

International Journal of Geographical Information Science

ISSN: 1365-8816 (Print) 1362-3087 (Online) Journal homepage: <http://www.tandfonline.com/loi/tgis20>

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To cite this article: Nikhil Kaza & Lewis D. Hopkins (2012) Intentional actions, plans, and information systems, International Journal of Geographical Information Science, 26:3, 557-576, DOI: [10.1080/13658816.2011.603337](https://doi.org/10.1080/13658816.2011.603337)

To link to this article: <https://doi.org/10.1080/13658816.2011.603337>



Published online: 03 Nov 2011.



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Intentional actions, plans, and information systems

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(Received 04 October 2010; final version received 26 June 2011)

If urban development plans were just target patterns to be achieved, conventional data structures in Geographic information systems (GIS) would be sufficient. Urban development plans have a strong spatial component, but recent literature in planning emphasizes that plans are about actions and relationships among them. These relationships include interdependence, substitutability, priority, and parthood. In order to support planning, GIScience should devise data structures and queries to support reasoning with these relationships. This article shows how relationships encoded within each of a set of plans, using a recently developed data model, can be used to infer the relationships of actions among these plans. Simple databases and use cases based on real situations in McHenry County, Illinois are used to demonstrate that these relationships can be encoded and queried. The results demonstrate that previously discovered semantic relationships can be used to discover additional relationships across plans, thereby enriching the decision making. The approach provides a systematic way of structuring the information in plans to support making and using plans.

Keywords: plans; planning support systems; substitutability; interdependence

1. Introduction

Conventional geographic information systems (GIS) cannot support reasoning with plans: How does an action affect previous actions, actions of others, and actions that come after? How can we embed a decision to commit to a particular action in the reasoning already embedded in plans? How can we use the information available at the time of action, including the information in plans, to decide what to do? How can we reason efficiently, but still imperfectly and incompletely, using any information made newly salient by our particular focus of attention? Recently articulated conceptions of plans in GIS and GIScience (e.g. Couclelis 2009), artificial intelligence (AI) (e.g. Pollack and Horty 1999), and urban development (e.g. Hopkins 2001) converge in suggesting that spatial representation is insufficient and that substitutability with respect to intentions and effects and interdependence among actions are crucial relationships that need to be captured in information systems supporting planning. By representing these actions only as spatial entities, we lose the underlying logic that binds these actions together. This article is an attempt to augment spatial reasoning with plan-based reasoning in response to the challenge from Couclelis (1991).

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If plans for urban development simply agreed on spatial patterns to be achieved, then conventional GIS data structures would be sufficient to represent these plans after they have been created. In observed urban development planning, however, organizations continually make and use plans and thus depend on the logic within these plans. Many different organizations have distinct goals and distinct plans, and many of these organizations have multiple plans of their own because resource and time limitations necessitate the creation of partial plans. Newly salient intentions arise and existing intentions fade. New actors emerge and other actors disappear; coalitions form and dissolve around particular issues, intentions, or actions. These actors commit to plans, even though these plans are partial and changeable. Plans, much less than any one plan, do not resolve all the interdependencies and uncertainties of decision making. Nor will there be time, resources, or motivations to make plans completely consistent within, much less among, organizations. These plans have spatial attributes and could be represented in an ontology that takes advantage of and builds on recent advances in GIScience (e.g. Klosterman 1997, Worboys 2005, Carrera and Ferreira 2007, Goodchild *et al.* 2007).

An example sets the stage for the kind of problem addressed in this article. There is no access to Interstate 90 (I 90) in McHenry County, Illinois. A regional plan prefers to have an interchange at Illinois Route 23 (IL 23) and I 90 (I in Figure 1). The plan also recognizes that the expansion of IL 23 south and north of Marengo, implied by an interchange, is detrimental to the ecologically sensitive Kishwaukee Basin and recommends its protection. The neighboring county, however, in its transportation investment plan recommends completion of an interchange at US 20 and I 90 (J in Figure 1). McHenry County's

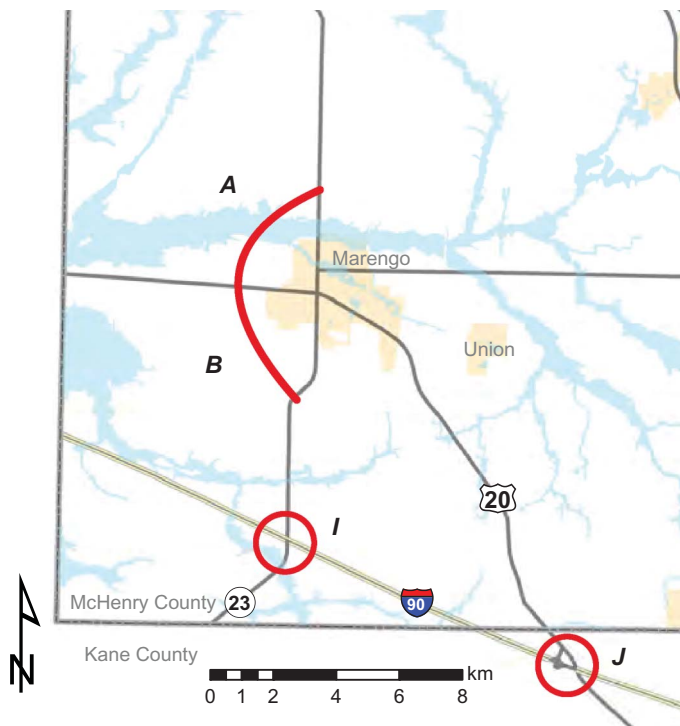


Figure 1. Reasoning with multiple plans about interdependent actions.

own comprehensive plan favors this alternative and suggests expansion of US 20. The expansion of US 20 is complementary to this interchange, as is the expansion of IL 23 north of Marengo, but not south. All these complementary actions are represented in various plans, but not in any one plan. Building both interchanges so close to one another is infeasible. The choice between which interchange gets built is hammered out among various interest groups and various governments. The process is politically fractious and requires careful negotiation *after* the plans are made. These plans, however, can be used and are useful in such processes, especially if there are tools to help recognize how proposed actions in different plans are interdependent and whether they are substitutes for each other.

This article is part of a larger project to develop information systems capable of supporting the making and using of urban development plans. A data model that enables the encoding of actions and relationships among them was devised (Hopkins *et al.* 2005a, 2005b) and a simplified application of the underlying ideas was implemented for McHenry County, Illinois (Finn *et al.* 2007). This article builds on this data model to enable reasoning within and among plans. That is, rather than just querying a database about relationships among actions that have been encoded and stored, this article focuses on devising heuristics for extending knowledge of substitutability and interdependence within a plan to recognize potential substitutability and interdependence among plans.

The main argument of this article is that we should be able to use the information structure within a plan, or a subset of actions within a plan, to reason about relationships between actions across plans, or across subsets within plans. In the remainder of this article, we simplify this by referring only to inferring relationships among plans because multiple plans and subsets within plans are equivalent. Such capabilities support the fundamental question of plan-based reasoning: Given the information available at the time of action, including the information in plans, what should we do? An Information System of Plans (ISoP) with such capability will support the use of plans, and, by extension, the revision and thus the making of plans.

First, we clarify the conceptions of plans: how they work and how they are used. Second, we describe how an information system and its users could use heuristic reasoning to recognize and evaluate substitutability, recognize and cope with interdependence, and combine these capabilities to reason from multiple plans. Then we illustrate this process with an example, a set of simple use cases, of how such an information system would work. In conclusion, we argue that this approach frames a different perspective on using plans for which ISoPs will be useful. Such an approach and such systems show promise for practice despite remaining hurdles to implementation. The approach advances GIScience by confronting the challenge of moving from GIS representations of urban development plans as target patterns to ISoPs for plan-based reasoning.

2. Conceptions of plans

Concepts of plans have been emphasized recently in the GIScience, AI, and urban planning literature. The general convergence is best understood by first considering the work in each field. Urban planning has moved away from thinking about plans as outcomes and instead focuses on the underlying logic. AI has moved away from thinking about plans as goal-seeking sequences of actions and instead explicitly considers both strategic and non-strategic uncertainty of actions in multi-agent situations. GIScience has reoriented its focus from representing entities in space to representing entities with both spatial and temporal relationships.

2.1. Plans in GIS

Couclelis (1991, 2009) emphasized that conventional GIS are not sufficient to represent plans. Information systems to support the use of plans should account for intentions, actions, and multiple plans. Howarth and Couclelis (2005) emphasized the need to consider purpose, goal-directed action, or intent as a crucial limitation of conventional GIS data models. Even recent expositions of unified concepts of representing fields and objects and their temporal attributes in GIScience, such as Goodchild *et al.* (2007), are insufficient for representing plan relationships.

Recent work building on GIScience has focused on representing actions. Actions are intentional events and *occurents* (Worboys 2005). They have many attributes including the actor whose responsibility is to perform the action, the jurisdictional authority (or any other capability) under which the action may be sanctioned, location, and temporal attributes of the actions themselves. To build a road is an action with attributes such as the Department of Transportation (DOT) as a responsible actor and a particular alignment. Actions are events that deliberately bring about a change in the world, by changing (or creating) assets, changing capabilities, or preventing an otherwise natural (unintentional) change.

Plans interact with and inform intentions and, therefore, purposeful (teleological) action is influenced by planning. Representing intentions only as spatiotemporal entities would require ignoring the rich information content that makes the intention useful in reasoning about action. A plan to build a new road (an action), when the congestion level in the system reaches a threshold, should not be represented as a new link on a network at a specified time because this ignores the logic behind the intention. It should be represented as a contingent event, where continual monitoring of the congestion levels triggers the building of the new road (Worboys 2005) and relationships to other parts of the road network will be consistent with assumptions on which creating the new link was based. Furthermore, plans are provisional. Plans may leave actual choice of action to the future, while circumscribing the choice set. For example, a plan could specify that a school could be built at either of two locations, which precludes any other location from future consideration, while not fixing the location. This would be represented as an event, building a school as an object with multiple possible location attributes, rather than an invariant underlying geography with two possible schools at different coordinates (Frank 1997, Galton 2001). Another plan could specify that because a road is slated to be built in different alignments depending on a congestion threshold, one location for the school would be preferred over the other because of access considerations. To represent these relationships, we need to bring to bear concepts that inform the relationships of actions within plans, rather than just representing agents acting on a geographical blanket.

2.2. Plans in AI

Reasoning with plans is a longstanding focus of AI research. Plans in conventional AI are conceived in terms of ends-means reduction, a sequence of steps to achieve a given goal state. Representation of plans in AI involves representing an initial state and the ways each potential action might change the state. While initial work was done assuming deterministic transformations of the states through actions (McCarthy 1969), more recent work has focused on the uncertain effects of actions in achieving goals (Majercik and Littman 2003). Most of the work in AI, however, has focused on the creation of a plan. An example of plan creation is programming an autonomous agent to play the game of chess against

an opponent, where rules of the game are unchangeable and actions produce deterministic effects, even when there is strategic uncertainty.

Faced with dynamic and uncertain environments, for example, in robotics, AI researchers have expanded their analyses into creating more flexible planning programs. Pollack (1992) and Pollack and Horty (1999) showed why intent is valuable in representations sufficient for using plans in AI. Bratman (1987), Pollack (1992), and Pollock (2006) provided different conceptions of how partial commitment to intentions and using multiple plans can support effective decision making.

Pollack and Horty (1999) building upon Bratman *et al.* (1988) argued that plans are a mechanism to inform commitment, so that resource-bounded agents can reason further about decisions and coordinate with other actors. Plans work in part through implied commitment to the actions chosen in the plan, or to the implicit intentions, or the explicitly expressed intentions of these actions. Even though commitment is not absolute, it increases efficiency of future reasoning by narrowing the focus of consideration and increasing predictability of actions. Reasoning with commitments requires consideration of when to alter commitments and how to interpret commitments of others.

Commitment management, as described by Pollack and Horty, implies inertia to proceed in accordance with the action chosen in a prior plan. However, a dynamic environment requires some kind of reasoning to account for newly recognized alternatives, environments, or intentions that invalidate the prior plans. This is one of the justifications for reasoning with multiple plans. If different plans were created with a focus on different possibilities or issues, then these plans are likely to present different sets of alternatives and different criteria for evaluation. Faced with a particular decision situation that shapes attention in a particular way, consideration of these plans becomes feasible within our bounded capabilities, even if that was not the case when the plans were made.

The labels for two recent AI projects, SharedPlans (Grosz and Kraus 1999) and Teamwork (Cohen and Levesque 1991), emphasize their focus on collaboration, situations in which two or more actors seek to achieve a common intention. Collaborative coordination can be supported by such automated reasoning systems that assume a sustained commitment to shared intentions. Geospatial agents, as reviewed in Sengupta and Sieber (2007), have been programmed to pursue goals (intentions), which enables simulations of interactions among intentional agents.

In contrast, this article focuses on situations in which actors have different, perhaps overlapping, and changing intentions. Urban development plans occur in such strategic coordination situations with changing intentions and emerging actors, which make such automated reasoning systems infeasible. Coordination is an important justification for the usefulness of reasoning with multiple plans because it is unlikely that all interdependent actions can be considered in the scope of any one plan, especially when the actions are under the authority of different agents.

Assessing alternatives, including alternatives that arise in elaborating plans, requires an evaluation in relation to intentions and a consideration of whether the intentions themselves remain sufficient in the current situation. If commitments to intentions and actions can be sustained, benefits from coordination will be sustained. However, in some circumstances, these coordination benefits will be insufficient to compensate for costs derived from sticking with intentions or alternatives that are no longer valid. To reason about what to do requires consideration of substitutability of alternatives with respect to intentions and interdependence among actions. In contrast to work in AI that seeks to automate such reasoning, we focus on computer-assisted human reasoning because the situations in urban planning cannot be completely specified.

2.3. Plans in urban development

Urban development plans, in contrast to the procedural focus on steps to achieve a goal state of AI plans, focus on representing intentions and outcomes. The implied expectation is that the steps toward a future state will arise among many actors over a long time subject to constraints and influence. Urban plans are usually considered documents that lay out the future of a place (e.g. Kelly and Becker 2000, Berke *et al.* 2006). These futures include projected infrastructure investments, such as locations of new roads, interchanges, extensions of sewer lines, new schools, and other public infrastructure. Each of these actions, as considered in the plan, is not yet realized. Each of these actions could have any number of attributes including location and a future date of its realization. Thinking about these as mere unordered lists of actions suggests that plans are final. It suggests that the planning processes have resolved all the interdependencies and considered all the constraints, and the final task, once the plan is formulated, is merely to act them out at prespecified times. In other words, plans are meant to be implemented. A variant of this view presumes that the mode of implementation is that any decision and proposed action that comes after making a plan should be evaluated for its consistency with the stated goals in the plan. This view assumes that the goal statements are stable regardless of future events or knowledge. Current data models in GIS are reasonably well suited for this view.

Recognizing that observed urban development planning is much more dynamic and multiorganizational (e.g. Friend and Jessop 1969), a more recent view of urban development plans focuses on how plans work: as agenda, policy, vision, design, and strategy (Hopkins 2001). Each of these modes implies a type of relationship among actions and a relationship of actions to intentions, which have been elaborated in a data model for encoding plans (Hopkins *et al.* 2005b, Kaza and Hopkins 2007).

An agenda is a list of actions to be taken. The actions have no internal relationships; the list is unordered. However, items in an agenda may have attributes that could create order, such as date of completion or a priority rank. Agendas could also account for constraints, such as cumulative costs relative to a budget constraint. In such cases, agendas become designs.

A design is a collection of prespecified relationships among actors, actions, assets, activities, and the relationships that bind them to achieve an intention. A design for urban systems is not elaborated as a situation that needs to be solved, but as a solution that has already been worked out. Designs could be about actions of actors or expected outcomes of those actions. These relationships include spatial, temporal, and functional relationships. For example, the proximity relationship between a school and residential zone is a spatial design. The sequence of actions in a highway project is a temporal design. The relationships between travel and wait times to the population density in transit oriented development are essentially functional designs.

A policy is an if-then statement, which is applied repeatedly given a situation (Kerr 1976). The given situation (the 'if' clause) may be attributes of the state of the world, actions, or a collection of these. The action prescribed (the 'then' clause) is taken by an actor and, thus, depends on capabilities of the actors to whom the policy is intended to apply. An example of a policy is to zone parcels commercially, if adjacent to the intersection of a collector and an arterial. This policy is triggered when areas for new development are zoned in light of street network plans.

Strategy involves uncertain outcomes and contingent actions. The initial node of the strategy is an action (or set of actions) contemplated by the actor. Because of the uncertainty of expected consequences of an action, planning necessarily involves considering

various unrealized but possible consequences. At a decision node, the actor can list a choice of actions that may be available to be taken and the uncertain consequences for each of those choices. Listing all possible outcomes is unrealistic, so a strategy is always incomplete at best. Unlike a decision tree, which is a methodological object to choose a particular path based on quantifiable objectives and probabilities, the strategy mode of plans is a frame for representing relationships among decisions and among their consequences. This frame changes over time, in light of new knowledge about intentions, alternatives, and states of the world. An example of a strategy is to trace the decision sequence of building a sewer trunk line and the optimal locations of pumping stations based on the topographical characteristics (actions that you can control) in anticipation of urban expansion (futures that you may not be able to control), which may or may not be realized (Hopkins 2001, Chakraborty *et al.* 2011).

The indeterminacy of relationships among actions in plans provides useful opportunities to expand on existing plans. It is imperative to acknowledge that to consider and encode all possible contingencies and interdependencies between various sets and subsets of actions is an unreasonable expectation of plans and planners. The plans specify only relationships between specific combinations of actions that are of particular interest to a particular decision maker at a particular time. Since these interests change over time, it is useful to consider planning as a continual process that makes and remakes plans.

2.4. Representation for reasoning with plans

Plans are partial considerations of decisions in light of various other decisions and situations. As Bruce and Newman (1978) pointed out in their elaboration of plans in the story of Hansel and Gretel, Hansel's pebble plan was contingent on the parents' plan to abandon him and his sister in the middle of the forest. Since plans are limited in scope, they interact crucially with other plans and others' plans. They are continually being discarded or modified as is warranted when new information is presented. As Bratman (1987) and other AI researchers have argued, the making and remaking of plans does not happen on a *tabula rasa*. Hoch (2007) argued that previous dialogues, intentions, and plans crucially frame new plans and realize actions in urban development, just as others have argued in AI. We argue that plans do not just represent a future state of the world, as conventional urban planning would have it. Neither are stepwise procedures for achieving goal states sufficient, as conventional AI would have it. A standard GIS' representation of space, even a dynamic one, is insufficient for plans because plans cannot be represented as mere spatial targets or actions related only spatially. There is a need to represent the relationships among actions and the intentions for those actions (Laurini 2001).

The project reported here focuses on devising an information system for urban development planning that relates actions to intentions and represents multiple plans that are not necessarily consistent. While spatial relationships are important, planning is mainly about sets of interrelated actions that have space as one of many attributes. Since agents, including persons, organizations, and institutions, are only boundedly rational, they cannot consider all such relationships and commit irrevocably to a complete plan prior to taking action. Instead, they make partial and overlapping plans. The contention of this article is that reasoning about actions, in light of multiple plans, will benefit from using the discovered spatial, temporal, and functional relationships between actions based in part on information in these plans. Unlike most AI projects we are not trying to automate this reasoning because planning situations are insufficiently specified. Unlike agent-based modeling, we are not trying to simulate the consequences of fully specified, interacting

agents. Rather, we are trying to articulate information systems to assist humans in using the information in plans to interact with one another, effectively.

In the next sections, we describe the information content in a plan that explicitly identifies structural relationships among actions and between actions and intentions. We argue that because plans already recognize these relationships within a plan, such recognition could formally frame the deduction of additional relationships of actions and intentions among plans in a computer-supported system for reasoning with plans.

3. Capabilities for reasoning with plans

An information system for reasoning with urban development plans requires three underlying capabilities: recognition and evaluation of alternatives with respect to intentions, recognition and analysis of interdependence, and coping with multiple plans that are incomplete and subject to change. The first two are framed in Table 1 and discussed in this section. Coping with multiple plans is summarized in Table 2 and discussed in Section 4.

Substitutability with respect to intentions enables consideration of newly recognized actions with respect to prior intentions or choice among actions with respect to newly recognized intentions. Interdependence among actions enables consideration of whether newly considered plans suggest changes in previously adopted plans. These interdependencies may be spatial, temporal, or functional, and thus build on concepts from GIScience. Substitutability and interdependence matter within and among plans. These capabilities cannot be automated independent of users. The capabilities explained in this section are thus heuristic, intended to assist plan users in reasoning among their own and others' plans by themselves and with others.

For example, in a transportation plan, two alignments for a road connecting points A and B are substitutable with respect to the intent of increasing road capacity or reducing travel time between A and B. The focus of representation in this case might be primarily spatial. The timing of construction may not be important. For an economic recovery plan, however, only shovel-ready projects are substitutes with respect to the intent of creating jobs soon. The newly salient intent of job creation can rely for efficiency of decision making on actions from existing plans, but based on different criteria. The transportation plan and economic recovery plan are likely interdependent. Job-creating projects will yield greater net benefit if they are also good projects from the transportation planning perspective and vice versa, though newly salient criteria of timing becomes pertinent.

3.1. Recognizing alternatives

Decisions are about choosing among alternatives. It is, thus, useful to identify which action sets are alternatives to each other. Plans inform decision making, so identifying and circumscribing alternatives is useful. Plans already constrain alternatives when choices about an action are deferred to the future. For example, a strategy that, under the contingency of a particular congestion pattern, keeps alive two possibilities, expanding mass transit service on a particular line or building a ring road, has not made a firm commitment. The strategy has, however, circumscribed the choice set. If either of these choices is an alternative to a congestion-pricing scheme that is advocated by another plan, then both choices are alternatives to that scheme. The plan about congestion pricing may come after the plan about ring roads and mass transit service, so an ability to recognize the expansion of the alternative set is necessary.

Table 1. Reasoning using a single plan.

Identification characteristics	Two actions are potentially	
	alternatives when	interdependent when
Geographic attributes	Share same location, are within a buffer, or have overlapping locations. Same action is proposed at different locations E.g., bike path and side walk are proposed along the same alignment. Multiple alignments for the 'same' road	Share topological relationships such as connectivity and contiguity E.g., connectivity between two bike paths; interchange and rezoning parcel next to it.
Nongeographic attributes	Share same responsible actor, duration, etc. E.g., DOT is responsible for building two roads in the same year.	Share temporal relationships. E.g., build ring road before building connectors Share functional relationships. E.g., Acquisition of RoW is necessary for building a road.
With respect to intents	Intents of the two actions are the same. E.g., expansion of a road and building a transit stop are both intended to reduce traffic on a link	Interact with each other's intents. E.g., Reducing the number of road lanes intending to make it more pedestrian friendly. Changing set backs on adjacent parcels intends to induce walking
With respect to effects	Produce the same effect. E.g., building the transit stop and expanding the road may reduce the link traffic (but not have same effect on air pollution)	Produce effects together that are different from sum of individual effects. E.g., building two stretches of bike paths together is better than building each individually.
Part of a design	Designs themselves are substitutable and design relationships are preserved in the substitution of parts. E.g., spatial arrangements of a design for a house, when the designs are translated as whole in space or in time. i.e. build the house now or 5 years later; build the house here or at a different location	By definition. E.g., in a transportation network, every link is interdependent with another, and actions about one can potentially affect any other link.
Part of strategy	Proposed as a response to the same set of possible futures; or partially substitutable if share a possible future. E.g., could build treatment plants at two possible locations, in response to possible pattern of urban development. If both new road and a transit investment, in a transportation strategy, change congestion on a link, in roughly the same way, and then they are substitutes.	Action sequences in a path of the bipartite graph (strategy) are interdependent. E.g., building a sanitary trunk at a location, may result in a pattern of urban development, which then necessitates building a new treatment plant. Then the trunk and the plant are interdependent

Note: RoW, rights of way.

Table 2. Distributive and transitive properties of semantic relationships.

Relation (B, C)	Relation (A, B)	Substitutes		Interdependent			
		Partial	Complete	Prior	Complements	Contingent	Part of
Substitutes	Partial	Nontransitive	A is partially substitutable with C if the evaluative criteria are the same				
	Complete	Possible partial substitutes when B and C are equivalent	Alternatives when using effects or attributes	Not determined when using relationships in policies or strategies A is prior to C	Under certain conditions, A is prior to C	Under certain conditions, A and C are complementary	C is contingent on A' when B and C are equivalent
Interdependent	Prior						
	Contingent		Possibly, A is prior to C		A is contingent on C		
	Part of		C'' which is generated from $(C \setminus B) \cup A$ could be substitutable to C				A is part of C

Two actions are perfect alternatives with respect to the specified criteria if they satisfy the criteria to exactly the same extent. The criteria can be intents, effects, constraints, utility, or any number of other measures. Imperfect or partial substitutes are two or more actions that perform equally well with regard to particular criteria and fare differently or are not comparable with regard to other criteria. Two actions can be imperfect substitutes if they share the same intent but produce different effects or are spawned by completely different intents, but are considered substitutable due to restrictions on capabilities. For example, budgetary constraints may force a choice between upgrading an existing road and building a new road; they are substitutable with respect to the constraints even if they share neither intent nor effects, such as realized traffic or development patterns. If an actor is willing to trade-off as equivalent the performance of each action with respect to a particular subset of criteria, then they are perfectly substitutable for that particular actor.

Two actions may be substitutable if they share the same geographic attributes or if the same action is proposed at different locations. For example, a school can have two potential sites and therefore the choice of one precludes another. By the same token, a school and a park may be proposed on the same site and therefore the choice of one precludes another. It is useful to note that the fuzziness of geographical attributes of an action is not necessarily linked to error in measurement or representation in GIS (e.g. Campari 1996), but is fundamentally about the partial commitments that plans make.

Similar fuzziness exists with the temporal attribute of the action. Choosing to defer an action is a choice between two substitutable actions with two distinct time attributes. An action $A_{t,actor_1}$ is substitutable in some degree with actions $A_{t+\epsilon,actor_1}$. The degree to which ϵ renders an action not substitutable for the original action is a judgment call by the decision maker. Nevertheless, heuristically, any actions that differ only in the temporal attribute could be considered potential alternatives. For example, choosing to build a road now and choosing to build it 10 years later could be potential alternatives.

Actions are carried out by actors and are, thus, restricted by what actors are able to do. When explicit ownership of an action is assigned to actors, then capability restrictions may force a trade-off between actions that can be performed by the same actor. Thus, if two actions share the same responsible actor, then the pair is tagged as potential substitutes. Even when the effects of each action in the pair are not the same, doing one may preclude the other, and hence it is worth recognizing these trade-offs. From this list of actions that share the same actor, we can weed out the actions that are interdependent with each other because the presence of a design relationship between the two actions may override the capability restriction. For example, if the DOT is responsible for two actions, acquiring land and building an interchange, then it is clear that both actions have to be accomplished to build an interchange. In this case, these actions are not substitutable for each other. These interdependency relationships are elaborated in the Section 3.2.

We can also infer substitutability relationships from preexisting designs in plans. One set of interrelated actions is substitutable for another set of actions as a whole in the same fashion as individual atomic actions are substitutable. The two designs could share the same location and the same responsible actor, and they could be translations of the same design in time. Both of them could have the same effect or could serve similar intents. For example, a design to build a school at a particular location and an expansion of the adjacent road, would be substitutable for the same set of actions at a different location because the goals are the same in both cases. Designs are substitutable when their intents are the same or their effects are the same. These two designs could be in different plans, for example, one in a plan by the city and another in a plan by a neighborhood group.

Other criteria can be used to discover the substitutability of designs by discovering whether the actions that compose the design can be substituted. Such substitution of the parts of a design should, however, preserve the relationships within the design. For example, if *Precedes* (A, B) (i.e., if A precedes B) is a part of a design, then as long as the change in the attributes of A (say change from $A_{t_1, actor_1}$ to $A_{t_2, actor_2}$) does not affect the precedence relationship with B, then the two As are substitutable with respect to the design. When the relationships within the design are altered, if the effect remains the same, then the designs are substitutable for each other with respect to effects.

Similarly, we can use strategy to decipher substitutability relationships. Actions that are potential responses to a contingent state are alternatives with respect to each other. If building a new school and expanding an existing school are possible responses to a contingent event of a threshold population growth, then they are alternatives to each other. Representation of the strategy as a graph allows us to derive general principles through which these relationships can be deduced. Most importantly, if two actions are alternatives from a contingent state, then all the succeeding subgraphs from those actions are alternatives.

A single plan will have strategies and designs identified within it. We can use the substitutability rules derived from the attributes of the actions heuristically to identify potentially substitutable actions across plans. If two actions A_1, A_2 in one plan are substitutable with respect to a design, and another action B_1 in a different plan is substitutable for A_1 as part of a strategy of a different actor, then A_2 and B_1 are potential substitutes. The substitutability of B_1 and A_2 is not explicitly identified in either plan because it has not been considered while making either plan. When reasoning with the information provided in the plans, however, heuristic tools suggesting that this potential substitutability be considered can help make more informed decisions. Such reasoning among plans is discussed in Section 4.

3.2. *Recognizing interdependence*

This section provides a template for identifying actions that are interdependent based on temporal and functional relationships. Of the many interdependent relationships that are useful for urban planning, temporal relationships including sequencing, simultaneity, and functional relationships which include composition and priority are discussed here in relation to event-based approaches in GIScience. Recognizing how an action affects other actions under consideration is the task of making interdependence explicit as summarized in the right-hand column of Table 1. For example, building a school is dependent on the acquisition of a site. Building a new interchange is complementary to rezoning a neighboring parcel into higher intensity uses. Some of these interdependencies are recognized in designs within a plan.

Grenon and Smith (2004) distinguished two different modes of representing event relationships. One is SNAP shots of states arranged on the temporal axis, and the other is focused on the processes (existence, modification, etc.) that occur in a SPAN of time. Both kinds of representation are useful, and the proposed reasoning system considers both modes of representation without too much emphasis on the rigorous and exact translations between the two. Activities such as shopping, travel, or residing are processes, and the levels of activity such as volume of sales transactions or traffic count on a link are also SNAP shots of states. Thus, an action A_1 can occupy an interval of time (t_1, t_2) , and its purported outcome S1 may occupy (t_3, ∞) with $t_3 \leq t_2$. If on the one hand A_2 has to precede A_1 and occupies an instant of time, then it should occur before A_1 . If on the other hand A_2 brings

about S_2 that is a prior for S_1 , then A_2 has to occur before t_3 . It may be the case that the only information available is that A_1 takes 2 years to complete, irrespective of the start date. The precedence relationship of A_1 and A_2 is still valid and useful.

If action A occurs or need to occur before or after B , then, they share temporal relationship. Allen and Ferguson (1997) discussed the representation of temporal events and relationships and reasoning with them. The key temporal attributes of and relationships between events are precedes lags, succeeds, simultaneity, occupies, and overlaps. Actions individually may have attributes such as beginTime, endTime, and requiredTime from which the temporal relationships between actions can be deduced. Grenon and Smith (2004) argued that reasoning with partial orders is sufficient for most purposes of planning. In other words, the events need not be completely ordered in time and the relationships need not be immediately apparent or deducible. For example, A precedes B and C precedes B taken together make no claim about the precedence or any other relationship of A and C .

If the precedence relationship between two actions is not deducible from the partial order, then the actions may or may not be simultaneous. The requirement of simultaneity is a much stronger relationship than an absence of precedence order. Simultaneity often indicates complementarity, but not vice versa. Building the interchange and building the ring road segments in Figure 1 are complementary, but they need not be simultaneous. On the other hand, actions such as ceding the right of way (RoW) and rezoning the RoW consistent with the neighboring parcel can be simultaneous and often are complementary actions.

An action can also be functionally prior to another either temporally or functionally. If action A occurs before or after B , then they share a temporal relationship. In this section, we are primarily concerned with the functional priority relationships of actions. An action A is functionally prior if it is necessary before the occurrence of B . In other words, if we decide to do B , we have implicitly decided to do A . Thus, functional priority is dependency or otherwise called contingency. An action A is functionally prior to B , if it is necessary before the occurrence of B .

These functional relationships should be generated from the local and legal context. If we decide to build an airport, we then have also committed to acquire the land and zone it appropriately. Similarly, building a road requires that RoW be in place, trunk sewers be extended, and utility easements be in place. These functional relationships between actions are well understood by planning experts and can be encoded from existing reference books such as Watson *et al.* (2003). Standard land-use planning texts such as Berke *et al.* (2006) could also be used to crystallize existing professional knowledge to identify functional relationships; for example, 'Churches, community centers, clubs, and other local community serving institutions will have land reserved in convenient locations, on circulation networks' (p. 389). Thus, the functional relationship of access of the community service facilities translates into a spatial relationship between circulation networks (bus routes, roads, etc.) and the land reserved for them.

One way to look at the composition relationship is to view it as a design relationship among multiple actions. In other words, the sequential actions in constructing a highway, such as land acquisition, grading of alignment, bridge construction, paving, and so on, constitute a design. Once the design is specified, we can encapsulate the lower order actions and specify the relationships between higher order designs. If, however, there are interdependence relationships between lower order actions and some other actions not included in the design, encapsulation loses information. On the other hand, such encapsulation preserves tractability of reasoning without resorting to decomposition to atomic actions and relationships. Composition (mereological) relationships are studied in the abstract representations

of geography in Casati and Varzi (1996). Similar reasoning could be applied to actions and events in understanding the relationships between them. Parthood relationships are typically considered partial orderings that are reflexive (A is a part of itself), antisymmetric (If A is a part of B and vice versa, then A is B), and transitive (If A is part of B and B is part of C , then A is part of C). We argue that recognizing actions in the urban development context as parthood relationships, among other design relationships such as spatial, temporal, and functional, will help us in uncovering relationships among actions. For example, if action A is part of B and B is temporally prior to C , and if D is part of C , we can conclude that A is temporally prior to D . We now turn to such reasoning among multiple plans.

4. Reasoning with multiple plans

Given two sets of substitutable actions, can we infer substitutability between actions across the sets? Given a set of interdependent actions, if some elements of this set are replaced with substitutes, will the interdependence still hold? In the earlier sections, we have identified substitutability and interdependence relationships through consideration of attributes of actions and the relationships of actions to one another. We have also identified various types of reasoning about substitutability and interdependence relationships.

In this section, we use relationships that are already represented to discover other relationships or to determine whether relationships change with consideration of other actions or attributes. For example, if a ring road and arterial connectors to the center of the city are interdependent because they are complementary, and if two alternative locations of the ring road are specified in another plan, what is their relationship with the arterial connectors? Heuristic approaches to identifying some of these relationships focus on transitivity and persistence of substitutability and interdependence relationships. These heuristics are summarized in Table 2 by considering what might be inferred from two given relationships of actions, A with B and B with C , for the relationship of A and C .

When actions in a pair are completely substitutable, then partial substitutability is transitive provided the evaluative set remains the same. If a subsidy and a regulation are perfect substitutes for each other with respect to a particular environmental effect, then any action that is partially substitutable for either is partially substitutable for the other with respect to the effect. However, caution is recommended for this mode of reasoning. Consider the case described in Figure 2. While A and B as a pair are partially substitutable for A and D with respect to the intent of creating a bypass around the Marengo area, D and E are alternative locations for the same project. The combination of actions A and E is partially substitutable for the combination of A and D . However, the presence of the connectivity



Figure 2. Partial substitutability of alternatives.

relationship between A and D and the absence of connectivity between A and E make them poor substitutes. Such judgments can only be made if there is an explicit record of the connectivity relationships between A and D as a design. Consider, for example, a highway and a transit project that are partial substitutes with respect to congestion, budget, and green house gas reductions, but complete substitutes with respect to congestion alone. It might be useful to recognize in such situations that there are also other complete substitutes with respect to congestion, such as congestion pricing.

Complementarity of two actions is often due to the specific configuration of these actions, so that the effects they generate are superadditive. Thus, if substitutes of these actions are considered, then it is unlikely that they retain the same configuration of relationships as between the original actions. This makes complementarity between substitutes likely. In Figure 2, while D is substitutable for E , A and E are not complementary by virtue of nonconnectivity. This suggests that a particular configuration of relationships between A and D (in this case connectivity) is a necessary prior for complementarity. When these particular configurations are explicitly identified, we can use substitutable parts to preserve interdependence of the whole if the configuration is not disturbed. When the location of A is shifted to A' so that A connects to E then (A, A') and (D, E) are pairwise substitutes and A' and E are complements.

On a similar note, functional dependence (unidirectional dependence such as priority) is not necessarily retained. If acquiring a RoW has to occur prior to building a road at a location L_1 , which is substitutable for another location L_2 , then acquiring RoW at L_1 is not useful to build a road at L_2 . However, such recognition may prompt questions about the degree of substitutability and the attributes over which the substitutability is evaluated. That is, if RoW is already acquired at L_2 , then building a road at L_2 may become more attractive in comparison to building a road at L_1 .

It is possible, however, to infer some interdependencies that are not already discovered. If an action A is equivalent to another B (i.e. A is the same as B except for a translation in space or time), then all the functional priors of A similarly translated are priors to B . If the priors of B are not explicitly recognized, then the planner should be prompted to do so or to give sound reasons why such is not the case. Both functional and temporal priority relationships are partial orders among actions. Since translation as an operation in space and time is uniquely invertible, the same partial order is preserved in the translation.

Functional priority is preserved between equivalent actions. However, if two actions are substitutable due to other constraints, such as capability or intent, then the functional priors of each may not be priors of the others. Similar reasoning holds for temporal priority. If B is substitutable to C with respect to an intent, but A and B are part of a design with temporal relationship such as lag, (A, B) , it is not necessary that lag, (A, C) holds. Therefore, B and C are not substitutable with respect to the design even when they substitutable with respect to the intent. The lag time of acquiring RoW for a highway or a light rail may be different, even when the two projects are substitutes with respect to intent.

Composition relationships, on the other hand, are transitive. Especially in the naive sense we are interested in, these relationships can be represented as another partial order. A is a part of B , which is a part of C , and thus A is a part of C . Exceptions to these rules and more sophisticated analysis of composition relationships are left for further work.

In Section 5 we demonstrate how these relationships and the ways in which they are likely to be sustained or disrupted in the face of newly considered intentions or actions can be used to support using and making plans. These use cases demonstrate that a database can be created and that queries can be written that would assist planners in reasoning with multiple plans.

5. An ISoP that supports reasoning with multiple plans

To demonstrate how these ideas can be applied, we created a small ISoP based on the work in McHenry County, Illinois. Examples from this system illustrate how computer-supported reasoning with plans would work and are not meant as outputs from a real plan inference engine. The main point is to demonstrate that information about intent, interdependence, and substitutability are crucial to reasoning with plans.

These databases are action centric and include 101 action items: 50 from the 2020 Unified Plan for McHenry County¹, and 51 from 10 other plans including plans for local municipalities, regional planning agencies, regional transit agencies, neighboring counties, and conservation districts in two separate databases. The Unified Plan includes three designs, and all the other plans in the databases include another three designs. The relationships among strategies and designs within each plan are identified and encoded in the databases along with other attributes such as intent, effects, and responsible actors. Where pertinent, locational attributes of these designs and their constituent actions are also encoded. Details of these databases and the encoding of heuristic support for queries are provided in Kaza (2008).

We return to the example described in Section 1. Figure 3 illustrates the operationalization of multiple plan databases of the content in Figure 1. The plans have much more complex information within them, but we focus here on the information pertinent to our use cases. The city of Marengo's comprehensive plan called for building or connecting all four segments of the ring road and also argued for protecting the Kishwaukee basin by not extending utilities as shown in Figure 3a. The McHenry County's Unified Plan argues for an expansion of US 20 and the northeast and the southern segments of the ring road as in Figure 3b. The regional planning agency, Northeastern Illinois Planning Commission (NIPC), specified a full directional interchange between IL 23 and I 90. The expansion of IL 23 and the ring road west of Marengo (southwest and northeast segments) are complementary to the interchange as shown in Figure 3c. On the other hand, McHenry Conservation district has the intention of acquiring properties along the Kishwaukee basin as in Figure 3d. The soil conservation district is interested in protecting the high-quality soils in the southwest corner of the county. The neighboring Kane County proposes a full directional interchange between US 20 and I 90.

From the various heuristics, it is also possible that these two interchanges might be identified as possible substitutes. That is, a user might have queried the database of plans for proposed projects including 'I 90,' projects with Actor identified as the 'Illinois Department of Transportation,' (IDOT) projects labeled 'interchanges,' or projects with the intent of 'interstate access for McHenry County.' The response would be a list of projects, the plan in which they are included, the intent, the location, and the responsible party for the project. The response to those queries would suggest that the interchanges are substitutes, because there are norms about distances between interchanges on toll roads and no one plan is proposing both of them.

The NIPC plan explicitly recognizes the interdependence relationships between expansion of IL 23 and the interchange between IL 23 and I 90 because they are part of a design encoded in the information system as having these design relationships. The Unified Plan recognizes the design that includes the expansion of US 20 and building the northeast segment of the ring road. Because of the connectivity relationships between US 20 and

¹The McHenry County Unified Plan used in the project was a draft plan and was never officially 'adopted.'

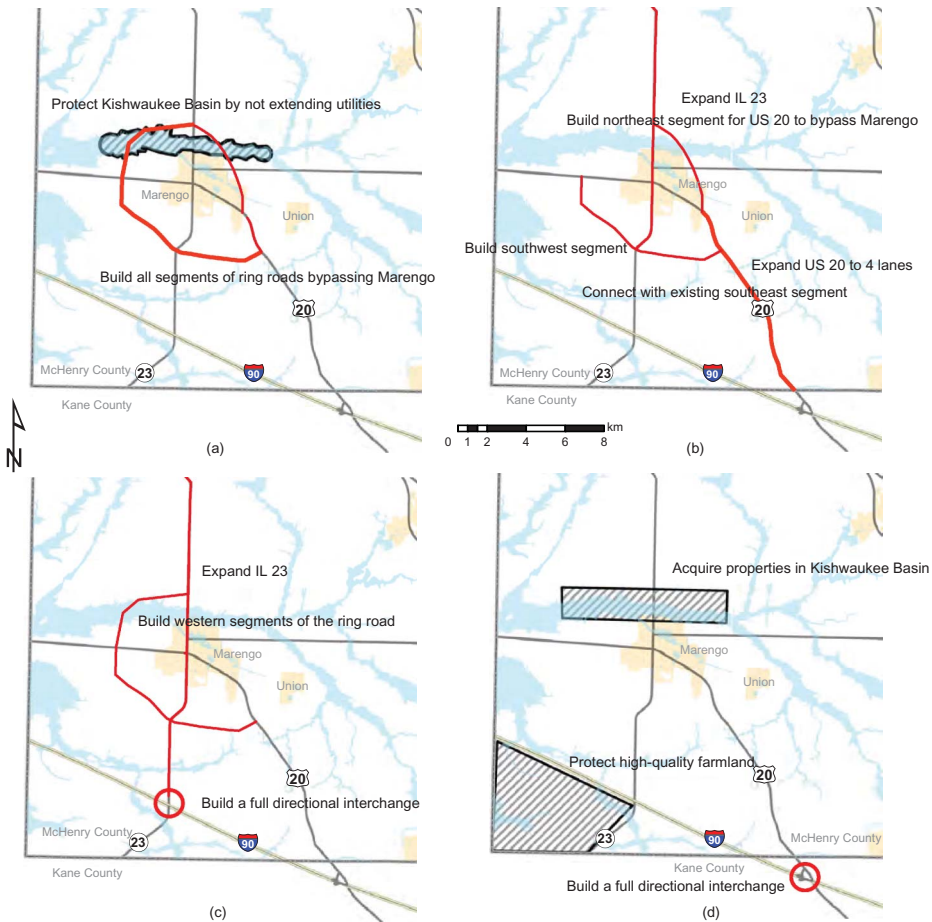


Figure 3. Heuristic reasoning with interdependence and substitutability: (a) Marengo's Comprehensive Plan (b) McHenry Unified Plan (c) Northeastern Illinois Planning Commissions Common Ground Plan, and (d) Other plans such as Kane County Transportation Improvements Plan, McHenry County Conservation District's unannounced plan.

I 90, the user can then infer the interdependence relationship between expansion of US 20, the interchange in Kane County, and the northeastern segment of the ring road in various plans. Once such inference is made, these elements, in different plans, constitute a design from the perspective of a particular user and recognition of such relationships and can be encoded into a user's view of the database for future use.

The potential substitutability of constituent parts of the designs (two interchanges with different road expansions and constructions in two different plans) allows us to use heuristics to make judgments about other actions that compose the designs. It also raises questions about effects that may be newly important and interdependence with other plans. The designs in and of themselves may be potentially substitutable because they share the same intent to provide interstate access to McHenry County. Furthermore, within the Unified Plan the northeast segment of the ring road and the south ring road are substitutable because they have the same intent to divert traffic away from Marengo. However,

the other parts of the designs (expansion of IL 23 and US 20) are not substitutable, because the interdependence relationships are not preserved.

The interchange at IL 23 and I 90 also adversely impacts the soil conservation group plans of protecting the high-quality farmland southwest of Marengo. Thus, by recognizing the substitutability of the two interchanges, the soil conservation group would identify the interchange at US 20 and I 90 as a complementary action to its own designs of protecting the farmland from development.

Expansion of IL 23 north of Marengo, which is a project in the Unified Plan, is complementary to either interchange, in contrast to expansion of IL 23 south of Marengo, which is complementary to an interchange at IL 23 but not to an interchange at US 20. The interchanges themselves are alternatives, so the user can investigate the nature of substitutability between the action items that make up the designs for each interchange, but are not necessarily substitutable element by element with respect to all intents, effects, or interested parties.

This sets the stage for another example of how the system could support additional interest groups. Another coalition is championing the acquisition of the parcels along the Kishwaukee River, just north of Marengo, by the McHenry Conservation District. Irrespective of which interchange gets built, the parcels along the IL 23 corridor north of Marengo will be provided with higher access to a transportation network. Hence, the conservation district would prefer to speed up the acquisition of land regardless of which interchange is to be built. Furthermore, the acquisition is partially substitutable for Marengo's actions of not extending the utilities in the Kishwaukee Basin. If a user also identifies that an interchange at IL 47 and I 90 (not shown in Figure 3 and east of the region shown in the figure) is an alternative to either of these two interchanges, then since the Kishwaukee Basin is not affected by the building of that interchange, the conservation district interests may view an IL 47 interchange as a complementary action to their own conservation efforts. From this reasoning, the conservation district might decide to advocate for the interchange at IL 47 because this interchange would serve the intent of improved access from I 90 to McHenry County, but not have a direct effect on the Kishwaukee basin and would reduce the likelihood of the other interchanges being built because they are substitutes from the perspective of the IDOT because of norms about distance between interchanges.

These illustrations demonstrate how the encoding of intentions and interdependence relationships among actions in plans and heuristic support for reasoning among plans could support many users of plans. Substitutability and complementarity are the important questions dependent on intention of actions. Whether actions can be inferred to be substitutable or complementary depends importantly on interdependence in design or strategy relationships among actions within and among plans.

6. Caveats and conclusions

The widely recognized limitations of conventional GIS as support for urban planning present two related challenges: (1) devising an appropriate data model for data in plans and (2) devising queries that can use these data to support planning. In the larger project of which the present research is only a part, we have developed a data model for plans that recognizes the importance of focusing on actions and their relationships as designs or strategies in plans. In this article, we have explained the kinds of reasoning that should be supported so that users of plans can decide what to do, that is, support plan-based decision making.

We have argued that databases of plans must include attributes of actions (or projects), including in particular the intent of the action and the relationships among actions. The tools for querying these databases should focus on heuristic reasoning about substitutability and complementarity with respect to intentions and the dependence of these on interdependence among actions. Interdependence among actions is the fundamental structure of plans and we have demonstrated through examples how such interdependence affects substitutability and complementarity.

This work is intended as the theoretical basis for building ISoPs. However, irrespective of the availability of computer-supported reasoning, the above methods are useful in thinking about plans in different ways than in the past. Plans are not simply outcomes; they are information about intent and relationships among actions. The argument is that by structuring the information in multiple plans in consistent fashion, we can begin to reason with these plans by discovering alternative actions and interdependent decisions. The use cases above suggest that such reasoning is useful and that the technical aspects of such an ISoPs are feasible. Many obstacles remain, to implementation of such systems, not least of which is organizational willingness to share plans in a consistent manner that is amenable to reasoning. The long and sometimes painful experience of building standardized spatial data frameworks in GIS should provide us with useful insights for building information systems that support reasoning with plans.

Acknowledgements

The authors are greatly indebted to Mike Worboys, Robert Laurini, Varkki Pallathucheril and Kieran Donaghy for all the comments and insights that they generously gave on previous versions of this work.

We also thank the editors and anonymous referees for their comments that improved the manuscript. These ideas were developed while working on related projects funded by the U. S. Army Construction Engineering Research Lab, the University of Illinois at Urbana-Champaign Research Board, and the Illinois Department of Natural Resources. This acknowledgement does not imply endorsement of ideas presented in this paper, for which we take sole responsibility.

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