ADVANCED PLANNING AND SCHEDULING INITIATIVE MRSPOCK AIMS FOR XMAS

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ABSTRACT

This paper will outline the framework and tools developed under the Advanced Planning and Schedule Initiative (APSI) study performed by VEGA for the European Space Agency in collaboration with three academic institutions, ISTC-CNR, ONERA, and Politecnico di Milano. We will start by illustrating the background history to APSI and why it was needed, giving a brief summary of all the partners within the project and the roles they played within it. We will then take a closer look at what the APSI study actually consisted of, showing the techniques that were used and illustrating the framework that was developed within the scope of the project. This will be followed by an elaboration on the three demonstration test scenarios that have been developed as part of the project to validated the framework and demonstrate in an operational environment its applicability, illustrating the re-use and synergies between the three cases along the way. We will finally conclude with a brief summary and outline future directions to be further investigated and expanded on within the context of the work performed within the project.

INTRODUCTION – WHAT IS APSI?

Background

The usage of AI technology and techniques within the field of planning and scheduling for space is growing. There are already many classical planning and scheduling applications used within the European Space Agency and in other agencies around the world. Some of these being very manual in nature and some being very automated tools. Currently only a handful make use of advanced AI techniques (e.g., Jonsson et al., 2000, Knight et al., 2001, Ai-Chang et al., 2004, Cesta et al, 2007). In most cases these systems and procedures can potentially be enhanced by the use of AI techniques at various stages of the planning and scheduling cycle. This is where the APSI study comes in who's aim is to provide a framework to support the development of new and existing AI technologies within the space planning and scheduling domain by providing a core underlying AI modeling infrastructure.

Study aims and goals

The Advanced Planning and Scheduling Initiative, or APSI, is an ESA programme to implement AI techniques in planning and scheduling that can be applied generically to different types and classes of space mission operations. The goal of the APSI is twofold:

- On one hand, the initiative is aimed at creating a software framework to improve the costeffectiveness and flexibility of mission planning support tool development.

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- On the other, the APSI strives to bridge the gap between advanced Artificial Intelligence (AI) planning and scheduling technology and the world of space mission planning.

The final output of the project is a (as much as possible) general software framework for supporting rapid development of AI planning & scheduling prototypes. Moreover the programme also includes the development of three different case study prototypes to demonstrate the validity and reusability of the proposed approach.

Project distribution

To make best use of the vast knowledge in the field of AI in the two year period that the study was scheduled for, the project was performed in collaboration with three academic partners, all well versed in the field of AI planning and scheduling techniques.

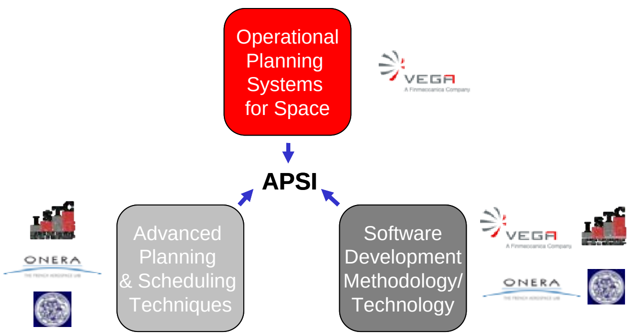

Figure 2: APSI Project Distribution

VEGA was prime contractor in the study overseeing the whole project with the academic partners being ISTC-CNR (based in Rome, Italy) ONERA (based in Toulouse, France) and Politecnico di Milano (based in Milan, Italy). The initial phase of the project consisted of a collaboration on all fronts to establish a common knowledge base of the problem domain and a common understanding of how we could represent and model these ideas. ISTC-CNR then had the responsibility to develop these ideas into the framework and underlying structures of the model. In parallel to this, VEGA and ESA researched, selected and defined possible scenarios from present and future missions that could be useful candidates for basing test case scenarios on for which demonstration tools would be developed. In the second phase a set of case scenario tools was to be developed, starting one after the other, making use of the developed framework and where necessary feeding back additionally required functionality into the framework. Each of the academic partners were responsible for the development of a single test case scenario, which started their development one after the other and focusing on different selected target missions. For this to succeed the main APSI framework had to be put into place.

The framework concept

The APSI framework follows the timeline-based approach which has been proposed in (Muscettola et al 1992), since then used in a number of space related tools (e.g., Jonsson et al., 2000, Chien et al, 2000) and studied in several works (e.g., Frank and Jonsson, 2003). In particular the APSI framework uses the generic term of “component” to identify a modelling primitive that refer to feature endowed with a temporal behaviour. Specific examples of components in the framework are the multi-valued state variables, a-la (Muscettola et al 1992), and the resources, a-la (Cheng & Smith, 1994). At implementation level the APSI framework is broken down into several functional layers. It uses components to represent the problem domain that can be reasoned on. In conjunction with this it provides two forms of consistency features that can used to define the characteristics of the domain. These are the value duration feature, used to represent the allowed upper and lower bounds of a duration for a given state variable value, and the transition constraint, used to define the possible permitted transitions among values of a given state variable. This allows for the definition of the correct physical behaviour between them.

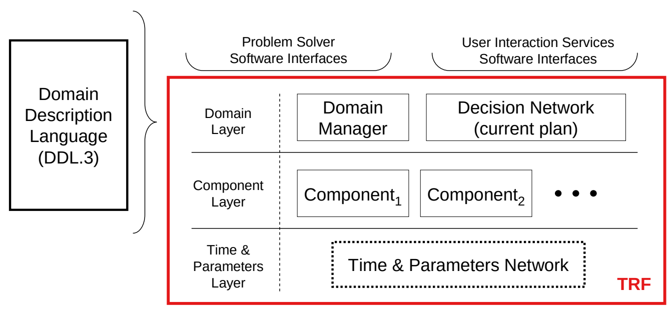

Figure 1: APSI Timeline Representation Framework

More is needed than just the definition of state variables and consistency features to model a given Space related problem. We also need to define how the various components interact with each other within the system. These inter-component relationships are realised within the APSI modelling framework by specficing what is commonly known as the domain theory. A domain theory can be seen as collections of synchronisations or rules which define the consequences of a component’s values based on the values taken on by other components defined within the model.

The core of the framework can be seen as comprising of three reasoning layers, these are the Domain management layer, Component layer and the Time & Parameters layer (see Figure 2). The term User here can refer to a physical human user or another process or system.

The Time & Parameters layer provides functionality to compute the effects of temporal assertions over a set of temporal elements within the framework. Being at the bottom of the hierarchy, the Time & Parameters layer does not impose any assertions on reasoners at higher levels

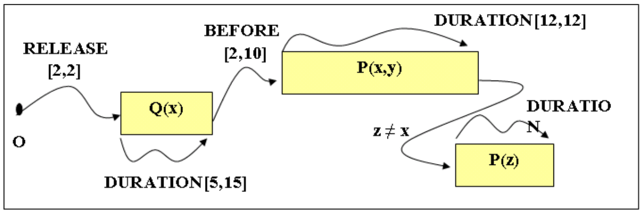

*Figure 3: **a network of decisions***

within the hierarchy. It also does not pass back any assertions either. Its main functionality is to maintain a data structure, a hyper-graph that contains temporal elements as nodes and temporal assertions as edges of the graph. Figure 3 illustrates a simple network of state-variables with transition and duration constraints specified.

The Component layer is used to compute the effects of component decisions over a set of Behaviors. It can also impose or retract temporal assertions on temporal elements. Consistency features of the component can be used to distinguish which behaviors are consistent and which are not. The result of which can be passed back to its higher levels detailing the relationships among component decisions that have been used to update the component's behaviors.

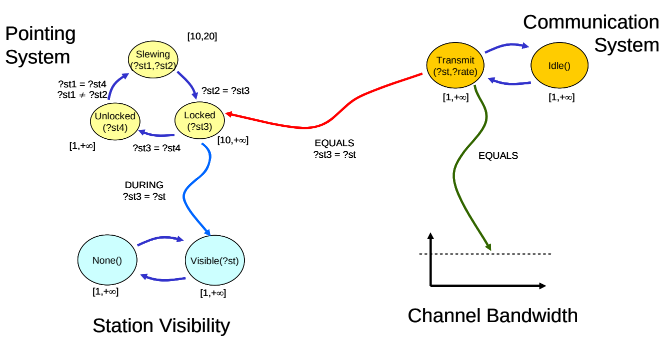

*Figure 4:**The Pointing System state variable and Domain Theory***

In the next layer, the Domain management layer, the effects of relationships over a set of component decisions is computed. The Domain management layer maintains a decision network data structure that represents a hyper – graph of component decisions representing the nodes and the relations between them representing the edges of the graph as can be seen in Figure 3. As with the Component layer, the Domain management layer can impose or retract temporal assertions on temporal elements. In addition to this it can also impose or retract component decisions on components. The Domain management layer also has associated with it a Domain theory. It can use this domain theory to distinguish which of its evolutions are consistent and which are not. Using this theory it can determine sub-goals and pass back to the higher levels goals that must be achieved. Figure 4 illustrates a set of state variable and the domain theory imposed on these variables.

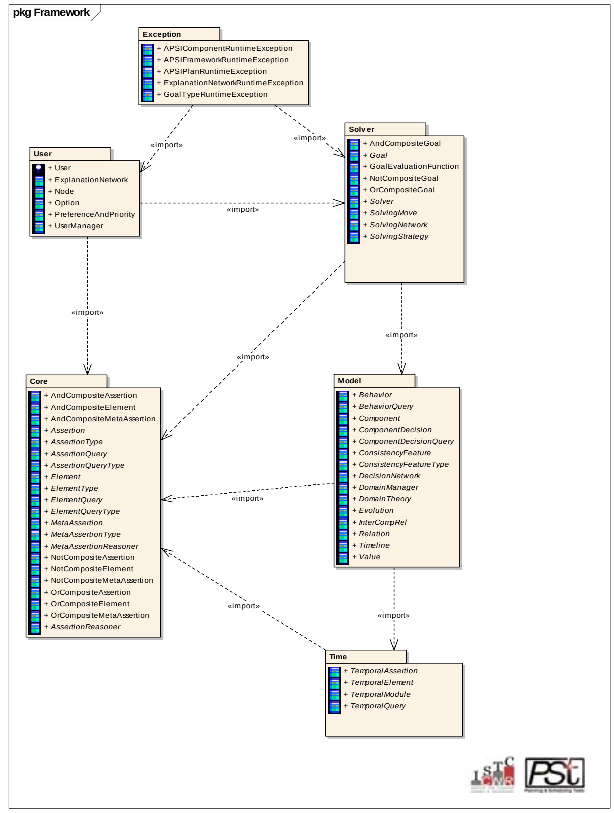

Figure 5:APSI library packages

Within the APSI framework these concepts are realised as a set of packages containing classes corresponding to the reasoning layers describe above. An overview of these packages and classes can be seen in Figure 5. This is just a brief insight to the inner workings of the APSI framework. For a more detailed description of the framework please see (Cesta et al. 2009).

Validating the framework

To validate the framework and its applicability to space based problems, it was required that three test case scenarios be defined and selected with resulting tools, built on top of the framework, being produced. The objectives of these case tools being to identify missing functionality within the framework that would need to be added and to demonstrate that the framework could support the modelling of various classes of problems found within the space domain. In support of this, it was necessary to obtain support from the operational staff of the missions that the cases were being based on.

We illustrate this concept in the sections that follow by describing how a typical APSI based application would be constructed, followed by each of the test case scenarios and the tools developed for them.

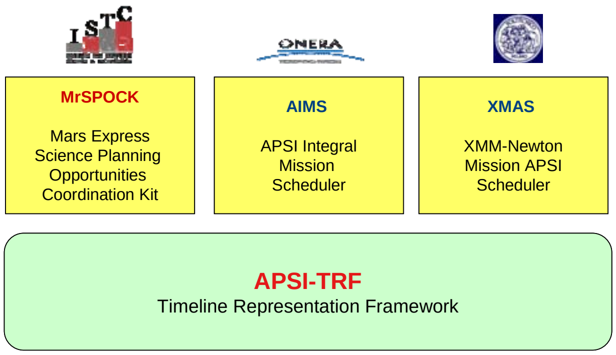

Figure 6: APSI Validation Tools

Typical APSI Application Construction

A typical application built on top of the APSI framework will need a set of additional components to provide a complete system. The application domain is considered individual for each development using the APSI framework, although this is generally defined using the DDL3 language.

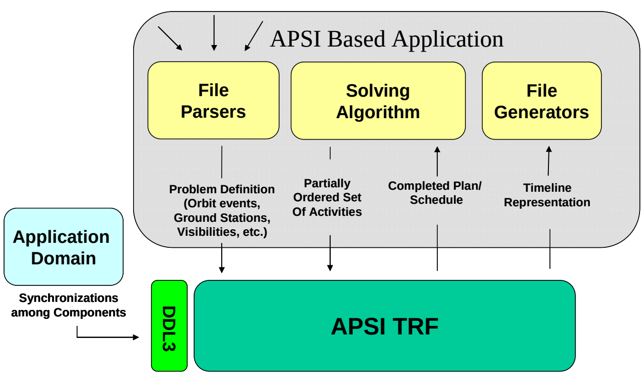

Figure 7: APSI based Application Construction

In addition to the domain definition, the problem definition also needs to be defined within the constructed system. These are nominally a set of mission specific partial timelines produced by other entities of the planning chain that are fixed in nature.

If a specific solving algorithm is required within the system, this is required to be constructed as well. The solver would nominally take the model provided by the framework and determine a partially ordered set of activities to use for construction of the plan or schedule. The framework is used to then propagate these activities to produce a completed and consistent plan or schedule back to the solving routine. The solver can then either accept the results or iterate again over the set of activities, taking into account the results.

A final component of an APSI based application is the output generators that are needed to translate the APSI internal representation of the derived timelines into the desired output formats usually required by the end users of the system or for integration with other systems. Figure 7 illustrates the typical blocks needed to construct an APSI based application.

Mr.SPOCK – Case #1

The first case selected to be developed by the project has been supported by the Mars Express mission planning team based at ESOC in Darmstadt, Germany. It is aimed at the pre-optimisation of the long term planning of maintenance windows and downlink opportunities during the nominal Medium Term Planning (MTP) cycles with the Planning and Scheduling Team (PST). The Mars Express satellite is a scientific observation platform with optical and non-optical instruments used to observe the planets atmosphere, surface and sub-surface structures. It orbits the red planet approximately every 6.5 hours, making scientific observations at various points in it's path. Most observations are carried out at pericentre when it is nearest to the planets surface and over a period of about 68 minutes around pericentre.

MrSPOCK is designed to allocate three different types of decisions over the user defined planning horizon. These are the selection of *Maintenance* windows around apocentre events, the selection of *Communication* windows among the set of available ground stations and the selection of *Science* operations windows around pericentre events. These decisions have to satisfy a large set of *hard* and *soft* constraints to produce optimal or near-optimal solutions for a given *objective function*. The objective function being dependent on the number of pericentres for science operations, the total volume of data for downlink operations and the uniform distribution of uplink windows. To define the characteristics of the planning problem the tool takes as input a description of the problem consisting of a set of problem files, a description of the main domain constraints and the initial state at the beginning of the planning horizon. In combination with this a set of parameters for the optimization algorithm also has to be specified along with a set of *weights* for the adopted objective function. These weights represent the main adjustable parameters for driving the search towards specific types of solutions.

The optimization procedure used for MrSPOCK has been based on *Genetic Algorithms* (GA). GA is a well-known and effective computational paradigm for function optimization inspired from the study of population genetics. This was considered an appropriate approach due to the multi-objective nature of the planning problem. Indeed the GA is combined with a constructive heuristic procedure that instantiate the temporal plan which represent the complete and detailed output of MrSPOCK.

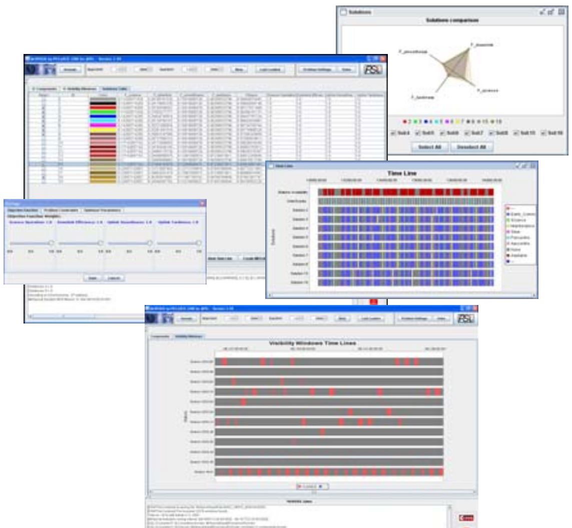

Figure 8:MrSPOCK results and user interface

There were initially many teething problems encountered, being this was the first case of the three test case scenarios and really the first time that the framework was fully exercised in the context of an application. Due to these issues the development of MrSPOCK took the longest of the three cases. This experience permitted the team to gain a fruitful know-how for the design and implementation of new tool approaches that has been exploited for the remaining two cases.

For a more detailed description of the case #1 tool, MrSPOCK, please see (Cesta et al. 2009).

AIMS – Case #2

In the second case we obtained the support from the INTEGRAL (INTErnational Gamma-Ray Astrophysics Laboratory) long term planning team of the Integral Science Operations Centre (ISOC) based at ESAC in Madrid, Spain. The INTEGRAL mission, an ESA mission managed in cooperation with Russia and the USA, aims at observing gamma-ray emissions from regions of the universe whilst revolving around the earth in a highly elliptical orbit. Each revolution lasting 72 hours in length of which only 58 hours can be used for observation time due to the effects of the Earth's radiation belt. The satellite itself holds four instruments for observing space regions which are all fixed in the same direction.

The main aim of the tool is to optimise the satisfaction of the scientific objectives expressed in the yearly announcements of opportunities. These announcements of opportunities, or AO's as they are commonly called, are generated by the user community prior to the commencement of the next long term planning period which nominally covers one year. Not only do AO's for the next planning period have to be considered but also AO's from the previous planning period which were not scheduled are included, albeit with a higher priority than previously.

To solve this optimisation problem, the tool uses a local search algorithm that combines the best ideas from the state-of-the-art local search algorithms such as hill-climbing, tabu search, and simulated annealing. This local search algorithm uses the underlying APSI framework to maintain flexible consistent schedules within each revolution and to determine the amount of observation time that can be added to the observations already scheduled within a revolution. In other words, the APSI framework is used to efficiently manage the basic scheduling constraints and the local search algorithm, built on top of it, is used to manage the optimization criterion and specific constraints.

Figure 9: AIMS results and user interface

Due to the advances that the case #1 tool had brought to the framework and the debugging performed on the framework during the development of the first case, the second case, AIMS, took less time to develop from conception to final tool.

For a more detailed description of the case #2 tool, AIMS, please see (Verfaillie & Pralet 2009).

XMAS – Case #3

For the third and final test case scenario, the support of the XMM-Newton long term science planning team was obtained, also based in ESAC, Madrid. The XMM-Newton satellite was launched in 1999 with the aim of providing a space-based X-ray observatory that is open to the scientific community. Like INTEGRAL, XMM-Newton also has a highly elliptical orbit around the Earth but lasting only 48 hours per revolution. Within these 48 hours, and again due to the Earth's radiation belt, only ~36 hours of the revolution are usable for observation time.

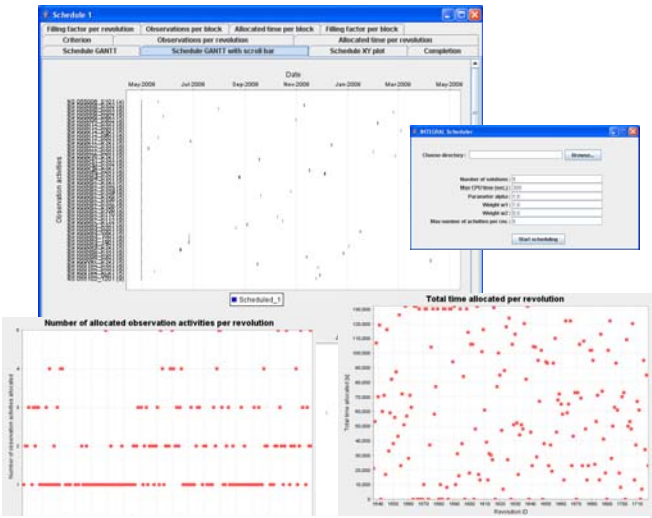

Figure 10:XMAS results and user interface

Following detailed analysis of the XMM-Newton planning problem, it could be seen that the planning required was very similar to that developed for the INTEGRAL tool. There were some subtle differences between the two missions though. Long-tern planning for the XMM-Newton mission required a more dynamic initial plan with a lower filling factor to allow for the provision of short term changes to be made to the plan without major re-planning of the long-term plan. For these reasons it was decided to take the most current release of the AIMS tool at the time to base the case #3 development upon. In the process, aligning the input file formats between the AIMS tool and those needed for the XMAS tool, creating a common set of input file formats.

For a more detailed description of the case #3 tool, XMAS, please see (Lavagna & Castellini 2009).

Tool Results

The table that follows (Table1-1) summarises the initial drivers for the selection of the three prototype tools developed and the results achieved from the users perspective of using the tool. In each case it can be clearly seen that the tools have enhanced the current planning situations for the selected missions and, in some cases, even provided additional value to that originally foreseen for the tools usage.

Table1-1 APSI Tool Results Summary

	Initial Problem	**Result**	**Added Value**
MrSPOCK	Many cycles with several changes	Better initial skeleton LTP	More Apocentre time available for VMC science
AIMS	Manual process taking ~2 weeks to reach a good solution	Tools configuration in 2 days + coffee break for good result	Tool extension made by users. <1day configuration + coffee break for good result
XMAS	Mostly manual process with over 400 observation requests	All mission specific requirements satisfied. Effective production of observations in LTP	Under evaluation

Conclusions

Within this paper we have shown you a brief glimpse of the APSI framework and touched lightly on the three test case scenario tools that have been developed to demonstrate the capabilities of the framework. The one question that we have hopefully placed in your mind is how can APSI be of use to me? APSI can assist in the development and integration of AI techniques within the planning and scheduling for space domain by providing an underlying framework that facilitates the modelling of planning and scheduling problems. Tools can be built upon this framework to support existing applications and technologies, or to create and test new innovative AI techniques and technologies.

We do not proclaim that the APSI framework is suitable to every situation of a space planning and scheduling problem or that it is a complete framework that can be used of the shelf. There are always additional concepts that could be developed and evolved within the framework. As new technologies emerge within the AI field so must the APSI framework to include these. To cope with this aspect, one of the main characteristics of the APSI framework is its flexibility (via a plug-in based schema) that allows enriching it with new functionalities and/or modules. For instance, this was the case of the second prototype: AIMS. Its implementation required the introduction of a new module that afterwards, as part of the APSI framework, was reused for the design and implementation of the third case study prototype, XMAS.

The above considerations on the realization of the three prototypes suggest a general schema for implementing domain-specific decision support tools, namely: (1) implement any additional component types that are required by the application context; (2) extend and/or tune the general solving procedure where necessary; (3) define a model where the component types are instantiated with domain-specific characteristics and are logically bound by synchronizations. Of course, these three steps cannot alone provide a complete deployable software tool. Nonetheless, they provide a means to reduce the gap between prototype and final application by factoring away all the major algorithmic and modeling design choices.

In summary the achievements of the project are as follows:
Framework

- The use of a core modular framework for the development of prototype AI-based planning and scheduling applications/modules has been successfully demonstrated
- The framework supports timeline-based planning, concentrating on reasoning about time and resources
- The framework provides
  - An organisation of an AI-based planning application in a hierarchy of solvers
  - Data models and algorithms implementing temporal, component and domain reasoning levels

Tools

- Resolution of typical operational problems in the planning chain
- Basic planning/scheduling functionality provided in the framework found adequate for supporting the implementation
- Performance of the applications matches operational expectations
- Demonstration of cost-effective implementation of close-to-operational solution
- Two prototypes could be used operationally

Considerations:

- Identification of suitable operational problems difficult (lack of resources, data, problem dimension, problem suitability,etc.)
- Core modelling in framework, specific application modelling in the application layer (e.g. constraints not supported by the framework)

Current and Future Works

Current works include a thorough evaluation of the APSI framework, with implementation of alternative case studies, and the evaluation of the current prototypes on the real operational environments.
Future activities foresee, starting from the results of the current project, to extend the APSI framework with respect to the following principal directions:

- Consolidation of the Modelling Framework: this activity entails the formalization of the modelling framework and characterization of its expressiveness. Also, to extend the modelling framework to address uncertainty of the effects of actions and partial observability.
- Consolidation and extension of the internal data representation and algorithms. In particular, to extend the underlying APSI framework domain and problem representation in order to support the additional planning algorithms. Also, providing a methodology to handle hard/soft constraints in the framework (e.g. integration of soft constraints in the optimisation criterion).
- Consolidation of the core framework to ensure its stability and re-usability
- Operational deployment of APSI prototypes by the beginning of 2010
- Re-use of the APSI software as platform for the prototyping of AI-based planning and scheduling applications in ESA (on-board autonomous controller deliberative layer, rover on-ground planning, EO mission planning, etc.)

In addition to these we expect the following to also be part of the on-going works:

- Generalisation of the specific solvers for integration in a re-usable solver toolkit
- Further assessment of the usability of the APSI framework to support operational mission planning facility development

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