Streszczenie rozszerzone-ang.

1 What Is the Thesis About?

This thesis is aimed at the discussing of *temporal planning with fuzzy constraints and preferences.* Planning constitutes one of the form of rational behavior and reasoning – in particular. Intuitively, we often refer *planning* to a deliberation process that chooses and organizes *actions* in order to achieve goals that are desired or required. Actions are executed in a given *domain.* Making actions often modifies initial domains. For example, an action 'move' may change a robot/satellite position.

A natural extension of (classical) planning is *temporal planning.* Informally speaking, temporal planning may be viewed as classical planning involved in 'timing'. 'Timing' can be understood in many ways: as a duration of action performing or as temporal constraints imposed on the action materialization. *Temporal planning* is aimed at different issues. The most typical are the following ones:

- time optimization of action execution,
- types of temporal constraints that may be imposed on action execution,
- representation of temporal constraints,
- construction of plans which respects temporal constraints that are required.

In general, temporal constraints are divided into two classes: *the qualitative and quantitative temporal constraints.*

In order to reinforce reality of investigations, temporal planning is often considered together with a new component called 'preferences'. They introduce some piece of rationality to temporal planning. Preferences may be imposed on action execution, task performing or on a choice of different components such as: situations, solutions, etc. Unfortunately, temporal planning sometimes forms an acting under uncertainty. The notion of 'uncertainty' may refer to different situations in temporal planning. It may mean that our preferences were set imprecisely or that temporal constrains – imposed on action performing – is not rigid. All these situations constitute a subject of *temporal planning with fuzzy constrains and preferences.*

2 Motivation

Nowdays, there exist at least three different approaches to planning in Artificial Intelligence and in close-related branches of computer science. One of them is a planning paradigm "planning as satisfiability of formulas'. The main alternative approach to planning via graph search was introduced and broadly developed and recently supported by some techniques of the graph-plan analysis from. There is also a couple of typical problems - naturally associated to planning. One of such problem is an old Hamiltonian optimization problem – commonly known as the *Traveling Salesman Problem* (TSP) - solved by M.M. Flood in and developed by Menger and I. Heller. This problem may be briefly characterized as follows: Given a list of cities and the distances between each pair of cities, what is the shortest possible route that visits each city exactly once and returns to the origin city?

An alternative problem – associated to planning (and scheduling) is the so-called *Multi-Agent Problem* (MAP). This problem – or even better – a class of similar problems may be represented by the so-called *Nurse Rostering Problem* – specified as follows: having a set of actions and agents find a schedule that satisfies all constraints imposed on these actions.

Meanwhile, a taxonomy of temporal constraints (such as these in TSP or MAP) is heterogeneous. In fact, as mentioned, they are usually divided into two groups: the *qualitative* and the *quantitative* ones. The quantitative ones are usually rendered in terms of *Temporal Constraints Satisfaction Problem* and *Simple Temporal Problem* – as its specification when numeric constraints are restricted to a single interval.

Unfortunately, these planning problems, planning paradigms and the taxonomy of temporal constraints are involved in different difficulties and they show some essential shortcomings or lacks. Namely, they may be specified as follows.

PlanParadigms:

1. Neither methods of the the first paradigm (such as STRIPS), nor of the second one (such as Davis-Putnam procedure) seem to have enough sufficient expressive power to exploit them in contexts of temporal planning with different constraints and preferences.
2. At least, an expressive power of these methods is not clear.
3. Finally, these planning paradigms – are rather considered purely methodologically as a reservoir of planning methods – developed, somehow, independently of concrete planning problems as their subject 'specification'.

PlanProblems:

1. No temporal extensions of these problem (MAS and TSP) are known and no approach to a construction of a taxonomy of temporal extensions of MAS and TSP is proposed.
2. In a consequence, no approach to modeling and representation of these extensions are known in a specialist literature.
3. Finally, majority of research on TSP (partially on MAS, as well) refers to these problems as to the discrete ones (for example, in a graph-based representation), putting aside a real time aspects in their solving.

TempConst: 1. The representation of temporal constraints does not overcome a dualism: 'quantitative-qualitative' and that there is no 'bridge' between a conceptualization of quantitative and qualitative temporal constrains.

2. In addition, majority of works refer to Allen's algebra as a sufficient conceptual basis to represent temporal constraints. Meanwhile, these fuzzy temporal constraints – integrated with preferences in particular – require a more sophisticated representation (than Allen's algebra). This new representation should be sensitive for combined formulas (representing both temporal constraints and preferences).

3. Finally, approaches to the representation of Allen's algebra oscillate more around meta-logical features of Halpern-Shoham logic such as PSPACE-completeness, decidability etc. than around a question: 'How to make Allen's interval relations computably useful and operationally explorable?'.

It seems that overcoming these difficulties and dualism towards a more holistic approach may support a more successful and general investigations in a temporal planning. This conviction constitutes a motivation factor of the thesis analysis as well.

3 The Problem Formulation

Due to above observations – this PhD-thesis is aimed at solving the following research problems:

1. *How to introduce a simple taxonomy of problems in temporal planning and scheduling with fuzzy constrains and preferences, which satisfies the following conditions:*
   - *it is (relatively) exhaustive,*
   - *it contains a precise description of basis problems of each*,
2. *How to manage and model fuzzy temporal constrains and preferences – due to this taxonomy – in order to either:*
   - *grasp a computational side of them or,*
   - *extend an expressive power of planning methods and tools or,*
   - *give new formal tools for plan monitoring.*

4 Objectives of the Thesis

According to these motivation factors – the objectives of the thesis may be summarized as follows:

Goal: The main goal of the thesis is a depth-analysis and exploration up-to date the conceptual tissue of temporal planning with fuzzy constraints and preferences to:

- propose a new mathematical (formal) foundations for the components of temporal planning with these constraints and
- elaborate new ways of representation and modeling of these components.

This main goal may be decomposed in the following subgoals (as their conjunction) – chronologically ordered as below:

Go1 To identify main difficulties and weaknesses of current approaches to temporal planning and to representation of temporal constraints and preferences.

Go2 To propose new temporal version of Traveling Salesman Problem and Multi-Agent Problem as a basis for a subject-specification of temporal planning.

Go3 To give a mathematical foundation for temporal constraints with fuzzy Allen's relations in a distinguished role in terms of algebra and real and abstract analysis.

Go4 To propose a new hybrid approach to fuzzy temporal constraints and preferences on a base of the convolution-based representation of fuzzy Allen's interval relations in the context of Temporal Multi-Agent Problem.

Go5 To incorporate this new approach to propose new fuzzy temporal and preferential extensions of STRIPS and Davis-Putnam procedure.

Go6 To propose a logic-based approach to fuzzy temporal constraints and preferences in the context of Traveling Salesman Problem.

Go7 To incorporate this new approach in plan supervising – for the construction of the hybrid plan controller.

Go8 To propose a synthesis of these two approaches: the convolution-based and the logic-based one via complementation the construction of the plan controller by a convolution representation of the agent's move trajectories.

By the way, the computational and programming-wise (in terms of PROLOG-solvers) aspects of Multi-Agent Schedulo-Planning Problem are undertaken in the thesis.

As mentioned, this PhD-thesis is amied at the representing and modeling of different components of temporal planning with fuzzy constraints and preferences. It is also focused on in-depth-analysis up-to-date of teh conceptau tissue of these problems. Therefore, it is focused neither on finding optimal solutions of the problems from this area, nor on experimental results and analysis from this area.

5 Structure and Content of the Thesis.

Although considerations of the thesis oscillate around an issue of temporal planning with different components and around methods of their modeling, contributions of this PhD-work may be clearly divided into two complementary parts.

1. **Part I (of Contributions)** is aimed at:
   - *representing and modeling* temporal planning and fuzzy temporal constraints and preferences in terms of convolution-based models and
   - *investigating* some computational and programming-wise aspects of this convolution-based approach.
2. **Part II (of Contributions)** is aimed at:
   - *representing* components of temporal planning – preferences, temporal constraints – in terms of some Multi-Valued Halpern-Shoham logic,
   - *modeling* them by means of a newly proposed interval-based fibring semantics, and
   - *putting forward* a general method of the hybrid plan controller construction exploiting the proposed approach.

The detailed content of further thesis chapters is the following:

***Introduction 1*.** This chapter forms a conceptual and (partially) historical introduction to issues of temporal planning as a unique extension of classical planning. Classical planning is described in different paradigms. In particular, classical planning as graph-searching (for example, as based on STRIPS) and as satisfiability (via Davis-Putnam procedure) were discussed. Finally, temporal planning is presented as an extension of classical planning by temporal aspects of acting.

***Introduction 2*.** This chapter forms an introduction to temporal and fuzzy temporal constrains and and their taxonomy. It also describes preferences as a separate component of temporal reasoning and temporal planning. Fuzzy temporal constraints are divided into two classes: the quantitative and the qualitative ones. The quantitative temporal constraints are briefly discussed in terms of Constraints Satisfaction Problem and its specification in the so-called *Simple Temporal Problems* (STP). The qualitative fuzzy temporal constraints – the main focus of this chapter – are properly discussed in terms of fuzzy Allen's relations. Two different approaches to their representation are presented here: Ohlbach's integral-based depiction and DeCock-Schockaer's depiction in terms of relational calculus and t-norms.

Contributions. Chapter 1. This chapter has an intermediate character between 'Introduction 1' and 'Introduction 2' and further parts of the PhD-thesis. Different difficulties of earlier approaches to temporal planning and fuzzy temporal constraints are detected and briefly discussed. One of the difficulty is a lack of a subject-specification of temporal planning, which is usually seen in a more methodological way. It forms a motivating factor to propose an outline of a small taxonomy of a subject-problems for temporal planning. Two classes of problems are introduced: the problems of the class of *Temporal Traveling Salesman Problem* (TTSP) and the problems of Multi-Agent schedule-Planning Problem (MA-SP-P). Both the paradigmatic problems (TTSP and MA-SP-P) are also defined in detail. Finally, some hints how to represent and model them are put forward in this chapter.

Contributions. Chapter 2. This chapter introduces a new mathematical approach to fuzzy temporal constrains and preferences. At first, fuzzy Allen's relations are represented by norms of the appropriate convolutions of the Lebesgue integrable functions – in a polemic reference to Ohlbach's ideas. Secondly, a new holistic approach to fuzzy temporal constraints – on a base of the convolution representation of fuzzy Allen's relations – is elaborated. This new holistic approach forms a combination of the quantitative and the qualitative fuzzy temporal constraints. The first ones are the constraints of MA-SP-P. The are encoded in the appropriate fuzzy intervals. The qualitative ones are just fuzzy Allen's relations imposed on these fuzzy intervals.

Next sections of the chapter present the temporal and preferential extensions of STRIPS and of Davis-Putnam procedure in a theoretic depiction. In addition, some metalogical features of the extensions are also discussed.

The qualitative temporal constraints are represented by Allen's relations and they are imposed on the quantitative ones. This combination allows us to introduce a new definition of *fuzzy temporal constrains* and *preferences* on a base of the last one.

***Contributions. Chapter 3*.** Investigations of this chapter forms a conceptual continuation of investigations of chapter 2 and they refer to computational and programming-wise aspects of fuzzy temporal constraints and thero representation. At first, the convolution-based depiction of fuzzy Allen's relations is applied to STRIPS and Davis-Putnam procedure in the appropriate temporal and preferential extension. Secondly, the PROLOG-solvers for chosen cases of the Multi-Agent Schedule-Planning Problem are presented. Analyses of this chaper are carried out in the subject context of Multi-Agent Schedule-Planning Problem.

Contributions. Chapter 4. This chapter addresses an alternative, algebraic-logical approach to representation of temporal constrains and preferences. These components are rendered in terms of a new Multi-Valued (Preferential) Halpern-Shoham logic. A 'fuzziness' is introduced here by preferences. This formal system is further interpreted in some interval-based fibred semantics. It allows us to consider combined formulas representing both preferences and actions – temporally constrained. Investigations of this chapter oscillates around Traveling Salesman Problem and its modeling.

Contributions. Chapter 5. This chapter describes a general method of the hybrid plan controller construction and it extends a purely theoretic investigations of chapter 4 towards an application area. The controller construction runs as follows.

1. At first, the robot motion environment is specified in Linear Temporal Logic (LTL) extended by Halpern-Shoham Logic (HS).
2. This LTL+HS-description is encoded by the appropriate Büchi automaton and it represents a required, planned situation.
3. Next, the second Büchi automaton is constructed for a real situation of the robot task performing.

These two automata form a construction basis for their product automata. Its representation in terms of PROLOG plays a role of a desired plan controller.

Contributions. Chapter 6. This chapter describes an attempt of a synthesis of earlier approaches to fuzzy temporal constraints and preferences. It is discussed here how the analysis-based and the logic-based representations might complement each other in the plan controller construction. For example, trajectories of agent moves in a logic-based description may be interpreted as the appropriate functions in Sobolev spaces.

Contributions. Chapter 7. This chapter contains concluding remarks and announces a promising direction of a future research.

Appendixes. The thesis contains also 8 Appendixes. Appendixes 1-7 contain more advanced results from a thematic scope of the thesis, such as metalogical features of fuzzy logic systems for Allen's relations. Appendix 8 contains a couple of mathematical definitions used in the proper body of the thesis.

6 How to Read the Thesis?

Contributions of the thesis – as it has been signalized – do not have any simply linear structure, but rather a *bi-linear*. It follows from the fact that the proposed taxonomy of temporal planning problems may be viewed as containing two classes of problems. The first class contains problems of Multi-Agent Schedule-Planning Problem-type. (M-AS-P). The second one – problems of Temporal Traveling Salesman Problem-type (TTSP). Problems of the first class show to be better graspable in analytic terms of the convolution-based approach. Problems of the TTSP-type – show to be suitable to be represented more logically, in terms of Preferential Halpern-Shoham logic.

In consequence, we have the following two lines of reasoning in the thesis.

A blue**The first line** leads from the chapter 'Detecting difficulties' by chapter 1 (presenting a convolution-based approach to fuzzy temporal constraints) up to chapter 2 (presenting computational aspects of the convolution-based approach in temporal planning).

B red**The second one** leads from the same chapter 'Detecting difficulties' by chapter 3 (describing fuzzy temporal constraints and preferences in terms of Preferential Halpern-Shoham logic) up to chapter 4 (describing a general method of the plan controller construction as an implementation of chapter 3).

For that reason, chapter 3 *should not* be considered as a continuation or extension of investigations of chapter 1 (or chapter 2). In fact, it presents an alternative and complementary approach to approaches presented in chapters 1 and 2.

7 A Short Justification of the Thesis Approaches

Two-dimensionality of the thesis analysis has just explained. It remains to justify a mathematical thesis approach and considering of temporal planning in mixed contexts.

Justification for mathematical approach, but against 'mathematism'. An idea to exploit mathematical tools and methods in the thesis approach stems from the author's belief that problems of AI – problems of planning in particular – should be operationally and computably graspable and expected results should be precisely measurable. This postulate seems to be feasible in a framework of any mathematical approach. The same mathematical approach may deliver a formal and precise conceptualization in a framework of a logical representation (of actions, temporal constrains or preferences). Finally, a better understanding of logical and mathematical foundations of temporal planning may be useful for AI-appliers – as it allows us to better understand what we do in a broad area of temporal planning.

Nevertheless, this work does not constitute any manifesto of 'mathematism'. In fact, *purely* mathematical approaches – based on a mathematical idealization – are often insufficient in temporal planning or they have reached limits of applications. In addition, a purely mathematical description seems to sometimes deliver too 'static' framework to describe the whole dynamism of temporal planning, its problems and their specification. Some examples for this fact may be found in this work as well.