An Adaptive Multi-Agent Organization Model Based on Dynamic Role Allocation

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Abstract

Organizations involving multiple agents require adaptation mechanisms to guarantee robustness, especially in critical domains. A template is presented for analysis and design of organizations with adaptation by dynamic role reallocation. This adaptive organization model can be used both for qualitative and quantitative domains, shown in two application cases made to evaluate the applicability of the model.

1. Introduction

Robustness of a multi-agent organization functioning in critical domains is essential. Unpredictability can both be in the internal functioning of the system itself (e.g., an incorrect functioning agent), or external to the system (e.g., a sudden increase in environmental pressure). To enable an organization to be robust, capabilities are required that allow the organization to adapt in order to continue functioning adequately.

An approach could be to model a multi-agent system in which each of the agents have those specific capabilities, and show the effectiveness of the system as a whole. However, it is hard to generalize results obtained beyond the specific agents. Recently, an abstraction level higher than the concept agent has become in use: the organizational level (see e.g. [3,8]). At this level, templates can be specified to aid analysts in modeling multi-agent organization models. These templates, for example, include specification of roles, possibly in the form of required behavior. In a given application, agents can be allocated to such roles. The templates can be reused in domains for which the characteristics comply to the ones specified for the template. Once the correctness of the template is proven (given certain domain assumptions) for a desired property, each model which complies to the specified template will satisfy that property as well, making the approach reusable. Of course, for each new case in which the template is used, an instantiation with domain-specific knowledge is still required.

This paper presents such an organizational model for the analysis of multi-agent organizations with the ability to adapt to unpredictable circumstances, maintaining the robustness of the system. The essential part of the organizational model is the specification of roles, since those can be seen as the engines of the organization. The approach taken distinguishes a number of aggregation levels, starting with the highest level dynamic property desired (i.e., robustness) and refining this property in a number of steps until the level of role behavior has been reached. Interlevel relations between dynamic properties at the different aggregation levels have been specified and verified using the model checker SMV [16]. The applicability of the model has been evaluated by using it to analyze two application case studies in different domains, one qualitative, and one quantitative.

The remainder of this paper is organized as follows. Section 2 introduces the modeling approach used to specify the organization model, which includes both a structural and a behavioral specification of the organization. The structural model within the template is specified in Section 3, whereas Section 4 presents the behavioral model, without taking into account adaptation. The adaptation model is presented in Section 5. Section 6 presents a qualitative application of the template in the domain of incident management and presents simulation results. In Section 7 a quantitative specialization of the model is specified. Section 8 is a discussion.

2. Modeling Approach

This Section presents the modeling approach used to specify the adaptive multi-agent organization model. First, the framework used to model organization structure is explained, thereafter the method for describing the behavior of such an organization. For describing the structural part of the model for adaptive multi-agent organizations, the AGR (Agent-Group-Role) modeling approach introduced in [6] is used. Here three basic concepts are used to model a multi-agent organization: agent, group, and role. An agent is an active communicating entity which plays roles within groups. Groups are sets of roles; a role is an abstract representation of an agent function or service.

The approach presented in [7] is used to specify dynamic properties on multiple aggregation levels: following AGR, the functioning of the particular roles, the functioning of groups, and of the organization as a whole. In general, behavioral properties are expressed as temporal relations over input states and output states of roles over time. Specification of dynamic properties is done in the *Temporal Trace Language* (TTL) [12]. Properties at the different levels can be structured in a hierarchy by means of interlevel relations. At the lowest level role properties describe the behavior of an individual role whereas transfer properties describe the dynamics of (intragroup) transfer between roles. For the roles within a given group, such role properties, together with the transfer properties, entail the group properties that characterize the behavior of the group as a whole. The group properties for the different groups, together with the inter-group relationship properties (for transfer between groups), entail the overall organization properties. Properties about the environment are treated the same way as roles.

3. Adaptive Organization Model: Organizational Structure

This Section presents the structural model within the adaptive organization model; see Figure 1. Here, small ovals denote roles, bigger ovals denote groups, solid arrows denote transfers between roles, and dashed lines denote inter-group interaction. The model is composed from two parts. The structure of one (the lower layer in Figure 1) is dependent upon the specific domain of application. The other structure (top layer, depicted in gray), the *Change Group*, by which adaptation of the organization takes place, is generic for any type of application. All the agents participating in the organization have an *Adaptor* role in this group. This role has the ability to monitor the existing agent-role allocations, and role, group and organization properties (hence, the group has a meta-view on the organization). In case it is observed that a property is not satisfied, an Adaptor role makes decisions about change in performing a role for which errors have been observed. The specification of the Adaptor role is addressed in Section 5. In the lower part of Figure 1, *Worker*

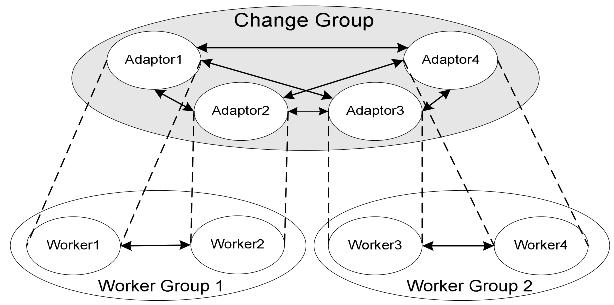

Figure 1. Adaptive Organizational Model

Groups are shown of which each one addresses a particular part of the tasks within an organization.

In incident management there would, for example, be a fire fighting group, medical group, and a police group. Notice that names in small ovals such as Worker1, .. Worker4, used here denote the roles in these groups, not the agents allocated to these roles. The adaptativity in the model is in the flexibility of allocations of agents to these roles, not in the change of the roles themselves. Such an allocation change may involve, for example, that for an agent A that was allocated to role Worker1 within Worker Group 1, its allocation is changed to an allocation to role Worker4 in Working Group 2.

4. Adaptive Organization Model: Organizational Behavior

The behavioral model within the adaptive organization model takes the form of a hierarchy of dynamic properties at the different aggregation levels of the organization (see Figure 2). The relationships between the different levels within the hierarchy have been verified using the SMV model checker; cf. [16]. The highest organizational properties express what one wants a particular organization (as a whole) to establish, e.g., based on *performance indicators* of an organization. Such organizational properties are refined into more specific properties for particular aspects or parts of an organization (Section 4.1). These are further refined to the aggregation level of the particular groups within the organization (Section 4.2).

4.1. Organization-Level Properties

The organization properties, expressing satisfactory functioning of the organization, can take various forms. For the adaptive organization model robustness is a main organization property to be achieved. An organization is said to be robust in case all relevant aspects of the organization are well maintained, despite environmental or internal fluctuations. Therefore, to achieve the goals of the organization a number of aspects X_1, …, X_n can be distinguished that have to be maintained; e.g., [1] p. 58, 83. Examples of such aspects in the context of incident management are fire fighting, health care, and traffic care. Thus, a main property for the organization is that the organization functions well for the combination of these aspects $X_1,…,X_n$. Organization property OP expresses that at all points in time proper maintenance of the combination of aspects is satisfied:

OP = ∀t:TIME state(γ, t, O) |= satisfied(combination(X1, … Xn))

Here state(γ, t, O) |= satisfied(combination(X1, … Xn)) denotes that within the state state(γ, t, O) in trace γ at time point t in organization O the state property satisfied(combination(X1, … Xn)) holds, with the infix predicate |= denoting the satisfaction relation between a state and a state property. Notice that a state property can have different truth values at different points in time.

Other relevant organization properties (e.g., survival) are assumed to be entailed by this primary organization property OP. The organization property OP is refined using properties for different aspects of the organization: For any of the aspects X, the property OAP(X), expresses that at all points in time aspect X is maintained in a satisfactory manner:

OAP(X) = ∀t:TIME state(γ, t, O) |= satisfied(X).

These properties are assumed to relate to the overall organization property by ∀X OAP(X) ⇔ OPl: as long as all aspect properties are satisfied, the organization as a whole functions in a satisfactory manner. To this end it is assumed that:

satisfied(combination(X1, … Xn)) ↔ ∀X satisfied(X).

Then the bi-implication above can be rephrased as

∀X state(γ, t, O) |= satisfied(X) ⇔ state(γ, t, O) |= ∀X satisfied(X)

which is an axioms for the predicate |= within TTL.

4.2. Group-Level Properties

In order to achieve the robustness of the organization, depending on circumstances, the organization needs to spend a certain effort on each of the distinguished aspects. As circumstances may change, it is here that adaptive control is possible and needed. In the organizational structure within the model, for each of the aspects a *Worker Group* is included to provide sufficient effort at each point in time as required to maintain this aspect, given the circumstances at that point in time.

GP1(X, G) : group provides required effort

For all time points t the effort provided by group G for aspect X is sufficient for the aspect.

∀t:TIME, E:EFFORT [state(γ, t, G) |= group_relates_to(G, X) ∧ provides_group_effort_for(G, E, X)
⇒ state(γ, t, O) |= satisfies_required_effort_for(E, X)]

Here the antecedent denotes that within the state state(γ, t, G) at time point t of group G in trace γ the state property group_relates_to(G, X) ∧ provides_group_effort_for(G, E, X) holds, expressing that group G relates to aspect X and provides effort E. Moreover, state(γ, t, O) |= satisfies_required_effort_for(E, X) expresses that at time t in trace γ the effort E is the effort required to satisfy aspect X. It is assumed as part of the organization model that when the effort provided by group G relating to X satisfies the required effort for aspect X, then X is considered satisfied:

group_relates_to(G, X) ∧ provides_group_effort_for(G, E, X) ∧ satisfies_required_effort_for(E, X) → satisfied(X)

Therefore, group effort property GP1(G, X) relates to the corresponding aspect property OAP(X) as follows:

GP1(X, G) ⇒ OAP(X).

The current roles within the group G are the ones that actually provide the effort for X. Each role has a particular effort it can provide, based on the role specification. In order to provide the required effort, sufficient effort of specific roles within a group is needed that together deliver enough combined effort, expressed in GP2. Here the ROLECOMBINATION and EFFORTCOMBINATION denote sorts for combinations of roles and of efforts, respectively. The latter sort is a subsort of EFFORT.

GP2(X, G) : roles provide required effort

For all time points t the total effort E1,...,En provided by the roles R1,...,Rn within group G addressing aspect X provides a combined effort satisfying the effort required for X.

∀t:TIME, RC:ROLECOMBINATION, EC:EFFORTCOMBINATION:
[state(γ, t, O) |= group_relates_to(G, X) ∧ group_has_roles(G, RC) ∧ provides_effort_combination(RC, EC)
⇒ state(γ, t, G) |= provides_group_effort_for(G, EC, X) &
state(γ, t, O) |= satisfies_required_effort_for(EC, X)]

This property relates to the previous one as follows:

GP2(X, G) ⇒ GP1(X, G)

4.3. Role-Level Properties

One role property is present on the lowest level not devoted to adaptation: Each of the active worker roles performs a certain amount of work:

RP1(R) Worker Contribution

For all t the Worker role R delivers an effort E.

∀t :TIME ∃E :EFFORT state(γ, t, R) |= provides_role_effort(R, E)

5. Adaptive Organization Model: Organizational Adaptation

This Section presents the adaptation properties for the organization model. First, the adaptation properties on how the organization can achieve or maintain its goals under changing circumstances are introduced. Thereafter, the Adaptor role properties are presented which form the engines of the adaptation process.

5.1. Adaptation Properties

Within the organization the aspects distinguished are monitored all the time: it is verified whether the provided effort is expected to stay sufficient for the required effort. To this end a signaling property is specified, based on desired effort. The property indicates those cases and time points that the effort observed for a certain aspect is close to becoming insufficient to satisfy the effort required for that aspect. The margin between the time point of signaling not satisfying the desired effort and the time point that the required effort is at risk of not being satisfied, is assumed large enough to have time to adapt. The adaptation mechanism within the organization has to guarantee that the effort will satisfy the desired effort again within a certain duration, without dissatisfying the required effort in the meantime; this to prevent property GP1 not being satisfied. This adaptation is expressed by the group adaptation property AP1.

AP1(X, G, d): Group adaptation for desired effort

For all time points t, in case the current effort E provided by group G for aspect X is not satisfying the desired effort, then at a later point in time t2 (where t2 > t and t2 < t+d) the organization has changed such that the effort provided satisfies the desired effort and in between will still satisfy the required effort.

∀t:TIME, G:GROUP, E1, E2:EFFORT:
[[state(γ, t, O) |= group_relates_to(G, X) &
state(γ, t, G) |= provides_group_effort_for(G, E1, X) &
state(γ, t, O) |= satisfies_required_effort_for(E1, X) &
state(γ, t, O |= not satisfies_desired_effort_for(E1, X)]
⇒ ∃ E2:EFFORT, t2 > t [t2 < t+d &
state(γ, t2, G) |= provides_group_effort_for(G, E2, X) &
state(γ, t2, O) |= satisfies_desired_effort_for(E2, X) &
∀t1 [t ≤ t1 ≤ t2 ⇒
state(γ, t1, O) |= satisfies_required_effort_for(E2, X)]]]

This property relates to the previous properties as follows:

AP1(X, G, d) ⇒ GP1(X, G)

The group property for adaptation can be related to adaptation properties of individual roles:

AP2(X, G, d) : Role adaptation for desired effort

For all time points t, in case the current effort combined from role efforts E1,…,En provided by the roles R1,….,Rn in G is not satisfying the desired effort, then at a later point in time t2 (where t2 > t and t2 < t+d) the organization has changed such that the effort combined from efforts provided by the roles within G satisfies the desired effort and in between will still satisfy the required effort.

∀t:TIME, RC1:ROLECOMBINATION, EC1:EFFORTCOMBINATION
[[state(γ, t, G) |= group_relates_to(G, X) ∧
group_has_roles(G, RC1) ∧
provides_effort_combination(RC1, EC1) &
state(γ, t, O) |= satisfies_required_effort_for(EC1, X) &
state(γ, t, O) |= not satisfies_desired_effort_for(EC1, X)]
⇒
∃ t2 > t, RC2:ROLECOMBINATION, EC2:EFFORTCOMBINATION
[t2 < t+d & state(γ, t2, O) |= group_relates_to(G, X) ∧
group_has_roles(G, RC2) ∧
provides_effort_combination(RC2, EC2) &
state(γ, t2, O) |= satisfies_desired_effort_for(EC2, X) &
[∀t'≤ t2 [t'> t ⇒
∃RC3:ROLECOMBINATION, EC3:EFFORTCOMBINATION
state(γ, t', O) |= group_relates_to(G, X) ∧
group_has_roles(G, RC3) ∧
provides_effort_combination(RC3, EC3) &
state(γ, t', O) |= satisfies_required_effort_for(EC3, X)]]

This property relates to the others as follows:

AP2(X, G, d) ⇒ AP1(X, G, d)
AP2(X, G, d) ⇒ GP2(X, G)

Next Section presents role properties for adaptation.

5.2. Adaptor Role Properties

By an Adaptor role M, decisions about taking up or switching between Worker roles are made. As input information is used about the effort E currently being delivered by the different Worker groups G for a certain aspect X as expressed in provides_group_effort_for(G, E, X). In the model the decision mechanism is indicated by a relation expressing that an aspect has urgency: has_urgency(X_1, E_1, …, X_n, E_n, X) indicating that aspect X needs to be addressed in the context of efforts E_i, for aspects X_i. This relation can be specified as only deriving one aspect to be addressed (i.e., the most important aspect) or multiple aspects (e.g., all aspects currently not being addressed properly). The relation takes into account which effort E suffices for the required effort to be delivered for aspect X: satisfies_required_effort_for(E, X) and which effort E suffices for the desired effort for aspect X: satisfies_desired_effort(E, X). A simple form of an urgency relation that is taken by default is: **has_urgency(X_1, E_1, … X_n, E_n, X_i)** ↔ not satisfies_desired_effort(E_i, X_i). This expresses that all aspects for which the desired effort is not satisfied are urgent. Based on the input on urgency, the Adaptor role M generates in an intermediate state an indication of the aspect that needs to be addressed.

RP1(M) Aspect Urgency

At any t, if at t Adaptor role M observes the group efforts for each of the aspects, and has a urgency relation that indicates X an urgent aspect at that time,

then at some t' ≥t it will generate that X needs to be addressed.

∀t, X_1, .., X_n, E_1, .., E_n, X, M
state(γ, t, G_1) |= provides_group_effort_for(G_1, E_1, X_1) & … &
state(γ, t, G_n) |= provides_group_effort_for(G_n, E_n, X_n) &
state(γ, t, M) |= has_urgency(X_1, E_1, …, X_n, E_n, X)
⇒ ∃t'≥t state(γ, t', M) |= to_be_addressed(X)

Based on this, appropriate role(s) R within the Worker Group(s) WG for the aspect(s) is/are determined, and that a candidate is to be found for the role:

RP2(M) Role Change Determination

At any t, if at t Adaptor role M generated that X is an urgent aspect, and role R in WG is responsible for this aspect,
then at some t' ≥t it will generate that a candidate for role R in WG has to be found.

∀t, X, R, WG, M [state(γ, t, M) |= to_be_addressed(X) &
state(γ, t, M) |= role_responsible_for(R, WG, X)
⇒ ∃t'≥t
state(γ, t', M) |= to_be_found_candidate(M, ChangeGroup, R, WG)]

Finding the right Adaptor to be allocated to the role is the next step in the process, assuming shared knowledge of the capabilities of the Adaptors. An Adaptor may only have a partial view on this, and simply choose a local optimum. The mechanism states that the Adaptor will perform the role itself in case it has the capabilities or otherwise appoints another Adaptor which has the capabilities and is preferred.

RP3(M) Candidate Selection: Own Selection
∀t:TIME, M,R:ROLE, WG:GROUP, C1,C2:CAPABILTIES
[state(γ, t, M) |= to_be_found_candidate(M, ChangeGroup, R, WG) &
state(γ, t, M) |= required_capabilities(R, WG, C1) &
state(γ, t, M) |= has_capabilities(M, ChangeGroup, C2) &
state(γ, t, M) |= capabilities_match(C1, C2)
⇒ ∃t2>t [state(γ, t2, M) |= shared_allocation(M, ChangeGroup, R, WG)]]

Finally, the following relationship is assumed to hold, given that roles $R_1,\ldots,R_n$ are devoted to Group G addressing aspect X:

RP1(M) & RP2(M) & RP3(M) & RP4(M) & RP5(M) &
RP1(R1)& .. & RP1(Rn) ⇒ AP2(X,G,d)

This logical relationship is an assumption imposed on the domain of application. It is assumed that by adding more roles to the group involved, the effort for an aspect X can be strengthened so that the required effort is kept satisfied, and the desired effort will become satisfied again within duration d. In many qualitative and quantitative domains this assumption is fulfilled, for example, in the domain addressed in Section 6 in this paper. In quantitative cases it gets the form of the assumption that by adding role efforts for X, the total sum of efforts can be increased until a certain value is reached, which relates to the Archimedean principle for the real numbers: $\forall a,b>0 \exists n \in \mathbb{N}\ n*a > b$. In qualitative cases the assumption can be related to an assumption on the availability of the right capabilities within the organization, as is shown in Section 6.

The full property hierarchy is shown in the AND/OR tree in Figure 2. All relationships expressed within the tree have been verified using the SMV model checker under the assumptions as stated before.

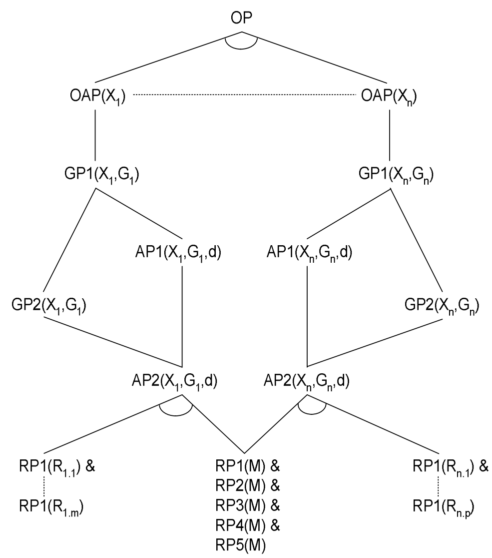

Figure 2. Property hierarchy

6. A Qualitative Application of the Organizational Model

This Section presents one of the two case studies undertaken to evaluate the applicability of the adaptive organization model presented above. It provides an analysis of the functioning of incident management organizations, in which adaptation of the organization by dynamic role reallocation is often observed. The qualitative model was made on the basis of extensive documentation of one of the disasters that took place in the Netherlands [17]. First, domain specific variants of properties are introduced, after which simulation results are presented.

6.1. Domain Specific Properties

On the highest level of this qualitative incident management model, the property OP is defined. For incident management, the aspects to be maintained are fire fighting, health care, and traffic care:

OP(disaster)
For all time points t each aspect for incident management in the organization is satisfied.
∀t:TIME [state(γ, t, O) |= satisfied(fire_fighting) ∧
satisfied(health_care) ∧ satisfied(traffic_care)]

On a lower level each individual aspect X is satisfied within the organization, for example, for the traffic care aspect of the organization:

OAP(traffic_care)
For all time points t aspect traffic care is satisfied in the organization.
∀t:TIME [state(γ, t, O) |= satisfied(traffic_care)]

The group responsible for the aspect traffic care is the police department. Property GP1 requires a definition of satisfaction of the required effort. The effort of a group is defined as an abstract name; the required effort is satisfied in case within duration d a route plan for ambulances is created which passes all wounded people from the start of the incident:

satisfies_required_effort_for(police_effort, traffic_care) ↔
∀t,t0:TIME [present_time(t) ∧ memory(t0, incident_started) ∧ t0+d < t]
→ ∃t2 ∃R:ROUTE_PLAN [t2 < t0+d ∧
memory(t2, proposed_route_plan(R)) ∧
∀W :WOUNDED memory(t2, passes_wounded(R, W))]

Here it is assumed that there are memory states. The desired effort is defined by:

satisfies_desired_effort_for(police_effort, traffic_care) ↔
∀t,t0:TIME [present_time(t) ∧ memory(t0, incident_started) →
t0 + rd > t] ∨
∃t2 ∃R:ROUTE_PLAN [memory(t2, proposed_route_plan(R)) ∧
∀W :WOUNDED memory(t2, passes_wounded(R, W))]

Here 0 < r < 1. In other words, the desired effort states that the correct route plan should be present before the required deadline already. The desired effort is always satisfied in the time interval from the start of the incident until rd after this start. It is not satisfied in the time interval starting rd after the start of the incident where no route plan was proposed yet. In view of property AP1 this means that after a correct route plan has not been generated by the police department within rd from the start of the incident, adaptation will be initiated at this time point, in order that the required effort will still be guaranteed before d after the start of the incident. As soon as indeed a route plan is proposed, the required effort remains satisfied and the desired effort becomes satisfied again.

Failure of the satisfaction of desired effort means that there is no role within the police department which has generated the correct route plan. By property AP2, this ultimately results in an adapted police department with roles which do perform the desired effort. To enable this change, the Adaptor within the Change Group uses the standard default definition of the urgency relation, in this case specifically for the police:

has_urgency(fire_fighting, fire_brigade_effort, health_care, health_effort, traffic_care, police_effort, traffic_care) ↔
not satisfies_desired_effort_for(police_effort, traffic_care)

expressing that the traffic care aspect has urgency when no route plan is generated within the desired duration.

6.2. Simulation Results

In order to show how a multi-agent organization functions using the organizational model as presented above, simulation runs have been performed based on observations at the Volendam bar fire as described in [17]. In order to be able to simulate these adaptation processes, the lowest level properties (i.e. role properties) as presented in the Sections above have been translated into the executable subset of TTL called *leadsto* [4] which is used as an input for a simulation tool as described in [4]. Figure 3 shows the result of the simulation using this tool. In the Figure the left side shows the atoms that occur during the simulation run whereas the right side shows a timeline where a dark gray box indicates an atom being true whereas a light gray box indicates false.

As can be seen in the trace, at time point 0 the bar fire starts: incident_started(bar_fire_volendam). Three wounded people are present at the scene, at different locations, namely “zuideinde”, “pellersplein”, and “zeestraat”:

wounded_location(wounded_1, zuideinde)
wounded_location(wounded_2, pellersplein)
wounded_location(wounded_3, zeestraat)

Note that in reality much more wounded are present. Based on these circumstances an Adaptor role observing the current state of affairs at the scene derives that both the desired and required effort concerning traffic care are being delivered by the police, since they have until time point 4 to come up with a correct plan:

internal(adaptor_role_1|ChangeGroup)|satisfies_desired_effort(police_effort, trafic_care)
internal(adaptor_role_1|ChangeGroup)|satisfies_required_effort(police_effort, trafic_care)

At time point 2 the route planner within the police group proposes a route plan which consists of merely one drive up route which is the location “zuideinde”:

output(route_planner|police)|proposed_route_plan(zuideinde)

This plan however only passes the wounded person at the location “zuideinde” and not the other wounded:

passes_wounded(zuideinde, wounded_1)

Since the requirement is that the route plan should pass all wounded, the current proposed plan does not satisfy the requirements. However, due to the fact that the police has 4 time points before the desired effort needs to be provided, it takes until time point 4 before this failure is addressed (they could also have thought out a new, correct, route plan before the fourth time point). At that time point, an Adaptor role derives that the police effort does not satisfy the desired effort regarding traffic care, which causes an urgency for the traffic care task:

internal(adaptor_role_1|ChangeGroup)|has_urgency(fire_fighting,.., traffic_care)

As a result, the role immediately derives that traffic care needs to be addressed:

internal(adaptor_role_1|ChangeGroup)|to_be_addressed(traffic_care)

Since the route planner is the role responsible within the police department for this task, a candidate must be found to take over the role:

internal(adaptor_role_1|ChangeGroup)|to_be_found_candidate(adaptor_role_1, ChangeGroup, route_planner, police)

The capabilities required for the role are navigation skills, a skill present at the particular Adaptor role, which therefore starts a shared allocation with the role itself (following the properties in Section 5.2):

shared_allocation(adaptor_role_1, ChangeGroup, route_planner, police)

As a result of this new shared allocation, the role outputs a new route plan which described a route that circles the scene and therefore passes all the wounded:

output(route_planner|police)|proposed_route_plan(circle_scene)

As a result, the desired effort is satisfied again. Note that during the entire adaptation process the required effort was always fulfilled since the requirement stated by the guidelines says that a route plan that passes all wounded should be present within 6 time points, which is the case within the simulation. Would there however not have been any adaptation, the required effort would not have been satisfied after time point 6.

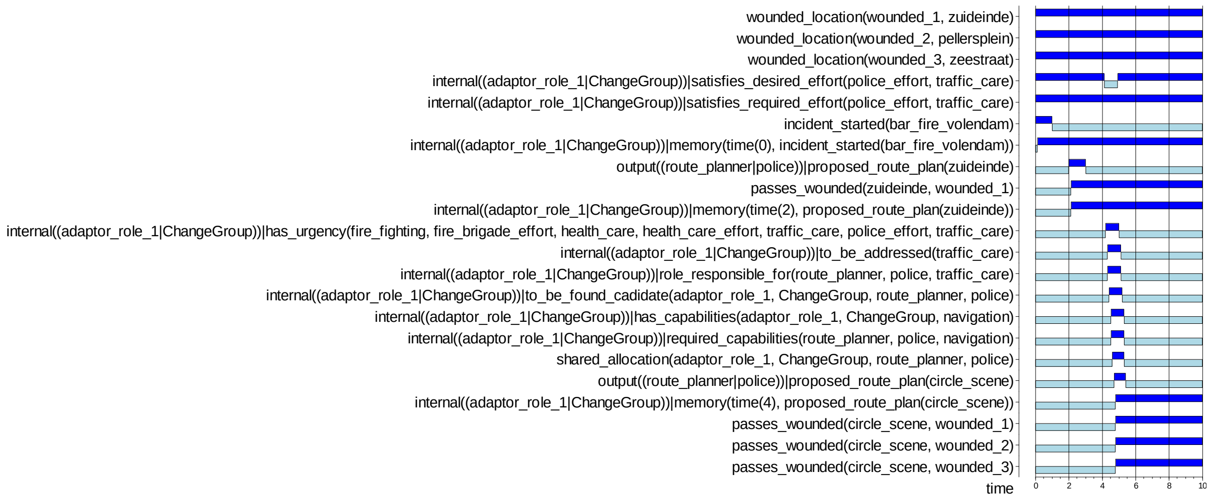

Figure 3. Simulation results using the adaptive organizational model

7. Quantitative Specialization of the Adaptive Organization Model

For domains that can be quantified, the adaptive organization model can be specialized. As a starting point each aspect X can be quantified by some value V (real or integer number), indicated by has_value(X, V). For each aspect a lower bound V1 and upper bound V2 is specified (indicated by lower_bound(X, V1) and upper_bound(X, V2)). The aspect is satisfied whenever its value is between these values: **satisfied(X)** $\leftrightarrow$

$\forall$V1,V2, V:VALUE [[has_value(X, V) $\wedge$ lower_bound(X, V1) $\wedge$ upper_bound(X, V2)] $\rightarrow$ V1 $\leq$ V $\wedge$ V $\leq$ V2]

Each of these aspects has a particular type of role attached to it, in which work is performed which contributes to that particular aspect. On the highest level, each aspect simply needs to be satisfied, expressed by the property OP in the following manner:

OPquantitative

For all time points t each aspect X has a value V which is below the upper bound V2 and above the lower bound V1.

$\forall$t:TIME state(γ, t) |= $\forall$X:ASPECT, V1,V2, V:VALUE
[has_value(X, V) $\wedge$ upper_bound (X, V2) $\wedge$ lower_bound (X, V1)] $\rightarrow$
V1 $\leq$ V $\wedge$ V $\leq$ V2]]

On the lower level of OAP(X), the same is expressed per aspect X. The effort required to maintain each of the aspects throughout the organization can change over time. A value to be maintained might for example express that a certain percentage of environmental pressure needs to be dealt with, which means more effort in case of more environmental pressure. The group properties which express the effort being delivered by the groups addressing the aspects can again be reused from the model. However, the definitions for required effort and desired effort can be tailored towards the quantitative perspective. Here the assumption is made that V depends on E in a monotonic manner (when E is increasing, either V is increasing or decreasing). First of all, the required effort for each group is satisfied in case the current effort is between the minimum effort required (based either on the upper or lower bound of the aspect value) and the maximum effort (again from either the upper of lower bound of the aspect value).

satisfies_required_effort_for(E,X) $\leftrightarrow$
$\forall$V1,V2:VALUE, E1,E2:EFFORT
[[upper_bound(X, V1) $\wedge$ lower_bound(X, V2) $\wedge$
required_effort_for_value(E1, V1) $\wedge$ required_effort_for_value(E2, V2)$\wedge$
is_max_of(Emax, E1, E2) $\wedge$ is_min_of(Emin, E1, E2)]]
$\rightarrow$ Emin $\leq$ E2 $\wedge$ E $\leq$ Emax]

For the desired effort, the effort should be farther away from the bounds set. In other words, a parameter for a value ε with $0 < \varepsilon < 0.5$ is added, as follows:

satisfies_desired_effort_for(E,X) $\leftrightarrow$
$\forall$V1,V2:VALUE, E1,E2:EFFORT
[[upper_bound(X, V1) $\wedge$ lower_bound(X, V2) $\wedge$
required_effort_for_value(E1, V1) $\wedge$ required_effort_for_value(E2, V2)
$\wedge$ is_max_of(Emax, E1, E2) $\wedge$ is_min_of(Emin, E1, E2)]
$\rightarrow$ Emin + ε (Emax – Emin) $\leq$ E $\wedge$ E $\leq$ Emax - ε (Emax – Emin)]

The decision properties for the Adaptor role again are reused from the generic properties as specified in Section 5, and also the default urgency relation:

has_urgency(X_1, E_1, …, X_n, E_n, X_i) $\leftrightarrow$
not satisfies_desired_effort_for(E,X)

In other words, an aspect is considered to be urgent in case the effort is outside the bounds of the desired effort. For an application of this quantitative specialization, see [10].

8. Discussion

This paper presented a organizational model for the analysis and design of multi-agent organizations that are able to adapt to unpredictable events. The organization model was specified distinguishing a number of aggregation levels. At the highest level the goal for the organization as a whole is expressed and this is refined to lower aggregation levels until role properties are reached that have to be fulfilled by agents allocated to the role. The model has been formally specified and verified using the model checker SMV. Besides a generic template, also specific variants have been presented, addressing both quantitative and qualitative models. Applicability of the model was evaluated positively, using it to analyze two cases: social insects and incident management. For both cases simulations have been performed, based on translating the lowest level properties to an executable format.

Research as described in [2, 13, 14, 15] has some similarity to the approach presented in this paper: when only looking at the agents, they adapt their behavior based on an event. The difference is however that in this paper, the adaptation of the behavior of the agents is described using the roles they play. As a result, it abstracts from the specifics of the agent involved in this change behavior, but poses a requirement upon the adaptation behavior of the agent in the form of a role.

In the domain of organizational modeling for multi-agent systems several frameworks have been extended with capabilities to model organizational change as well. [9] for example introduces an approach where a Change Manager is present, deciding what to change within the organization, and following a model from a well known social scientist. Such a model is however concerned with centrally directed organizational change whereas this paper concentrates on adaptation brought about by individuals within the organization detecting unsatisfactory occurrences in the organization. In MOISE+ [11] a central director for change is present as well; decision rules as detailed as presented in this paper are not presented.

In order to incorporate new behavior which is not pre-specified, the approach presented in this paper can be enriched with adaptation of role properties or addition of roles. Such adaptations could for example include a new specification of role behavior. This is however future work and is not addressed in this paper.

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