in normal nodes.

There were four network configurations being examined:

- basic configuration Ψ_1 – the graph of 100 nodes and 272 arcs, composed of four subgraphs 0-24,5-49, 50-74 and 75-99, which are connected by unique arcs;
- configuration Ψ_2 – after removing an arc which connects nodes 64 and 85 (marked as a dotted line);
- configuration Ψ_3 – after adding a new arc (marked as a dash line) connecting nodes 24 and 45 with weight equal to 2000;
- configuration Ψ_4 – change in the weight of the new arc from 2000 to 5000.

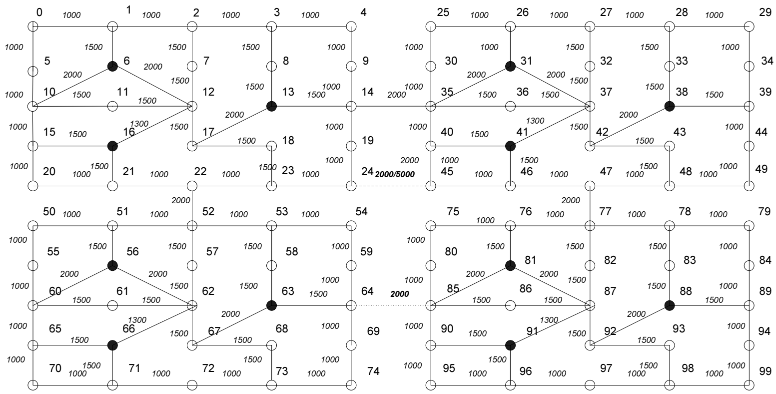

Fig. 3. Transport network and its modifications

The goal of such configuration choice was to show the system working without perturbations (configuration Ψ_1), the system after a crisis, which caused cutting of one arc (configuration Ψ_2), the results of attempting to limit the consequences of the crisis, introducing two different by-pass arcs: one of good quality (configuration Ψ_3) and the second of bad quality, i.e. increasing the travel time (configuration Ψ_4).

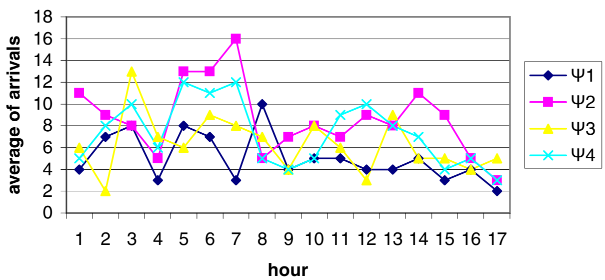

Fig. 4. Vehicles arriving at node 14

Figures 4 and 5 present the numbers of arrivals to the selected nodes 14 and 24, and the table 1 contains the average numbers of vehicles arriving in selected nodes for each examined configuration. The numbers of arrivals at nodes 14 or 24 increase after removing arc 64-85 (configuration Ψ_2) in comparison to the basic configuration Ψ_1). This is because there is only one travel path between sub-graphs 50-74, 0-24 and 25-49, 75-99, which must contain node 14. Adding a new connection between 24 and 45 brings an even distribution of traffic between arcs 24-45 and 14-35 (configuration Ψ_3). The number of vehicles arriving at node 24 increases, because previously they arrived to node 14 through nodes 9 or 13. The modification of a new arc in configuration Ψ_4 results in connection 14-35 being used more often by the vehicles.

The obtained results are highly intuitive and confirm the proper definition and realization of the model. The traffic balance of configuration Ψ_2 stems from the fact that the

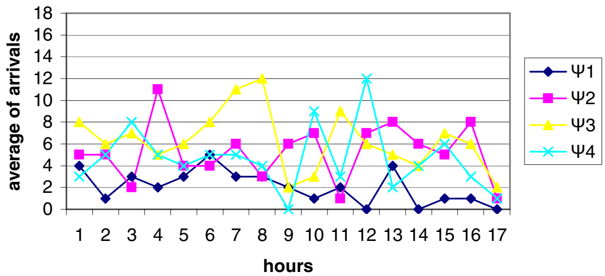

Fig. 5. Vehicles arriving at node 24

Table 1. Average of vehicles arrivals at selected nodes counted in time

configuration	—Ψ_1—	—Ψ_2—	—Ψ_3—	—Ψ_4—
Node 14	5.06	8.65	6.29	7.29
Node 24	2.06	5.24	6.29	4.65
Node 35	5.12	8.41	5.94	6.88
Node 45	1.76	3.82	5.35	5.47
Node 22	4.12	6.59	6.94	5.88
Node 47	4.94	6.18	6.70	7.41
Node 77	5.29	6.47	7.29	6.82
Node 64	4.94	1.06	0.65	0.76
Node 85	5.12	0.65	0.88	0.94
Node 99	0.12	0.41	0.29	0.24

edges belong to the only path between the sub-networks—the transit. The reaction of the traffic to adding the bypass and the following balancing of the alternative bypasses via changing of the weights can be regarded as correct and effective.

5 Concluding Remarks

The article is concerned with the application of agent approach to the problem of management of critical situations. Design assumptions and the proposal of the overall architecture of a (sub-)system dedicated to the discovery of crises and the support of anti-crisis activities are described.

One of possible applications is the management support for a transportation enterprise that operates in highly dynamic and uncertain environment of a road network that is a kind of the generator of critical situations. Considerations are carried out on the basis of the model of the network that plays here a role of a real system. Some parameters of the model are, in turn, subjects of monitoring in the designed layered architecture, other form a means for management. The particular organization of the enterprise including an originally proposed anti-crisis policy is modelled also. A conclusion that can be formulated at the point is that the implemented policy allows for the achievement of balanced traffic in the network also in the face of critical situations.

Simulation experiments partially presented in the paper confirm the main ideas of the approach. Future work will concentrate on its application to the transportation enterprises of different organization in order to justify and deepen solutions and conclusions elaborated so far.

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