A Combinated Model of Planning and Scheduling

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Abstract. This paper presents an approach to deal with Planning and Scheduling features, which are now required in many real-worls problems, as a model that interleaves a planner and a scheduler, both playing a similar role in the problem solving process. Planning studies action selection for obtaining good quality plans. On the other hand, Scheduling studies the suitable resources application over any plan. Additionally, in the State-of-the-Art, there are two approaches to solve these problems: extended Planning and extended Scheduling. The first approach results in a high computational complexity, and the second approach uses a rigid plan template (embedded planner) avoiding the possibility of re-planning. Hence, this paper analyses the challenging points to work in a collaborative way such as: i) problem modelling, ii) structure definition, iii) functional behaviour and iv) resolution of planning/scheduling conflicts under a mixed initiative in a plan whose actions are very dependent on numeric features.Consequently, this model promises to be efficiently enough to obtain executable and consistent plans.

1 Introduction and Motivation

In Artificial Intelligence (IA), Planning and Scheduling (P&S) processes have been studied and applied separately. The first one studies the selection of actions to be performed to obtain desired goals. The second one considers the requirements for execute those actions.

However, the IA Planning Community has tried to solve real-world problems requiring handle parameters like duration tasks, execution costs, limited resource usage, optimization criteria, temporal constraints, persistent effects, etc., to solve a great variety of problems, such as logistic plan elaboration, crisis management, autonomous spatial vehicle navigation (planetary explorers and observation satellites),

© A. Gelbukh, C.A. Reyes-García. (Eds.) *Received 01/06/06*
Advances in Artificial Intelligence. *Accepted 03/10/06*
Research in Computing Science 26, 2006, pp. 103-112 *Final version 18/10/06*

optimization of touristy routes, airports traffic control, energy distribution systems, etc. [1, 2, 3].

Therefore, it is practically impossible to separate P&S features, because the selection of an action in a plan is usually conditioned to several temporal constraints, resource availability and criteria to be optimized [4]. Although it is clear that real-world problems require features of those IA processes; those processes have been hardly related to each other, mainly because P&S have been considered as disunited problems and, obviously, because this is the most immediate approach.

Consequently, P&S processes complement each other perfectly, which clearly motivates the challenge in designing flexible models to integrate maximal capabilities from both processes, especially if we consider that they use similar techniques (search in graphs, use of heuristics, management and reasoning of constraints, etc. [5].)

Question of what is the best design to interleave these processes still remains open [2,5,6]. In this way, we try to answer that important question proposing an integrated model for these IA study areas in [4]. Through a description of the architecture of this system, the information flow inside this model (where we analyze the way in which both processes cooperate and communicate mutually), its key information to decide which P&S technology is more appropriated to use for solve real-world problems, we contribute in this paper with a detailed analysis of main advantages and challenges obtained of using this system.

2 The Planning and Scheduling Problem

The P&S problem involves the execution of a sequence of actions, which must satisfy several constraints (temporal and resource availability), in order to achieve the problem goals, while trying to optimize a metric function.

Let us assume a problem inspired by a interplanetary explorer's scenario (this problem was introduced in the International Planning Competition 2002, http://ipc.icaps-conference.org). This problem requires that a collection of interplanetary explorers navigate to planet surface, finding samples, taking images, and communicating them back to a control base (lander). Explorer utilization must be coordinated for avoiding the bottleneck of the communication between the explorer and the lander, which must be performed only when the lander is visible from the explorer.

Furthermore, the explorer consumes energy in its various activities and it can only be recharged at locations that receive sunlight (recharging energy actions are very limited and need to be carefully planned to manage energy). There are plans that without energy recharge cannot obtain their goals. This is a clear example of a real-world problem that makes it necessary to include temporal constraints and resource availability into planning, as they modify the plan structure, because the plan generation is highly influenced by the scheduling constraints.

The requirements to model a P&S problem, i.e. in Rovers Domain, contain:

i) **Initial state** (IS) and problem goals (G), with the propositions that are true at the beginning of the problem and the facts that need to be achieved, respectively. i.e. the initial state may be: sunlight locations, the initial quantity of energy of the explorer; whereas the goals may be: communicated and received data of the samples (i.e., rock, soil and images of the explored planet).

ii) **Actions**, with their durations, conditions and effects for the study of different alternatives to achieve the goals, i.e. camera calibrating, image taking, etc.

iii) **Resources**, their availability to execute actions in the plan. They are implicit in action definition (conditions and/or effects). Actions can modify their propositional state (calibrated, available, etc,) or their numeric value (decrease energy in 15 units).

iv) **Metric function** that needs to be optimized as a multi-criteria function that allows finding solutions with the consideration of several weighted criteria that plays an important role in the plan, i.e. minimize the energy used and the plan makespan (total duration).

v) **Resources and/or time constraints**. They can model the requirements of the real-world problem. They can be of the obligatory type (strong constraints) or of the preference type (soft constraints), i.e. deadlines (they limit the duration time to obtain something) or time windows (sunlight is available from 5' to 20').

3 An Integrated Planning and Scheduling Model

Once we had established the dependency between P&S processes for solving real-world problems, we reviewed the State-of-the-Art about their integration. Furthermore, we proposed an integrated model for these IA processes in [4]. En this way, different approaches have been studied [2, 5, 8, 9]. From a planning point of view, a planner is extended to handle time and resources (this is known as the temporal planning approach) [8,12,13]. From a scheduling point of view, a scheduler is extended to insert a planning component, by providing a previously planned set of activities and, usually, the order in which these activities must be respected [5]. Those approaches have high computational complexity, making intractable some problems, and re-planning was not possible [14] over the rigid plans, respectively.

However, the architecture of this integrated approach provides a general and flexible model. It is a general model because each process is solved using existing techniques. Additionally, it is a flexible model because both P&S processes have a homogeneous role in problem solving. Then, this model creates a collaborative and strongly coupled integration structure for both IA processes.

3.1 Description of the Integrated Model

The architecture of this integrated model for P&S processes is depicted in Figure 1; it has two modules, one for each process.

The planning module acts as a plan repairer or re-planner [14] when is found a time/resource conflict (adding or deleting actions to make the plan executable) or as a simple planner when it needs to achieve some problem goals. The scheduling module checks and validates the feasibility of the plan, considering its constraints. The scheduler allocates actions satisfying resources/time constraints; it also informs and collaborates with the planner when it detects scheduling conflicts that require re-planning techniques [14]. However, this structure needs a data structure called Action Network (AN) [4], that is shared between both modules (see Figure 2).

AN follows the philosophy of Temporal Constraint Networks (TCN) [10] and Consumable Resource Networks (RCN) [11] to represent the plan [4], whose nodes represent time points where actions begin/end. Labeled edges represent: i) the usage of a resource (note that time is a resource too), ii) causal links between different actions, and iii) temporal constraints between nodes.

This architecture requires an input plan, with the corresponding domain and problem. This model could start from an empty plan, but it becomes such a complex task when there are many State-of-the-Art planners that generate plans efficiently. We can use a classical planner to tackle that task. Obviously, this type of planner gives executable plans, but if we provide a non-executable plan, there will not present conflicts, because one of the objectives of this model is precisely to repair a given plan and make it executable.

3.2 Used Technology in the Integrated Model

Planning finds executable plans without considering resource requirements; when planning conflicts are presented, the planning module inserts actions to support propositions or new sub-goals. Different planning technology is used, i.e. flaw repair [14] and decomposition [12]. Otherwise, the scheduling module requires to validate and guarantee the feasibility about time and resources of the AN. A feasible plan is a consistent plan. From the AI point of view, scheduling algorithms are used for checking and maintaining the plan arc-consistency, through MAC and AC-3 algorithms [20], with the involved resources and their constraints in the AN, this is a special case of the Problem of Satisfaction of Constraints (CSP) [10].

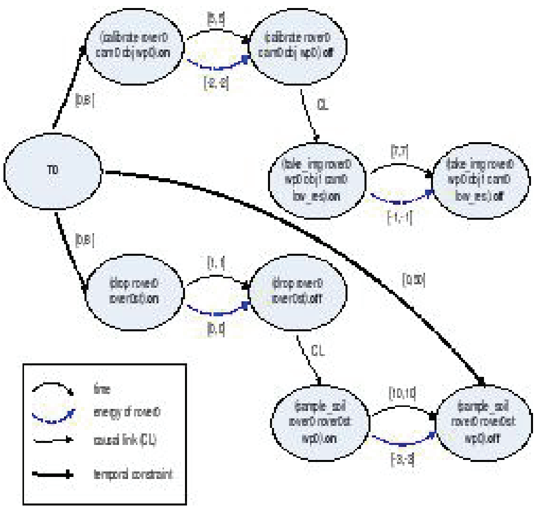

Figure 1. Integrated model of P&S processes

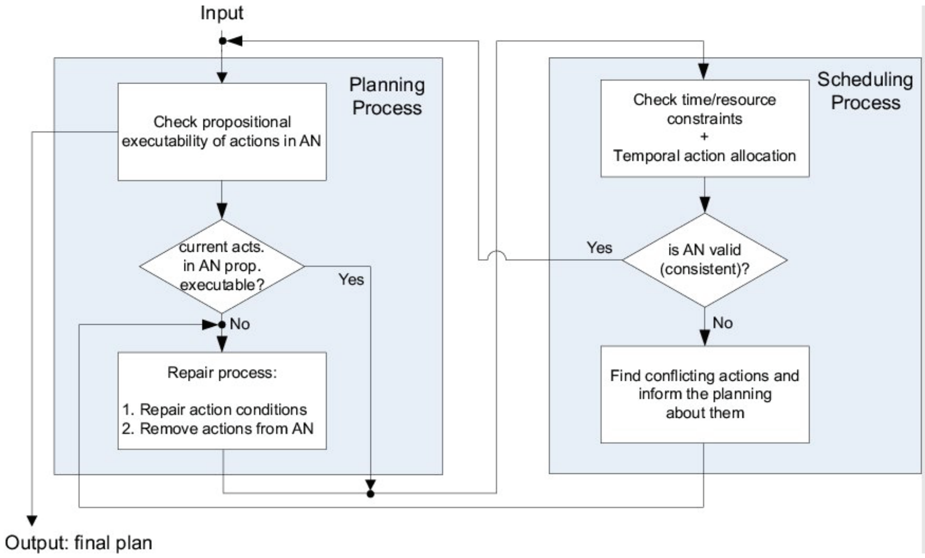

Figure 2. Action Network

3.3 Information Flow in the Integrated Model

Figure 3 and 4 depict the information flow inside the integrated model. The objective is to verify all actions in the AN to find a plan completely free of conflicts. This verification is performed from the planning and scheduling point of view (rev_PLN and rev_SCH) applying next algorithm,

1: rev_PLN $\leftarrow$ IS
2: rev_SCH $\leftarrow \emptyset$
3: **while** $\exists$ a $\in$ AN / a $\notin$ rev_SCH **do**
4: {Planning part; reasoning on causal link}
5: a $\leftarrow$ earliest action that can be planned (executed) in AN
6: rev_PLN $\leftarrow$ rev_PLN $\uplus$ {a}
7: **if** number_of_conflicts (rev_PLN) > 0 **then**
8: solve_PLN_conflicts (rev_PLN)
9: {Scheduling part; reasoning on time and resources}
10: **for all** ai $\in$ rev_PLN / ai $\notin$ rev_SCH **do**
11: **if** $\exists$ a consistent allocation of ai in rev_SCH **then**
12: rev_SCH $\leftarrow$ rev_SCH $\uplus$ {ai}
13: **else**
14: solve_SCH_conflicts (rev_PLN, heuristic parameters)

Figure 3. General scheme for integrating P&S

First, one action is selected (step 5), and then two main tasks are performed. One is to solve the planning conflicts that make the plan no executable, using solve_PLN_conflicts (step 8). This type of conflict is basically caused by unsupported action conditions or by mutually exclusive relations between plan actions [4]. When the planning conflicts have been solved, the other task is to eliminate scheduling conflicts. This type of conflict is caused by insufficient time and/or resources, using solve_SCH_conflicts (step 14). In both cases, the planner performs the same task (see Figure 3) with the technology before mentioned. During the process of solving the planning problem, the planner eventually calls the scheduler to obtain advice and make the most convenient decision [4].

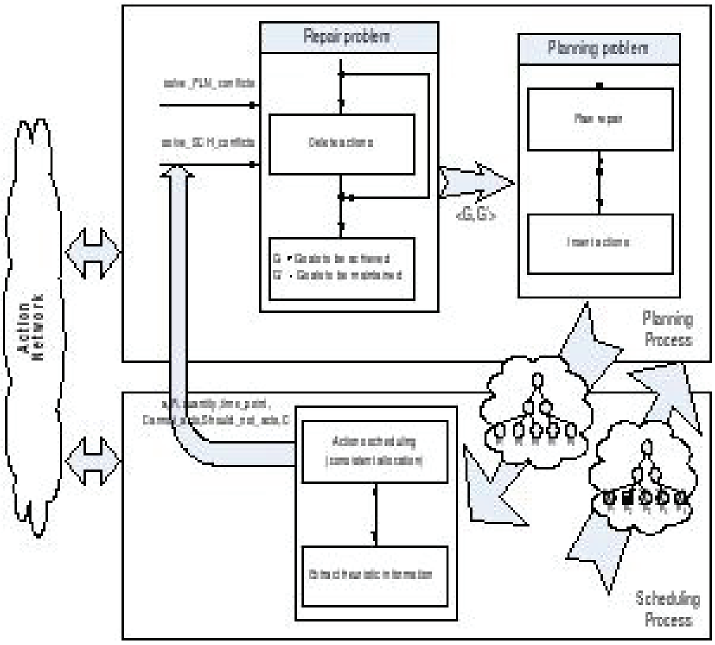

Figure 4. Information flow in the integrated model [4]

About the key points of the information flow in this model, there are two calls (step 8 and 14 of Figure 3) to the planning module (which is the executor):

i) solve_PLN_conflicts, where planner calls itself in order to fix planning conflicts in rev_PLN. It tries to solve the planning repairing problem [14].
ii) solve_SCH_conflicts implies solving a scheduling conflict through planning, because the scheduler detected an over-subscripted resource [19] and this one is a constraint violation. Then, the planner investigates other actions or the consistent allocation of resources from rev_PLN. If planner finds a solution to the conflict, then it allocates the solution using rev_SCH. Additionally, the scheduler provides important heuristic information to the planner on which actions cannot (and should not) be removed from the AN and other heuristic parameters. The first case is the set

of actions that only gives support to problem goals or they provide a unique way to attain the sub-goals or goals. The second case is the set of actions that helps to obtain sub-goals, however, they are not unique. Furthermore, the scheduler supplies a set of constraints in order to guide the planning search as much as possible, that planner must hold the constraints while it tries to solve the problem. Moreover, the planner shows the scheduler the planning decision points (where different plans are obtained). The last one decides which is the best plan.

It is obvious that the planner has a central role in this collaborative task, with the intelligent guidance given by the heuristic information provided by the scheduler.

4 Main Advantages of the Integrated Planning and Scheduling Model

Any system is evaluated for the advantages it provides, in this sense we have concluded that the proposed system is a very viable system because of the quality and quantity of its advantages, which will be described next,

a) **Flexibility**, both modules effectively work in a strongly coupled form, where one module takes into account the relevant information and valuable advice provided by the other module. Then, both processes knowingly communicate and collaborate each other to successfully build a partial plan.
b) **Modularity**, in every module there is only one process that maintains its remarkable work capacity at any time so that it can apply all its techniques when they are required.
c) **Generality**, the proposed architecture considers using this model to solve problems in any domain, because this model expressly applies existing techniques in the State-of-the-Art for each mentioned process.
d) **Conflict earlier detection**, both processes build and verify the execution and consistency of the plan step-by-step due to the mutual collaboration, in other words action-by-action, labeling the allocated actions once these were revised for each module. Consequently, the modules will opportunely detect the presence and type of a conflict; this could be for unsupported action conditions, mutually exclusive actions/propositions (planning problems) or insufficient resources (scheduling problem).
e) **Conflict immediate solution**, as soon as this model detects a conflict, it tries to instantly solve it, applying the P&S technology before mentioned.
f) **Available operative information** between both modules, through the use of two physical key points that interchange information, i.e., an advice when a conflict is detected or the system needs to find out which one is the best plan. One module cannot work without the appropriate guidance from the other one.
g) **Common heuristic information**, the scheduler extracts heuristic parameters from the planning process, and uses its own heuristic parameters in order to be able to choose the best plan.
h) **Common optimizing criteria**, each process has its own optimizing criteria. They

communicate each other and combine their criteria to make the final decision.

i) **Flexible interface**, this model may contain many sub-modules in order to finally achieve an effective communication.

j) **Architecture simplicity**, this is one of the best advantages of our system, because it freely allows inserting other required modules in order to obtain better plans without making significant changes.

5 Main Challenges of the Integrated Planning and Scheduling Model

Because there is not a common language between P&S processes, one of the main challenges is the design of an interface for mutual communication. From a planning perspective, there is a well-accepted language to define planning domains, which is actually called PDDL3.0 [7]. Another challenge of this system is that the mentioned language has some limitations for describing scheduling features, such as finite persistent of actions effects (the camera remains calibrated only during 20') and temporal constraints between actions (image taking must be done 6' before finishing the calibrated effect).

6 Conclusions and Related Work

From the 90's, combining P&S capabilities during resolution of real-world problems is a hot topic of research in IA [2,6,8,15,18]. There are two approaches to solve these problems: extended Planning and extended Scheduling. The first approach results in high computational complexity [8,12,13], and the second approach uses a rigid plan template (embedded planner) avoiding the possibility of re-planning [5]. Additionally, there have been some successful integration models, such as HSTS [16] and ASPEN [17], however, these systems only work in the domains they were designed. Thus, the search of a general and flexible design that integrates the P&S processes still remains open [2, 5, 6].

Otherwise, the architecture of our novel integrated approach proposed in [4] provides a general and flexible model. It is called a general model because each process uses existing technologies. On the other hand, it is flexible because both processes have a homogeneous role in problem solving. Then, this model creates a collaborative and strongly coupled integration structure of both IA processes.

Notoriously, this model has many advantages and they are considerably important, as they have been studied in this paper. We have concluded that the proposed system is a very viable system because of the quality and quantity of its advantages This model is based on the common idea of the dynamic interleaving of processes, where both are playing similar roles, not embedded one inside each other. Thus, the planner has the central role in this collaborative task (with the intelligent guidance given by the heuristic information provided by the scheduler).

One of their main challenges is the design of an interface for mutual processes understanding (note that they use different languages). Additionally, the planning language has some limitations for describing scheduling features, such as finite persistent of actions effects and temporal constraints between actions. Its modularity makes easy to face these challenges, because it successfully helps to insert required modules. Thus, its flexible architecture allows improvement. Because each process keeps its own maximal capabilities for early detection and immediate conflict solving, this integrated model guarantees obtaining the best solution plan. Consequently, this model promises to be efficiently enough to obtain executable and consistent plans.

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