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CENTRALISED VERSUS MARKET-BASED CONTROL UNDER ENVIRONMENT UNCERTAINTY: CASE OF THE MOBILE TASK ALLOCATION PROBLEM (MTAP)

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- Abstract -

This paper aims at comparing the centralised versus the market-based approach. This is done in the context of the mobile task allocation problem (MTAP) from the perspective of environmental uncertainty. MTAP is defined as an optimization problem for planning the assignment of service tasks to mobile workers. Environmental uncertainty is introduced through the injection of stochastic tasks and dynamic travel delays. A multi-agent simulator is employed to experiment the behaviour of each approach in reaction to different uncertainty levels. Preliminary results suggest a tentative conceptual model to evaluate the suitability of each approach to address MTAP in function of uncertainty. It is suggested that uncertainty's effect on achieved performance is moderated by the *timeliness of decision making, workers' degree of local knowledge, and problem's complexity and size.*

Keywords: *Information system structures, operations management information systems, market-based computation, environment uncertainty, multi-agent simulation.*

JEL Classification: M15 - IT Management

1. INTRODUCTION

The ability to solve Resource Allocation Problems (RAP's) with two distinct approaches, namely the centralized and the distributed approaches, gave the opportunity to numerous management studies to investigate the advantages and drawbacks of each approach in the decision making process for efficiently allocating resources.

Conventionally, the hierarchically-structured centralized scheme was adopted by default to address RAP's (Ygge and Akkermans 1999). However, recent technological advancements in ICT and the proliferation of mobile communication and portable computing may raise the debate of which approach to choose for addressing distributed RAP's.

Despite the significant dissimilarities between both approaches design-wise, the differences are not limited to the structural scope, but also include the decision making procedure, the type of input information, and the reaction mechanism to face external uncertainty. This paper aims to investigate both approaches in the context of distributed applications of RAP's where direct monitoring turn to be unfeasible and high rates of uncertainty are the main characteristics of such applications. In this study the Mobile Task Allocation Problem (MTAP) is taken as a representative case for distributed RAP's facing environmental uncertainty.

By the use of a multi-agent simulator, we examine the effect of environmental uncertainty on the performance exhibited by each approach. Applied on the MTAP, we address the question of whether uncertainty, reflected by dynamism and delays, can bias the choice of the decision making approach to be used for such applications.

This paper is structured as follows: in section 2, we present most outstanding studies comparing both approaches at hand and determine the originality of this research. Description and mathematical definition of the MTAP is provided in section 3, along with models of the studied uncertainty. Section 4 provides a description of the multi-agent simulator used as a method of research to answer our research question. Initial results are presented in section 5. Finally section 6 discusses the obtained results and interprets them to finally suggest future work.

2. LITERATURE REVIEW

Resource allocation is a major application in management science. Decisions regarding resource allocation are almost always coupled with hard optimization problems. Such management problems are cross disciplinary and applicable on a wide range of applications concerned with managing scarce resources.

Starting with organizational design, Malone and Smith (1987) compared four different taxonomies of coordination in an organizational context ranging from fully decentralized markets to hierarchical structures. Malone and Smith's study was extended by Tan and Harker (1999) to focus on two divergent structures, the hierarchically-centralized and the distributed market-based approaches. Their cost-based comparison study claimed to prefer centralized approach for its lower coordination costs, measured by number of exchanged messages; however, they did not address the uncertainty issue, besides, recent ICT innovations dramatically reduced communication costs and improved reliability.

In the field of power management, Ygge and Akkermans (1999) contrasted both approaches in demonstrative application of allocating cool air resources. Their study pointed to the importance of global information to reach good decisions. They also demonstrated that local information + market communication = global knowledge leading to the possibility for market-based approaches to attain centralized approach performance.

In the domain of logistics and transportation, Mes et al. (2007) compared two centralized heuristics to a hierarchy of agents cooperating via markets. Their findings implying the preference of their market approach over the centralized heuristics can be attributed to the proposed market-design making global information available to all agents, restricting the feature of the local knowledge of distributed techniques.

Mahr et al. (2010) compared both approaches for a drayage problem with uncertainty. Their relevant study compared centralized control to a distributed market-based approach from a heuristic point of view, i.e. their focus was not framed on the exclusive features of each approach. Thus, it is not clear whether their findings can be generalized to more flexible applications where any-time changes can dramatically alter the global solution.

Based on the fact that a rigorous comparison of the conventional centralized approach against the promising market-based approach contrasting their particular features is missing from the body of literature. This study aims to answer the critical question of when and how each approach can be better adopted for flexible applications, like managing teams of mobile maintenance engineers in real-time environment where uncertainty is rated high. We refer to such optimization problems as: mobile task allocation problems (MTAP) (Al-Yafi and Lee 2009).

3. THE MOBILE TASK ALLOCATION PROBLEM (MTAP)

MTAP is a generalized form of the Vehicle Routing Problem (VRP) thoroughly discussed in Toth and Vigo (2002). MTAP consists of efficiently assigning a set of geographically dispersed tasks to teams of mobile workers. Each task is coupled with a bonus score given to the worker successfully executing it. Tasks' bonus points can be perceived as their priority and an indicator to the associated customer satisfaction. The objective function of MTAP is to optimize the net benefit achieved by the workers; the net benefit is interpreted as the total collected bonus points minus the total travel costs. The main constraint to be respected is the schedule length of each worker, e.g. total travel time plus execution time should not exceed 8 hours for each worker.

To mathematically represent MTAP; the mixed integer program formulated by Vansteenwegen et al. (2009), to model the team orienteering problem (TOP) (Chao et al. 1996), is adopted and customized to reflect the uniqueness of MTAP as following:

$$\max \sum_{d=1}^{m}\left[\sum_{i=1}^{n}\left(\alpha_d S_i y_{id} - \beta_d\left(\sum_{\substack{j=1\\ j\neq i}}^{n} c_{ij}x_{ijd} - c_{l_d i}x_{l_d id}\right)\right)\right]$$

Subject to:

$$\sum_{d=1}^{m} y_{kd} \le 1; \qquad \forall k = 1,\dots,n \qquad (1)$$

$$\sum_{i=1}^{n}\left(T_i y_{id} + \sum_{j=1}^{n} t_{ij}x_{ijd} + t_{l_d i}x_{l_d id}\right) \le T_{\max}; \qquad (2)$$

$$\sum_{i=1}^{n} x_{ikd} = \sum_{j=1}^{n} x_{kjd} = y_{kd}; \quad \forall k \in \{1,\dots,n\} \wedge k \neq ft_d \wedge k \neq lt_d \tag{3}$$

$$x_{ijd}, y_{id} \in \{0,1\}; \quad \forall i, j = 1,\dots,n; \quad \forall d = 1,\dots,m.$$

Where:

α_d, β_d are normative operators for worker d. For simplicity, both factors are set to 1 $\forall d = 1,\dots,m$, i.e. each bonus point collected by worker d equals to the cost of one unit of traveled distance by the same worker, and this for all workers.

$x_{ijd} = 1$ if a visit of task i is followed by a visit to task j in the schedule of worker d, 0 otherwise.

$x_{i_0 i d} = 1$ if task i is the first scheduled task for worker d, 0 otherwise.

$y_{id} = 1$ if task i is visited by worker d, 0 otherwise.

ft_i and lt_i are the first and the last scheduled tasks in worker i's schedule, respectively.

u_{id} is the position of task i in the schedule of worker d. $u_{id} \in \{1,\dots,n\}$

Constraint (1) ensures that each task is visited once at most. Constraint (2) ensures operating within schedules length. Constraint (3) ensures that, apart from the first and last scheduled tasks in schedule d, each visited task has only one arc entering it and exactly one exiting it, this constraint is assumed to prevent routes disruptions.

In order to introduce uncertainty to the MTAP, we model two types of random events happening during the execution phase, i.e. while workers are executing the assigned tasks. These events are: 1) arrival of urgent dynamic tasks and 2) delays during travel, caused by traffic jams, and during tasks execution at the customer's location.

4. RESEARCH METHODOLOGY

As the aim of this research is not to find the best solution for the MTAP using one approach or another, but rather to compare the capabilities of the centralized approach against those exhibited by the market-based with their respective features; MTAP is solved using a simple "greedy" algorithm to represent the centralized approach, and similarly, a basic contract-net protocol (Smith 1980) is implemented to solve MTAP from a market-based perspective.

Solutions obtained by each approach are directly compared during execution. This is where variable rates of uncertainty are introduced. For the centralized approach, a periodic update of the system's global state is done by the central solver to re-adapt workers' schedules in response to uncertainty; however, in the market-based approach, uncertainty is handled in real-time by the concerned agent giving him an active role in the decision making, and according to its own utility may initiate an auction if necessary.

In order to solve MTAP by both approaches and to study their reaction in face of uncertainty; a multi-agent simulator, MTAP-MaSim (Al-Yafi et al. 2009), is implemented and run on randomly generated datasets of MTAP inputs. Uncertainty is randomly introduced according to a discrete event engine incorporated in MTAP-MaSim. Dynamic tasks are injected in the system according to a Poisson distribution with variable arrival rates λ ranging from 60 minutes for least degrees of dynamism to 5 minutes for extremely dynamic environments. Similarly, delays are randomly generated according to a normal distribution function with standard deviations ranging from 10% to 90% for most extreme cases.

5. EXPERIMENT SETTINGS & RESULTS

Datasets containing 150 tasks to be assigned to 25 workers are randomly generated and fed to our simulator to generate the planning phase schedules. Every worker has a schedule horizon of 8 hours and each task is normally-distributed with 20 minutes of mean duration and 5 minutes of deviation. For the centralized approach, the central solver updates are regularly scheduled every 10 minutes to update current schedules.

Each experiment is run on 20 independent datasets for each approach replicating same uncertainties. We judge our experiments on datasets of such dimensions valid to generalize our results for a given studied value of uncertainty.

Figure 1 shows results obtained from experiments conducted to observe the effect of dynamism on the performance of each approach. The superiority of the centralized approach in cases of low dynamism can be accredited to the global knowledge of the system, and the ability to solve MTAP as a batch problem on the central solver's side.

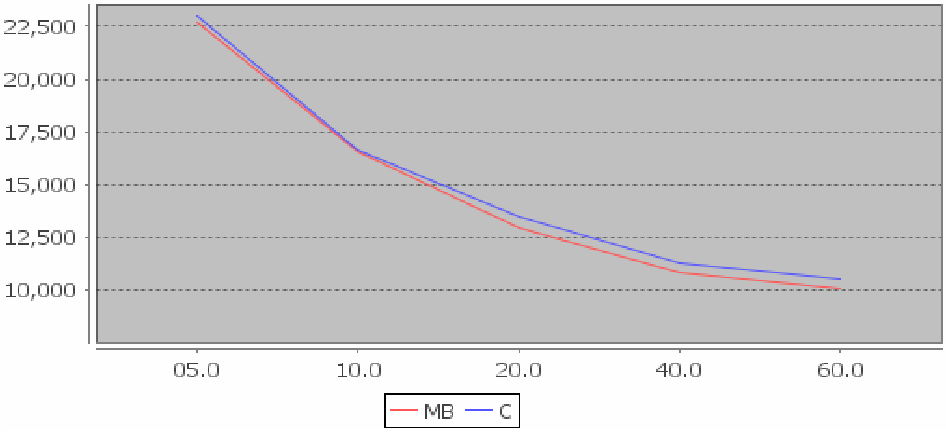

Figure1. Experiment results for the case of dynamic tasks showing the progress of the market-based approach as dynamism increases. (MB: Market-Based, C: Centralized).

The positive effect of high rates of dynamism (10.0 and 5.0) on the performance achieved by the market-based approach, to join the centralised performance, is due to the real-time decision-making done by the agents. In cases of extreme dynamism; instantaneous reactions, even with limited knowledge, worth more than global knowledge used at a later stage, as it is done by the centralized approach.

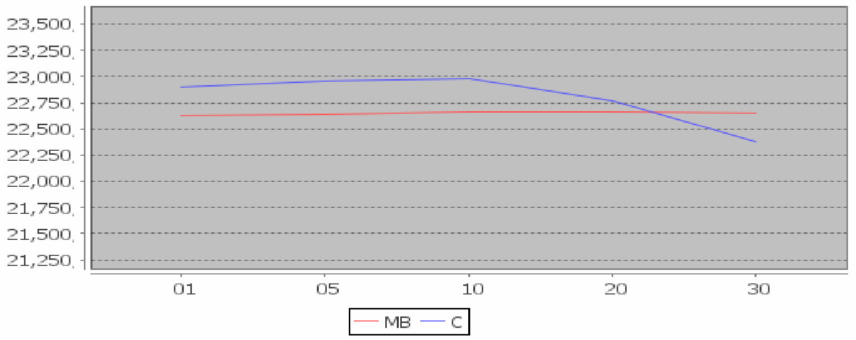

Figure2. Experiment results of varying the central update rate. (MB: Market-Based, C: Centralized).

A confirmatory set of experiments were conducted to affirm the previous explanation. In this experiment, the arrival rate of dynamic task was fixed “very highly dynamic” (i.e. dynamism rate 5.0) and the central update rate was varied from 30 minutes to 1 minute (real-time). Figure 2 shows the deterioration of performance achieved by the centralised approach as the update rate increases. The observed performance is benchmarked with the stable performance achieved by the market-based approach.

The next set of experiments is to observe the effect of travel delays on both approaches' performance. Travel delays were randomly calculated by sampling from a Normal distribution with the mean value equals to the static travel duration, and a standard deviation varied from 0% (no delays) to 100% (extremely dynamic) of the mean value. Figure 3 shows the obtained simulation results. It can be seen that both approaches reacted similarly. This can be explained as follows: even if agents can react in real-time when delays are perceived, no strategy other than waiting is possible when applied; thus, the deterioration in performance is similar for both approaches and the real-time reaction virtue of the market-based approach has no benefit over the centralised approach.

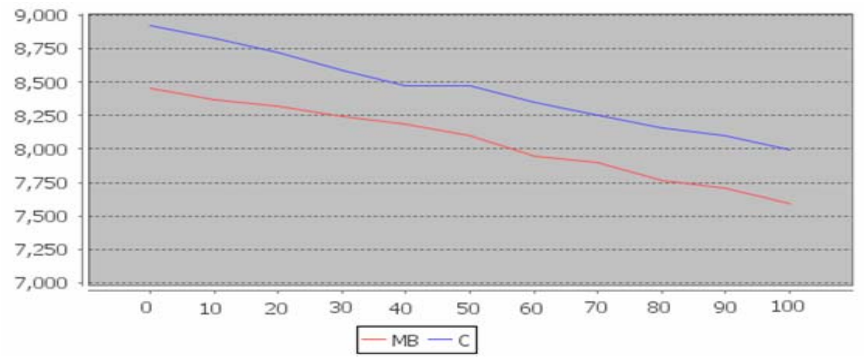

Figure3. Experiment results for the case of travel delays showing the similar pattern of performance deterioration for both approaches. (MB: Market-Based, C: Centralized).

6. DISCUSSION & FUTURE WORK

From the previous results and scenario analyses, the behaviour of each approach was examined to explain the demonstrated outcomes. Given that uncertainty (with its studied dimensions, dynamism and stochasticity) directly affects performance, it is proposed that this direct link is in function of further moderator constructs. These are "Context flexibility", Degree of local knowledge, and problem size. Figure 4 shows a conceptual model attempting to describe these constructs and their relationships.

Context flexibility can be defined as the vulnerability of the actual decision to external uncertainty and the way new decisions are taken according to the changes. In other words, how much of the current solution can be altered due to uncertainty and how the modifications are applied accordingly. Most related problems in the literature are avoiding this feature by adding assumptions that no changes can be done starting from a certain moment or event, e.g. in the traveling repair man problem (Larsen et al. 2002), no changes are allowed on a route if the travel has already started. This relaxation significantly reduces the flexibility and eliminates several real-life situations that may lead to significant different outcomes, especially for problem instances where travels are long and costly.

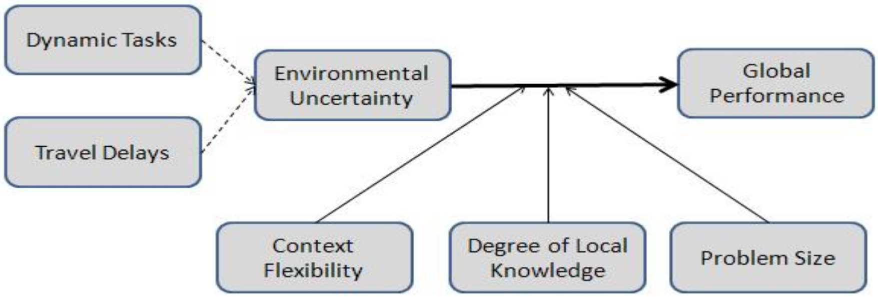

Figure 4. Proposed conceptual model depicting moderator constructs affecting uncertainty effect on performance.

The degree of local knowledge refers to agents' experience in accurately perceive the surrounding environment and ability to take appropriate actions to reduce its negative impact. An example can be workers' ability to forecast travel jams and taking alternative routes. This construct can directly favour the market-based approach since it is highly controlled by agents' experience in both, anticipating uncertainty and taking suitable actions. The higher is agents' experience the better decisions are taken, given that agents act rationally.

Problem size refers to the number of resources to manage along with their particular constraints. Given that most VRP are NP-Hard problems, problem size represents a big hassle for heuristics used by the centralised approach as necessary computation resources and time grow dramatically with problem size. This leads to unfeasibility for a real-time monitoring of agents. Furthermore, considering the availability of global information timely at the central decision making point would be an unrealistic assumption.

Future work is to include the discussed moderator variables in the simulation model and observe their respective effects on the performance achieved by each approach. This is investigated through specific simulation experiments.

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