Representing Plans as a Set of Constraints – the <I-N-OVA> Model

Austin Tate
Artificial Intelligence Applications Institute
The University of Edinburgh
80 South Bridge, Edinburgh EH1 1HN, UK
a.tate@ed.ac.uk

Abstract

This paper presents an approach to representing and manipulating plans based on a model of plans as a set of constraints. The <I-N-OVA>[1] (*Issues – Nodes – Orderings/Variables/Auxiliary*) model is used to characterise the plan representation used within O-Plan and to relate this work to emerging formal analyses of plans and planning. This synergy of practical and formal approaches can stretch the formal methods to cover realistic plan representations, as needed for real problem solving, and can improve the analysis that is possible for production planning systems.

<I-N-OVA> is intended to act as a bridge to improve dialogue between a number of communities working on formal planning theories, practical planning systems and systems engineering process management methodologies. It is intended to support new work on automatic manipulation of plans, human communication about plans, principled and reliable acquisition of plan information, and formal reasoning about plans.

Motivation

The <I-N-OVA> (*Issues – Nodes – Orderings/Variables/Auxiliary*) Model is a means to represent plans as a set of constraints. By having a clear description of the different components within a plan, the model allows for plans to be manipulated and used separately from the environments in which they are generated. The underlying thesis is that plans can be represented by a set of constraints on the behaviours possible in the domain being modelled and that plan communication can take place through the interchange of such constraint information.

As shown in figure 1, the <I-N-OVA> constraint model underlying plans is intended to support a number of different uses of plan representations:

- for automatic manipulation of plans and to act as an ontology to underpin such use;
- a common basis for human communication about plans;

[1] <I-N-OVA> is pronounced as in "Innovate".

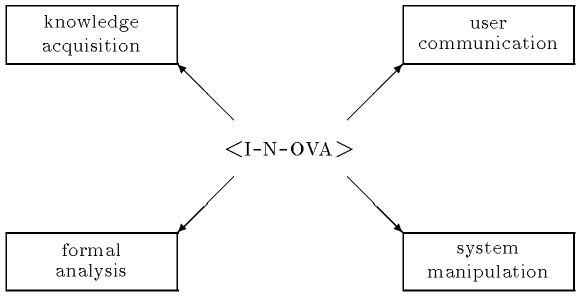

Figure 1: <I-N-OVA> Supports Various Requirements

- a target for principled and reliable acquisition of plan information;
- formal reasoning about plans.

These cover both formal and practical requirements and encompass the needs of both human and computer-based planning systems.

Our aim is to characterise the plan representation used within O-Plan [Currie & Tate 91],[Tate et. al. 94c], to link this to emerging work on process modelling in the workflow community, and to more closely relate this work to emerging formal analyses of plans and planning. This synergy of practical and formal approaches can stretch the formal methods to cover realistic plan representations as needed for real problem solving, and can improve the analysis that is possible for production planning systems.

Representing Plans as a Set of Constraints

A plan is represented as a set of constraints which together limit the behaviour that is desired when the plan is executed. Work on O-Plan [Currie & Tate 91],[Tate et. al. 94c] and other practical planners [Allen et. al. 90] has identified different entities in the plan which are conveniently grouped into three types of constraint.

The set of constraints describes the possible plan elaborations that can be reached or generated as shown in figure 2.

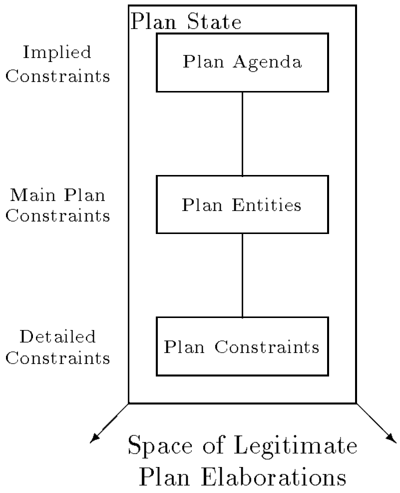

Figure 2: Constraints Define the Space of Plan Elaborations

The three types of constraint in a plan are:

1. Implied Constraints or "Issues"[2] – representing the pending or future constraints that will be added to the plan as a result of handling unsatisfied requirements, dealing with aspects of plan analysis and critiquing, etc. The implied constraints are the issues to be addressed, i.e., the "to-do" list or agenda which can be used to decide what plan modifications should be made to a plan by a planner (user or system).

2. Plan Entities or Plan Node constraints – the main plan entities related to external communication of a plan. They describe a set of external names associated with time points. In an activity planner, the nodes are usually the actions in the plan associated with their begin and end time points. In a resource centred scheduler, nodes may be the resource reservations made against the available resources with a begin and end time point for the reservation period.

[2] We have previously used a variety of different names for these constraints: *Agenda Entries* reflecting the chosen method of representation in O-Plan; *Flaws* as suggested by Sam Steel of Essex University in the mid 1980s and reflecting the original concentration of representing the outcome of plan critics which found interactions in the teleological structure that had to be corrected; *To-do list entries* reflecting common usage in business; *Pending Processing Requirements* reflecting the notion that they implied future plan manipulation or constraints; and others. We have settled on *Issues* suggested by Craig Wier of ARPA in 1994 as being an easily understood term that reflects both the need to handle problems and the positive opportunities that present themselves.

3. Detailed Constraints – associated with plan entities and representing specialised constraints on the plan. Empirical work on the O-Plan planner has identified the desirability of distinguishing two special types of detailed constraint:

   - Ordering or Temporal Constraints (such as temporal relationships between the nodes or metric time properties).
   - Variable Constraints (especially co-designation and non-co-designation constraints on plan objects).

   These two constraint types are highlighted since they may form part of other constraints within a temporal reasoning domain such as occurs in planning and scheduling problems. Knowing that these constraints have such "cross-associations" has been found to simplify the design of constraint handling mechanisms and ease implementation issues [Tate 93b],[Tate et. al. 94d].

   Other Detailed Constraints relate to input (pre-) and output (post-) and protection conditions, resources, authority or control requirements, spatial constraints, etc. These are referred to as:

   - Auxiliary Constraints

   Auxiliary Constraints may be expressed as occurring at a time point (referred to as "point constraints") or across a range of the plan (referred to as "range constraints"). Point constraints can be used to express input and output constraints on nodes or for other constraints that can be expressed at a single time point. Range constraints relate to two or more time points and can be used to express protection intervals, etc.

The <I-N-OVA> Model

A plan is represented as a set of constraints of three principal types. To reflect the three main types of constraint identified and their differentiation in the model, the constraint set for a plan is written as <I-N-OVA> (*Issues – Nodes – Orderings/Variables/Auxiliary*). I stands for the the issues agenda or implied constraints, N for the node or plan entity constraints, and OVA for the detailed constraints held as three types (O for ordering constraints, V for variable constraints, and A for the other auxiliary constraints).

The auxiliary constraints are given 4 sub-types: Authority, Conditions, Resources and Other and all may be stated as point (related to a single time point), range (related to two time points) or multi-point constraints. Further sub-types are possible for any of the Auxiliary Constraints and the nature of these reflects on-going work on knowledge modelling for planning, scheduling and process modelling domains (e.g., [Tate 93a], [Tate et. al. 94b], [Uschold et. el. 95]).

The <I-N-OVA> constraint model for plans contains a hierarchy of constraint types and sub-types as follows:

```
Plan Constraints
  I   - Implied Constraints
  N   - Node Constraints
  OVA - Detailed Constraints
        O - Ordering Constraints
        V - Variable Constraints
        A - Auxiliary Constraints
            - Authority Constraints
              - subtypes
            - Condition Constraints
              - subtypes
            - Resource Constraints
              - subtypes
            - Other Constraints
              - subtypes
```

The node constraints in the <I-N-OVA> model set the space within which a plan may be further constrained. The issues and OVA constraints restrict the plans within that space which are valid.

The <I-N-OVA> model currently assumes that it is sufficiently general for each node (referred to as N constraints) to be associated with just two time points, one representing the begin of the node and the other representing the end of the node. Further research may indicate that a more general, multiple time point association of nodes to time points may be necessary.

Hierarchical or abstraction level modelling is possible for all constraint types within the <I-N-OVA> model. To reflect this possibility, an <I-N-OVA> model which is described hierarchically or with levels of abstraction will be referred to as a Hierarchical <I-N-OVA> model. This will be written as Δ-<I-N-OVA>.

The Δ is a triangle pictogram used to represent hierarchical expansion. It can be written in an alternate all character version as H-<I-N-OVA>.

The Triangle Model of Activity

The <I-N-OVA> auxiliary constraints incorporate details from the Triangle Model of Activity used to underpin the Task Formalism (TF) domain description language [Tate et. al. 94a] used for O-Plan [Currie & Tate 91],[Tate et. al. 94c]. The Triangle Model seeks to give a clear description of activities, tasks and plans in a common framework that allows for hierarchical decomposition and time relationships along with authority, pre- and post-conditions, resources and other constraints. The Triangle Model can be used as a basis for planning domain modelling and for supportive task description interfaces.

The aim in the Triangle Model is to simplify some of the notions for expressive plan and activity representations from AI planning. It seeks to relate these notions to existing systems-engineering requirements capture and modelling languages and methods (like SADT [Ross 85], IDEF [Mayer & Painter 91], CORE [Curwen 90], HOOD [HOOD 89], etc.), and to recent work on Process Interchange Format (PIF) [PIF 94], workflow standards [WfMC 94] and enterprise modelling frameworks [Uschold et. al. 1995].

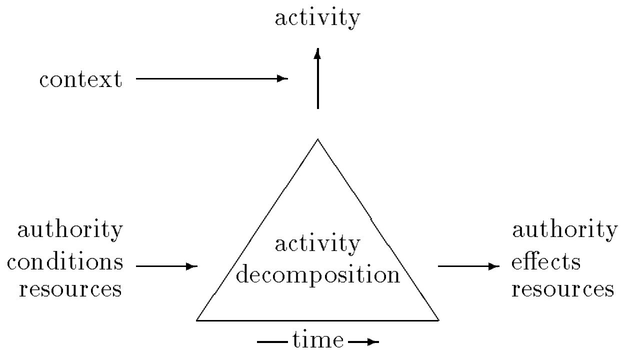

Figure 3: O-Plan Triangle model of Activity

Figure 3 shows the Triangle Model of Activity. The vertical dimension reflects activity decomposition, the horizontal dimension reflects time. A context allows for the relevance of a particular decomposition to be made to depend on the situation in which it may be used. Inputs and outputs are split into three principal categories (authority, conditions/effects and resources). Arbitrarily complex modelling is possible in all dimensions. Types and sub-types are used to further differentiate the inputs and outputs, and their semantics.

"Entry" to the model can be from any of the three points in the triangle: it can be used from the top vertex to ask for activity expansions or decompositions, or from the right side to ask for activities satisfying or providing the output requirement (authority, goal or resource). These two points are used mostly by AI planners to date. The third point from the left side can reflect non-intended triggering conditions for an action and will be needed when improved independent processes are modelled within planers as in the EXCALIBUR [Drabble 93] extension to Nonlin [Tate 77].

The activity decompositions shows the expansion of the activity to a greater level of detail if that is modelled. It can include details of protection conditions that span points within a decomposition.

Variables may appear in an activity description. Differentiation between those variables used in the external specification (outside the triangle) and those only used within the activity decomposition (internal to the triangle) is possible.

The O-Plan time model defines a set of time points which can be related to an absolute start of time (for metric time statements) or which can be related to one another (for relative time relationships). Temporal relationships between an activity (referred to as *self*) and the sub-activities within a decomposition may be stated with reference to the two "ends" of any activity. Arbitrarily complex temporal relationships (e.g., [Allen & Koomen 93]) are possible in the general Triangle Model.

The "intentions" or "rationale" behind the use of a particular activity can be related to the features of this Triangle Model. Causality or teleology modelled via activity pre-conditions/post-conditions has been used in AI planners for many years to record the plan rationale (e.g., in Nonlin [Tate 77]). In the richer model now in use in O-Plan, rationale in terms of resource usage and supply, authority requirements or delegation may also be stated. This makes it possible to use a uniform approach to the modelling of authority, product flow and resource requirements.

Relationship of Triangle Model to O-Plan TF Schemas

The Triangle Model of activity maps directly to an O-Plan Task Formalism (TF) schema. TF is the domain description language for O-Plan. The following shows the components of a simplified schema. "..." indicates repetition of the previous component. Further detail is available in [Tate et. al. 94a].

```
schema <schema_name>;
   ;;; public information
   vars    <var> = <var_restriction>, ... ;
   expands <pattern> ;
   only_use_for_authority <authority_statement>,...;
   only_use_for_effects   <effect_statement>,...;
   only_use_for_resources <resource_statement>,...;

   ;;; private information
   local_vars     <var> = <var_restriction>,...;
   vars_relations <var> <relation> <var>,...;
   nodes          <node_number> <node_form>,...;
   orderings      <node_end> ---> <node_end>,...;
   time_windows   <time_window_spec>,...;
   authority      <authority_statement>,...;
   conditions     <condition_statement>,...;
   effects        <effect_statement>,...;
   resources      <resource_statement>,...;
   other_constraints <constraint_statement>,...;
end_schema;
```

Domain Operators, Tasks and Plans

Figure 4 illustrates the dependency relationships between domain, task and plan knowledge. Tasks and Plans are both based upon the entities in the Domain model. Plans also are elaborations of a specific Task.

- *Domain* knowledge describes "fixed" things like facilities, organisational relationships, procedures, systems, products and the types of resource available. This knowledge is likely to be highly reusable for many different requirements.

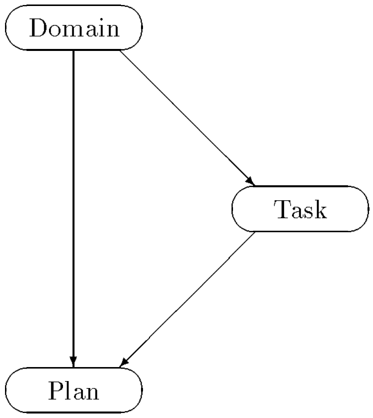

Figure 4: Dependencies between Domain, Task and Plan Knowledge Partitions

- *Task* knowledge describes the objectives such as the goal or goals which the plan is designed to achieve, the activity to be carried out, the actual resources available, the time available, etc.
- *Plan* knowledge describes a particular way (currently under exploration) in which the specified task objectives can be achieved in the current domain.

<I-N-OVA> is intended to underpin domain, task and plan modelling needs in a planning system whether human, computer or mixed agents are involved. Communication between planning agents in O-Plan takes place via Plan Patches [Tate 89] which are also based on the Triangle Model of Activity and the <I-N-OVA> constraint components.

Relationship of <I-N-OVA> to Work in Systems Engineering

There is a deliberate and direct mapping from the O-Plan Triangle Model of Activity and the <I-N-OVA> Constraint Model of Plans to existing structured analysis and diagraming methods such as IDEF and R-Charts. Other researchers have recognised the value of merging AI representation concepts with structured analysis and diagramming techniques for systems requirements modelling [Borgida et. al. 85],[Ramesh & Dhar 94] and the earlier work on the Programmer's Apprentice [Rich & Waters 88].

Modelling Processes and Activities

IDEF0 [Mayer 92] is a functional modelling method and diagraming notation that has been used for modelling processes[3]. Figure 5 shows the basic component.

[3] IDEF3 [Mayer & Painter 91] is a later, more comprehensive IDEF method specifically targeted at the modelling of processes.

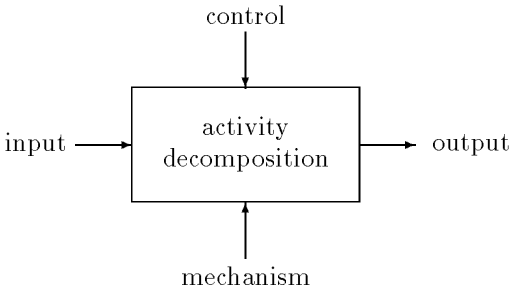

Figure 5: IDEF0 model

IDEF modellers usually use “control” for authority-related triggers and “mechanism” to reflect resource availability. A criticism of IDEF is the lack of direct support for modelling the different types of output and their intended destination. Experienced IDEF modellers use the arc labels, naming conventions and the “notes” system in an IDEF support “kit” to encode this information.

R-Charts [Ushakiv & Velbitskiy 93] are one of the ISO approved diagraming conventions for program constructs (ISO/IEC 8631 [ISO/IEC 89]). Figure 6 shows the basic component which explicitly acknowledges the importance of control (or authority) related outputs.

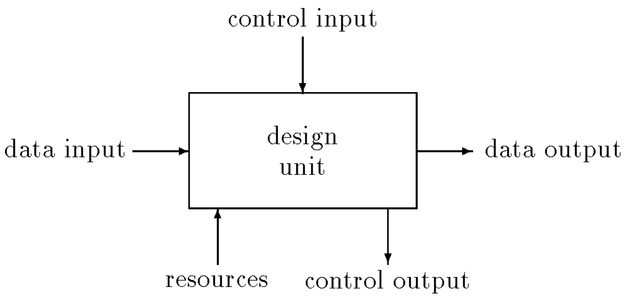

Figure 6: R-Chart Model

The O-Plan Triangle Model represents all three types of input and output more uniformly and directly and will allow for improved support tools.

Capturing Design Rationale in Systems Development

Work in systems enginering and other fields is addressing the need to capture and make use of the rationale behind designs, decisions or regulations. An example is the Remap (for “Representation and maintenance of processes knowledge”) system [Ramesh & Dhar 94] which uses the IBIS (Issue-based Information System) concepts. The issues are explicitly maintained as in the <I-N-OVA> model, and the Remap system allows for the ways in which the issues are resolved to be recorded and used.

Relationship to Other Work

A general approach to designing AI-based planning and scheduling systems based on partial plan or partial schedule representations is to have an architecture in which a plan or schedule is critiqued to produce a list of issues or agenda entries which is then used to drive a workflow-style processing cycle of choosing a “plan modification operator” and then executing it to modify the plan state. Figure 7 shows this graphically.

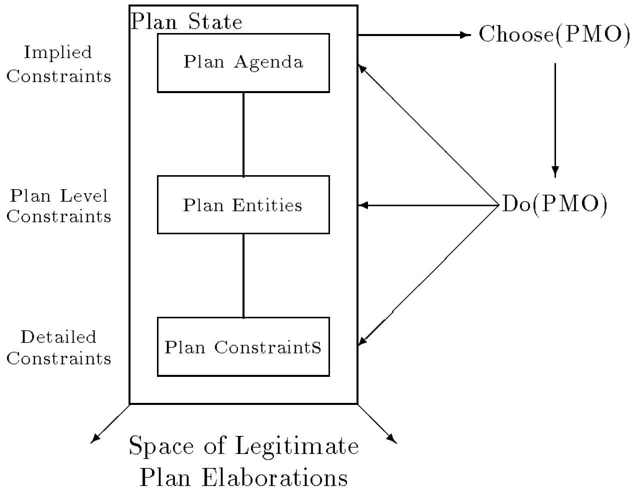

Figure 7: A Framework of Components in a Planning/Scheduling System

This approach is taken in systems like O-Plan [Currie & Tate 91],[Tate et. al. 94c], RT-1 [D'Ambrosio et. al. 87], OPIS [Smith 94], DIPART [Pollack 94], TOSCA [Beck 93], etc. The approach fits well with the concept of treating plans as a set of constraints which can be refined as planning progresses. Some such systems can act in a non-monotonic fashion by relaxing constraints in certain ways.

Having the implied constraints or “agenda” as a formal part of the plan provides an ability to separate the plan that is being generated or manipulated from the planning system itself. The benefits were first noted by McDermott [McDermott 78] and are used as a core part of the O-Plan design.

A recently described approach to Mixed Initiative Planning in O-Plan [Tate 94] proposes to improve the coordination of planning with user interaction by employing a clearer shared model of the plan as a set of constraints at various levels that can be jointly and explicitly discussed between and manipulated by user or system in a cooperative fashion.

Relationship to Formal Studies of Plans and Planners

The Nonlin QA Algorithm [Tate 77] establishes the modifications that are needed in terms of plan step ordering and variable binding to ensure that a given statement has a required value at a given point in a partially ordered network of nodes. This has been a basis for the formal work by Chapman [Chapman 91] on the Modal Truth Criterion. However, the MTC uses a simplification of the plans being represented in practical planners such as Nonlin [Tate 77], O-Plan [Currie & Tate 91],[Tate et. al. 94c] and SIPE-2 [Wilkins 88]. It took a non-hierarchical view and ignored specialised domain knowledge of activity condition types and constraints. Many of these were those very features that allowed planners like Nonlin and SIPE-2 to solve problems at a scale that was beyond the more theoretically based planners. Drummond [Drummond 93] explains that formal approaches have concentrated on goal achievement aspects of planners in a simplified environment that is not representative of the approaches actually taken in practical planners.

Recently however, formal representations have begun to address issues of realistic plan representations and to model hierarchical planning [Barrett & Weld 94],[Kambhampati & Hendler 91],[Penberthy & Weld 90], [Yang 90]. In particular, Kambhampati has described a formal truth criterion for plans which are represented with greater levels of realism. He describes plans as a 5 tuple <S, O, B, ST, L> [Kambhampati 94a] where:

```
S     a set of plan steps or nodes

O     a partial ordering over S

B     a set of variable binding co-designation
      and non-co-designation constraints

ST    a symbol table mapping each plan step or
      node to a domain operator

L     a set of auxiliary constraints (mainly
      intended for pre- and post-conditions)
```

This representation can be related directly to the N (incorporating the S and ST parts) and OVA (incorporating the O, B and L parts) of the <I-N-OVA> model[4].

Hendler and Kambhampati are also studying hierarchical approaches to formal methods in planning [Kambhampati 94b],[Kambhampati & Hendler 91]. Work is underway by Kambhampati and by Young [Young et. al. 94] to understand aspects of the use of "condition types" [Tate et. al. 94b] used to provide domain semantic information to Nonlin, O-Plan and other practical planners.

The <I-N-OVA> model also has a direct relationship to the *plan recipes* described by Traum and Allen [Traum & Allen 94]. They view plans as a set of actions (*c.f.* N) and a set of constraints relating various properties of these actions (*c.f.* OVA). The issues element (I) of <I-N-OVA> is not directly modelled.

A Framework for Further Study

To provide a framework for further study, the following classification of models related to <I-N-OVA> is provided.

	partial plan	partial plan with issues
single level model	<N-OVA>	<I-N-OVA>
hierarchical model	Δ-<N-OVA>	Δ-<I-N-OVA>

A base model <N-OVA> is used to represent a basic plan without hierarchy or abstraction modelling and not including implied constraints (the issues agenda). The other models extend this basic model along these two dimensions[5]. They are all supersets of <N-OVA>, and are collectively termed *Super*-<N-OVA> models.

The <N-OVA> element most closely relates to the model being studied by Kambhampati today [Kambhampati 94a]. The Δ-<I-N-OVA> element is the closest to the plan representation used within O-Plan today.

Summary

The <I-N-OVA> Constraint Model of Plans and its relationship to the O-Plan Triangle Model of Activity has been described to assist in more closely relating new work in formal descriptions of plans and planners to practical work on realistic planning systems. <I-N-OVA> is intended to act as a bridge to improve dialogue between the communities working in these two areas and potentially to support work on automatic manipulation of plans, human communication about plans, principled and reliable acquisition of plan information, and formal reasoning about plans.

Acknowledgements

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[4] The use of the term "Auxiliary Constraints" in <I-N-OVA> was adopted as a means to relate to this formal work. In fact the <S, O, B, ST, L> constraint set acts as a refinement filter on all possible plans, whereas <I-N-OVA> also defines the candidate set from which the solutions may come (through the N component). This needs further study to relate the two approaches.

[5] Non-determinism is a property of the system (human or computer based) which manipulates the plans and is not necessarily represented in the constraint model. However, it is usual to include explicit dependency information in a plan via constraints to support non-monotonic planners. This may indicate that it would be useful to define a third dimension to this framework for further study.

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