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Arranging Cooperative Business Activities in Dynamic Coalitions of Rational Actors

VADIM A. ERMOLAYEV, SERGEY U. BORUE, VYACHYSLAV A. TOLOK, NATALYA G. KEBERLE, SERGEY L. PLAKSIN {eva,bsu,tolok,kenga,psl}@zsu.zp.ua
Zaporozhye State University, Zhukovskogo, 66, 69063, Zaporozhye, Ukraine

Abstract. The paper addresses cooperation issues in dynamic distributed business process management enabled by the coalitions of task performing economically rational agents. Tasks are understood as partially ordered sets of activities performed in interaction between participants according to a defined set of rules in order to achieve a common goal. Agents represent intelligent actors having their roles as organizational unit members and possess their own knowledge on how to decompose and/or perform an activity. These actors form task coalitions in the course of business process performance. Workflow model of the performed business process is thus generated "on-the-fly" and may be further used for the performance analysis and fine-tuning. Main focus of the paper is the formal model for the distributed co-ordination of coalition formation via contracting negotiation. Negotiation process is performed each time the new activity appears in the course of the task execution within the Arrangement Phase preceding to activity performance. Semantic inter-agent-operability issues are resolved by the use of Task and Negotiation ontologies. B2B mediation in Capital Investment Consulting scenario is used to illustrate the approach.

Keywords: cooperation, coalition, rationality, B2B, agents, workflow

1. Introduction

The tasks performed by the organizations composed of human or artificial actors may be characterized by the intrinsic features of distribution and uncertainty. Distribution means that a task is performed part-by-part by different executives. They are mainly self-interested and act relatively autonomously by taking their rational decisions and facing the consequences on their own. These actors differ from each other by their capabilities to perform certain activities, by the limitations on their resources, by their states and corresponding state constraints, by beliefs about the outer environment and their fellows as well as by their personal intentions, goals and priorities. Otherwise, the players, when acting within an organization, are seeking for collaborators in order to do the work rationally in the most optimal way, though these collaborative coalitions are pretty uncertain. Uncertainty also has many dimensions. The actors are not subjectively certain about the commitments and intentions, to say more generally about the possible behavior of another actors. Uncertain are also their subjective readiness to co-operative work, subjective estimation of predictability and credibility one executive has about the other(s). The flow of the activities is also highly uncertain. The actors take their subjective decisions on how, when and whom to collaborate with either by forming more or less stable teams based on collective commitments and regulated by team conventions, or by choosing the optimal bid by a kind of trade-off negotiation each time they need a partner to the coalition.

The approaches providing the means to model the actors and the activities in the flow of their co-operative performance, to analyze and to predict their behavior, to recommend and to provide corrective influences in order to somehow optimize their joint proactive efforts and thus to co-ordinate distributed teams of self-interested actors performing under conditions of uncertainty are therefore highly desirable for various application domains: E-Business, E-Government, Virtual Enterprise Management, Distant Education, others. An important aspect is that co-ordination strategies based on actors' benevolence should not be anymore contraposed to that based on self-interest. As Lesser mentioned in [Lesser, 1999] "…there is more in common among cooperative and self-interested coordination mechanisms than currently believed — especially as the environments within which these mechanisms operate become more complex in terms of…the increased level of information uncertainty and incompleteness…"

Serious efforts are applied today to solve this challenging problem. Major standardization effort in process, workflow modeling and management belongs to WfMC[1]. The major accomplishments of WfMC in the field are: the Process Model – workflow and activity representation, XPDL – XML binding of PDL. As it was mentioned in [Tate, 1998], "...cooperation and coordination of the planning, monitoring and workflow of the organizations can be assisted by having a clear shared model of what comprises plans, processes and activities...". Known are the efforts aiming to define the basic shared concepts and models: SPAR [Tate, 1998] ontology, the Enterprise Ontology [Uschold et al., 1998], Process Specification Language [Schlenoff et al., 1999] (ordered hierarchies of activities), ToVE [Fox and Gruninger, 1998] (shared terminology for a virtual enterprise), O-Plan research [Tate, 2000] (manipulating plans of task execution) and others. Various examples of both theoretical and practical

[1] Workfolow Management Coalition. http://www.wfmc.org/. Last accessed on Nov. 4, 2001

solutions for diverse application domains may be found in [Klusch, 1999], [Omnichini et al, 2000], [Nwana et al., 1997], [Tambe et al., 1999], [Kendall et al., 1997], [Lesser, 1998], [Neiman et al., 1994]). In E-Business for instance the models for coalition formation based on pre- and post- negotiation patterns are proposed in [Tsvetovat et al, 2000] having COALA [COALA] as the general-purpose testbed for studying co-operative behaviors in agent coalitions. A comprehensive survey of negotiation approaches to distributed service provision may be found, for example, in [Faratin, 2000]. The authors overview known approaches to formalize, model and design distributed open organizations with agents, their coalitions performing tasks in [Ermolayev and Plaksin, 2002]

There is a consensus that the key challenge in the field is the problem of appropriate co-ordination – managing interdependencies between activities [Malone and Crowston, 1991]. It is also easy to notice that distributed co-ordination is the same kind of collaborative, highly uncertain processes and the coordinables [Ciancarini et al., 1999] are distributed, often constrained, have limited resources and conflicting subjective intentions.

The paper discusses the formal approach to distributed coordination of dynamic coalition formation among rational (possessing noticeable self-interest in trying to maximize their utility) and co-operative (attempting to reach optimal activity performance by collaborating with each other) agents. These agents are used to model functional actors able to perform specialized activities within organizations. Agent coalitions are dynamically formed in the process of a task execution. Negotiation on incorporating a member to the task coalition is performed each time the necessity to allocate a new activity appears in the course of task execution. This negotiation process is considered as a special type of coordination and is performed within the so-called Arrangement Phase preceding to activity performance.

Presented approach has been developed and verified by applying it to several modeling cases of project planning [Borue et al., 2000], personnel (PhD) recruiting [Ermolayev and Tolok, 2000], production management [Ermolayev et al., 2000]. Gradual enhancement of the framework was primarily motivated by the desire to cope with more sophisticated collaborative interrelationships and behaviors, than 100 per cent altruistic commitment to gain the organizational goal. Such complex, dynamic and undeterministic interrelationships and behaviors are typical to e-Business domain.

The reminder of the paper is structured as follows. Section 2 presents the motivating modeling example and the scenario from e-Business domain. Section 3 presents basic formalisms for an organization, an actor, a task, an environment used in the proposed framework for cooperative task performance by dynamic coalitions of executives. Section 4 presents the formal computational model for the Arrangement Phase execution. The contribution of Section 5 is informal evaluation of the proposed mechanism of activity allocation and dynamic task coalition formation. Section 6 gives some conclusions.

2. Motivating e-Business Scenario

Suppose ABC is a consulting company in the field of Capital Construction Investment (Fig. 1). Assume ABC organization comprises the following staff of actors: Project Managers, Construction companies' representatives, Construction materials supply companies' representatives, Transportation companies' representatives, Community officials' representatives. Each of the actors presents the capabilities and the interests of the "wrapped" organizations. From the other hand, it is ABC fellow member and should be concerned about company's success and revenues. The environment, ABC works within, is inhabited by the perspective investors. The investors seek for effective investments in the field.

To be successful on the market ABC needs to provide attractive investment plans leading to minimal risks. These investment plans should balance on the mutual interests of both the investors and the represented companies from one hand as well as upon the constraints on the resources and on the executives involved. The investors and the wrapped executives may also have overlapping, conflicting and/or coherent interests, commitments and intentions. For example (Fig. 1), transportation wrappers T_1 and T_k. have conflicting preferences and may possess conflicting intentions with respect to I3 investment proposal. T_1 will face more severe competition in case T_k. will get better facilities for air cargo transportation. Participation in I3 proposal implementation may however increase T_1 utility – it is a carrier with good reputation and has chance to get a contract for construction materials on-site delivery. The proposition of I3 may be of the lowest preference to C_n. The company it wraps will rather support the proposition of I1 (implementation of this proposition may indirectly make Airbus shares more valuable) and will never get a contract in frame of I3 proposal because of the lack of capabilities (the company has the licence for housing construction only).

To provide credible investment proposals in response to the investors' queries ABC should be capable to model (simulate and evaluate) the processes of corresponding projects' implementation, reason about the possible behavior of the executive organizations participating in the project and reason about the risks as well as about the possible overall project success or failure. It should also provide reasonable recommendations on corrective influences for the critical project steps.

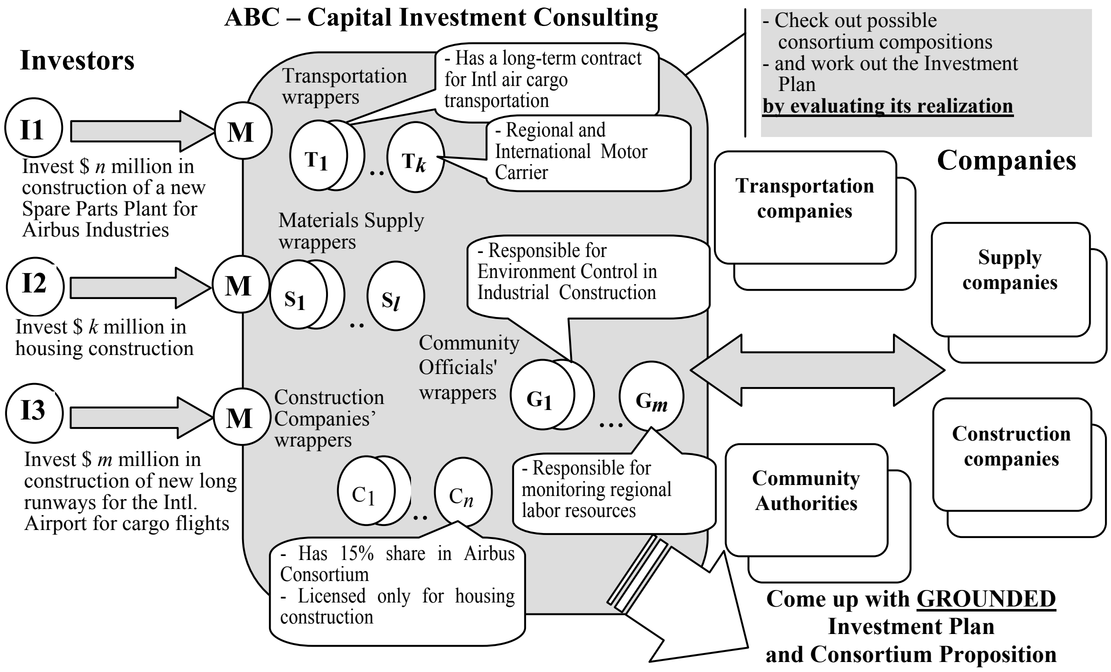

Figure 1. ABC organization, actors' interests and investors' intentions.

Human investors and their assistant agents **I1**, **I2**, **I3** provide external influences in the form of tasks "Work out investment proposal ...". ABC organization is modeled by Multi-Agent System (MAS), comprising executive agents with specializations: **M**, **T**, **S**, **G**, **C**. The combination of their commitments, goals and intentions forms the degree of uncertainty, that affects the execution of the tasks provided by the investors and may result in success or failure of the task execution. Actor instances are modeled by software agents. The class of problems, ABC organization is assumed to solve, may, thus, be classified as distributed planning for distributed plans [Wooldridge, 2002, p. 218] in B2B domain. The complications B2B environment brings up are characterized by the attributes of openness, dynamism and non-determinism caused by its uncertainty. ABC members (and ABC as a whole) may be considered as autonomous, rational, proactive distributed cooperative problem solvers [Durfee et al., 1989] acting cooperatively in the processes of Planning and Investment Plans Evaluation, thus producing relevant workflows "on-the-fly".

As far as the focus of the paper is negotiation on sub-task allocation, the following example will further on be used to illustrate the technique under discussion. Suppose a perspective human investor coming up to a User Assistant agent **I3** (Fig. 2, phase 1) to generate the proposition "*Work out the proposal for the investment of USD 300 million in construction of new long runways for the Intl. Airport to enhance cargo flight reception capacities. The result is required within 1 week starting from now.*" ABC Project Manager agent (**M**) receives this proposition from **I3** as a task in a formalized way (Fig. 2, phase 2). This task is further analyzed, decomposed (Fig. 2, phase 3) and collaboratively performed by the dynamic coalition of ABC member actors (Fig. 2, phase 4). The guidance on how to decompose the task and who are capable to perform its parts is distributed among the virtual knowledge bases of the participant agents and is formalized by *Task Model* (Section 3.2) and *Task Ontology* [Ermolayev et al., 2002]. Agents join this task coalition via negotiation on activity allocation in frame of an Arrangement Phase (Section 4). Semantics of the knowledge the agents are exchanging with each other within the Arrangement Phase is formalized by *Negotiation Ontology* [Ermolayev et al., 2002].

3. Organizations, Environments, Processes and Tasks

Analysis of real world business processes merely reflects the fact that there basically exist no executives in modern organizations, which are capable to perform one or another practically important job entirely by themselves. These jobs are rather performed as cooperative processes by the groups of human and/or artificial actors.

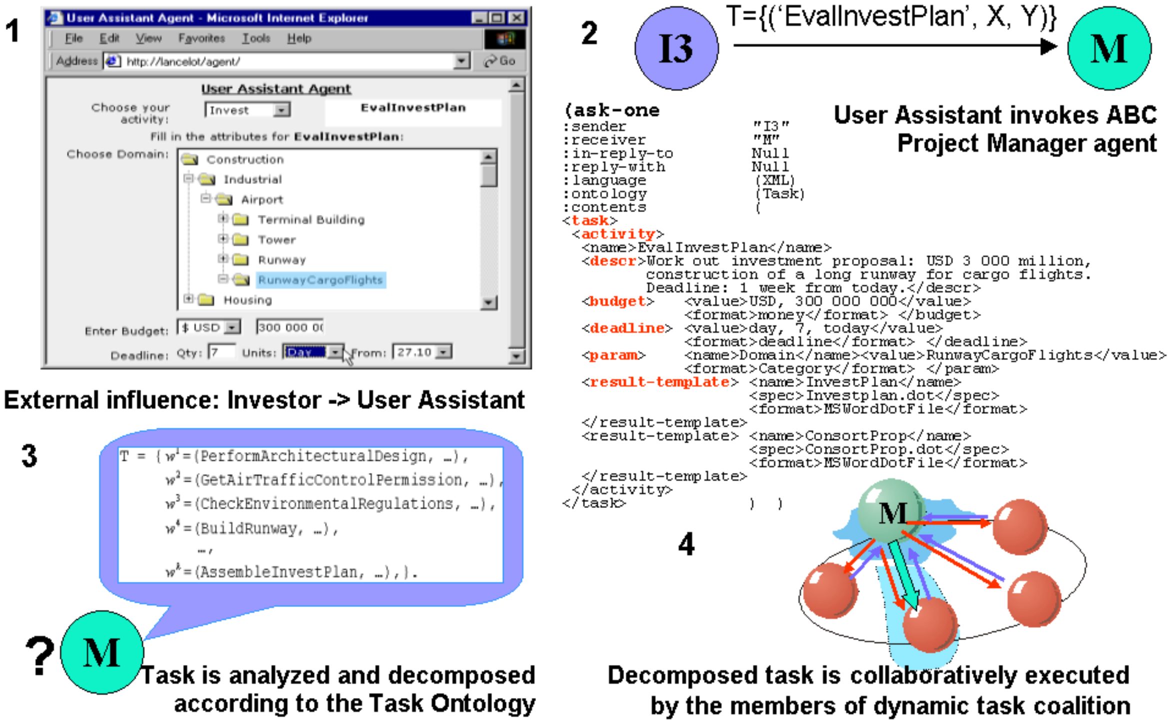

Figure 2. Processing user's request to work out an investment proposal.

3.1. Organizations and Environments

Each of these executives occupies a definite position within one or another level of an organization and is characterized by his/her/its capabilities, commitments, authority. Each of the executives possesses its own knowledge on what does this or that job mean, how it may be decomposed into the partially ordered set of simple activities, which of these activities should be allocated to its peers or subordinates. Normally, the execution of a job is initiated by the executives of the upper organizational levels, whose/which knowledge of a job is rather abstract and general. The parts of a job get more detailed context while going down the organizational structure to the executors with more specific capabilities and authorities. The activities, being atomic simple ones for a boss, may be evidently considered as complex jobs by its sub-ordinates. Normally, at any level, an executor co-operates with its super-ordinate(s), fellow-peers and its sub-ordinate(s) (if any) and has no need to be aware of all the executives of the upper, of his own or of the lower levels. In case the structure of an organization is presented in a form of graph (see Fig. 2), the sphere of actor A awareness may be limited by the nodes of the upper (P_1 and P_2) and lower levels (S_1, S_2, S_3) adjacent to A as well as the nodes of the same level two branches away from A via a super-ordinate (F_1, F_2, F_3). An organizational unit (e.g., a subsidiary, a department) of level l consists of an executive of level l plus all its sub-ordinates (e.g., $\{A, S_1, S_2, S_3\}$). Some executives may participate in several organizational units (e.g., $\boldsymbol{S_3}$ in $\{A, S_1, S_2, \boldsymbol{S_3}\}$ at level l and $\{P_3, \boldsymbol{S_3}, F_3, F_4\}$ at level l-1). Such executives may belong to the spheres of awareness of outside actors and may accept external influences from the members of different organizational units. The executives capable to accept external influences from the exterior of their organizational unit are called Proxies (e.g., A, $\boldsymbol{S_3}$). A proxy, when viewed from the outside of the organizational unit, is seen as a simple executive – *a reactive component*. It represents its organizational unit (*a reactive system*) in another organizational unit of a higher level (recall ADEPT [Jennings et al., 2000] in which agents represent both departments and individuals). Organization is evidently the set of its organizational units at level 1. In accordance to the principles of organizational structuring (see, e.g. [Gasser, 1992]) it is therefore assumed that an organizational unit is the set of active entities (actors) possessing respective capabilities and communicating according to the given shared cluster of patterns. The actors are modeled by economically rational [Nwana et al. 1997] software agents designed in frame of [Ermolayev et al., 2000]. The capabilities of an agent are provided by the set of macro-model programs for activity performance.

Organizations and their functional units act within an environment. A functional system provides the environment for its functional components, which, in turn, may expand into functional systems of the lower

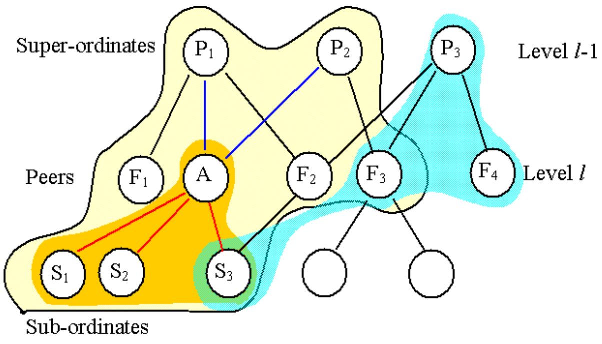

Fig. 2. A graph model of an organization.

level(s). These environments are accessible, non-deterministic, dynamic and discrete in the sense of [Russel and Norvig, 1995].

3.2. Tasks

As far as in frame of this paper the mission of an organization is simplified to the rational function of performing business processes and thus to increase its utility, it is assumed that the environment is modeled by a generator function providing *tasks* T[2] (refer to [Decker, 1995] for a similar terminology) as the sets of activities w^i :

$$\mathrm{E} \rightarrow \mathrm{T} = \left\{ w^1, w^2, ..., w^k \right\} \tag{1}$$

The tasks are accepted by Proxies. Organization is thus tailored to perform the tasks provided by the environment as external influences.

It is assumed that a task $\mathrm{T} = \left\{ w^1, w^2, ..., w^k \right\}$ is the set of atomic (for the given actor) activities. Actors within an organization are capable to perform the atomic activities belonging to the sets of their permissible atomic activities W_A. They are as well capable to generate sub-tasks without any external influence reacting to some events (internal to the organization) or in the course of performing of one or another atomic activity.

An actor, say *A*, involved in task execution has its own beliefs on how to perform atomic activities and how much effort should it spend to accomplish the activity w^j, provided that it possesses certain working *capacity* $N_A(w^j)$ related to this certain atomic activity.

Capacity is understood as actor's ability to accomplish the activity per unit time interval τ. It may be **unlimited** in case at any time *A* is able to concurrently accomplish as many w^j-s per τ as needed, and **limited** in case if the maximal quantity of concurrently running w^j-s is constrained with an upper bound. If, for instance, *A* is evaluating the delivery of construction materials to the cite (`('BuildRunWay', X, Y)` activity, Fig. 2, phase 2), than $N_A(w^j = (\text{"}deliver\_1\_tone\_of\_concrete\text{"}, ...)) = 4$ in case *A* has 1 ready-mix truck able to deliver up to 4 tones of concrete per τ and will be doubled if *A* gets one more carrier of the same type. In case $N_A(w^j)$ is limited it may be evenly, or not really evenly distributed over the activities w^j to be performed.

Activity w^j may be constrained by the *deadline* d_{w^j}. The deadline is the point in time after which w^j results are not needed anymore by the customer agent. For example, the construction company will not need any concrete on Sunday instead of Friday. This means that w^j customer agent's results *desirability* function value:

$$des_{w^j}(t, d_{w^j}) = \begin{cases} tdf(t), t \leq d_{w^i} \\ 0, t > d_{w^i} \end{cases} \tag{2}$$

falls down to zero after the deadline has passed and promises changing incentive $tdf(t)$ as a kind of a trade-off over time.

These beliefs form executives' subjective Partial Local Plans (PLP) for performing certain atomic activities. PLPs are formalized by the Task Ontology coded in standard OIL [Horrocks et al., 2000] and differ from, say, GPGP [Decker, 1995] by the fact they do not contain the subjective beliefs on what would be the actions of the fellow actors. Alternatively, the updates of the information on changing fellows' capabilities, fellows' credibility evaluations are performed by the actors individually in the course of their cooperative work (Section 4.3). The actors are involved into the cooperative task execution either by the results of negotiation on allocating the task or the activity, or by accepting a targeted directive from the super-ordinate.

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[2] Environment considered hereafter may therefore be classified as a task environment in a task oriented domain [Rosenschein and Zlotkin, 1994]

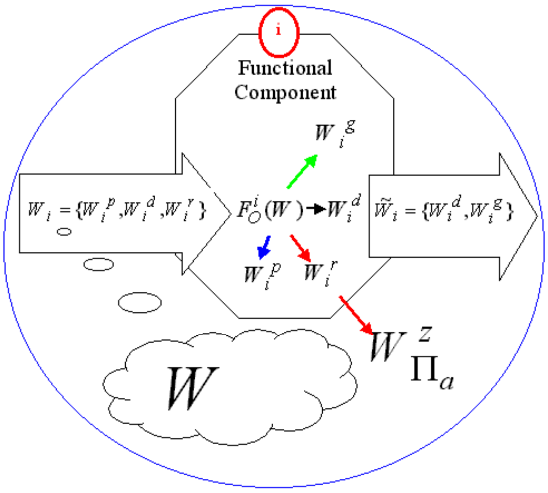


Figure 3. Model of a Functional Component.

After an influence is perceived by an actor it may:

– Accept and perform some of the activities contained within the task (e. g., `('EvalInvestPlan', X, Y)` at Fig. 2, phase 2)

– Decline some of the activities

– Decide to allocate a (sub-)set of the activities to one its fellows according to it's beliefs on the fellows' capabilities, credibility (Section 4.3), and their readiness to perform the activity (Fig. 5b)

– Require the performance of some new activities, the execution of which (as it knows from its knowledge formalized by the Task Ontology) is essential to successfully complete the overall accepted task execution (e.g., $w^1,...,w^k$ at Fig. 2, phase 3)

Main actor functionality is thus not to deliberate about the environment by mapping the receipts to its beliefs and intentions, but rather to react to environmental influences in a pro-active, rational and cooperative manner.

3.3. Actors as Reactive Components

Actors are thus considered to be reactive components of a reactive system (organization) [Connah and Walvish, 1990]. The model of an actor as a reactive component (see Fig. 3) is built upon the idea of "absorption" and "generation" of activities from the set of the permissible activities $W = \{w^1, w^2,...\}$ of this actor. It is considered that the sensory input of the actor *i* admits a task $W_i \subseteq W$. A certain part of its activities W_i^p may be performed ("absorbed") by the given actor and the remaining part of activities may be either allocated to another system's components (fellow actors) – W_i^d , or rejected – W_i^r . An actor may as well generate additional set of activities W_i^g to facilitate to the execution of activities W_i^p . W_i^g as well as W_i^d may be totally or in part allocated to another components:

$$W_i \to F_O^i(W) \to \widetilde{W}_i , \quad (3a)$$

where: $W_i = \{W_i^p, W_i^d, W_i^r\}$, $\widetilde{W}_i = \{W_i^d, W_i^g\}$, $F_O^i(W)$ - macro-model program.

In a special case actor *i* may generate a new set of activities W_i^g without been invoked by incoming influence W_i - i.e. may "summon" a new task:

$$F_O^i(W) \to \widetilde{W}_i , \quad (3b)$$

where: $\widetilde{W}_i = \{W_i^g\}$, $F_O^i(W)$ - macro-model program.

3.4. Process of Task Execution

Process Π_a of task execution begins with the acceptance or the generation of the new task $W_a \subseteq W$. Task W_a , as well as the derived tasks $\widetilde{W}_a$, are considered to be linked to process Π_a and labeled with the unique identifier of this process. The component is considered to be *linked to process* Π_a in case it has absorbed the part of W_a , $\widetilde{W}_a$, or has generated W_a^g .

Process Π_a is considered to be completed in case all the components stopped to absorb the atomic activities of the tasks linked to process Π_a . The set of activities $W^z_{\Pi_a}$ not absorbed in the process of Π_a is denoted as the set of *inexecutable* activities.

For practice the set of permissible activities of a functional component is constrained to be finite: $W = \{w^1, w^2, ..., w^n\}$.

3.5. Social Laws

Social laws are used in the presented approach to frame out actors' behaviors in organizations and task coalitions. These rules are hardwired into the design of the corresponding agents to provide for more reactivity in resource-bounded conditions. For brevity reasons only the rules regulating coalition formation are presented hereafter leaving that having no direct relationship to the arrangement of cooperative activities beyond the scope of the paper. By joining the coalition an actor pledges to follow some system (coalition) rules regulating the proportion of its benevolence and self-interest. These rules may be classified, following Jennings Commitment-Convention hypothesis [Jennings, 1996] as actor's Individual and Joint Commitments and Coalition Conventions:

Rule 1: **Relative co-operation commitment**. Coalition members are **relatively** committed to co-operatively achieve the overall goal: to accomplish the task with maximally achievable effectiveness (maximal quality, balanced load, minimal time, ...). The ratio of this commitment depends upon the discrepancy between the actor's autonomous intentions and the overall goal of the task coalition.

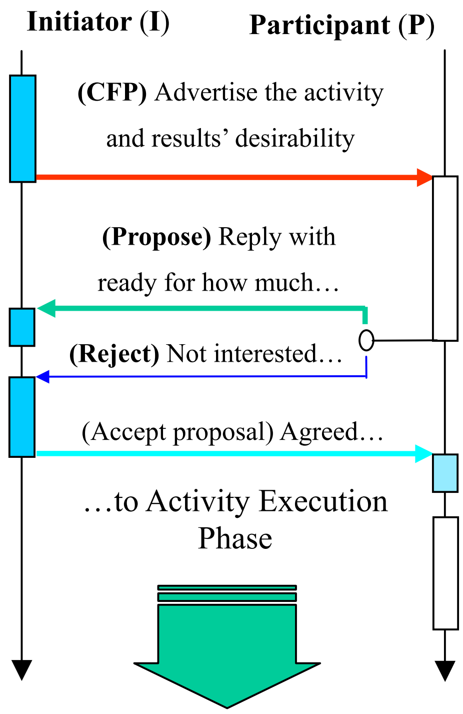


Figure 4. Arrangement Phase protocol.

Rule 2: **Activity arrangement convention**. Within the Arrangement Phase the coalition member ordering the activity(s) (the Initiator) pledges to truthfully advertise desirability functions related to the proposed activity(s). In response, perspective contractors (the Participants) are committed to truthfully report about their readiness to perform the activity(s) providing the information about their capacity share and about the duration of activity(s) execution in the form of parametric feedback [Ermolayev et al., 2000].

Rule 3: **Results delivery commitment.** Since an atomic activity is accepted by the actor for the performance the actor pledges to unconditionally accomplish this activity and to bring up the results to public immediately after the work is done.

4. Arrangement Phase: Activity Allocation and Task Coalition Formation

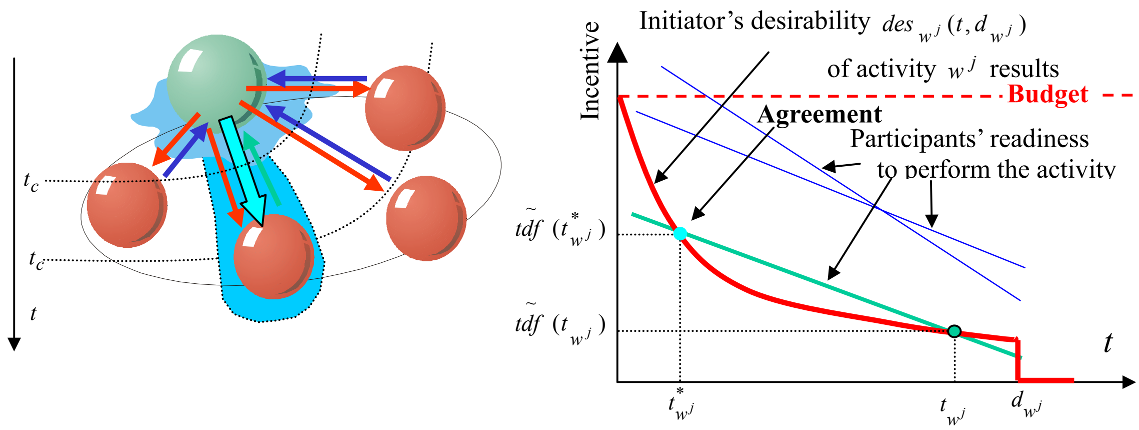
It is assumed that before an activity (a sub-task) is allocated to an actor and the actor proceeds with its performance preliminary Arrangement Phase (AP) takes place. AP is organized in frame of a simplified FIPA Contract Net Protocol [FIPA, 2001] (Fig. 4.). In the course of the AP the employer-agent (initiator - **I**) searches for the optimal bid for the activity performance by advertising its desirability function (2) and the perspective employee(s) (participants - **P**) are indicating their current readiness to spend the part of their capacity for the activity performance in the parametric form. The participants express their readiness to contribute to the task coalition by replying with functions providing matches with the initiator's desirability within the time interval $]0, d]$. After analyzing the feedbacks and determining the optimal match (Fig. 5b.), the initiator allocates the activity to the chosen Contractor (Fig. 5a.). The participants of this negotiation process are both the members and not the members of the task coalition. In case if a newcomer is selected by the initiator to perform the activity the newcomer becomes the coalition member.

Time needed for the AP is considered to be negligible with respect to unit time interval duration τ.

4.1. Initiator: Conducting an Arrangement Phase

In frame of the reported research it is assumed [Borue et al., 1999], [Borue et al., 2000], that an Initiator needs to allocate an activity to another fellow actor in case it can't perform it itself due to high load or because of the lack of appropriate skill (specialization macromodel program). Initiator's routine for an AP is twofold (Fig. 5.):

- Initiate negotiation process by advertising activity specification and corresponding results desirability function (2) to the Participants possessing capabilities, as it believes according to (19.20), to perform the activity
- Collect and analyze parametric propositions from the Participants to chose the contractor



a. Coalition Formation **b.** Proposition and Feedbacks

Figure 5. Arrangement Phase. Negotiation on activity allocation and coalition formation.

In-depth discussion of Initiator's behavior in the course of solving these problems is given in [Ermolayev and Plaksin, 2001].

Activity description is provided in the form defined by the Task Ontology. Trade-off values of the results desirability function for the proposed activity w^j, essential for the accomplishment of the (sub-)task T, are derived from:

– The budget of the task T Initiator is performing — the proposed incentive for T accomplishment
– The PLP of task T providing the information on the possible effort to be spent for the accomplishment of T's constituents and the information on the partial order of T's activities

The decision on the Contractor choice is made in course of solving the problem of finding the optimal $\tilde{tdf}(t,d)$ bid among the feedbacks provided by the Participants.

4.2. Participant: Reasoning about the Proposed Incentive

Suppose at t_c a candidate agent **P**, participating in the negotiation on activity allocation, receives the proposition to perform a new activity w^n from the initiator agent **I**. This advertisement is accompanied by the results desirability function (2) providing the dependency of the proposed incentive upon time (Fig. 5b.) Reasoning function of **P** within the AP is to optimally plan the execution of the proposed activity together with the bulk of jobs **P** is already executing according to its previous commitments (Section 3.5). The rational goal of **P** is to maximize its overall utility by increasing incoming incentive.

Candidate contractor **P** at the time point t_c has the information on the distributions of the capacity shares $R_{w^i}(t)$, $R_O(t)$ with respect of the current bulk of activities W_c within the current activity period T_c.

At t_c **P** has already being performing or has committed and planned to perform the bulk of activities $W_c = \{w^1, ..., w^i, ..., w^k\}$. Activities w^i are performed by **P** within one or more unit time intervals $[t, t+\tau]$ each consuming $r_{w^i,t} \geq 0$ of agent's capacity per unit time interval. In case $R_{w^i}(t)$ is the discrete distribution function of agent's capacity share consumption with respect to w^i, then it may be denoted as:

$$R_{w^i}(t) = \{r_{w^i,t^i}, r_{w^i,t^i+\tau}, ..., r_{w^i,t^i+l^i\tau}\}, \quad (4)$$

provided that the execution of w^i starts at t^i and it is accomplished at $t^i + l^i\tau$. Current period of agent **P** activity $T_c = \left[t^s = \min_i t^i, t^e = \max_i (t^i + l^i\tau)\right]$ is associated with W_c. Overall agent's capacity consumption distribution function within T_c may thus be computed as:

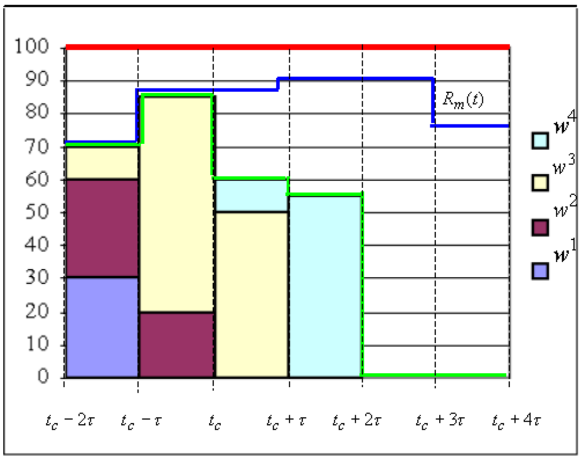


Figure 6. Agent's capacity share distributions for the activities $W_c = \{w^1, w^2, w^3, w^4\}$: $R_m(t)$ - blue line, $R_o(t)$ - green line.

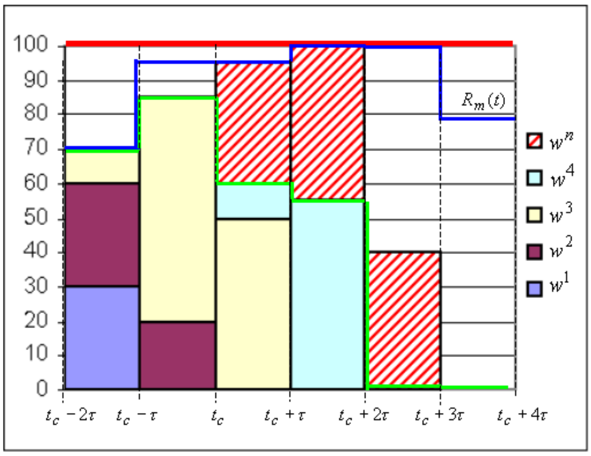


Figure 7. Computing the capacity share distribution for the newly proposed activity w^n with the estimated effort $S_{w^n} = 120\times\tau$.

$$R_o(t) = \left\{ \sum_i r_{w^i, t^s}, \ldots, \sum_i r_{w^i, t^s} \right\}. \tag{5}$$

Generally, the overall agent's capacity consumption may however be limited by the threshold function $R_m(t)$:

$$R_o(t) \leq R_m(t). \tag{6}$$

Unused capacity is rationally reserved for the emergency cases. One of the emergencies may be the necessity to accomplish the activity requiring unexpectedly much effort in the agreed time for the agreed incentive. Fig. 6 presents the observed values of $R_m(t)$, $R_o(t)$, $R_{w^i}(t)$ for the bulk of current activities $W_c = \{w^1, w^2, w^3, w^4\}$ within the current activity period $T_c = [t_c - 2\tau, t_c + 2\tau]$.

The goal of **P** is to rationally evaluate the proposed $tdf(t)$ and to feedback with its own $\tilde{tdf}(t)$ proposition. Deliberation scheme used by **P** is as follows:

- Compute capacity share distribution function $R_{w^n}(t)$ for w^n and time t_{cm} required to complete w^n having in "mind" capacity distribution $R_o(t)$ for the jobs of W_c and to determine the proposed $tdf(t_{cm})$ incentive value as the first point of the parametric feedback $\tilde{tdf}(t)$ (green dot on Fig. 5b).
- Try to maximize the incentive $\Pi = \sum_{w^i \in W_c \cup \{w^n\}} des_{w^i}(t_{cm_{w^i}}, d_{w_i})$ by redistributing capacity shares and, possibly, by reordering activities' performance. The solution of this optimization problem will provide the second point of the parametric feedback $\tilde{tdf}(t)$ (light-blue dot on Fig. 5b).

4.2.1. Computing Capacity Share Distribution

The first thing **P** needs to evaluate is the effort S_{w^n} **P** will spend to complete w^n according to the activity description. For our concrete delivery example (Section 3.2.) this evaluation is very simple. **P** will divide the total weight of concrete to be delivered to the construction site by the combined physical capacity of its ready-mix trucks (tones per τ). If we consider the graphical representation of w^n execution planning, **P** needs to gradually color the unused area between $R_m(t)$ and $R_o(t)$ starting from $t = t_c$ until the resulting colored area is not equal to S_{w^n}. Fig. 7 shows the result for the new activity w^n with estimated executor's effort $S_{w^n} = 120\times\tau$.

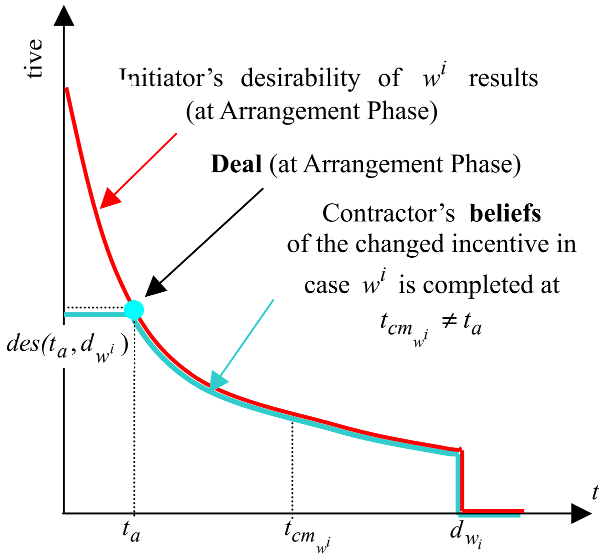


Figure 8. **P** expects **I** to pay incentive according to its advertisement even if w^i performance is postponed beyond the agreed time.

Next step of **P**'s deliberation is to compute the time t_{cm} required to complete w^n having in "mind" the capacity distribution for the jobs W_c. t_{cm} is actually computed as the minimal value satisfying the following constraint:

$$\sum_{t^n=t_c}^{t_{cm}} \tau(R_m(t) - R_o(t)) \geq S_{w^n} \tag{7}$$

Duration l^n of w^n will than be $\dfrac{t_{cm} - t^n + 1}{\tau}$. The capacity share consumption distribution function $R_{w^n}(t)$ at $\{t^n, t^n + \tau, ..., t^n + l^n \tau\}$ can now be easily determined as

$$R_{w^n}(t) = \begin{cases} R_m(t) - R_o(t), t_c \leq t < t_{cm} \\ S_{w^n} - \sum\limits_{t=t_c}^{t_{cm}-\tau} \tau(R_m(t) - R_o(t)), t = t_{cm} \end{cases}. \tag{8}$$

The intuition behind (8) is as follows: **P** had actually no idea about w^n at $t < t_c$, it is irrational to postpone w^n execution to $t > t_{cm}$, w^n will consume all **P**'s capacity if $t_c \leq t < t_{cm}$ up to the threshold $R_m(t)$, some capacity may be unused at the last unit time interval $t = t_{cm}$.

After t_{cm} is evaluated **P** can as well evaluate it's perspective income by determining the incentive value $\tilde{tdf}(t_{cm}) = tdf_{w^n}(t_{cm})$ proposed by **I** in case w^n is accomplished at t_{cm}.

4.2.2. Optimizing the Incentive

A very rational question **P** poses to itself at the next step is whether it is possible to obtain even more incentive by optimizing capacity shares among the bulk of activities $WS = W_c \cup \{w_n\}$. The answer is obtained as follows.

Assume $t_{cm_{w^i}} = t^i + l^i \tau$ is the accomplishment time of $w^i \in WS$, in case its capacity share distribution is $R_{w^i}(t)$. Then $t_{\max} = \max\limits_{w^i} t_{cm_{w^i}}$ is the time point starting from which **P** has not yet planned any activity performance.

Assume that the accumulative capacity

$$M_{WS} = \sum_{w^i \in WS, t_c \leq t \leq t_{\max}} R_{w^i}(t) \tag{9}$$

is denoted as the hypothetic capacity **P** would need to spend in order to accomplish all WS activities in course of one unit time interval τ. Analogously, the accumulative capacity M_{w^i} with respect to w^i is

$$M_{w^i} = \sum_{t_c \leq t \leq t_{\max}} R_{w^i}(t) \tag{10}$$

P estimates the overall incentive in the form of

$$\Pi = \sum_{w^i \in WS} \overline{des}_{w^i}(t_a, t_{cm_{w^i}}, d_i), \tag{11}$$

where $\overline{des}_{w^i} = \begin{cases} des_{w^i}(t_a, d_{w^i}), t \le t_a \\ des_{w^i}(t, d_{w^i}), t > t_a \end{cases}$, t_a is the time for which **I** and **P** had agreed before that **P** will accomplish w_i (see Fig. 8). **P**'s goal is to solve the discrete non-linear programming problem

$$\Pi \to \max . \tag{12}$$

The problem is solved by the variation of $t_{cm_{w^i}}$ values within the interval $[t_c, t_{\max}]$. This indirectly means the variation of the constituents $r_{w^i, t^i + j\tau}$ of capacity share distributions $R_{w^i}(t)$.

The constraints for the *varied* $R_{w^i}(t)$ within $[t_c, t_{\max}]$ are evidently as follows:

Activity deadline constraint

$$\forall w^i \in WS \quad t_{cm_{w^i}} \le d_{w^i} \tag{13}$$

Capacity distribution value constraint:

$$\forall t \in [t_c, t_{\max}], \forall w^i \in WS \quad 0 \le R_{w^i}(t) \le R_m(t) \tag{14}$$

Activity effort constraint

$$\forall w^i \in WS \quad \sum_{t_c \le t \le t_{\max}} R_{w^i}(t) = M_{w^i} \tag{15}$$

Threshold capacity consumption constraint

$$\forall t \in [t_c, t_{\max}] \quad \sum_{w_i \in WS} R_{w^i}(t) \le R_m(t) \tag{16}$$

Overall effort constraint

$$\sum_{w^i \in WS} \sum_{t_c \le t \le t_{\max}} R_{w^i}(t) = M_{WS} \tag{17}$$

Incentive optimization problem (12) with constraints (13-17) is solved iteratively by exhaustive search. The particularity of the solution is the way activity accomplishment times $t_{cm_{w^i}}$ are computed according to the varied capacity share distributions $R_{w^i}(t)$. At each optimization iteration the following simple algorithm TCM is performed:

```
TCM1: t = t_max ;
TCM2: If   R_w^i(t) ≠ 0
           then   t_cm_w^i = t ; Exit TCM;
TCM3: t = t − τ ; Goto TCM2;
End
```

After the solution of (12) together with the accomplishment times $t^*_{cm_{w^i}}$ are obtained the incentive value $tdf_{w^n}(t^*_{cm_{w^n}})$ proposed by the initiator agent **I** is used by **P** to form the second point of it's feedback $\widetilde{tdf}(t)$ (Fig. 5b). The parametric feedback of **P** is afterwards returned to **I** in the form

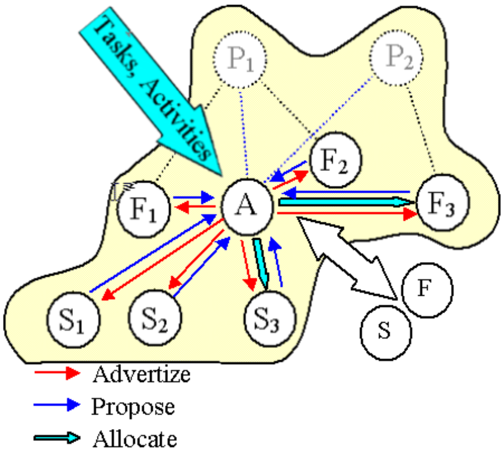


Figure 9. Interactions providing new knowledge to update Fellows' Capability Expectations.

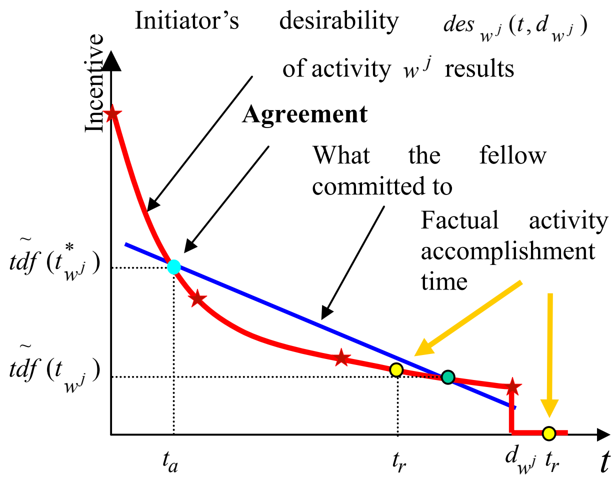


Figure 10. Inputs to fellow credibility adjustment.

$$\tilde{tdf}(t,d) = \left\{ \left(des_{w^n}(t_{cm_{w^n}}, d_{w^n}), t_{cm_{w^n}} \right), \left(des_{w^n}(t^*_{cm_{w^n}}, d_{w^n}), t^*_{cm_{w^n}} \right) \right\}. \tag{18}$$

4.3. Fellows Capability and Credibility Estimations

Actors accumulate the knowledge on the capabilities of their peers and sub-ordinates in the course of their cooperative performance. New portions of this knowledge appear each time an AP is conducted by an actor to allocate an activity to an executive within the sphere of its awareness (Fig. 9). Actor's subjective beliefs on the probability of its fellows' capability to perform the given activity are thus updated. These beliefs are autonomously maintained by each actor in the form of its Capability Expectations Matrix:

$$\mathbf{C} = \begin{array}{c} \\ F_1 \\ \ldots \\ F_n \\ S_1 \\ \ldots \\ S_m \end{array} \left[\begin{array}{ccccc} w^1 & \ldots & w^j & \ldots & w^k \\ c_1^1 & & c_1^j & & c_1^k \\ & & \ldots & & \\ & \ldots & c_i^j = (q_i^j, p_i^j) & \ldots & \\ & & & & \\ & & \ldots & & \\ c_{n+m}^1 & & c_{n+m}^j & & c_{n+m}^k \end{array} \right], \tag{19}$$

where dimensions $n+m$ and k change in the process of actor's evolution reflecting the appearance of new incoming activities and the actors' stuff within the proxy's sphere of awareness.

Capability estimations c_i^j change each time an actor negotiates with its fellows to allocate an activity. Element q_i^j in tuple c_i^j stands for the quantity of recorded negotiations with agent i concerning activity w^j. Element p_i^j stands for the capability expectation. The rule for c_i^j updates is as follows:

$$\begin{array}{ll} 1. & p_i^j \leftarrow p_i^j + \dfrac{r}{q_i^j}, \\ 2. & q_i^j \leftarrow q_i^j + 1 \end{array} \tag{20}$$

where r is equal to: 0 – if the fellow rejected the activity, 0.5 – if the fellow replied that it can accept the activity and 1 – if the activity was finally allocated to the fellow.

One more aspect providing influence on a Proxy decision to allocate an activity to one or another negotiation participant is its estimation of the participant's *credibility*. A self-interested actor, due to the appearance of the new highly attractive activity offers in the competitive environment or due to the peculiarity of its behavior, may lower previously declared capacity it is spending for the bulk of the activities under execution.

This will lead to the increase of the duration of these tasks execution and may seriously decrease the customer actors' desirability of these results (Fig. 10) and, thus, lower the credibility value for actor selling its' fellows short.

The mechanism of accounting actors' credibility values is merely the same as that of adjusting the beliefs on changing fellow capabilities (19). Credibility estimations change over time as an actor adapts its subjective beliefs by comparing the desirability values (Fig. 10) derived from 1-st — activity duration the executive committed to within the AP and 2-nd — actual time the executive consumed for providing the results. Corresponding credibility matrix elements are than recomputed due to the following:

$$Cr_{i,j} := Cr_{i,j} \times \begin{cases} 1, t_r \le t_a \\ p_{w^j}(t_a / t_r), t_a < t_r \le d_{w^j} \\ 0, t_r > d \end{cases}, \tag{21}$$

where: t_a is the time the parties have agreed to accomplish the activity w^j, t_r is the actual time of w^j results delivery, d is the deadline and p_{w^j} is the weight coefficient characterizing the current priority of w^j for the customer actor.

In addition, credibility threshold values associated with respective activities and stored in agents' PLPs (Section 3.2.) and are used by initiator actors to assess possible risks and alter their strategies.

5. Arrangement Phase Mechanism Evaluation

Criteria grouped by Sandholm [Sandholm, 1996] are used to evaluate presented AP mechanism evaluation: Pareto efficiency, individual rationality, stability, symmetry, computational efficiency, distribution and communication efficiency.

5.1. Pareto Efficiency

One of the important questions to be answered with respect to negotiation mechanism under evaluation is if it augments the overall utility (social welfare in the sense of, say, [Rosenschein and Zlotkin, 1994]) of participating actors. The answer is positive because the mechanism of an AP produces Pareto efficient solutions – the ones $\tilde{x}$ in which at least one of the participating actors does better, than in any other solution x and no other participant does worse in $\tilde{x}$, than in x.

There are two outcomes reachable in frame of an AP: 1-st – elaborate agreement and allocate negotiated activity ($\tilde{x}$) and 2-nd – defect from agreement (x). The parties are: an initiator and participant actors. An initiator does evidently better in $\tilde{x}$ than in x because: it will not increase its utility and may even suffer from various penalties (e.g., decrease in credibility (21), possible results delivery commitment violation penalty) in case it chooses x; its utility will be increased by $Budget$ - $\widetilde{tdf}(t^*_{w^j})$ in case it chooses $\tilde{x}$ and the chosen contractor will strictly follow its activity related commitments. A participant will not do worse in $\tilde{x}$ even in the most pessimistic case of not becoming a contractor. A contractor will add some points to its utility as well in case it will play fairly and relatively (Section 3.5.) obey the agreement. A contractor will receive less incentive than expected only if it delivers the results before the deadline but later than it was agreed. But in this case it will compensate the loss by extra incomes from other activities it performs concurrently (Section 4.2.2.).

5.2. Individual Rationality

A mechanism for multiagent encounters should be individually rational [Sandholm, 1996, p. 14] in order to be attractive to rationally motivated actors in open organizations. AP provides negotiated solutions in which pay-offs for participants are not less than the agents could get by not participating in negotiation. No one of them actually looses utility from participating in such an arrangement. The utility may be increased by the initiator and the contractor in case the agreement is reached and both of them obey the deal in a way to eliminate over-penalties.

5.3. Stability

Stability evaluation criterion demands the mechanism to motivate each party to behave in the desired manner. The preferable outcome of an AP (Section 5.1.) is to elaborate agreement and allocate the activity. This outcome is reachable in case there exists at least one participant capable to perform the activity advertised by the initiator in desired time and interested in the proposed incentive. It is also required that the initiator still considers such a participant to be credible enough for activity allocation (Section 4.3.). Under these constraints AP strategies of the initiator and of each of the participants are in Nash equilibrium in the sense that they provide rationally best response to the actions undertaken by both parties. AP mechanism is thus stable as far as it guarantees the attractiveness of being engaged into negotiation in case the deal is principally reachable. Presented AP mechanism is symmetric in the sense it allows agents acting identically to receive identical pay-offs. AP symmetry adds to its stability in open organizations composed of rational actors.

5.4. Computational Efficiency

Computational efficiency of AP mechanism is mainly determined by computational complexity of (12-17) problem solution which is NP-hard in the proposed methodology. It is evident that such an approach in resource bounded conditions may lead to unsatisfactory results. Let's figure out the bounds of satisfactory acceptance of the proposed mechanism. First constraint states that the environments under discussion are discrete (Section 3.1.). This immediately implies time granularity constraint: time needed to solve discrete non-linear programming problem (12) should be much less than the distance τ between two adjacent time points t_n and t_{n+1}. This limitation seems to be acceptable for the majority of e-Business problems decomposed in activities adequately modeled with time granularity measured in hours, days or weeks. One more aspect of influence on computational efficiency is the actual number of activities (threads) simultaneously executed by an agent. This number is not drastically big for a well-structured and horizontally scaleable organization like ABC Consulting (Section 2). And, finally, one more constraint deals with the granularity (dimension) of the discrete representation of customer agent's results desirability function (2). As far as these functions are typically smooth, not oscillating and may be presented by a considerably small number of characteristic points (e.g., red stars on Fig. 10).

5.5. Distribution and Communication Efficiency

Mechanism is considered to be distributed in case it has more than one points of control. In this sense AP mechanism is at least as distributed as any other implementing a kind of a Contract Net strategy. The control is actually distributed over the parties participating in AP as far as both the initiator and the participants take their decisions autonomously according to their subjective beliefs, preferences, intentions.
Communication efficiency is ensured by the non-iterative character of AP. All the arrangements are done in one round because the mechanism of parametric desirability adverts (2) and parametric feedbacks (18) provide vector responses reflecting all possible answers within the interval of initiator's rational interest.

6. Concluding Remarks

The paper discussed the formal model for the distributed co-ordination of dynamic coalition formation among the rational (possessing noticeable self-interest in trying to maximize its utility) and co-operative (attempting to reach optimal activity performance and utility increment by collaborating with each other) agents. These agents are the functional actors able to perform specialized activities within an organization. The coalitions are dynamically formed in the process of a task execution. The proportion of a coalition member benevolence and self-interest is regulated by Relative Co-operation Commitment, Activity Arrangement Convention and Results Delivery Commitment.

Negotiation on attracting a member to the task coalition is performed each time the new activity appears in the course of a task execution. This negotiation process is considered as a special type of co-ordination and is performed within the so-called AP preceding to activity performance. Within the AP conducted by the initiator agent in frame of a simplified FIPA Contract Net Protocol the participants are asked to evaluate if they are able to perform the proposed activity and to reply parametrically (18) in terms of incentive over time. As far as participants' capacity is limited, partially used to perform another activities and constrained by some reservation for the emergency cases, they perform quite a complex reasoning to reply to the initiator's query according to the scheme: 1-st. Compute capacity share distribution for the newly proposed activity and evaluate the time and the incentive required for its accomplishment; 2-nd. Try to optimize the overall incentive by redistributing capacity shares for the bulk of its activities and, thus, by solving discrete non-linear programming problem (12) constrained by (13-17). As far as it is assumed that the cardinality of the agent's set of activities within the current activity period is not very big, the problem is solved iteratively by exhaustive search. Task and Negotiation Ontologies [Ermolayev et al., 2002] are used to provide shared concepts to AP participants.

A participant while trying to postpone some of its less attractive activities in the course of maximizing its incentive may violate the earlier agreements on the accomplishment times of these activities, thus, selling its fellows short. Mechanism (21) to evaluate and to adjust the credibility values for the fellows is proposed to provide the possibility for the initiator agent to fill itself comfortable in a partially trusty environment.

Presented mechanism of the AP is informally evaluated according to the criteria of Pareto efficiency, individual rationality, stability, symmetry, computational efficiency, distribution and communication efficiency widely used in Game Theoretic Approach for multi-agent encounters assessment. The results of this evaluation show that the mechanism proves to be appropriate to model, arrange and control cooperative distributed task performance in open, but well structured organizations acting in accessible, non-deterministic, dynamic and discrete environments. Such organizations and environments are typical to e-Business domain.

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