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Modelling Team Coordination in Multi-agent Planning

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Outline

- team management and decision making
- multi-agent planning framework
- team coordination and uncertainty modelling
- case study: mine-field clearing and resource management
- computational experiments

Project MP020

- team composition and management
  - how to improve the performance of team/task/mission?
    - design the internal structure within a team so that its behaviour is reliable under uncertainty
    - assess the contribution of individual member within a team to achieve goals
  - how can a plan be adapted to unexpected events?
    - develop an adaptive team planning
    - analyse real time decision making for team coordination in which different team members or teams are pursuing in favour or conflicting goals cooperatively
  - how to incorporate uncertainty in team management?

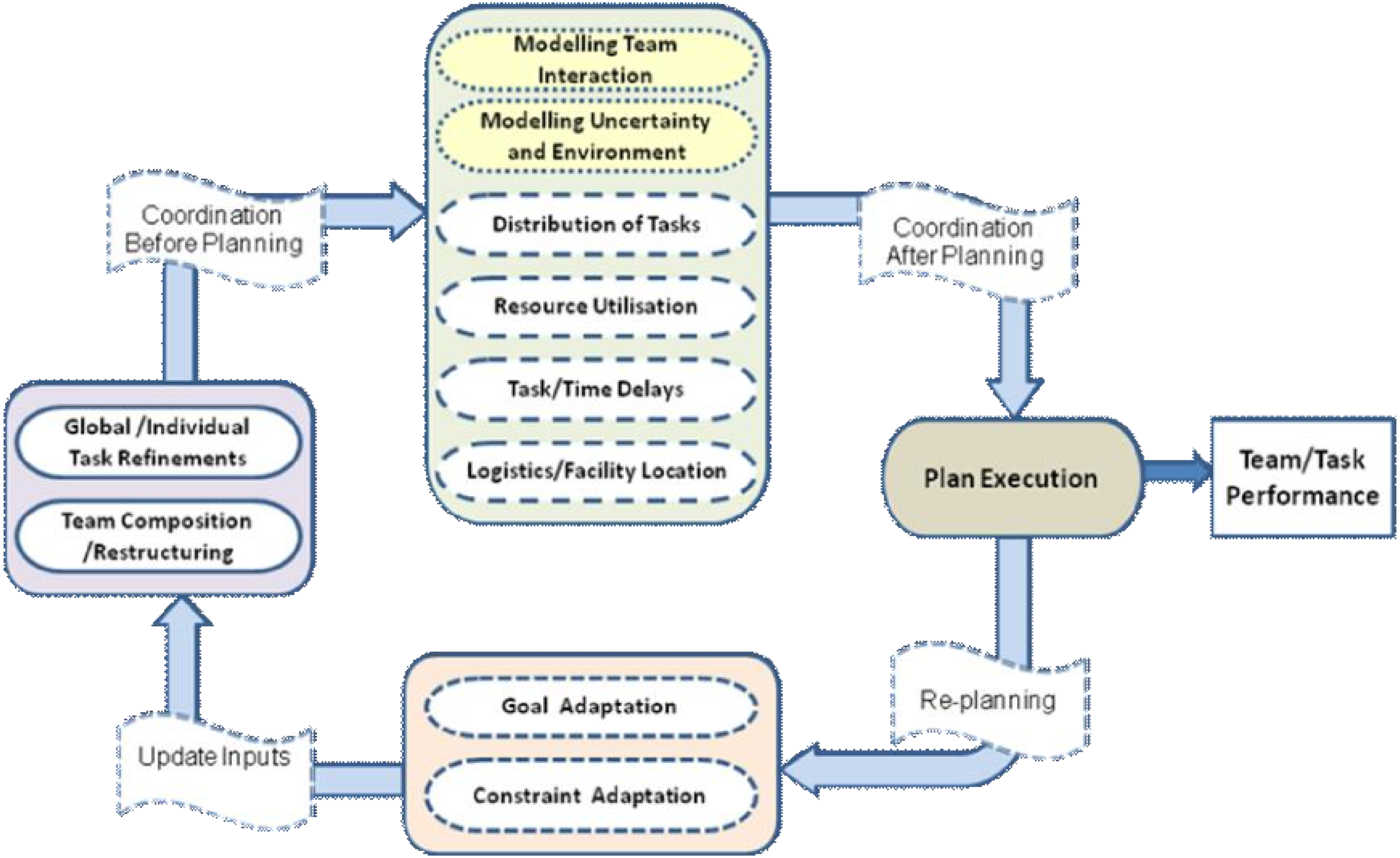
Project MP020

- multi-agent decision making under uncertainty
  - develop generic approaches for adaptive mission planning
  - consist of
    - team composition
    - mission planning
    - goal/task/target assignment
    - resource allocation
    - facility location and logistic planning
    - trajectory optimization and so on…
- computationally intractable for real-time dynamic (re-)planning
  - logic based restrictions, uncertainty, nonlinearity, NP-hard

Multi-agent planning framework

- integrates team composition and coordination
  - managing autonomous teams and their attribution to reach pre-specified or updated task/team based goals
- involves planning/re-planning with goal and constraint adaptation
  - to provide adaptation of the pre-computed plan in response to changes.
  - the goals and constraints defining the system of teams might need to be modified at any stage, even though, the global objective and constraints may remain the same
- defines dynamic rule-based feasible/optimal planning strategies for autonomous vehicles as real-world operations planners

Multi-agent planning framework

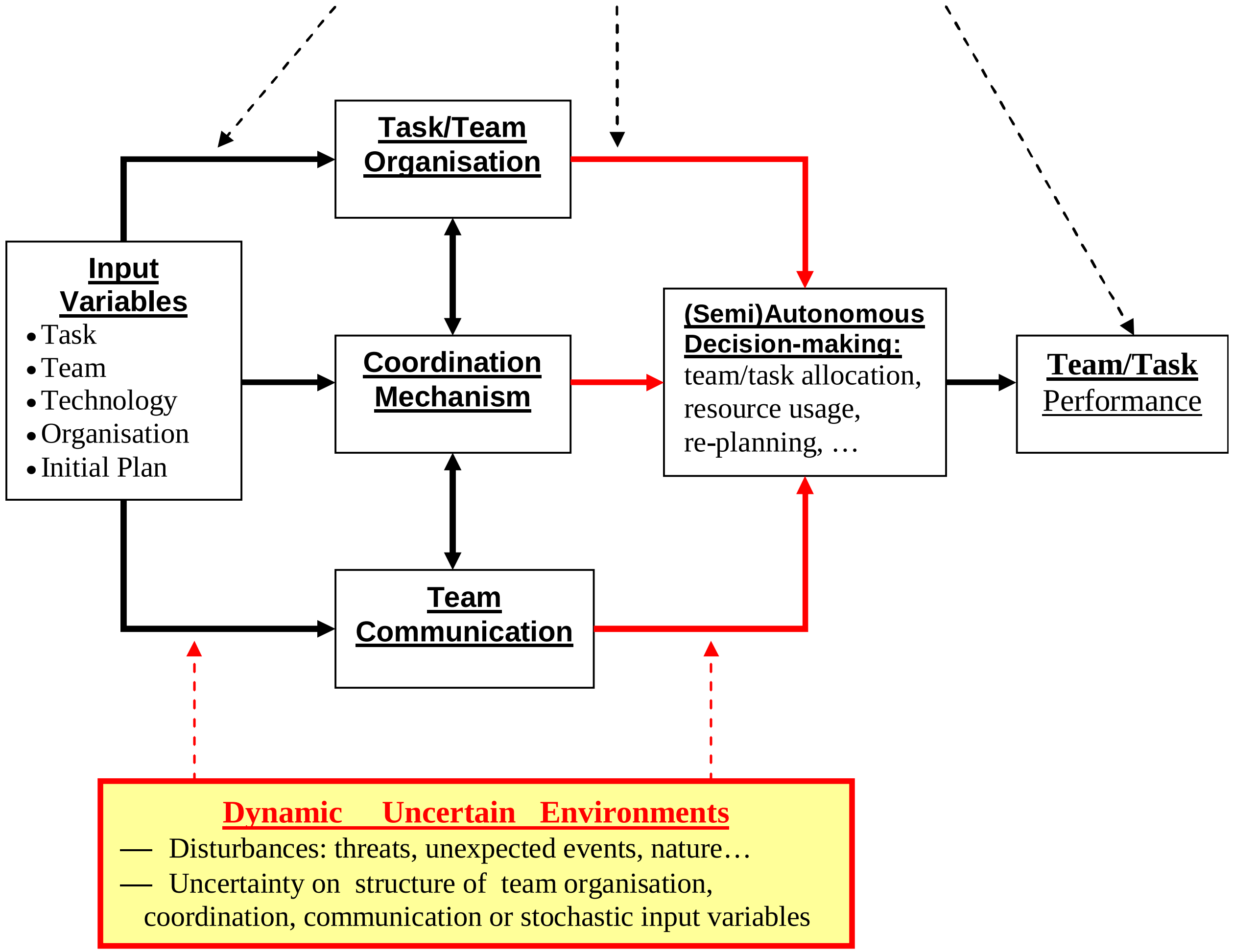


Uncertainty modelling

- Mission planning:
  - dynamic and uncertain environment
  - battle situation, weather conditions, threads, unexpected events...
- Team structure:
  - centralised or decentralised decision making under uncertainty
- Team coordination and communication :
  - lack of coordination
  - lack of information (global and local) or some error involves
  - lack of communication among team members or with commander
- Stochastic parameter uncertainty:
  - amount of resource at each type
  - probability of success

- No data available - Expert knowledge required

Performance Monitoring and Feedback Process



Coordination in a team

- goal coordination
  - prioritization of different objectives
  - multi-objective programming, goal programming etc.
- task coordination
  - assignment of tasks to agents in real time
- resource coordination
  - allocation of resources to agents
- team coordination
  - managing team members or teams

Mine-field clearing problem (IF041)

- how to manage a team of agents in dynamic and stochastic environment so that
  - required areas are searched safely, quickly and effectively,
  - unexpected and rapidly escalating situations are dealt by the team in a collaborative pattern to achieve their goals.
- effectiveness of an agent in this operation can be measured by
  - mines successfully cleared,
  - degree of control,
  - the distance travelled,
  - successfully completion of search under restrictions of time and fuel.

Mine-field clearing model

Mixed Integer Programming to maximize the number of locations analyzed.

Decision Variables: analyze or move to a new location

$$\max \sum_{t=1} \sum_{k=1} \sum_{i=1} \sum_{j=1} A_{k,i,j}(t)$$

$$L_{k,i,j}(t+1) \le \left(L_{k,i-1,j}(t) + L_{k,i+1,j}(t) + L_{k,i,j-1}(t) + L_{k,i,j+1}(t)\right).g_k(t) + L_{k,i,j}(t)$$

$$\sum_{i=1} \sum_{j=1} L_{k,i,j}(t) = 1$$

$$A_{k,i,j}(t) \le \left(L_{k,i-1,j}(t) + L_{k,i+1,j}(t) + L_{k,i,j-1}(t) + L_{k,i,j+1}(t)\right).g_k(t)$$

$$L_{k,i,j}(t) \le 1 - \sum_{p=1} \sum_{s=1}^{t-1} A_{p,i,j}(s).W_{i,j}.z_{p,i,j}(s)$$

$$A_{k,i,j}(t) \le 1 - \sum_{p=1} \sum_{s=1}^{t-1} A_{p,i,j}(s)$$

$$L_{k,i,j}(t) \le \sum_{p=1} \sum_{s=1}^{t-1} A_{p,i,j}(s)$$

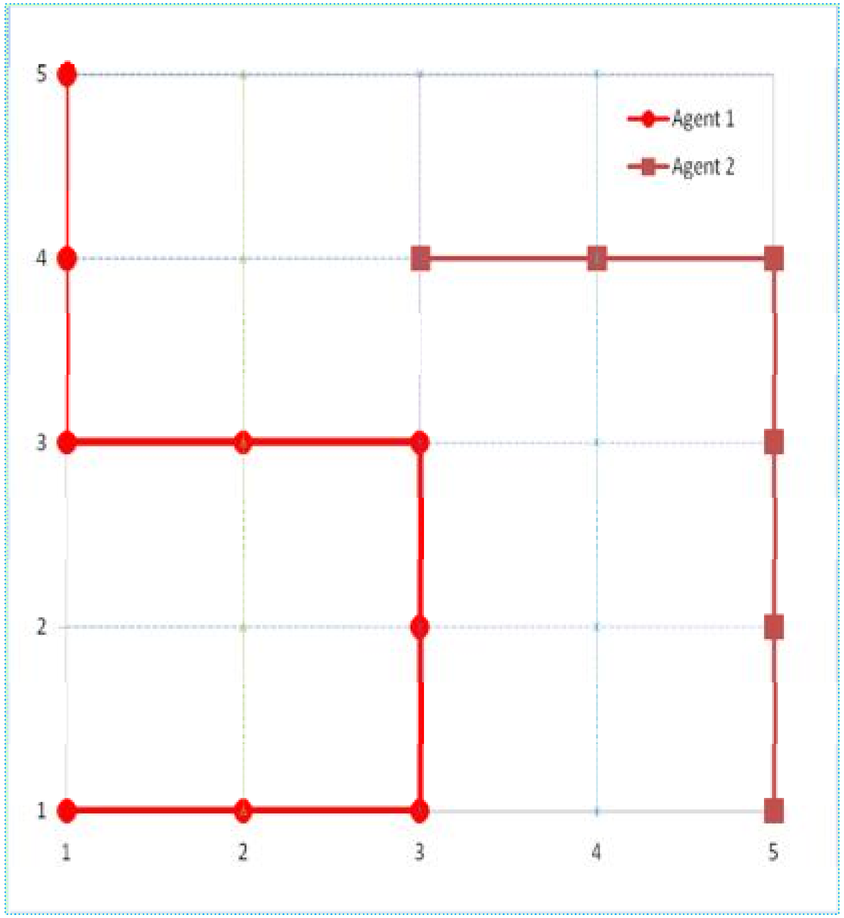
$$\sum_{i=1} \sum_{j=1} A_{k,i,j}(t) \le 1$$

$$\sum_{t=1} \sum_{k=1} \sum_{i=1} \sum_{j=1} A_{k,i,j}(t) \ge \underline{a}$$

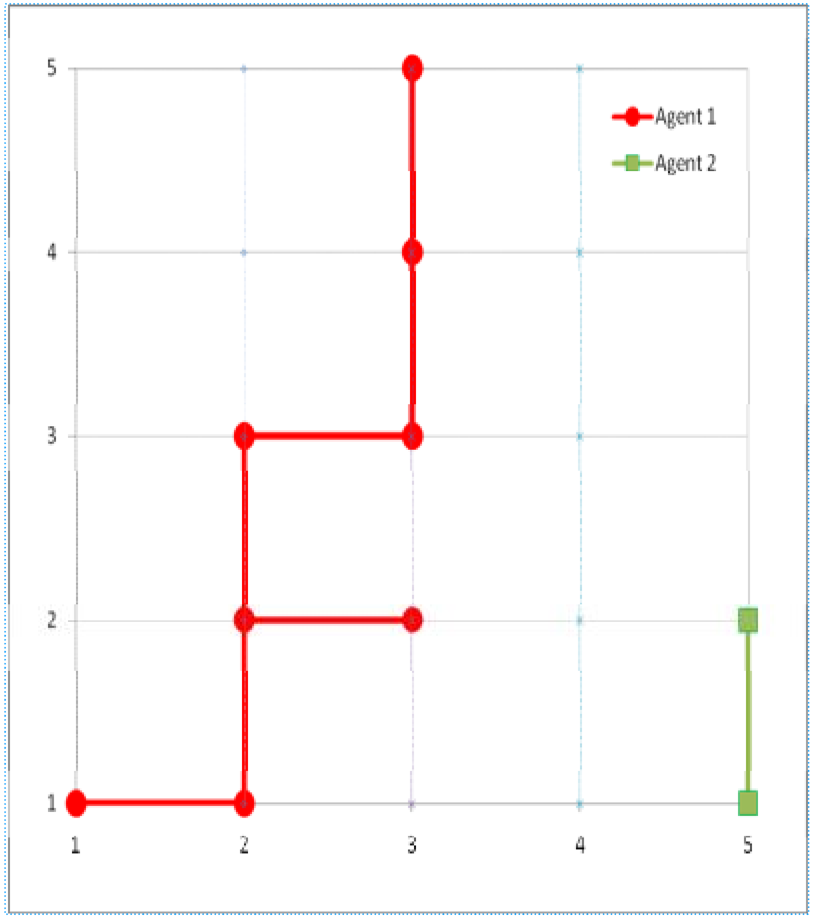
* SEAS/DTC annual conference Proceedings 2008

Mine-field clearing problem

Initial Optimal Location Plan



Actual Optimal Location Plan



Planning to optimality and feasibility

- Compute the optimal solution, from a centralized perspective, given the available information.
  - optimal team members' plan is not necessarily optimal for the team
  - individual goal and constraints might need to be adapted during the mission
  - optimal solution is not always required for team
- Feasible plan can be obtained by solving the constraint satisfaction problem
  - easier to obtain than optimal solutions

Problem statement

- Given assumptions of
  - different tasks require different types of resources
  - different teams can only accomplish certain tasks
  - each agent has varies capabilities for accomplishing different tasks
- how to assign different to tasks and different types of resources to teams so that the mission is accomplished with
  - minimum cost and loss with certain resource requirements or
  - minimum resource usage is achieved
  - maximize efficiency: maximize mission success => improve team (task) performance
- probability of team or task success:
  - success probability of each agent to accomplish any task depends on the amount of resources required - a continuous function of resources used.

$$s_{ij} = 1 - \frac{1}{1 + \sum_{k=1}^{K} w_{ijk} r_{ijk}}, \qquad \forall i \in A, j \in T$$

Notation

Consider a heterogonous team of multi-agents ;

$$\text{Agents (teams)}: \quad i = 1, \ldots, M$$

$$\text{Tasks}: \quad j = 1, \ldots, N$$

$$\text{Resource types}: \quad k = 1, \ldots, K$$

Decision Variables

$$x_{ij} = \begin{cases} 1, & \text{if task } j \text{ is assigned to agent } i \\ 0, & \text{otherwise} \end{cases}$$

r_{ijk} amount of resource type *k* required by agent *i* to accomplish task *j*

s_{ij} probability of success of team member *i* to accomplish task *j*

Model constraints

Overall team performanc e $\frac{1}{N}\sum_{i=1}^{M}\sum_{j=1}^{N}(s_{ij}x_{ij})a_j$

Eack task assigned to an agent $\sum_{i=1}^{M} x_{ij} \leq 1$

Each agent assigned to a task $\sum_{j=1}^{N} x_{ij} \leq 1$

Total resources available at each type $\sum_{i=1}^{M}\sum_{j=1}^{N} r_{ijk} \leq R_k$

Task not assigned to agent => zero success $s_{ij} - x_{ij} \leq 0,$

Different models considered

Deterministic:

$$\max \sum_{i=1}^{M}\sum_{j=1}^{N}(s_{ij}x_{ij})a_j$$

Stochastic:

$$\max \mathrm{E}\left[\sum_{i=1}^{M}\sum_{j=1}^{N}(s_{ij}x_{ij})a_j\right] = \sum_{e=1}^{S} p_e \sum_{i=1}^{M}\sum_{j=1}^{N}(s_{ij}^{e}x_{ij})a_j$$

Worst-case:

$$\max_{x,r}\ \min_{e}\ \sum_{i=1}^{M}\sum_{j=1}^{N}(s_{ij}^{e}x_{ij})a_j$$

$$\textit{where: } s_{ij}^{\mathrm{e}} = 1 - \frac{1}{1+\sum_{k=1}^{K} w_{ijk}^{e} r_{ijk}}, \qquad \forall i \in A, j \in T, e \in S$$

Robust-optimisation:

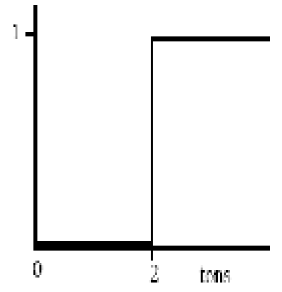
$$\max_{x,r}\ \min_{\tilde{s}_{ij}\in U}\ \sum_{i=1}^{M}\sum_{j=1}^{N}(\tilde{s}_{ij}x_{ij})a_j$$

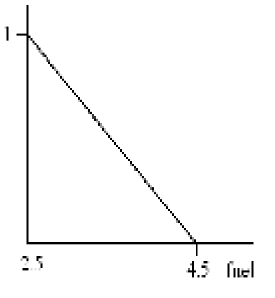
Consequences of actions*

Plan of Agent 1: P1 Chronicle	Duration	Fuel	Equipment	U(chronicle)	Probability
C1	[90 – 135]	[2.5 – 4]	[1.6 – 1.8]	[0.005 – 0.02]	[0.56– 1]
C2	[120 – 135]	[3.5 – 4]	2	[0.38 – 0.572]	[0 – 0.3]
C3	[120 – 150]	[2.5 – 3.5]	[1.6 – 1.8]	[0.01 – 0.020]	[0 – 0.2]
C4	150	3.5	2	0.1975	[0 – 0.06]

Plan of Agent 2: P2 Chronicle	Duration	Fuel	Equipment	U(chronicle)	Probability
C1	[85 – 130]	[2.5 – 4]	2	[0.44 – 1.02]	[0.64– 0.8]
C2	[100 – 145]	[2.5 – 4]	2	[0.25 – 0.83]	[0.16 – 0.2]
C3	[115 – 145]	[2.5 – 3.5]	2	[0.25 – 0.63]	[0 – 0.16]
C4	[130 – 160]	[2.5 – 3.5]	2	[0.06 – 0.44]	[0 – 0.04]

Specifications of delivery utility functions





* Utility Models for Goal-Directed Decision-Theoretic Planners,1993, P. Haddawy, S. Hanks, Computational Intelligence.

Computational experiments

- 8 different teams
- 5 different tasks
- 10 different types of resources
- Available resources

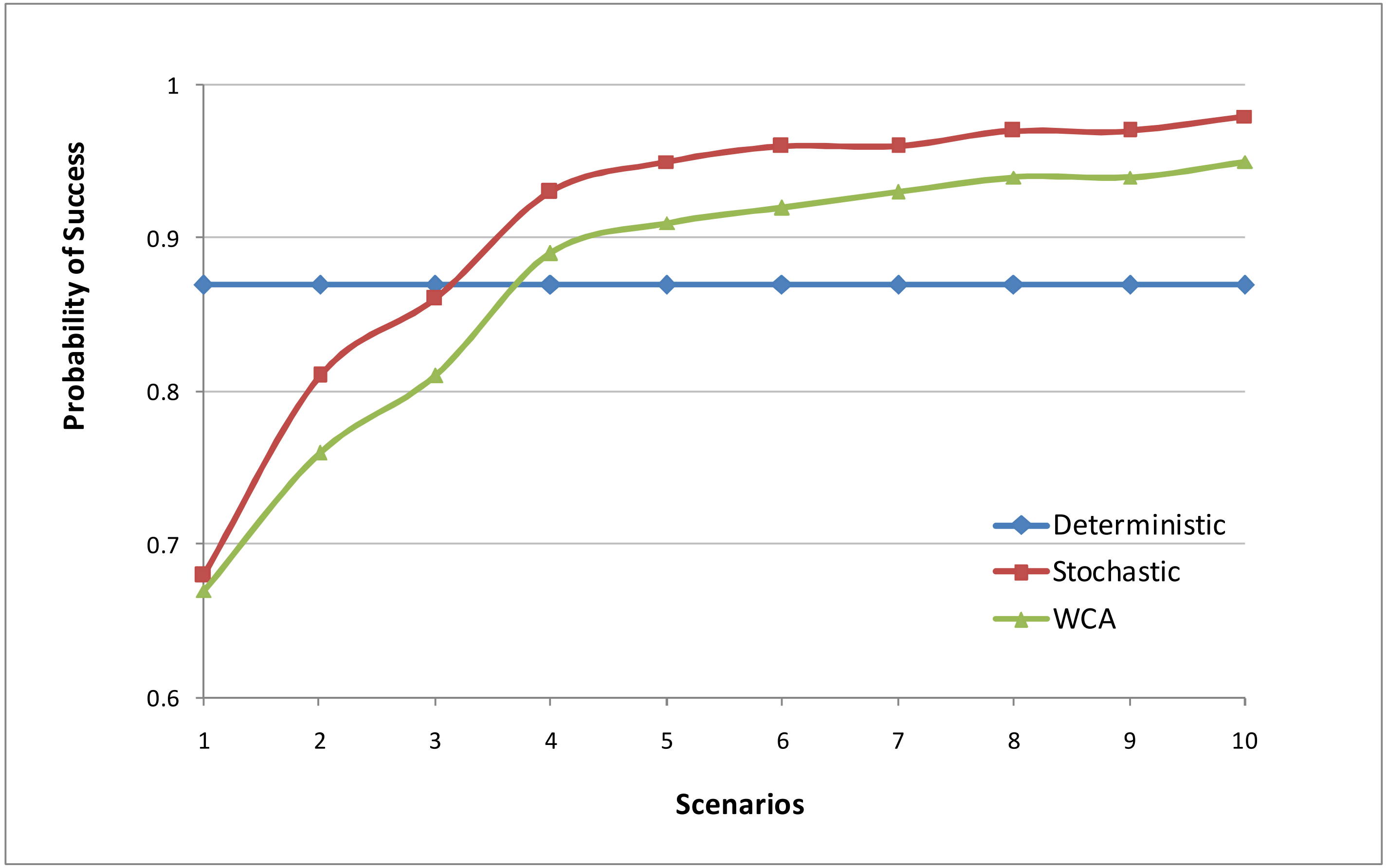
Type	Total Resources
k1	10
k2	8
k3	8
k4	4
k5	4
k6	4
k7	1
k8	1
k9	1
k10	1

- We compare the results under three different analysis:
  - Deterministic
  - Stochastic
  - Worst-case

Scenarios for the probability of success

- no data is available
- expert knowledge required
- different 10 rival scenarios for the efficiency with which the teams transform a resource into success
- each scenario has probability of 10%
- for each scenario
  - the efficiency is affected by a factor of w such that
  - w = [0.1 .... 2.0]

Probability of success per scenario



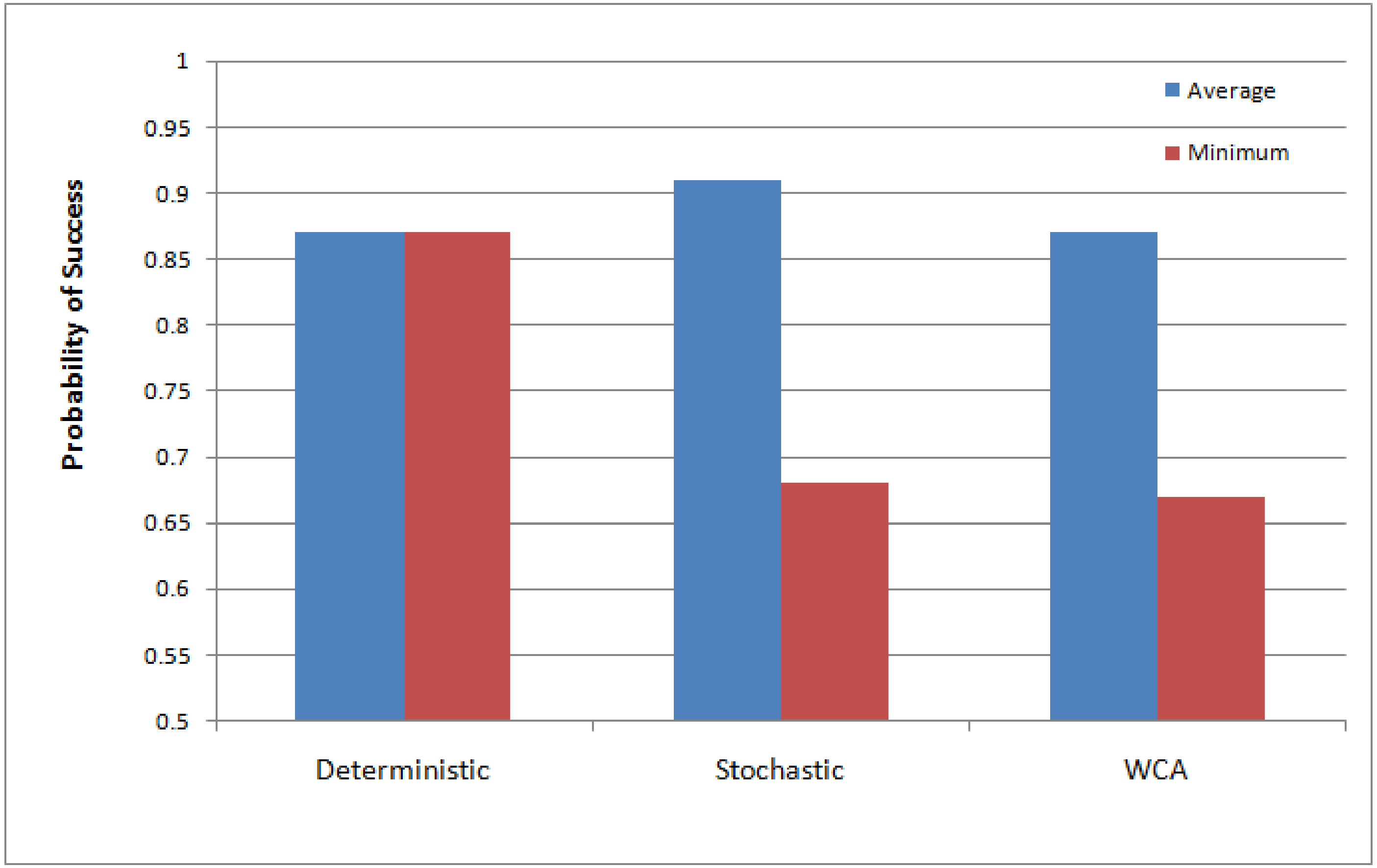
WC analysis gives lower bound to the overall success probability at each scenario

Teams assigned and resources allocated per task

Deterministic			Stochastic			Worst-case Analysis		
Team	Task	Resource	Team	Task	Resource	Team	Task	Resource
6	1	k1,k2	6	1	k1,k2	7	1	k1
5	2	k5,k6,k7	1	2	k4,k5,k6	3	2	k3,k4,k5
8	3	k3,k4	2	3	k8,k9,k10	8	3	k2
1	4	k8,k9	8	4	k2,k3	5	4	k6,k7,k8,k9
2	5	k10	7	5	k4,k5,k6,k7,k8	2	5	k10

- each task is accomplished by different team using different types and amount of resources
- each approach follows different strategies

Team performance: probability of success



Upper bound is provided by expected value and lower bound is provided by WCA.

Future work

- multi-agent planning framework
  - implement the integrated multi-agent planning framework using constraint programming and/or optimisation based approaches
  - utility theory for describing performance metrics as consequences of agents' actions and plans
  - collaborative/cooperative games theory for modeling interaction within a team
  - Markov decision process for modeling agent-environment interaction
- team modelling and management
  - applying methodologies for homogeneous teams to a general mission planning with heterogeneous teams with different internal structure
  - performance modelling of team members within a team