**PhD thesis proposal**
**Ecole Doctorale : Mathématiques, Informatique et Télécommunications de Toulouse**

**Institute:** Institut de recherche en informatique de Toulouse (IRIT, www.irit.fr)
**Group:** Argumentation, Decision, Raisonnement, Incertitude et Apprentissage (ADRIA, www.irit.fr/ADRIA) and Logic, Interaction, Language and Computation (LILaC, www.irit.fr/LILaC)
**Supervisors:** Andreas Herzig, Frédéric Maris
**Contact:** herzig@irit.fr, maris@irit.fr
**Title:** Multiagent temporal epistemic planning

**Description:**
The aim of the thesis is to model and solve complex real-world planning problems in which many (human or automatic) agents interact cooperatively and robustly via physical communication and sensing actions in order to attain common goals in a partially-unpredictable environment. Important aspects of the resulting plan is that it should take into account the beliefs of each agent which can change over time, that it should allow the simultaneous execution of actions, that it should be sufficiently flexible to allow individual agents to make certain choices themselves, and that it should be robust to the failure of certain actions or changes in the environment. In contrast, in classical planning it is supposed that the initial state is completely known, that actions are instantaneous and deterministic and that there are no other agents interfering with the planning agents. On the one hand, one would like to go beyond these restrictive assumptions in order to obtain the required level of expressive power, but on the other hand one would also like to have efficient algorithms solving real-world problems.
We aim at an extended theoretical framework incorporating the following aspects:

- **Multi-agent:** most of the above applications require the intervention of and cooperation between several agents (each agent being either artificial or human).
- **Temporal:** to take into account the durative (non-instantaneous) nature of certain actions, conditions and goals, as well as the fact that actions may overlap temporally (which is essential for the correct modelling of problems requiring concurrency of actions).
- **Epistemic:** in order to model the beliefs of each agent (the epistemic aspect, including higher-order beliefs) as well as the physical state of the world (the ontic aspect), allowing the dynamic and interactive discovery of knowledge via sensing and communication actions with epistemic conditions and effects.
- **Contingent:** to allow the construction of plans which are robust to the fact that agents may have incomplete knowledge of the initial state, that beliefs may be inconsistent with the current world state (due to exogenous or unobserved events) and that the results of certain actions may be unpredictable.
- **Flexible plans:** so that, if possible, each agent (or group of agents) has a certain degree of autonomy concerning, for example, the choice of start and end times of actions or even the actions used to achieve a subgoal, subject to constraints guaranteeing the correctness of the plan. This is important to avoid imposing arbitrary and centrally-decided choices on human agents.

Certain limited combinations of these five aspects have previously been studied. Some authors of the dynamic epistemic logic community have started to investigate multi-agent epistemic planning [1]. We have studied temporal planning combined with a certain degree of flexibility and have built a temporal planner which has participated in the International Planning Competition [8]. In earlier work we provided a first approach to planning under incomplete information [7]. In recent work, it has been shown how multi-agent epistemic contingent planning can be transformed into classical planning without increasing the PSPACE complexity of planning [4,5,6]. These promising first results indicate that it may be possible to re-use the large body of existing work on classical planning, but no study has combined all five aspects cited above, and very few actual implementations are available even for limited combinations of these five aspects.

**Objectives –** We propose the following concrete objectives:

1. A new **language and semantics** for expressing planning problems to allow modelling the following five aspects of planning: multi-agent, temporal, epistemic, contingent and flexible plans. The aim is to propose a standardised language which could be used by the whole community. Theoretical

questions which will be addressed at this stage include the expressive power of the language, the decidability of planning in this language, the possibility of automatically avoiding temporally cyclic problems [3] (which cannot be solved by certain planning algorithms). Practical considerations include its simplicity of use and conformity with existing languages such as PDDL and compatibility with dynamic epistemic logics.

2. Original **algorithms** and/or transformations to simpler versions of planning which have already been widely studied. This may involve the choice of encodings into well-studied problems for which efficient solvers already exist, such as SAT, CSP or SMT, as well as the redefinition of important notions in classical planning such as landmark actions. This objective will be tackled in different stages of increasing difficulty, leading to the following milestones:
    a. Algorithms and software for multi-agent temporal epistemic planning;
    b. Addition of the flexible plans aspect to these algorithms and software;
    c. Addition of the contingent aspect to these algorithms and software.
3. New **benchmark problems** for multi-agent temporal epistemic contingent flexible planning. These will firstly be used to test our own planners and will then be proposed to the research community via the International Planning Competition.
4. The **complexity analysis** of the different subproblems engendered by combinations of the above five aspects. We will look for tractable fragments. From a practical point of view, such fragments can lead to the discovery of polynomial-time relaxations of computationally hard problems which can be a valuable source of information to heuristics [2].

**Methodology –** We will begin by assuming that planning is performed off-line by a central planner and that all agents cooperate to achieve common goals. At each stage, limiting computational complexity will be a priority. We believe that this is vital given the undecidability of dynamic epistemic logic-based planning in the general case [1]. Methodologically, certain of the objectives 1-4, above, will necessarily be tackled in parallel. Of course, the interaction between the different aspects which we aim to combine in a single planner may lead to interesting new theoretical questions and practical challenges which are worthy of study but which are impossible to predict before embarking on this research.
The work on the PhD project should also benefit from interactions within the MAFTEC working group of the GDR IA (https://www.irit.fr/~Frederic.Maris/maftec) whose focus is on multi-agent, flexible, temporal epistemic and contingent planning.

**References**


**[1]** **G. Aucher, T. Bolander, (2013).** "Undecidability in Epistemic Planning", in *Proceedings of the 23rd International Joint Conference on Artificial Intelligence (IJCAI-2013)*, Beijing, China, August 2013.

**[2]** **M.C. Cooper, F. Maris, P. Régnier, (2014).** "Monotone Temporal Planning: Tractability, Extensions and Applications", *Journal of Artificial Intelligence Research (50)*, June 2014.

**[3]** **M.C. Cooper, F. Maris, P. Régnier, (2013).** "Managing Temporal Cycles in Planning Problems Requiring Concurrency", *Computational Intelligence (29-1)*, pp 111-128, February 2013.

**[4]** **M.C. Cooper, A. Herzig, F. Maffre, F. Maris, P. Régnier, (2016).** "A Simple Account of Multi-Agent Epistemic Planning", in *Proceedings of 22nd European Conference on Artificial Intelligence (ECAI-2016)*, August 2016, The Hague, pp. 193-201.

**[5]** **M.C. Cooper, A. Herzig, F. Maffre, F. Maris, P. Régnier, (2016).** "Simple Epistemic Planning: Generalised Gossiping", in *Proceedings of 22nd European Conference on Artificial Intelligence (ECAI-2016)*, August 2016, The Hague, pp. 1563-1564.

**[6]** **H. Geffner, (2014).** "Non-classical Planning with a Classical Planner: The Power of Transformations", *JELIA 2014*, pp. 33-47, September 2014.

**[7]** **A. Herzig, J. Lang, P Marquis, (2003).** "Action representation and partially observable planning using epistemic logic", in *Proceedings of the 18th International Joint Conference on Artificial Intelligence (IJCAI-2003)*, August 2003, Acapulco, Mexico.

**[8]** **F. Maris, P. Régnier, (2008).** "TLP-GP: New Results on Temporally-Expressive Planning Benchmarks", in *Proceedings of 20th IEEE International Conference on Tools with Artificial Intelligence (ICTAI-2008)*, vol. 1, pp 507-514, Dayton OH, USA, November 2008.