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Multidimensional Adaptation in MAS Organizations

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***Abstract*—Organization adaptation requires determining the consequences of applying changes not only in terms of the benefits provided but also measuring the adaptation costs as well as the impact that these changes have on all of the components of the organization. In this paper, we provide an approach for adaptation in multiagent systems based on a multidimensional transition deliberation mechanism (MTDM). This approach considers transitions in multiple dimensions and is aimed at obtaining the adaptation with the highest potential for improvement in utility based on the costs of adaptation. The approach provides an accurate measurement of the impact of the adaptation since it determines the organization that is to be transitioned to as well as the changes required to carry out this transition. We show an example of adaptation in a service provider network environment in order to demonstrate that the measurement of the adaptation consequences taken by the MTDM improves the organization performance more than the other approaches.**

***Index Terms*—Adaptation, multiagent systems, organizations, performance.**

I. INTRODUCTION

IN THE LAST few years, open and dynamic agent-based systems have emerged as one of the most promising areas for developing applications. In these systems, dynamic agent organizations that adjust themselves to gain advantage in their current environments are likely to become increasingly important [1]. Dynamic adaptation refers to modifications in the structure and behavior of an organization, such as adding, removing, or substituting components, which are done while the system is running and without bringing it down [2]. Thus, the organization is able to adapt itself according to parameters and factors that are unknown at design-time and that may also change at runtime.

According to Horling and Lesser [3], organization adaptation eliminates the need to determine all possible runtime conditions *a priori*, which is unknown in many systems. Before this can occur, the space of organizational options must be mapped, and their relative benefits and costs must be understood. To date, however, few models have emerged that incorporate mechanisms for adaptation, which focus on changes in different dimensions of the organization according to the heterogeneous impact that these changes cause in the components of the organization. One main reason is that current approaches do not provide support for specifying the requirements of organizations that are to be achieved. The other reason is that, without this support, it is difficult to measure the impact on the costs of applying the adaptation and on the performance of the whole organization without carrying out the adaptation. Most of the existing approaches focus the adaptation on specific dimensions of the organization. Works such as [4] and [5] propose adaptation models that are based on changes in the agent relationships in order to obtain better performance, other works such as [6] propose an adaptation in terms of norms by changing the regulations of the system, and other works are focused on changes in the roles played by the agents [7], [8]. Also, few models provide mechanisms for measuring the impact of the adaptation on the whole organization. Most approaches consider an adaptation decision that is focused on the increase of the utility [6], [9]. However, the costs associated with carrying out the adaptation process and the costs/benefits affecting other agents as side effects of the adaptation have not been widely taken into account.

In these models, it is also difficult to measure the impact of changes on other elements of the organization since they do not provide mechanisms to predict how other elements of the organization would be affected by a change. An adaptation decision taken by individual agents (as in the work of [4]) is carried out since it is assumed that a change in a pair of agents does not affect other agents of the organization. Similarly, other works such as [7] do not consider how a role swap between a pair of agents would affect other agents of the organization. Thus, the impact of an adaptation should consider both the costs associated to carrying out the process and the benefits or costs of the adaptation to all of the components of the organization. Based on the concept of organization transitions, we presented an organization transition model in [10] for organization adaptation. This model allows us to specify the requirements of the organization that is to be achieved. We provided a mechanism that calculates the organization with a high utility expectation, which can be transitioned to according to the costs associated to the transition. The adaptation considered in this mechanism is a 1-D transition that is focused on role reallocation.

In this paper, we propose a novel approach for organization transitions called multidimensional transition deliberation mechanism (MTDM). The MTDM provides decision-making support that considers transitions in different dimensions such as role reallocation, agent population, and structural topology. By specifying the requirements of the final organization that is to be achieved, the MTDM accurately predicts the impact of the transition in terms of two aspects: the costs associated to the organization transition and the benefits or costs that this

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transition causes not only to the agents involved in the change but also to the whole organization. Moreover, since several transitions on different dimensions are considered, the range of adaptation solutions is increased. The remainder of this paper is organized as follows. Section III presents the organization transition model. Section IV describes the MTDM. Section V explains in detail an application of the mechanism in an RPN environment. Section VI shows the results of the example evaluation. Finally, Section VII presents some concluding remarks.

II. RELATED WORK

In the last few years, several works have appeared that deal with adaptation in MAS organizations. In [11], we analyzed the most relevant approaches by comparing them based on what they support for different phases of the organization adaptation life-cycle. As far as we are concerned, there is little support for representing and evaluating accurate costs related to the adaptation process; therefore, complex deliberation processes about the suitability of adaptation cannot be carried out. One of the main consequences of this lack of support is that changes regarding different dimensions of the organization are not usually considered in current adaptation approaches.

Most of the works on adaptation view this process as a mechanism for maximizing organization utility. These approaches usually consider a specific set of changes that can be carried out. Matson *et al.* [9] propose a role reallocation model that is oriented to maximizing the organization utility. This type of adaptation is widely used in other works in the field [7], [8], [12]–[14] and consists of changing the roles played by agents and the services provided by agents. We also approached this type of adaptation in our previous works [10], [15].

Some approaches consider changes in other dimensions. As an example, Kota *et al.* propose a self-adaptation approach in [4] that is focused on task-solving environments. Adaptation consists of enabling each pair of agents to continuously and autonomously evaluate (and change if necessary) their relations based on past interactions in order to obtain better performance. Mathieu *et al.* [16], [17] propose a similar approach that defines an adaptation process for changing the relationships between agents. They consider situations in which an agent can learn skills provided by other agents, and then, the number of interactions is minimized. Wang *et al.* [18] propose an approach for a structural topology adaptation that considers changes in the relationships between roles and the roles played by agents. In a similar work, Kamboj *et al.* [19] focus on organizational structure adaptation based on two primitives: spawning (creation of a new agent) and composition (merging several agents).

The work of Horling *et al.* [20] proposes a system that changes the interactions between consumers and transporters in order to overcome insufficient resources. The work of Bou *et al.* [6] evaluates the utility of the organization in terms of norms. Thus, the adaptation consists of changing the regulations of the system to obtain better utility.

If adaptation is approached as a reactive process that is guided by changes, the impact of the final organization that is to be achieved cannot be accurately measured until the adaptation process ends, making the behavior of this new organization difficult to simulate. The suitability of the adaptation should not only determine the benefits of the process but also the costs associated to it measured in terms of the cost required to carry out the process and in terms of how other agents are affected by the changes. However, in current approaches, the costs associated with carrying out the adaptation process and the costs/benefits affecting other agents as side effects of the adaptation have not been widely taken into account.

An adaptation model is presented in [21] in which metrics can be used to allow designers to make design-time tradeoffs between flexibility and computational costs. Nevertheless, since this design must be specified before running the system, this measurement is not computed or updated with any knowledge of how the organization is behaving at runtime. The costs of applying changes and the impact that these changes have on the rest of the agents cannot be specified in this approach. As an example, the process for an agent a being reallocated to play a role r is carried out without any cost associated to the process. Moreover, this reallocation process does not have any effect (positive or negative) on the rest of the agents of the organization.

The adaptation model proposed by Hübner *et al.* in [22] is aimed at providing support to suit the organization to its environment and to efficiently achieve its goals. This approach provides great flexibility so that it can be applied to a wide range of applications because individual agents are in charge of carrying out the adaptation phases. Different methods can be implemented at the agent level depending on the domain, allowing the use of heterogeneous mechanisms for designing and selecting adaptation solutions. However, methods for measuring the suitability/goodness of an adaptation are not provided by the adaptation model itself. If this behavior is implemented at design-time, this suitability/goodness could not be determined depending on how the organization is performing at runtime. Furthermore, this model does not provide support for specifying the costs for each individual change; instead, it takes into account costs that are specified for the whole organization.

The approach of Kota *et al.* [23], [24] provides mechanisms to evaluate the performance of agent relationships at each time-step of the organization's life-span. Costs define the resources consumed by agents in terms of messages that are sent, and benefits define the speed of task completion. However, the impact of changing a relationship only takes into account the benefits/costs for the agents involved in the change. There is no support for measuring how other agents are affected by a change, i.e., how tasks received by other agents can be reallocated due to a relationship change in other agents.

In the model proposed by Campos *et al.* [25], adaptation is aimed at improving goal accomplishment. This approach considers adaptation costs (in time and/or resources) that should be taken into account in order to decide the adaptation frequency. However, these costs are not taken into account in either the design or the selection of the reorganization since changes are introduced with the aim of increasing the utility of the current goals. As an example, in the peer-to-peer scenario presented in [25], adaptation is focused on modifying relationships to obtain a network with the shortest latencies. However, these modification costs could be so high that it might be more beneficial to adapt to a suboptimal network that has a lower adaptation cost associated to it.

Weyns *et al.* present a middleware for dynamic organization management [26]. Adaptation is carried out in a distributed fashion. It is automatically triggered by external events (e.g., when an agent stops playing a role) and changes in the environment, which are described as laws. In this model, the communication cost for merging and splitting organizations is measured. However, this cost is not taken into account to determine whether an adaptation is required. As we stated previously, adaptation is automatically caused when a law is triggered.

In [27], an adaptation model based on conventions is proposed. The objective of adaptation is to maximize the agent utilities and the organization utility. In that approach, adaptation costs are defined. However, mechanisms for measuring these costs and the impact that changes cause in all of the agents of the organization are not provided. Gaston *et al.* [28] propose a distributed mechanism for adaptation relationships in task allocation environments. However, in that approach, agents are not able to evaluate the impact of an adaptation decision since a global view of the organization is not represented.

As can be observed, there is no approach that provides mechanisms to measure the impact of changes on all of the elements of the organization and the costs required to carry out the process. Current approaches do not focus on allowing the specification of the requirements of the future organization that is to be achieved and do not focus on the adaptation as the process for achieving this organization. By specifying the requirements of the future organization to be achieved, the changes associated to the adaptation are those that are necessary to change the current organization into the future one. Based on this aim, the MTDM proposed in this paper accurately predicts the impact of the adaptation in terms of two aspects: the costs associated to the adaptation and the benefits or costs that this transition causes not only to the agents involved in the change but also to the whole organization. This support incorporates mechanisms for adaptation that focus on changes in different dimensions of the organization according to the heterogeneous impact that these changes produce in the components of the organization.

III. ORGANIZATION TRANSITION MODEL

The MTDM uses the organization definition presented in [10], which define the elements of the organization at a specific moment and the concept of organization transition. We summarize the main components of this model in the following.

A. *Organization*

Organization models allow us to represent both the elements that make up the organization and the interactions among these elements. Several approaches can be found in the literature for modeling agent organizations based on the requirements of the applications. Current organization models have been compared and reviewed by works such Vázquez-Salceda *et al.* [29], Dignum [30], or Argente *et al.* [31].

Although several approaches can be used to model organizations, we use the following adaptation of the organization model proposed in [32] since we found it to be appropriate for the requirements of the model proposed.

An *organization* at a specific moment t is defined as a tuple $O^t = \langle O_O^t, O_R^t \rangle$, where O_O^t stands for *Organizational Objects* and represents the individual objects of the organization. It is defined as $O_O^t = \{R^t, S^t, A^t\}$, where R^t represents the set of roles contained in the organization at a specific moment t, S^t represents the services that the organization is offering at a specific moment t, and A^t represents the population of agents at a specific moment t.

O_R^t stands for *Organizational Relationships* and represents relationships of the organization by means of a link between the objects. It is defined as $O_R^t = \{offers^t, provides^t, plays^t, acquaintance^t\}$, with the following conditions.

1) $offers^t = \{(r, s) \in R^t \times S^t\}$ represents the relationships between roles and services, where (r, s) represents that role r offers service s at moment t.
2) $provides^t = \{(a, s) \in A^t \times S^t\}$ represents the relationships between agents and services, where (a, s) represents that agent a provides service s at moment t.
3) $plays^t = \{(a, r) \in A^t \times R^t\}$ represents the relationships between agents and roles, where (a, r) represents that agent a plays role r at moment t.
4) $acquaintance^t = \{(a, a') \in A^t \times A^t\}$ represents the relationships between a pair of agents, where (a, a') represents that agents a and a' are connected by an acquaintance relationship at moment t. These relationships define the structural topology of the organization.

Given an organization O^t at a specific moment t, in order for an agent a to be able to play a role r at time t, agent a must provide all of the services s that r offers at time t

$$\forall (a, r) \in plays^t | (r, s) \in offers^t \rightarrow (a, s) \in provides^t.$$

B. *Organization Transition*

The concept of *organization transition* was first introduced in [21], and it allows us to relate two different organizations at different moments, current (c) and future (f). It is the mechanism by which an organization is adapted into a new one. This mechanism is based on individual changes that are applied to the objects and relationships of O^c in order to obtain the objects and relationships of O^f.

An *event*(ε) defines each individual change that can be applied to an object or to a relationship during the organization transition in terms of addition or deletion. An addition event applied to an object or to a relationship [e.g., $add\_agent(a)$ and $add\_provides(a, s)$] causes it to be added to the specific set of O^f, while a deletion event applied to an object or to a relationship causes it to be deleted from the specific set of O^f. Given two organizations O^c and O^f, we define $\tau = \{\varepsilon_1, \ldots, \varepsilon_n\}$ as the *set of events* that cause a transition to O^f when all of them are applied to O^c.

IV. MULTITRANSITION DELIBERATION MECHANISM

The MTDM is a multistage mechanism that is based on a model proposed by Zott [33] in the strategic management research area for analyzing the performance of business firms. This model simulates the firm's performance when several changes in resources, operational routines, or competencies are carried out. Then, it determines how costly a reconfiguration is and selects a specific solution to be applied.

The MTDM is a multistage mechanism that is based on the models used in the strategic management research area for analyzing the performance of business firms [33]. The model proposed by Zolt is aimed at analyzing the firm's performance by simulating the consequences when several changes in resources, operational routines, or competencies are carried out. These changes are proposed through imitation or experimentation. Then, it determines how costly a reconfiguration is and selects a particular solution to be applied.

Similarly, the MTDM calculates transitions in different dimensions to other organizations with high expected utility based on the cost for transition to these organizations. The benefits and costs of transition are measured in terms of organization transition impacts (OTIs). Then, the MTDM decides which transition is finally implemented and provides the sequence of changes required to carry out the transition. Algorithm 1 represents the MTDM, which is composed of three stages that are described in the following sections.

Algorithm 1: Transition Deliberation Mechanism

```
1: INPUT: $O^c$
2: OUTPUT: $\tau$, $OTI(\tau)$
3: $O^f \leftarrow O^c$
4: do:
5:     $O_R, OTI(\tau_R) \leftarrow role\_realloc\_trans(O^f)$
6:     $O_A, OTI(\tau_A) \leftarrow acquaintance\_trans(O^f)$
7:     $O_P, OTI(\tau_P) \leftarrow ag\_population\_trans(O^f)$
8:     $O^f, OTI(\tau^f) \leftarrow deliberation(O_R, O_A, O_P)$
9: while$OTI(\tau^f)$ is improved
10: $\tau \leftarrow Sequence\_of\_events(O^c, O^f)$
11: return$\tau$, $OTI(\tau)$
```

1) The first stage calculates transitions in multiple dimensions from the current organization. Lines 5–7 obtain three different future organizations that could be achieved with high expected utility based on the cost for transition to these organizations. The benefits and costs of transition are measured in terms of OTIs.
2) With the three organizations obtained from the previous stage, a deliberation process (line 8) selects which of these three organizations has associated the high expected utility based on the transition costs. This process is carried out iteratively while an organization is found, which can be achieved with a better OTI. Because a loop execution is introduced, several changes in different dimensions can be selected through different iterations.
3) After obtaining the future organization O^f, which is to be transitioned to, a sequence of required events τ is obtained (line 10). These events allow us to transform the current organization O^c into O^f.

A. Calculating the Organization Transitions

The first stage calculates the organization with the highest potential for improvement in utility based on the transition cost for several transitions in different dimensions: changing the roles played by agents, changing the structural topology, and changing the agent population. In order to measure this, we define the concept of OTI. The OTI is a measurement of the effects of an organization transition in terms of organization utility based on the costs for carrying out this transition. Computing the OTI becomes essential in order to empirically specify the value of this transition in terms of time consumption, money, resources, and so on.

The application of the set of events τ associated to an organization transition provides us with information regarding what changes must be carried out in order to fulfill the transition. Each event ε has an associated impact $i(\varepsilon)$. This impact represents the costs/benefits that the application of this event causes in the organization. This impact shows the effect of this event in the components involved in the change and also how other components are affected by this event. Moreover, the impact shows the cost for carrying out the application of the event.

Therefore, for any set of events τ that allow a transition from a current organization O^c to a future organization O^f, we define the OTI that is associated to this transition as the impact of applying all of the events of τ: $I(\tau) = \sum_{\varepsilon \in \tau} i(\varepsilon)$.

Each organization transition that is focused on a specific dimension obtains the future organization O^f that could be transitioned to, which minimizes the OTI. In the following sections, we define each organization transition and the computation of the events that are associated to each one.

1) Role Reallocation Transition: The organizational relationships $provider$ and $plays$ represent the services that are provided by each agent and the roles that are played by each agent, respectively, at a specific moment. Nevertheless, for a given cost, an agent can provide other services and can play different roles that it is not currently playing. The organization transition that focuses on these changes is called the role reallocation transition.

Given a specification of the organizational objects of the final organization that is to be achieved O_O^f and the organizational relationships $offer^f$ and $acquaintance^f$ that are to be achieved, some agents could be reallocated to provide other services and to play other roles that they were not playing in O^c. A role reallocation transition entails the application of a specific set of events τ_R composed of $provider$ and $plays$ relationships, which transforms the $provider^c$ and $plays^c$ relationships into $provider^f$ and $plays^f$, respectively. Each one of these role reallocations determines a different O^f that could be transitioned to by applying a set of events τ_R with an associated $OTI(\tau_R)$.

The OTI related to the role reallocation transition measures how costly it is for agents to acquire the services to play a specific role, to start playing this role, to stop playing a role that is currently being played by an agent, and to stop providing the services required for this last role. This impact also measures how beneficial it is for the agents involved in the role reallocation and for the organization to have these agents change their roles.

To calculate the OTI of a role reallocation transition, we need to estimate the impact related to the events required for each agent that is reallocated to play a new role. We define the impact of agent a_x for acquiring the services offered by a new role r_n that are not already provided by the agent as $I_{AS}(a_x, r_n) = \sum i(add\_provides((a_x, s_n)))$, for every service s_n that $(r_n, s_n) \in offers^f \wedge (a_x, s_n) \notin provides^c$. Once the agent a_x provides these services, it can start playing the role r_n for an impact of $i(add\_plays((a_x, r_n)))$. Thus, the whole impact of a_x for playing r_n is defined as

$$I_{PL}(a_x, r_n) = I_{AS}(a_x, r_n) + i\left(add\_plays\left((a_x, r_n)\right)\right). \quad (1)$$

The impact of agent a_x to stop playing the current role r_c is defined as $i(delete\_plays((a_x, r_c)))$. Once a_x does not play this role, it can stop providing the services required to play r_c that are no longer required for playing other roles in O^f for an impact of $I_{DS}(a_x, r_c) = \sum i(delete\_provides((a_x, s_c)))$, for every service s_c that $(a_x, s_c) \in provides^c \wedge \nexists r_d | (r_d, s_c) \in offers^f \wedge (a_x, r_d) \in plays^f$. Thus, the whole impact of agent a_x to stop playing a current role r_c is defined as

$$I_{SP}(a_x, r_c) = i\left(delete\_plays\left((a_x, r_c)\right)\right) + I_{DS}(a_x, r_c). \quad (2)$$

Therefore, we define the impact of role reallocation for agent a_x from role r_c to role r_n by taking into account the impact related to stop playing r_c in order to play r_n

$$I_R(a_x, r_c, r_n) = I_{PL}(a_x, r_n) + I_{SP}(a_x, r_c). \quad (3)$$

Thus, the OTI associated to the set of events τ_R that causes a role reallocation transition from O^c to O^f can be written as

$$OTI(\tau_R) = \sum_{a_x \in A} I_R(a_x, r_c, r_n)$$

where $(a_x, r_c) \in plays^c \wedge (a_x, r_n) \in plays^f$.

Let Θ_R denote the set of all of the possible sets of events τ_R that define a different role reallocation transition from O^c and obtain a different O^f. The challenge of the role reallocation transition is to find the specific set of events $\widehat{\tau}_R$ that minimizes the role reallocation transition impact

$$OTI(\widehat{\tau}_R) = \arg\min_{\tau_R \in \Theta_R} OTI(\tau_R). \quad (4)$$

The application of the set of events of the minimal impact $\widehat{\tau}_R$ to O^c would cause a transition to a future organization O_R, which can be transitioned to at the minimal OTI. The implementation of the algorithm (line 5 of Algorithm 1) considers both, the role swap between agents and the change in the number of agents that play a specific role.

2) Acquaintance Transition: Organizational relationships represented in $acquaintance$ define the structural topology of the organization, by defining which agents are related to each other at a specific moment. Acquaintances between a pair of agents can be modified at a given cost, and this may change the performance not only of the agents involved in the relationship but also the utility of the whole organization. The organization transition that is focused on changes regarding acquaintances between agents is called the acquaintance transition.

Given the specification of the organizational objects of the final organization that is to be achieved (O_O^f) and the organizational relationships $offers^f$, $provider^f$, and $plays^f$ that are to be achieved, some acquaintances can be created between a pair of agents that were not related in O^c, and some acquaintances between agents that were related in O^c can be deleted. An acquaintance transition entails the application of a specific set of events τ_A composed by $acquaintance$ relationships, which transforms $acquaintance^c$ into $acquaintance^f$. Each one of these specific $acquaintance^f$ relationships defines a future organization O^f, which represents a specific structural topology and can be achieved by applying a specific set of events τ_A with an associated $OTI(\tau_R)$.

This OTI defines how costly it is for a pair of agents to create an acquaintance relationship between them or to delete an existing relationship and how these modifications affect the utility of the organization.

The impact of adding an acquaintance relationship between a_x and a_z is defined as $i(add\_acquaintance((a_x, a_z)))$. This represents the cost of relating these agents from this moment on and how this relationship affects the utility of the organization. The impact of deleting an existing acquaintance relationship between a pair of agents a_x and a_z is defined as $i(delete\_acquaintance((a_x, a_z)))$. This represents the cost for these agents to no longer be related and how this affects the utility of the organization.

Let Θ_A denote the set of all of the possible sets of events τ_A that define a different acquaintance transition from O^c and obtain a different O^f. The challenge of the acquaintance transition is to find the specific set of events $\widehat{\tau}_A$ that minimizes the acquaintance transition impact

$$OTI(\widehat{\tau}_A) = \arg\min_{\tau_A \in \Theta_A} OTI(\tau_A). \quad (5)$$

The application of the set of events of the minimal impact $\widehat{\tau}_A$ to O^c would cause a transition to a future organization O_A, which can be transitioned to at the minimal OTI. Each execution of the algorithm (line 6 of Algorithm 1) takes into account the addition or deletion of a single relationship in the organization, but several iterations can be carried out due to the loop (lines 4–9 of Algorithm 1).

3) Agent Population Transition: Organizational objects $agents$ represent the population of agents at a specific moment. Nevertheless, the population of agents can be changed at a given cost, which may imply that the number of agents playing a specific role or the number of acquaintance relationships of some agents also changes. The organization transition that focuses on these changes is called the agent population transition.

Given the specification of the organizational objects $roles^f$ and $services^f$ of the final organization that are to be achieved and the organizational relationships $offers^f$ that are to be achieved, some agents that were not in O^c can be added into the organization, or some agents that were in O^c can be deleted from the organization. An agent population transition modifies the agent population $agents^c$, and this may also cause modifications in the $provides$, $plays$, and $acquaintance$ relationships. Thus, an agent population transition entails the application of a set of events τ_P, which causes the modification of $agents^c$, $provides^c$, $plays^c$, and $acquaintances^c$ into $agents^f$, $provides^f$, $plays^f$, and $acquaintances^f$, respectively. Each one of these specific $agents^f$, $provides^f$, $plays^f$, and $acquaintances^f$ defines a future organization O^f, which represents a different configuration and can be achieved by applying a specific set of events τ_P with an associated $OTI(\tau_P)$.

The impact of adding an agent a_x into the organization is defined as $i(add\_agent(a_x))$. Moreover, acquaintance relationships between this agent and a set of agents $A' \subset A$ may be created with an associated impact that is defined as $I_A(a_x) = \sum_{a_j \in A'} i(add\_aquaintance((a_x, a_j)))$.

Finally, this agent may also provide some services and may play a specific role r_n based on the services provided. Thus, we define the impact of agent a_x playing role r_n as $I_{PL}(a_x, r_n)$ from (1).

We represent the whole impact of adding an agent a_x as

$$I_{AA}(a_x) = i\left(add\_agent(a_x)\right) + I_A(a_x) + I_{PL}(a_x, r_n). \quad (6)$$

The impact of deleting an agent a_x from the organization is represented as $i(delete\_agent(a_x))$. Moreover, acquaintances that involve this agent must be deleted with an impact defined as $I_D(a_x) = \sum i(delete\_aquaintance((i, j)))$ for all $(i, j) \in acquaintance^i | i = a_x \vee j = a_x$.

Finally, deleting a_x from the organization has an impact of stopping a_x from playing the role r_c that it is playing as well as the impact of stopping a_x from providing its services. This impact is represented as $I_{SP}(a_x, r_c)$ from (2). We represent the impact of adding an agent a_x as

$$I_{DA}(a_x) = i\left(delete\_agent(a_x)\right) + I_D(a_x) + I_{SP}(a_x, r_c). \quad (7)$$

Let Θ_P denote the set of all of the possible sets of events τ_P that define a different agent population transition from O^c and that obtain a different O^f. The challenge of the agent population transition is to find the specific set of events $\widehat{\tau}_P$ that minimizes the agent population transition impact

$$OTI(\widehat{\tau}_P) = \operatorname*{arg\,min}_{\tau_P \in \Theta_P} OTI(\tau_P). \quad (8)$$

The application of the set of events of the minimal impact $\widehat{\tau}_P$ to O^c would cause a transition to a future organization O_P, which can be transitioned to at the minimal OTI. Each execution of the algorithm (line 7 of Algorithm 1) takes into account the addition or deletion of a single agent and relationship, but several iterations can be carried out if several executions are carried out due to the loop (lines 4–9 of Algorithm 1).

B. Deliberation

Once the organizations that minimize the OTI for each dimension are calculated, the second stage of the MTDM (line 8 of Algorithm 1) decides which transition is finally implemented depending on the deliberation strategy. The deliberation strategy used in this implementation is focused on selecting the transition that minimizes the OTI. Thus, it can be observed that, even though a single operation is carried out by the acquaintance transition algorithm and the agent population transition algorithm, the MTDM could decide that several operations must be carried out since a loop is introduced (lines 4–9 of Algorithm 1). Thus, the future organization that is selected to be transitioned to can be composed of a combination of transitions (e.g., changing relationships between some pairs of agents and then swapping the roles played by some of those agents). Since the number of changes is limited, an organization that minimizes the OTI is found in a bounded number of iterations.

An infrastructure for supporting an initial support regarding the role reallocation transition is presented in [15]. The implementation of the acquaintance transition algorithm (line 6 of Algorithm 1) calculates the organization that can be transitioned to by adding or deleting a single acquaintance, while the agent population transition algorithm (line 7 of Algorithm 1) calculates the organization that can be transitioned to by adding or deleting an agent.

C. Calculating the Sequence of Events

Finally, once the final organization O^f that is transitioned to is selected, this stage obtains the specific sequence of events τ that allow this transition from O^c to O^f and the impact associated to applying these events $OTI(\tau)$ (line 10 of Algorithm 1).

V. ORGANIZATION TRANSITIONS ON AN SPN

Service provider networks (SPNs) represent environments for modeling agents that provide services to other agents. In order to show the performance of the MTDM, we model an SPN as an organization that is composed of agents that play different roles according to the services that they offer. Each service involves different kinds of data resources, and external agents of the organization request these resources in order to retrieve them. In this example, we assume that each service s_y is provided by the role r_y.

Each agent of the organization is directly connected to other agents through bidirectional links. This is represented in the organization by acquaintance relationships. A single acquaintance (a_x, a_y) or (a_y, a_x) is sufficient to determine that agents a_x and a_y are directly connected. We represent the acquaintances of agent a_x at the current moment by $L(a_x)$: $L(a_x) = \{(i, j) \in acquaintance^c : i = a_x \vee j = a_x\}$. Depending on the number of acquaintances, an agent a_x has an associated specific bandwidth BW_{a_x} that is computed as the division of a global bandwidth BW between the number of acquaintances of a_x: $BW_{a_x} = BW/|L(a_x)|$. The global bandwidth BW in this example is defined as constant for every agent.

A link between a pair of agents a_x and a_z, which are directly connected, has an associated bit rate $BR(a_x, a_z)$, which represents the transfer speed when data resources are transferred through this link. This bit rate is computed as the lowest bandwidth of both agents: $BR(a_x, a_z) = \min(BW_{a_x}, BW_{a_z})$. When agents are asked for a data resource that belongs to a service that is not provided by them, they must retrieve this data resource from any other agent of the organization by requiring a time for retrieving these data. There exists a path that connects any pair of agents a_x and a_z. The path that has the minimal number of links between a pair of agents is the path through which all of the transferences between these agents are carried out.

Each agent a_x receives a number of requests from agents for a service s_y in a time period between t' and t, which is represented as $R(a_x, s_y)_{t'}^{t}$. If the agent provides the requested service, it can send the data resource immediately, making the time required to have the data available be null: $AT(a_x, R(a_x, s_y)_{t'}^{t}, s_y) = 0$.

If the agent does not provide the requested service, it must retrieve the data resource from another agent of the organization through its nearest provider $NP(a_x, s_y)$. This agent is the agent that is directly connected to a_x, which defines a path that has associated to it the minimal number of links for accessing an agent provider of service s_y. Thus, the whole time required by a_x to have the data available can be calculated as $AT(a_x, R(a_x, s_y)_{t'}^{t}, s_y)$

$$\frac{R(a_x, s_y)_{t'}^{t} \times Avg.(s_y)}{BR\left(a_x, NP(a_x, s_y)\right)} + AT\left(NP(a_x, s_y), R(a_x, s_y)_{t'}^{t}, s_y\right). \tag{9}$$

With $Avg(s_y)$ being the average size of an individual data resource of the service s_y. The first addend of (9) corresponds to the time required for a_x to obtain the data from its nearest provider $NP(a_x, s_y)$, while the second addend corresponds to the time required for this agent to, in turn, obtain the data requested. Depending on the acquaintances between agents, a higher or a lower number of internal requests would be required.

In an SPN environment, data are usually transferred through links in both directions. Therefore, the transference time for each link between two agents a_x and a_z represents the whole time required for transferring all of the data demanded through this link in a period of time between t' and t (i.e., the requests for each service retrieved from a_x and from a_z during this period of time that require this link). This transference time is represented as $T(a_x, a_z)_{t'}^{t}$

$$\frac{\sum R(a_x, s_y)_{t'}^{t} \times Avg(s_y) + \sum R(a_z, s_w)_{t'}^{t} \times Avg(s_w)}{BR(a_x, a_z)} \tag{10}$$

for all s_y and s_w such that $a_z = NP(a_x, s_y) \wedge a_x = NP(a_z, s_w)$.

The delay time of agent a_x represents the time required by a_x to retrieve all of the data requested in a period of time. This is calculated as the maximum time required by all of the acquaintances of a_x to retrieve all of the data requested between t' and t

$$D(a_x)_{t'}^{t} = \max_{(i,j) \in L(a_x)} T(i, j)_{t'}^{t}. \tag{11}$$

In this example, the utility of the organization can be represented as being inversely proportional to the average delay time for retrieving all of the requests received in the organization

$$\bar{D}(O^t) = \frac{\sum_{a_x \in A} D(a_x)_{t'}^{t}}{|A|}. \tag{12}$$

We used this notation to provide a consistent sense of utility measurement so that the system maximizes it, i.e., the system minimizes the average delay time for the whole organization.

Other approaches from decision theory could be applied in order to represent a multiattributed utility that deals with both qualitative and quantitative factors in multiple criteria [34]. The objective of the organization in this example is to minimize the time delay, i.e., to maximize the utility. At design-time, it may be not possible to know what the best distribution of the services among the agents will be. Furthermore, according to the requests received, the best distribution may change while the system is running, and the organization must adapt to these new requirements. Therefore, organization transitions provide adaptation alternatives for improving this utility.

A. *Role Reallocation Transition Estimation*

The impact of role reallocation for an agent a_x is obtained by (3). This equation calculates the impact of playing a new role and of stopping in playing the current role. The term $I_{AS}(a_x, r_n)$ (1) represents the impact on the organization of agent a_x providing the services offered by the new role r_n. In this example, since a single service is provided by a role, this impact refers to the time required to transfer the whole database for the service s_n to the agent a_x from the nearest provider of a_x. According to (9), this transference time can be calculated as the availability time required for retrieving this database

$$\begin{aligned} I_{AS}(a_x, r_n) &= i\left(add\_provides\left((a_x, s_n)\right)\right) \\ &= AT\left(a_x, N(s_n), s_n\right). \end{aligned}$$

$N(s_y)$ is the number of files of the database provided by the service s_y. The term $i(add\_plays((a_x, r_n)))$ represents the impact of playing the new role r_n once the new database has been transferred. This impact measures how the average delay time would be affected if a_x plays the role r_n. Since the number of requests that will be received from time-step t on is unknown, this number can be estimated according to the requests that have been received between t' and t to evaluate this impact. Thus, this impact can be represented as the negative time associated to the time gained by the requests that would not be transferred throughout the network if a_x plays this role

$$i\left(add\_plays\left((a_x, r_n)\right)\right) = -AT(a_x, R(a_x, s_n)_{t'}^{t}, s_n).$$

The impact $I_{DS}(a_x, r_c)$ (2) represents the time required for deleting the database of the service provided by the current role r_c from agent a_x in an SPN environment.

The term $i(delete\_plays((a_x, r_c)))$ represents the impact of stopping a_x from playing the role r_c once the current database is deleted. This impact measures how the average delay time would be affected if a_x does not play the role r_c anymore. Similar to the impact $i(add\_plays((a_x, r_n)))$, this impact can be estimated as the time that would be required to provide the services requested between t' and t if agent a_x had not been playing r_c during this period. In this case, these requests correspond to the service s_c, and they would be retrieved from the nearest provider of a_x

$$i\left(delete\_plays\left((a_x, r_c)\right)\right) = AT\left(a_x, R(a_x, s_c)^t_{t'}, s_c\right).$$

B. Acquaintance Transition Estimation

In an SPN environment, an acquaintance addition between a pair of agents causes the time required for transferring any data between these agents to decrease since fewer links are required. This may also influence the nearest providers of all of the agents of the organization. However, as stated in Section V, the addition of a link between agents a_x and a_z causes the bandwidth for any link of these agents to be reduced to $BW_{a_x} \times |L(a_x)|/|L(a_x)| + 1$ for a_x and $BW_{a_z} \times |L(a_z)|/|L(a_z)| + 1$ for a_z.

Similarly, deleting the link between agent a_x and a_z causes the bandwidth for any link of these agents to be increased to $BW_{a_x} \times |L(a_x)|/|L(a_x)| - 1$ for a_x and $BW_{a_z} \times |L(a_z)|/|L(a_z)| - 1$ for a_z.

These bandwidth modifications may cause the bit rate of links that include one of these agents to be changed to $BR(i,j) = min(BW_i, BW_j)$ for all $(i,j) \in acquaintances^t$ such that $i = \{a_x, a_z\} \vee j = \{a_x, a_z\}$.

Similar to the role reallocation transition estimation, the impact of adding and deleting acquaintances between agents can be estimated according to the requests that have been received between t' and t. Since a modification of an acquaintance may influence the nearest providers of other agents, requests that would be received at each agent can be recalculated according to this modification. This causes a new delay to be calculated by following (11) and a new average delay time $\bar{D}_N(O^t)$ to be estimated according to (12).

In order to compute the impact of adding an acquaintance between a pair of agents a_x and a_z, the difference between the average delay time of the current organization and the average delay time of the new organization is calculated. Moreover, a fixed cost associated to the time required for setting up the link is represented as $c_{set}(a_x, a_z)$.

Thus, the impact for adding an acquaintance between this pair of agents is calculated as

$$\begin{aligned} &i\left(add\_acquaintance\left((a_x, a_z)\right)\right) \\ &\qquad = \bar{D}_N(O^t) - \bar{D}(O^t) + c_{set}(a_x, a_z). \end{aligned}$$

Similarly, a fixed cost associated to the time required to turn off a link between a pair of agents a_x and a_z is represented as $c_{off}(a_x, a_z)$. Thus, if two agents a_x and a_z are connected by an acquaintance, we can calculate the impact for deleting this acquaintance as $i(delete\_acquaintance((a_x, a_z)))$

$$\bar{D}_N(O^t) - \bar{D}(O^t) + c_{off}(a_x, a_z).$$

C. Agent Population Transition Estimation

In an SPN environment, the entrance or exit of an agent from the system has an impact on the delay of the whole organization. The impact related to the addition of an agent a_x is represented as $I_{AA}(a_x)$ by following (6). This impact involves a fixed impact $i(add\_agent(a_x))$ that represents the time required for setting up the new agent as $c_{set}(a_x)$. Moreover, the agent must be directly connected to another agent a_z in order to join the SPN with a fixed time for setting up the link $c_{set}(a_x, a_z)$ as stated in Section V-B. This causes the bit rate of links to be recalculated as stated in Section V-B. Finally, the agent must play a specific role r_n, which requires an impact of $I_{PL}(a_x, r_n))$ that can be calculated by following (1). This impact is composed of $I_{AS}(a_x, r_n)$ and $i(add\_plays((a_x, r_n)))$. As stated in Section V-A, the impact $I_{AS}(a_x, r_n)$ can be computed as the time required to retrieve the specific database $AT(a_x, N(s_n), s_n)$. Since agent a_x did not receive any previous request, we compute the impact $i(add\_plays((a_x, r_n)))$ as null. We assume that all of the requests received in the organization during t' and t would have been distributed among this new population of agents. Then, the requests that would be received at every agent with this new configuration and the average delay time for this new organization $\bar{D}_N(O^t)$ can be calculated by following (12). Thus, the impact $I_{AA}(a_x)$ can be calculated as

$$\begin{aligned} &\bar{D}_N(O^t) - \bar{D}(O^t) + c_{set}(a_x) + c_{set}(a_x, a_z) \\ &\qquad + AT\left(a_x, N(s_n), s_n\right). \end{aligned}$$

The impact related to the deletion of an agent a_x is represented as $I_{DA}(a_x)$ by following (7). This impact involves a fixed impact $i(delete\_agent(a_x))$ that denotes the time required to turn off the agent as $c_{off}(a_x)$. The deletion of all of the links requires a fixed impact to turn off these links, which can be represented as $c_{off}(a_x, L) = \sum c_{off}(i,j)$ for all $(i,j) \in L(a_x)$. This also causes the bit rate of acquaintances to be recalculated.

Finally, the impact on the organization of agent a_x to stop playing the role r_c is represented as $I_{SP}(a_x, r_c)$ and can be calculated by following (2). This impact is composed of $I_{DS}(a_x, r_c)$ and $i(delete\_plays((a_x, r_c)))$. As stated in Section V-A, the impact $I_{DS}(a_x, r_c)$ can be considered null, while the impact $i(delete\_plays((a_x, r_c)))$ can be estimated as $AT(a_x, R(a_x, s_c)^t_{t'}, s_c)$.

Similar to the addition operation, we assume that requests received at agent a_x would have been distributed between the rest of the agents of the organization if a_x is deleted.

Then, the requests that would be received at every agent and the average delay time for this new organization $\bar{D}_N(O^t)$ can be calculated by following (12). Thus, we can calculate the impact $I_{DA}(a_x)$ as

$$\begin{aligned} &\bar{D}_N(O^t) - \bar{D}(O^t) + c_{off}(a_x) \\ &\qquad + c_{off}(a_x, L) + AT\left(a_x, R(a_x, s_c)^t_{t'}, s_c\right). \end{aligned}$$

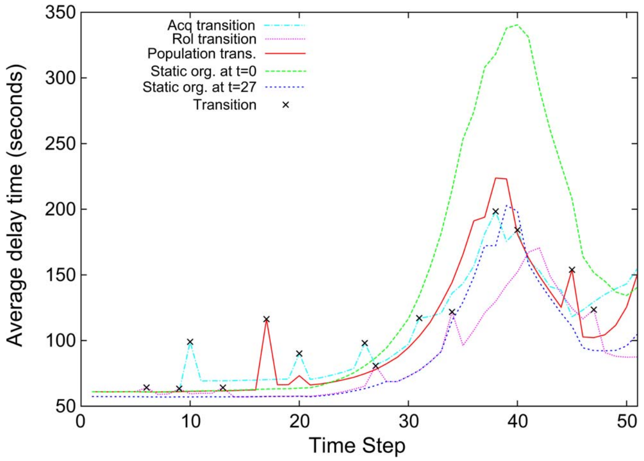

Fig. 1. Static and dynamic organizations.

VI. EVALUATION

To show the performance of the MTDM, in this section, we compare the average delay time for the organization (in seconds) on an SPN during 50 time-steps when different approaches for transitions are applied. The organization at the initial moment t^0 is composed of a set of ten agents $\{a_0, \ldots, a_9\}$. Each agent plays a different role $\{r_0, \ldots, r_3\}$ according to the service that each agent provides. At t^0, the distributions of roles are three agents playing r_0 and $_1$, and two agents playing r_2 and r_3. Each agent is connected to two agents by defining a ring topology. At t^0, the organization receives 100 requests that are distributed among all of the agents: 25% of these requests are for s_0, 40% are for s_1, 20% are for s_2, and 15% are for s_3. Then, in a period of time between two consecutive time-steps, each agent a_x receives requests for each service s_y according to the following formula:

$$R(a_x, s_y)_{t-1}^{t} = R\left(a_x, s_y\right)_{t-2}^{t-1} \times random(0.95, 1.05)\big) .$$

The number of requests received in two consecutive time-steps may change in an interval of ±5% ([0.05, −0.05]). However, these intervals may change in some agents for some services during the 50 time-steps in order to reproduce a dynamic scenario in which the demand for specific services changes during one execution. For fixed costs for acquaintance and agent population transitions, we apply a cost of 10 s for setting or turning off an acquaintance and a cost of 40 s for setting or turning off an agent. These values have been chosen in order to show heterogeneous costs.

Fig. 1 shows the average delay time for approaches that consider 1-D transitions and static organizations that do not consider transitions. The static organizations refer to the initial configuration t^0 and a configuration that has the best performance from t^{27} to t^{34} (static organization at $t = 27$). The figure also shows the time-steps in which transitions are carried out. In these time-steps, the time required to carry out the transition is also reflected in the figure. Note that approaches that consider transitions adapt the organization according to the changes in the demand for services. Although some static organizations may perform better at a specific moment than organizations with transitions, it can be observed that, when circumstances change, static organizations will not be able to respond to these changes, and thus, the average delay time may get worse. In this example, the demand for service s_1 is high from t^{21} until t^{37} and decreases from t^{37} on. Thus, note that s_1 increases its demand. Due to this circumstance, the role reallocation transition approach achieves an organization at t^{27} in which the number of agents playing s_1 increases. Similarly, the acquaintance transition approach creates acquaintances to improve the average delay time. However, static organizations do not respond to these changes, which are unknown at design-time, and the performance gets worse. Table I shows the mean average delay time of this execution and 40 executions for a 95% confidence interval. It can be observed that, in the current execution, the average delay time for the static organization configured as t^{27} is better than other approaches that take transitions into account. This is because the role distribution in this static organization is very good for this execution, while the acquaintance and the agent population approaches cannot change this distribution. Thus, the average delay time cannot be considerably improved by changing only acquaintances or the agent population. However, the role reallocation transition approach (which can change this distribution) clearly outperforms the other approaches. As can be observed in the table, several executions cause the performance of static organizations to get worse because these approaches do not adapt to the demand for services. In this example, it can be observed that the role distribution greatly influences the performance.

TABLE I
STATIC AND DYNAMIC ORGANIZATIONS

	Average delay time (seconds)	
Approach	Execution	40 executions
Acq. approach	101.97	98.56±7.12
Role approach	84.65	82.75±6.24
Pop. approach	101.16	104.3±8.15
Static org at t^0	131.01	125.41±13.21
Static org at t^{27}	88.5	110.64±12.85

In order to measure the influence of adaptation costs, Fig. 2 shows a comparison between the average delay time for approaches that consider 1-D transitions of role reallocation and acquaintance, and approaches that do not consider transition costs for deliberation. In an SPN environment, this corresponds to not considering the costs for retrieving the databases and the costs for setting and turning off acquaintances. As can be observed, approaches that adapt the organization without computing transition costs may transition to organizations with a reduction in average delay time but at a high cost, which makes the transition not worthwhile. It can also be observed that approaches that do not consider costs have a greater number of transitions than approaches that do take costs into account. Table II shows the mean average delay time for each approach. Approaches that consider costs and benefits (measured as impacts) for transition deliberation reduce the mean average delay time.

In order to evaluate the multitransition approach, Fig. 3 shows a comparison between the average delay time for approaches that consider single-dimensional transitions and the MTDM approach. In this experiment, at t^0, the organization receives 200 requests that are distributed among all of the

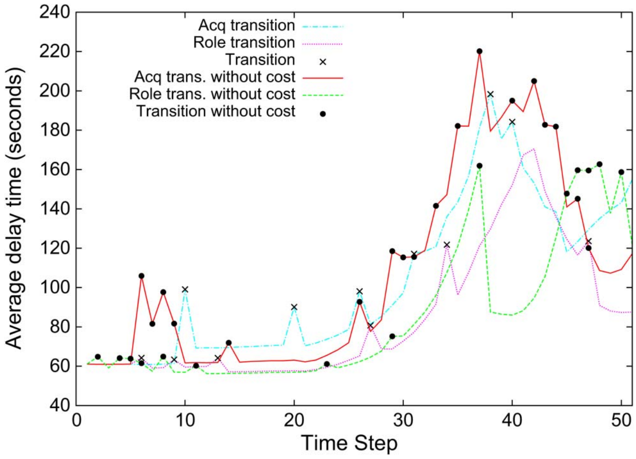

Fig. 2. Transitions with costs and without costs.

TABLE II
TRANSITIONS WITH AND WITHOUT COSTS

	Average delay time (seconds)	
Approach	Execution	40 executions
Acq. approach	101.97	98.56±7.12
Role approach	84.65	82.75±6.24
Acq. without costs	107.10	105.49±8.41
Role without costs	86.06	85.15±6.98

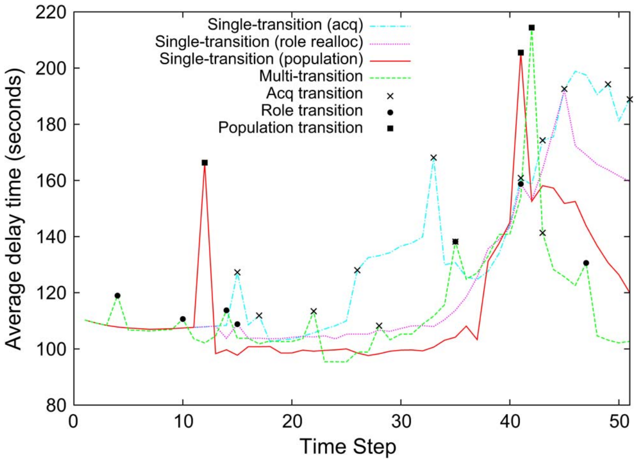

Fig. 3. One-dimensional transitions and MTDM.

TABLE III
ONE-DIMENSIONAL TRANSITIONS AND MTDM

	Average delay time (seconds)	
Approach	Execution	40 executions
Acq. approach	132.94	128.16±11.88
Role approach	122.27	124.62±10.77
Pop. approach	117.83	125.35±12.04
MTDM	114.24	112.2±6.59

TABLE IV
TRANSITION EFFECTIVENESS

	Percentage of transitions	
Type	Execution	40 executions
Acq. transition	36.36%	37.67±3.04%
Role transition	54.55%	53.96±3.29%
Pop. transition	9.09%	8.36±1.29%

TABLE V
ALGORITHM EXECUTION TIME

Agent population	Time (ms)
10	870.59±11.42
20	1045.68±14.36
30	1285.77±19.12
40	1512.86±25.05
50	1723.95±34.65

agents: 35% of these requests are for s_0, 35% are for s_1, 20% are for s_2, and 10% are for s_3. These percentages change during the 50 time-steps similar to the previous two experiments in order to change the demand of services.

As Fig. 3 indicates, considering several transitions makes the deliberation mechanism able to change different elements, while single-dimensional approaches are limited to a specific kind of change, which might not always be the best adaptation possible. As an example, at t^{10}, the transition achieved in the MTDM approach is by a role reallocation transition, while at t^{28}, the transition is achieved by an acquaintance transition. Thus, the average delay time is improved by these two changes. Furthermore, since several changes can be carried out at the same time-step, the possibilities of organization transitions are highly increased, and thus, better transition decisions can be made. As an example, at t^{35}, the transition is carried out by a population transition and an acquaintance transition. Table III shows the mean average delay time for each approach. It can be observed that the MTDM is able to find more possibilities for organizations to be transitioned to than 1-D transition approaches. Therefore, the organizations reached by the MTDM provide lower average delay time.

In order to evaluate the effectiveness of the algorithm, Table IV shows which percentage of transitions corresponds to each kind of changes. In this example, it can be observed that changes in the acquaintances and changes in the roles are the most frequent transitions. This behavior is caused because changes in the agent population are also involved in adding/deleting acquaintances and in reallocating some roles. Therefore, depending on the cost of adding or deleting agents in the system, the percentage of agent population transitions could increase. What is more, depending on the costs (or penalization) of acquaintance modifications and role modifications, a greater or a lower number of these transitions would be carried out. As stated in Section VI, setting and turning off an agent has a higher cost than setting or turning of an acquaintance. However, the three kinds of transitions are decided at different moments of each individual execution. In summary, we can conclude that the requirement of considering several dimensions for transition is beneficial because different kinds of changes are carried out during each execution.

Finally, Table V shows the average execution time required by the algorithm during 50 time-steps depending on the initial agent population. It can be observed that the time computation according to the agent population increases. However, we can observe the few computation times required in comparison with the time gained by adaptation in this domain. Otherwise, the time required for executing the algorithm should be considered in the transition computation cost.

VII. CONCLUSION

The MTDM presented in this paper provides a deliberation mechanism for organization adaptation based on a multidimensional transition criterion. The organization transition considers the impact of transition in terms of the utility caused by the transition, the costs associated to the transition, and how this transition would influence all of the components of the organization.

The contributions of this paper can be viewed from different perspectives. The MTDM provides an accurate estimation of the impact of the transition since the organization that is to be achieved is calculated by each transition. Thus, the impact associated to each change that is required to carry out the transition can be measured individually and more accurately than other approaches. The suitability of the adaptation must be considered by taking into account the benefits obtained by adaptation as well as the costs associated to this process. This issue is also important in human organizations since most organizational changes may encounter problems: they often take longer than expected and desired, the cost of managerial time may increase, and there may be resistance from the people involved in the change [34]. As we have observed in our experiments, in approaches that only focus on criteria to improve the utility, the costs for achieving these transitions may be so high that the mean utility gets worse. Another contribution of the MTDM is the possibility of including several transitions into the deliberation decision mechanism. Related to this issue, a future line work will be focused on extending the organization definition in order to consider a normative dimension. Therefore, changes in the specification of the norms would even increase the current range of adaptation solutions that can be found.

As we have observed in our experiments, approaches that consider 1-D transitions (roles, structural topology, population, etc.) offer a more limited range of solutions than the MTDM. Thus, in heterogeneous scenarios such as the SNP, in which several changes can affect the performance of the organization, a multitransition criterion for deliberation would provide better decisions for adaptation.

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