Abstract

La tesi si propone di sviluppare e implementare *Ant Task Allocation* (*ATA*), un algoritmo basato sul modello di divisione del lavoro osservato in colonie di formiche per risolvere un problema di scheduling. Le prestazioni di *ATA* sono confrontate con quelle di altri algoritmi multi-agente presenti in letteratura.

La tesi sostiene che per diverse classi di istanze del problema e per una determinata funzione obiettivo, l'algoritmo sviluppato ottiene dei risultati migliori rispetto agli altri algoritmi considerati.

Il problema studiato e' un problema di scheduling, non-deterministico, con macchine parallele e parte dell'informazione disponibile solo durante la risoluzione del problema stesso. Un ambiente industriale di verniciatura può essere portato come esempio di questo problema: dei camion escono da una linea di assemblaggio e devono essere assegnati a delle cabine di verniciatura. Le cabine possono avere le stesse caratteristiche oppure differire per la loro velocità di verniciatura. Un loro cambio di colore implica un ritardo temporale ed un costo. Il problema è complicato dal fatto che nessuna informazione sul colore dei camion da verniciare è conosciuta fino a quando questi non escono dalla linea di assemblaggio. L' obiettivo è quello di assegnare i camion alle cabine minimizzando il *makespan*, ovvero il tempo che intercorre dall'inizio della prima attività al completamento dell'ultima attività del sistema.

L'algoritmo proposto, che si basa sul lavoro di Cicirello *et al.* e sul modello a soglie presentato da Bonabeau *et al.* ispirato alla metodologia di suddivisione del lavoro osservata in colonie di insetti, definisce una serie di regole comportamentali delle cabine di verniciatura. Ogni cabina è considerata come un agente autonomo (formica) che richiede e vernicia dei camion (attività da svolgere). Il risultato è un sistema plastico ai cambiamenti dell'ambiente sperimentale dove gli agenti tendono a specializzarsi su un determinato tipo di lavoro in funzione delle loro caratteristiche e del loro stato.

Per sostenere la tesi, le prestazioni del sistema presentato sono state confrontate con quelle di altri algoritmi multi-agente presenti in letteratura tramite una analisi empirica su due classi di istanze del problema: una fabbrica di grosse dimensioni con cabine identiche ed una di medie dimensioni con cabine di differenti caratteristiche. La comparazione avviene tra *ATA*, la soluzione proposta da Cicirello *et al.*, un altro algoritmo insect-based di Campos *et al.*, un algoritmo market-based proposto da Morley ed un algoritmo non adattativo introdotto come punto di riferimento per il confronto delle prestazioni. Particolare attenzione è stata data alle condizioni sperimentali che hanno visto l'utilizzo di un generatore di istanze delle classi del problema, una ricerca dei parametri ottimali usando algoritmi genetici, e un'analisi statistica rigorosa.

Per completezza, l'analisi sperimentale mostra inoltre il contributo che ogni regola introdotta porta alla funzione obiettivo.

Original contributions

I hereby declare that this thesis has not been submitted, either in the same or in different form to this or any other university for a degree. The described research work is based mostly on work carried out by myself in collaboration with Mauro Birattari and Shervin Nouyan. My research was carried out at the *Institut de Recherches Interdisciplinaires et de Développements en Intelligence Artificielle* at the *Université Libre de Bruxelles* under the supervision of Marco Dorigo. The results of all these studies has already been registered as technical report [14]. A part of this work is ready to be submitted to an international scientific journal.

Chapter 1

Introduction

The use of Multi-Agent Systems (MAS) is rapidly increasing in a variety of fields of computer science, engineering and artificial intelligence in the last years. A multi-agent system can be described as a loosely coupled network of agents interacting to collectively solve problems which are beyond the capabilities of each individual agent [12]. Agents are autonomous systems capable of adapting to changing environments and able to exhibit goal-directed behaviors [31].

Systems that reflect the previous definitions are for example insect colonies. Social insect colonies use intelligent and distributed methods to collectively solve complex problems. Cooperation among individual insects is largely self-organized and does not require any supervision. The collective behavior that emerges from a group of social insects is referred to as *swarm intelligence*. The research area that deals with applying swarm intelligence to various problems has come under increasing attention in the research community in the last years [10]. One of the early studies of swarm intelligence investigated the foraging behavior of ants. Ants lay trails of pheromone, a chemical substance that attracts other ants. Deneubourg *et al.* [9] showed that this process of laying a pheromone trail that others can follow, is a good strategy for finding the shortest path between a nest and a food source. In experiments with an Argentine ant species, Deneubourg *et al.* constructed a bridge with two branches, one twice as long as the other, separating the nest from a food source. Within few minutes the ants mostly selected the shorter branch. Based on the idea of pheromone laying and following, Dorigo *et al.* [11] developed a way to solve the well known and NP-hard[1] Traveling Salesman Problem (TSP). The TSP is the problem of finding the shortest route that goes through a given number of cities exactly once. The algorithm, implemented by Dorigo *et al.* has obtained near optimal solutions.

In this thesis our interest is in using multi-agent algorithms to solve the Dynamic Task Allocation (*DTA*) problem. The *DTA* problem is an online, non-deterministic scheduling problem, that is, a decision-making process for assigning

[1]For a definition of the concept of NP-Hardness and NP-Completeness we refer the reader to [13].

tasks to agents working in parallel. Each task belongs to a particular type and if a working agent changes the type of task it performs, a setup is required and a given cost is incurred. In the *DTA* problem different agents can have different processing times for different task types. If this is the case, the *DTA* problem is said heterogeneous; otherwise, if all the agents are identical, the problem is said homogeneous (DTA_{Hom}). The objective for this problem is to minimize the makespan, that is, the time until all tasks in the system have been processed.

Different work has been done using multi-agent algorithms on the homogeneous case of the problem. Most of the proposed algorithms use paradigms based on the *specialization* concept, where agents tend to specialize for one type of task, to avoid unnecessary reconfiguration and in this way increase the efficiency of the system. Morley [18] is the first one that solved a painting problem similar to the homogeneous case of the *DTA* problem. His algorithm was adopted in the GM facility and was found that his system performs 10% better than the previously used centralized scheduler. Later, Campos *et al.* [6] proposed to solve the same problem with an insect-based approach. Subsequently, Cicirello *et al.* [7] proposed another insect-based algorithm introducing concepts not considered by Campos *et al.*

In this thesis, we present *Ant Task Allocation* (*ATA*), an algorithm for the homogeneous case of the problem based on the work of Cicirello *et al.* The algorithm of Cicirello *et al.*, especially for problems in which demands change dynamically, often takes much time to re-adapt or does not succeed to re-adapt at all. In order to overcome this problem we propose some modifications and additional rules to speed up the adaptation process.

Applying these algorithms to the heterogeneous case of the *DTA* problem, we found that they perform poorly because the agents do not consider their process speed to perform a task. Therefore, we propose a *Different Process Speed* (*DPS*) rule applicable to all the considered insect-based algorithms. This rule is inspired by division of labor as observed in different castes of *Pheidole* ants.

We compare all presented algorithms on the *DTA* problem. Additionally, we introduce a non-adaptive algorithm in the experimental analysis in order to have a performance reference. The comparison considers two possible real-world situations: a big painting factory with identical agents and a medium dimension factory with two heterogeneous subsets of agents. Particular attention has been payed to the experimental conditions; in fact, we have used two instance generators in order to obtain the two classes of instances of the problem and we have done a rigorous parameters tuning for each used algorithm. Furthermore, a statistical analysis has been done to study the data obtained. We will show that our algorithm achieves the best results for both the considered class of homogeneous and heterogeneous problems. Moreover, we will show that all adaptive algorithms in all situations achieve better results than the non-adaptive algorithm. Again, Campos' *et al.* algorithm does not obtain good results in both the experiments but we are grateful to him because his work has the merit of having introduced the insect-based approach to solve this problem. Moreover, the performance of the insect-based algorithms are ranked according to the time they was made. In fact the algorithm of Campos' *et al.* does not obtains good results, the algorithm of Cicirello *et al.* gives a significant improvement to the performance obtained by Campos' *et al.* as they show in paper [7] and our algorithm improves again the results of the solution of Cicirello *et al.*

Another set of experiments deals with the analysis of the proposed rules. First of all we show that *ATA* with all the introduced rules performs better than the original algorithm of Cicirello *et al.* Moreover, we observe that one of the proposed rules gives a large contribution to reduction in the makespan, two others a significant contribution to it and the last one does not give any apparent contribution to the results. Finally, we show that the *DPS* rule improves the performances of all the insect-based algorithms on the heterogeneous case of the *DTA* problem.

In Chapter 2 we give a formal description of the *DTA* problem and use the metaphor of a painting facility to describe it in a simple way. Chapter 3 presents the related work for the homogeneous case of the *DTA* problem. We present two approaches: the market-based approach with the algorithm of Morley and the insect-based approach with the algorithms of Campos *et al.* and Cicirello *et al.*. Afterwards, Chapter 4 introduces *ATA*, our algorithm for the DTA_{Hom} problem. In Chapter 5 we describe the *DPS* rule which is applicable to the insect-based algorithms in the heterogeneous case of the problem. Chapter 6 details the experimental setup and the instance generators. Furthermore, a summary of the algorithms and of the parameter is given. In the second part of this chapter, we analyze the obtained results. Finally, we conclude in Chapter 7.