# Towards a Typology of Spatial Decision Problems*

Salem Chakhar[†], Vincent Mousseau[†]

### Résumé

L'objectif de ce papier est de présenter une typologie des problèmes spatiaux. La typologie proposée est obtenue par un croisement entre les différents types d'entités spatiales associées aux actions potentielles (i.e. point, ligne, polygone ou réseau) et les différents modes qui peuvent être utilisés pour approcher les problèmes spatiaux (i.e. statique, temporel, temps réel ou séquentiel). La combinaison de ces deux dimensions donne exactement seize familles de problèmes spatiaux de base. La typologie obtenue n'intègre pas explicitement les problèmes impliquant des actions représentées par des entités composées. Néanmoins, elle reste adéquate pour décrire la plupart de ces problèmes du fait que ces derniers sont souvent décomposés en une série de problèmes de base impliquant chacun une seule action atomique.

**Mots-clefs :** Problèmes spatiaux, Actions potentielles, Typologie, Dynamic spatiale

### Abstract

The aim of this paper is to establish a typology of spatial decision problems. The proposed typology is obtained by a crossover between the different types of spatial entities associated with spatial potential actions (i.e. point, line, polygon or network) and the different modes that can be used to approach spatial decision problems (i.e. static, temporal, real-time or sequential). The combination of these two dimensions provides exactly sixteen basic families of spatial decision problems. The obtained typology does not include explicitly problems that involve actions based on composed entities. Nevertheless, it is still adequate to describe most of them since these last ones are usually decomposed into a series of basic problems, each one involves only one atomic action type.

**Key words :** Spatial decision problems, Potential actions, Typology, Spatial dynamics

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[*] An earlier version of this paper was presented at *The 58th Meeting of MCDA European Working Group, Moscow, Russia, October 9 to 11th, 2003.*

[†] LAMSADE, Université Paris-Dauphine, Place du Maréchal De Lattre de Tassigny, 75775 Paris Cedex 16, France. `{chakhar,mousseau}@lamsade.dauphine.fr`

# 1 Introduction

Spatial decision problems may be roughly defined as those problems in which the decision implies the selection among several potential actions or alternatives[1] that are associated with some specific locations in space. Examples of spatial problems include: facility location, health care planning, forest management, vehicle routing, administrative redistricting, etc. In all these examples of spatial decision problems, the potential actions are characterized at least with their geographic positions and the selection of the appropriate one(s) will depend on the satisfaction of some space-dependent constraints and the ’optimization’ of one or several space-related evaluation criteria.

Spatial decision problems are the concern of researchers from diverse disciplines (e.g. economists, planners, environmentalists and ecologists, politicians, scientists, etc.) that have different concepts and paradigms. Indeed, each of these researchers has a different perception and conception of real-world, which is in relation with its objectives and preoccupations. Thus, to improve the understanding of the aspects and the specificities of these problems and to establish an adequate framework for multidisciplinary researches, we think that the elaboration of a classification of spatial problems in a purely abstract form, devoid of any socio-economic, political, environmental, etc., contexts, is a good starting point.

The objective of this paper is thus to present a typology of spatial problems which is obtained by crossovering the different types of potential actions (as spatial entities) with the different modes that can be used to approach spatial decision problems. In fact, in spatial decision-making context, potential actions are usually assimilated to one atomic spatial entity[2] (i.e. point, line, polygon or network) or to a combination of several atomic spatial entities. Furthermore, spatial decision problems involve several spatial, natural or artificial, objects and phenomena, which have an inherent dynamic nature. In practice, however, this inherent dynamic nature of real-world may or not be taken into account. This depends on the nature of the spatial system to which the problem under consideration refers and equally on the objectives of decision-making. Hence, we may distinguish four ways for approaching spatial problems: static, temporal, real-time and sequential.

These ways of representing spatial potential actions and of approaching spatial decision problems are orthogonal and all combinations are possible. The combination of these two dimensions provides exactly sixteen basic families of spatial decision problems that will be detailed in §6. The obtained typology does not include explicitly problems that

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[1] The two terms ’action’ and ’alternative’ are slightly different. In fact, the term ’alternative’ applies when actions are mutually exclusive, i.e., selecting an action excludes any other one. In practice, however, we may be called to choose a combination of several actions (see, for e.g., example 5 in §6.3), which violates the exclusion hypothesis. In this paper, we adopt the term ’action’ since it encompasses both ’action’ and ’alternative’ terms.

[2] In this paper, ’spatial entities’ are conceptual abstractions of real-world objects, events and phenomena that are located in space or going on some locations in space (see §3).

involve actions based on composed entities. Nevertheless, the typology is still adequate to describe most of them since they are usually decomposed into a series of basic problems, each one involves only one atomic action type.

The rest of the paper is structured as follows. In section 2 we present some existing typologies. Section 3 is devoted to present some characteristics of spatial entities and to illustrate their inherent dynamic nature. Next in section 4, we distinguish the different possible ways for approaching spatial decision problems. Section 5 shows how spatial potential actions can be represented with spatial entities. Then, section 6 is devoted to present our typology. At this level, we first distinguish and detail two general typologies, and then a series of illustrative examples are provided in order to better appreciate the characteristics of eight different families of problems. Follows in section 7, we show how problems that involve complex actions can be represented and modelled as a series of atomic actions-based problems. Finally, section 8 concludes the paper.

## 2 Some existing typologies

An intuitive classification of spatial decision problems is the one based on the socio-economic and/or environmental domain to which the problem refers. We distinguish, for instance, facility location, land-use planning, service coverage, resource allocation, health care planning, vehicle routing, redistricting and forest management problems.

Spatial problems, as non spatial ones, can also be regrouped according to the quantity and the type of available information into (Leung, 1988; Munda, 1995; Malczewski, 1999): ($a$) deterministic problems ($b$) stochastic problems, and ($c$) fuzzy problems, which are respectively based on the use of perfect, probabilistic, and imprecise information.

Keller (1990) classifies spatial decision problems according to the number of criteria and the number of deciders that they involve. He identifies four classes: one class contains some problems that involve only one criterion and only one decision-maker, two classes containing some more problems which involve respectively only one criterion and several decision-makers or several criteria and only one decision-maker, and a class that contains problems that involve several criteria and several decision-makers. Keller (1990) points out that most of spatial decision problems belong to this last class.

Jankowski (2003) subdivides land-related decision problems into four common types: ($a$) *site* (or *location*) *selection*, concerned with the rank of a set of sites in priority order for a given activity (e.g. what site might best be for a particular type of business?), ($b$) *location allocation* concerned with stating a functional relationship between the attributes of the land and the goal(s) of the decision-maker(s) (e.g. where to locate a new fire station so that the least amount of the population has no more than 10 minutes response time?), ($c$) *land use selection* (or *alternative uses*) looking in ranking the uses for a given site in priority order (e.g. given a property, what can it be used for?), and ($d$) *land-use allocation* looking in defining the best uses for an array of sites (e.g. how much of the land should be allocated for the following uses: forestry, recreation, and wildlife habitat?).

The first classification seems to be of a general interest. However, it tells nothing about the specificity of each family of problems and focalizes only on the socio-economic and/or environmental contexts to which problems belong. The two next typologies are not specific for spatial context. Besides, groups in both of them are large, making it difficult to extract out their common and general characteristics. Moreover, in the second classification, one problem can be assigned indifferently to the three groups according to the accuracy of the available data, which may evolve over time. Additionally, in real-world problems we usually make use of a mixture of deterministic, probabilistic and fuzzy data, which complicates the assignment of the problem under study to a given class. The fourth typology focuses only on land-use and consequently ignores a large spectrum of spatial problems. Finally, all typologies do not include explicitly the temporal dimension of spatial decision problems and ignore the specificities of spatial potential actions.

# 3 Spatial entities and their dynamics

Maguire et *al.* (1991) distinguish four families of spatial entities: ($i$) physical objects such as buildings, highways, etc., ($ii$) administrative units like communes, counties, parks, etc., ($iii$) geographic phenomena such as temperature, disease distribution, wind fields, etc., and ($iv$) derived information representing non-real phenomena such as ecological and environmental impacts of a nuclear central, suitability for cultivation, etc. Notice that in geographical information system (or GIS) community, geographic phenomena (or non-real phenomena) are considered as spatial entities when they are geographically located with their proper attributes (e.g. temperature or precipitation in Paris), with the geometric forms that represent them on maps (e.g. Severe Acute Respiratory Syndrome, or SARS, disease distribution in southern-east Asia may be represented with several polygons corresponding to the affected countries or zones), or with both of them (Bedard, 1991).

Whatever their natures, spatial entities have several characteristics that distinguish them from non spatial data. These characteristics are generally regrouped into several dimensions. Stefanakis and Sellis (1997) enumerate six dimensions along which spatial entities are defined. The ones that are relevant in this paper are: ($a$) *thematic* (or *descriptive*) *dimension*, which describes non spatial characteristics of entities (e.g. soil type, parcel number, color, PH, civil address, etc.), ($b$) *spatial dimension* that describes the spatial characteristics of geographic entities in terms of *position*, *geometry* and *topology*, and ($c$) *temporal dimension*, which describes the temporal characteristics of geographic entities in terms of *temporal position* that represents the occurrence (e.g. date of facility construction), or duration (e.g. period of land ownership) of spatial entities in or over time, *temporal behavior* that refers to the evolution of geographic entities in time, and *temporal topology* that describes the spatial and functional relationships between geographic entities induced by their temporal position or behavior.

The association of thematic and spatial dimensions with temporal dimension confers an inherent dynamic nature to spatial entities. This dynamic nature is the result of a series of changes (natural or not) that touch one or several thematic and/or spatial characteristics of geographic entities. Basing on the works of Claramunt et *al*. (1997) and Frank (1999), Lardon et *al*. (1999) distinguish three types of changes induced by time over spatial entities: ($a$) *thematic changes* that refer to the ones that affect the descriptive characteristics of geographic entities without modifying their existence and their spatial extensions (e.g. evolution of the population of a town), ($b$) *spatial changes* that refer to changes in the spatial characteristics (i.e. position, geometry and topology) of entities that modify their spatial extensions (e.g. successive extensions of urban fabric of an agglomeration) or result in the movement of these entities (e.g. movement of fire fronts), without alerting their existence, and ($c$) *identity changes* that refer to changes that modify the identity of geographic entities: entities may be divided, regrouped, combined, etc., (e.g. definition of new cadastral or new pasture unities).

Actually, spatial entities are subject to a mixture of changes. A forest fire front or a flock of animals moves and changes form, velocity, and direction. Yet, a plane in navigation or an ambulance in service moves without changing its form. In the management of a hydraulic system, it is generally the level of water that changes. In a forest management problem, changes may affect the form (as a result of the plantation of new zones, or disappearance of some other zones following, for example, an excessive exploitation or a severe drought), the topological relations (as a result of the construction of new routes), and/or the thematic characteristics (introduction of new animal or vegetal species). Nevertheless, in practice attention is generally limited to only some aspects of changes as some ones are not pertinent to the problem under focus and because some others are conducted in a very low rhythm in comparison with human life (e.g. movement of continents).

In literature, dynamics of real-world is essentially addressed in database-oriented contexts where the main objective is to represent and digitize spatial entities and their dynamics. However, here, this dynamic nature should be appreciated in terms of the spatiotemporal evolution of the consequences and impacts of spatial potential actions. Indeed, spatial potential actions are often represented with one or a combination of several atomic spatial entities, and the consequences and impacts of these actions are usually assimilated and measured via the thematic and spatial characteristics of the spatial entities that represent them. In addition, consequences and impacts of spatial potential actions are dispersed over space and in time, which means that thematic, spatial and identity changes that affect spatial entities apply also to these consequences and impacts.

## 4 Modes for approaching spatial decision problems

Along with the nature of the problem and the objectives of the study, spatial entities may be classified into *static* or *dynamic*. Static entities are those which have not time-

varying characteristics (e.g. buildings, mountains). On the contrary, dynamic entities have at least one of their spatial or descriptive characteristics that vary in time (e.g. lacks, rivers, highways where traffic rate changes dynamically, etc.).
In several situations, the dynamic nature of real-world is considered to have no effects on the outcomes of the decision-making process. In practice, however, the high equity of spatial decisions and their long-term impacts on population and environment impose, to some extent, an explicit incorporation of the dynamic nature of real-world into problem formulation, modelling and resolution. Accordingly, we can distinguish two different perceptions of the decision environment:

- a *static perception* in which the inherent dynamic nature of geographic entities and of their functional and spatial interactions are not recognized because they have no significant effects on the achievement of the decision-making process, or because their handling is expensive and/or complicated, or
- a *dynamic perception* in which the evolutionary nature of the decision environment is explicitly integrated in the problem formulation and modelling.

An explicit integration of real-world dynamics requires the availability of perfect predictions of real-world changes. In some situations changes of real-world may be captured quite accurately through forecasting and projection of current trends. However, in several other practical situations, it is not possible (or difficult and/or expensive) to produce such predictions. The solution generally adopted in similar situations consists in a decomposition of the initial problem into several sub-problems, which are addressed sequentially in time. The idea of decomposing spatial problems into a series of sub-problems is also useful for addressing problems that involve decisions that their implementation is of high equity. The incorporation of the dynamic nature of real-world may also be imposed by the dynamic nature of the spatial system to which the decision problem refers.
Consequently, along with the nature of the spatial system to which the problem under consideration refers and the objectives of decision-making, and whether real-world dynamic nature is considered or not and the manner by which this dynamic nature is handled, spatial decision problems may be addressed according to one of four possible visions: static, temporal, real-time and sequential. The following paragraphs provide brief descriptions of these visions.

**Static vision** In static vision we consider that real-world is *stable* over time. Accordingly, this vision applies to problems with no or less equity and involves short or medium-term spatial decisions that have immediate consequences. In trip itinerary selection problem, for instance, decisions are generally tackled within ad hoc manner and the cost of a ’poor’ decision is simply put more time to arrive. Formally, in this vision the attention is focalized on a *unique decision*, which should be tackled basing on *punctual*

*information* that are available in the moment of making the decision and which represent a snapshot view of current (or predicted) real-world.
One possible way to take into account the dynamic nature of real-world while preserving a static vision is to make large enough all decision variables and parameters in order to be able to respond to any future evolution of real-world. This idea may be applicable in some simple situations. However, it will be unsuitable in several practical situations where changes are not linear. Moreover, a such practice may generate unnecessary expends if the parameters are over-evaluated. Thus, it is more interesting to approach spatial problems within a manner that integrates explicitly the dynamics of real-world. In practice this dynamic nature may be approached within a discrete or continues manners, which correspond respectively to temporal or real-time visions.

**Temporal vision** In temporal vision and contrary to real-time one, the time axis is approached within a discrete manner, i.e., we suppose that changes affecting real-world are conducted according to a low rhythm and that the essential of real-world dynamics can be resumed quite perfectly through time series-like functions. Formally, temporal vision focalizes on a *unique decision* which, contrary to the previous vision, should be tackled on the basis of *dispersed information* that represent predictions of real-world changes. Thus, this vision can be seen as an extension of the static one. It differs, however, by the strategic nature and the irreversibility of the decision to make, which impose a deeper understanding of this decision and demand the consideration of its future socio-economic, environmental and ecological impacts.
Practically, this formulation applies to problems with high equity that involve long-term spatial decisions. The problem of locating a nuclear central, for instance, involves strategic decisions which their consequences are dispersed over several dozens or may be hundreds of years. The negative effects of a nuclear central are nearly inevitable and the problem comes down to the minimization of long-term damages. This requires an explicit consideration of real-world dynamics—in terms of population growth, climatic changes, soil dynamics, future environmental impacts, for instance—during the decision-making process.

**Real-time vision** Contrary to temporal vision, in this one we consider that real-world is continuously changing and that changes affecting this real-world are often unpredictable. In practice, this vision applies to problems where: ($a$) a *series of decisions* should be tackled over time to reach one or several global objectives, ($b$) these decisions are *interdependent*, and ($c$) the decision environment is *dynamic*; it is subject to several changes that may result from natural phenomena and/or induced by decision-maker's previous decisions. Formally, this vision focalizes on a *series of decisions* which should be tackled under *time pressure* and basing on *instantaneous information* representing the state of real-world at the moment of decision-making.

In a fire fighting problem, for instance, fires start spontaneously (or accidently) and evolve in different directions as a response to previous decisions as well as to several exogen factors which the decider can not control as wind direction and velocity, temperature, forest density and type, etc. In such a context, decisions are taken under time pressure and the *timing* of these decisions will have major effects on the achievement of global objectives. At this level, it is important to notice that even though in temporal vision the dynamic aspects of real-world are explicitly integrated in the problem modelling, the timing of the decision to make is not relevant for the achievement of objectives. This is because the main aim of temporal formulation (as it is defined here) is to take into account the dynamics of real-world in such a way that the decision performed ’now’ remains ’optimal’ in long-term. In terms of a cost-benefit analysis, this means that it generates the ’best’ cumulated gain and the ’least’ cumulated negative effects.

**Sequential vision** Spatial problems may also be handled sequentially in time, where the initial problem is decomposed into a series of related static sub-problems. Formally, we assist to a *series of decisions* dispersed over time, each one is tackled basing on *punctual information* representing the state of real-world during the considered period of time. In practice, these decisions may be performed in different points of time—that correspond usually to the beginning of different planning periods—or defined simultaneously at the beginning of the first period as an *action plan*. In both cases, the time dimension intervenes implicitly in the problem modelling and resolution because it is not formally expressed in the problem formulation but it can be deduced.

In spatial context, it is usually the high level of uncertainty or the considerable financial, economic and human requirements that makes deciders behave as sequential decision-makers. In the first case, a sequential formulation permits to take into account impacts of pervious decisions and consequently to reduce (partially) the effects of uncertainty through a sequential information-acquisition process, while in the second case a such formulation permits particularly to subdivide the expends over several budgetary plans.

Static, sequential and temporal visions are more suitable to Simon’s (1960) decision-making process phases (i.e. *intelligence*, *design* and *choice* or *selection*) because they represent situations where "we have time to act". On the contrary, real-time vision requires that decisions are made under time pressure. Hence, it is concerned mainly with choice phase rather than intelligence or design ones.

On the other hand, these visions respond to different objectives. Selecting a particular vision depends on both the nature of the problem and the objectives of decision-making. Static and temporal ones occur generally in decision-aid perspectives. In static situation we suppose that the decision environment is stable, minimizing hence its effects on the decision-making process. In turn, in temporal vision, the dynamic nature of decision environment is explicitly integrated in the problem modelling and resolution. Consequently, static and temporal visions respond respectively to short-term and long-term decision-aid perspectives. Sequential vision applies to spatial context essentially when spatial management and planning problems are seen as pure investment ones in which financial aspects are the more relevant elements for the decision-maker(s). In this case, the elaboration of a sequential decision logic for handling the problem permits to reduce progressively the uncertainty, which will ameliorate the achievement of the decision-makers' objectives. The dispersed nature of sequential decisions does not means that dynamic aspects of real-world are put in consideration. In fact, each sub-problem represents a static decision situation but the fact that these problems are resolved successively implies that the decision-maker takes the new decision after appreciating the consequences of pervious ones. Accordingly, sequential formulation of (spatial) decision problems are mainly interested in the 'sequential search for information to be used in the decision-making process' (Diederich, 1999). Unlike the previous situations, real-time one manifests essentially in a problematic of control and tracking of dynamic spatial systems and/or of moving objects and/or phenomena and, contrary to the temporal vision, operates in continually changing environment.

Finally, it is important to notice that these visions of spatial dynamics, whose their characteristics are summed up in Table 1, may apply also to non spatial decision problems and are not always crisply defined.

| *Vision* | *Static* | *Temporal* | *Real-time* | *Sequential* |
|---|---|---|---|---|
| *Decision environment* | Stable | Dynamic | Dynamic | Stable |
| *Nature of information* | Punctual | Dispersed | Instantaneous | Punctual |
| *Type of decision* | Unique decision | Unique decision | Series of decisions | Series of decisions |
| *Objective* | Short-term decision-aid | Long-term decision-aid | Control of dynamic systems | Sequential search for information |

Table 1: Characteristics of the different visions of spatial decision problems

# 5 Representing spatial potential actions

Spatial potential actions are defined with at least two elements (Malczewski, 1999): ($a$) *action* (what to do?) and ($b$) *location* (where to do it?). In real-time decision situations, a third element is required to define spatial potential actions: ($c$) *time* (when to do it?). As it is signaled above, even though that in temporal situation the temporal dimension is explicitly integrated into the problem formulation and modelling, attention is essentially focalized on one decision and the time when this decision is performed is *a priori* with no importance. The same remark holds in sequential situation because the timing of the different decisions is not relevant for the problem formulation. Indeed, the different temporal points correspond to the logic succession of these decisions.

In each (spatial) decision problem, we assign to each potential action one or several decision variables, permitting to measure the performance of this action. These variables may be binary, discrete or continuous. Illustrating this with some examples inspired from Malczewski (1999). In a nuclear waste deposit location problem, for instance, the decision "locate the deposit at site $x$" is an action geographically located (via the site address, for example). The binary variable associated to each potential action (site) is the binary decision "construct the deposit at site $x$" or "not construct the deposit at site $x$". In a school location problem, we may be concerned with the size of the school in terms of the number of students to be affected to it. So, to each potential action and in addition to the binary locational variable, we assign a discrete variable which determines the size of the school. If we return to the nuclear waste deposit location problem, one may also be called to use a new continuous variable to measure the deposit area.

On the other hand, in (multicriteria) spatial decision-aid activity, we generally represent potential actions through one of four atomic spatial entities, namely *point*, *line*, *polygon* or *network*. Therefore, in a facility location problem, potential actions take the form of points representing different potential sites; in a linear infrastructure planning problem (e.g. highway construction), potential actions take the form of lines representing different possible routes; and in the problem of identification and planning of a new industrial zone, potential actions are assimilated to a set of polygons representing different candidate zones (see Table 2).

Even though a 'network' entity is a composed one, it is introduced here as an atomic primitive in order to handel some applications in which attention is focalized on the identification of some distribution networks. In a petroleum distribution problem, for instance, networks always refer to different policies of distribution, where nodes represent demand points and arcs represent routes between these demand points. Networks define different system of routes, each one is characterized with its level of coverage, transportation cost, deliverance rapidity and so on. The same remark holds for public services distribution (e.g. electricity and heat) where networks are the different possible spatial configurations, which differ with their implementation costs, coverage levels, their responses to congestion and saturation situations, etc.

| *Potential Action* | *Typical problem* |
|---|---|
| Point | Site selection: points represent different potential sites |
| Line | Highway layout identification: lines represent possible routes |
| Polygon | Evaluation of construction zones: polygons represent different zones |
| Network | Goods distribution: networks are the different distribution policies |

Table 2: Some examples of atomic spatial potential actions

The association between spatial entities and spatial potential actions means that these last ones have all the characteristics and the dimensions of the first, and that are subject to all the changes mentioned in §3. In fact and as it is underlined above, the consequences and impacts of spatial potential actions are often assimilated to the descriptive and spatial characteristics of spatial entities used to represent them. Accordingly, the performances of these potential actions according to different decision variables can easily be measured in terms of the descriptive and spatial characteristics that represent the consequences and impacts of these actions.

# 6 Proposed typology

One way to classify spatial decision problems is the one based on the type of the potential actions that they imply. Accordingly, we may distinguish four basic families of spatial decision problems, which correspond to the four atomic types of actions. This classification is mainly useful to define the types of operators and spatial routines susceptible to be used in the evaluation and comparison of potential actions. However, a such classification ignores the inherent dynamic nature of spatial problems. Earlier, we have seen that depending on the nature of the problem and the objectives of the study, a spatial problem may be formulated as a static, temporal, real-time or a sequential decision problem. Each of these visions requires a different form of data and calls for different modelling and resolution techniques. It follows thus that the adoption of a specific vision will have major effects on the problem modelling and resolution. Thus, to improve the understanding of the aspects and the specificities of spatial problems and to select the adequate modelling and resolution techniques, and to better define the spatial operators and routines susceptible to be used, a typology of spatial decision problems is detailed in the following paragraphs. The proposed typology is based on a crossovering of the different types of actions with the ways that can be used to approach spatial decision problems. It is summed up in Table 3. Two general classifications can be distinguished in this table: problem formulation and potential actions-oriented typologies.

## 6.1 Problem formulation-oriented typology

The first general typology contains four major families of spatial problems, which map to the four possible ways for approaching spatial decision problems. In the following paragraphs we will focus only on the modelling and resolution techniques and data structures required for each family of problems. Notice that the following descriptions apply to all types of potential actions; their presentation here will avoid redundancy.

| | *Static* | *Temporal* | *Real-time* | *Sequential* |
|---|---|---|---|---|
| *Point* | Punctual actions-based spatio-static decision problems | Punctual actions-based spatio-temporal decision problems | Punctual actions-based spatio-real-time decision problems | Punctual actions-based spatio-sequential decision problems |
| *Line* | Linear actions-based spatio-static decision problems | Linear actions-based spatio-temporal decision problems | Linear actions-based spatio-real-time decision problems | Linear actions-based spatio-sequential decision problems |
| *Polygon* | Polygonal actions-based spatio-static decision problems | Polygonal actions-based spatio-temporal decision problems | Polygonal actions-based spatio-real-time decision problems | Polygonal actions-based spatio-sequential decision problems |
| *Network* | Network actions-based spatio-static decision problems | Network actions-based spatio-temporal decision problems | Network actions-based spatio-real-time decision problems | Network actions-based spatio-sequential decision problems |

Table 3: The proposed typology

### 6.1.1 Spatio-static decision problems

This family regroups problems with less equity, where the dynamic nature of real-world is ignored. Techniques used to resolve spatio-static problems are fundamentally static because they do not integrate explicitly the dynamic aspects of real-world. Examples of techniques[3] include linear programming, multicriteria analysis, network analysis models, simulated annealing, neural networks, graph theory, multi-agents systems, genetic algorithms, flow analysis, etc. In all cases, evaluation and comparison of potential actions are based on punctual information issued from direct and punctual (in time) measurements of actions' attributes. These punctual information may also be issued from spatial and/or temporal total aggregations of dispersed data (e.g. average annual precipitation in a given region), an extrapolation of past data in the present time or a projection of current trends of real-world in the future. These information can be supported easily by conventional spatial data management systems (e.g. GIS).

### 6.1.2 Spatio-temporal decision problems

This family regroups problems with high equity where the dynamic nature of real-world is explicitly integrated in the problem modelling and resolution. This requires

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[3] It is important to notice that even that these techniques do not include explicitly the dynamic aspects of spatial decision problems, they, however, may be extended to capture these aspects and be very useful in many non-static decision problems.

anticipations of future facts and events. Several techniques can be combined with static models in order to predict future and integrate effects of natural, social, economic, etc., transformations in modelling spatial problems as, for instance, those based on probabilistic representations or those that use belief functions or fuzzy sets. However, these techniques are based on a total temporal aggregation, which generates problems of temporal compensation. Some more elaborated techniques are also available: animation (morphing) techniques, spatio-temporal Makovian models, time series, regression equations, etc. The explicit integration of time dimension in spatial decision-aid context requires the use of dispersed and evolutionary information that permit to retrace spatial and temporal evolution of spatial entities. These dispersed information may take the form of a series of time-indexed values (e.g. population of a town taken at different dates, mensual precipitations of a given region, etc.) or the form of a discrete function (e.g. representing population evolution of a town with a function $p(t)$, $t \in \mathbb{Z}$). In both cases, a temporal spatial data management system (e.g. temporal GIS) is necessary for handling evolution of facts and events over space and in time.

### 6.1.3 Spatio-real-time decision problems

This family regroups problems related to the control of dynamic systems or to the tracking of moving objects or phenomena. In dynamic system-related problems, we usually consider that geographic position does not vary over time while at least one of the other characteristics is time-varying. In these problems we are interested in the study of trajectories followed by spatial entities in order to analyze their evolution and behavior. In problems of tracking of moving objects or phenomena, the geographic position is time-varying; the other characteristics may or not vary over time. In both cases, we consider that real-world changes continuously. Equally in both cases, decisions need to be made under time pressure, especially in tracking problems where the *timing* of decisions has important effects on the achievement of objectives. Techniques used to handel spatio-real-time problems include dynamic programming, multiobjective dynamic optimization, differential equations, cellular automata, simulation techniques, system dynamics, etc. In real-time situation, the required information evolve continuously and are often represented through continuous functions (e.g. representing movement of spatial engine with function $m(x, y, z, t)$, $t \in \mathbb{R}$, which gives positions $(x, y, z)$ taken by the engine in different time instants $t$). A better handling of this kind of information necessitates the development of real-time spatial data management systems.

### 6.1.4 Spatio-sequential decision problems

Most of sequential problems are not spatial ones. However, several spatial problems may be formulated as sequential decision ones (especially by risk-averse deciders) mainly when there is a high level of uncertainty or when the decisions that they involve are of high equity. Tools as strategic choice approach and robustness analysis are often used to deal with non spatial problems characterized by a significant level of uncertainty. These tools may apply also to spatial problems essentially when only financial aspects of these problems are considered. However, they are of limited use when a variety of different social and environmental criteria should be included in the study. In addition, the two tools are more graphical technologies rather than formal mathematical formulations. There are many other more formal tools based on solid mathematical formulations such as Markovian decision models, dynamic programming tools, discounted utility-based models, etc. Nevertheless, most of these tools do not exploit the spatial characteristics of the problem components because they are initially conceived and used for non-spatial decision problems and they focalize only on the financial aspects of the problem. As in the first family, this one does not consider the dynamic nature of real-world and evaluation and comparison of potential actions are based on punctual information. However, in this case these information are often characterized with a high level of uncertainty and/or fuzziness, which require tools that are able to handel uncertain and fuzzy spatial data.

## 6.2 Potential actions-oriented typology

The second general typology is potential actions-oriented one. It is detailed hereafter. It contains four major families, which map to the four types of potential actions. Each of these families contains four sub-families which correspond to the four modes for approaching spatial decision problems. The following four paragraphs provide brief descriptions of these families. Then, in §6.3, we provide eight illustrative examples where the characteristics of eight sub-families of spatial problems are depicted.

### 6.2.1 Punctual actions-based spatial decision problems

Punctual entities are usually used to represent potential sites in location-related problems, particularly when only geographic position is considered. Punctual actions-based spatial decision problems may be further decomposed into four sub-families:

1. Punctual actions-based spatio-static decision problems
2. Punctual actions-based spatio-temporal decision problems
3. Punctual actions-based spatio-real-time decision problems
4. Punctual actions-based spatio-sequential decision problems

The first sub-family contains location problems in which the dynamic nature of the decision environment is neglected. Actually, most of practical location applications are handled as static decision problems. This may be true for facilities with no or less equity and with no or limited impacts on population and environment. However, facilities like airports, nuclear centers, hypermarkets, hospitals, universities, stadiums, and so on, have inevitably long-range impacts and depend on several socio-economic, environmental, ecological and political criteria which evolve over time.

As we have signaled above, spatial problems are formulated as sequential decision problems when there is a high level of uncertainty and/or when they are of high equity. Accordingly, some strategic location problems are approached sequentially in time. Considering the example of a multinational company which looks to open three new car assembling factories. Due to the fact that this investment project is of high equity and due to the high level of uncertainty (which may be related to demand, competition, foreign governments policies, etc.) that characterizes it, the responsible(s) may adopt a sequential decision-making strategy, where three-period planning horizon is defined. The original problem is thus decomposed into three inter-related static location decision problems, one for each period. The specificity of this situation, compared with the situation where a series of three non-related static problems are considered, is that the objectives of the three sub-problems are the same: minimize total implantation costs and maximize total coverage.

Punctual actions may also be useful in problems related to the control and tracking of dynamic or moving spatial punctual objects such as controlling and guiding ambulances and fire-fighter vehicles, military navies or aircrafts in navigation, etc.

As it is signaled above, the nature of the spatial entity by which decision actions are represented will determine largely the type of spatial and temporal operators and analysis routines susceptible to be used for evaluating and comparing these actions. Concerning punctual actions, all distance-based measurements (e.g. spatial and temporal distances, proximity) and several statistical and spatial operations such as buffering and interpolation are usually applied. Buffering operation and statistical analysis procedures are not specific for punctual actions and may apply to all types of actions.

Even though that the different sub-families cited above have the same nature (location), they have different objectives and require different data structures and different modelling and resolution tools. These differences have crucial impacts on the development of spatial decision-aid tools and their understanding will have good results on the efficiency of these tools. All these elements legitimacy, to some extent, the subdivision of punctual location problems into different sub-families. This is true also for families of problems based on other types of actions.

### 6.2.2 Linear actions-based spatial decision problems

Linear objects may represent several types of real-world decision actions such as highways and routes, rivers, gasolines, etc. Equally, problems of this category can be further decomposed into four sub-families:

1. Linear actions-based spatio-static decision problems
2. Linear actions-based spatio-temporal decision problems
3. Linear actions-based spatio-real-time decision problems
4. Linear actions-based spatio-sequential decision problems

Selecting an itinerary for making a trip involves a non strategic decision that has limited and immediate consequences, and can adequately approached via a static formulation. In turn, a highway construction problem involves a strategic decision that have long-term impacts on population, environment, ecology etc., and a temporal formulation will be more adequate. The static and temporal formulations differ essentially on the information on which the decision is taken: in the first case, we suppose that the selection of a particular itinerary has no long-term impacts, and static information are supposed to be sufficient for representing these impacts, while constructing a highway has long-term impacts which need to be explicitly incorporated in the problem modelling and resolution via the use of time-dispersed spatial information that reflect future evolution of these impacts.

Sequential formulation intervenes often when the linear planning problem is of high equity. In a such situation, the solution is to subdivide the original problem into several parts, which will be constructed in different dates.

Finally, real-time formulation manifests, for example, in the management of linear hydraulic systems (e.g. river) or highways traffic regulation, in shortest path problems for moving objects, etc.

In addition to statistical and buffering operations, the most used operations for linear actions are travel time and length measurements, and PointInLine operation, which tests the intersection of a point (e.g. bus station) with a line (e.g. trip itinerary).

### 6.2.3 Polygonal actions-based spatial decision problems

Polygons, which describe topological proprieties of areas in terms of their shapes, neighbors and hierarchy, are often used in regional planning and land-use-related problems, which Jankowski (2003) subdivides into four types (see §2):

- location selection problems concerned with the rank of a set of sites (i.e. polygons) in priority order for a given activity,
- location allocation problems concerned with stating a functional relationship between the attributes of the land and the goal(s) of the decision-maker(s),

- land-use selection problems looking in ranking the uses for a given site in priority order, and
- land-use allocation problems looking in defining the best uses for an array of sites.

In the first type of problems, polygons represent candidate areas for a given industrial, commercial or social activity. On the contrary, the three next types of problems involve only one area and polygons will represent different suitability measures of the area regarding to different objectives or uses.

On the other hand and identically to punctual or linear actions-based decision problem families, this one can be subdivided into four sub-families:

1. Polygonal actions-based spatio-static decision problems
2. Polygonal actions-based spatio-temporal decision problems
3. Polygonal actions-based spatio-real-time decision problems
4. Polygonal actions-based spatio-sequential decision problems

The first sub-family contains regional physical planning and land-use related problems, where the dynamic nature of the real-world is not considered. Regional physical planning and land-use related problems are usually characterized by impacts and consequences which are dispersed over space and in time. A static formulation of these problems may be suitable to take into account the spatial dispersion of impacts and consequences. However, it is insufficient for handling their temporal evolution.

As for the two previous paragraphs, some physical planning which are characterized with high equity and/or involve parameters of high uncertainty can be approached sequentially in time.

Polygons are also suitable for problems related to the control of moving phenomena (e.g. fire fronts, diseases dispersion, aquatic pollution, etc.). In such problems, a series of polygons will represent the temporal evolution of geographical position, geometry and spatial pattern of the phenomena under focus. Decisions will concern, for instance, the selection of the front of fire to handel first, the region which is more affected with the diseases and which will be treated immediately, etc.

Polygons may also be useful in several environmental applications such as the management of hydraulic dynamic systems. However, in such applications polygons intervene as decision spaces rather than decision actions.

Aside from the general statistical and buffering operations, PointInPolygon and PolygonInPolygon procedures are two typical examples of spatial interaction analysis applied to polygonal actions. PointInPolygon procedure tests if a point is inside a polygon, while PolygonInPolygon procedure tests if a polygon is inside another polygon. Other polygonal typical operations include adjacency tests and surface measurements.

### 6.2.4 Network actions-based spatial decision problems

Network structures intervene in a variety of real-world problems including shortest path, minimal spanning tree, maximal flow, travelling salesman, airline scheduling, telecommunication, transportation and commodity flow problems. The specificity of network actions in comparison with punctual or linear ones is that they have an inherent spatial information about connectivity which is relevant essentially in road and transportation or drainage network analysis. Identically to previous families, network actions-based one may be subdivided into:

1. Network actions-based spatio-static decision problems
2. Network actions-based spatio-temporal decision problems
3. Network actions-based spatio-real-time decision problems
4. Network actions-based spatio-sequential decision problems

In network related problems, we may be interested in the implementation of a network infrastructure or to its exploitation. Implementation of a network infrastructure has usually long-term impacts and should normally be approached through a temporal formulation. The implementation of a transportation network, for instance, should take into account urban growth, road expansions and soil type, in order to satisfy increasing demands, to avoid congestion and soil slippage or erosion problems. The same remark holds for several other public management and planning problems such as electricity and heat distribution, liquid waste evacuation, etc. Static formulation may be justified in small scale planning problems. In practice, however, networks management problems are usually of high equity and often approached according to a sequential formulation.

Network actions intervene also in a variety of socio-economic applications such as public transportation, automatic route finding in car and truck navigation, commodity flow problems, etc. In such problems, usually several networks are compared mainly in terms of travel time. The specificity of this type of problems is that there is not an explicit selection of a network action but only one action is dynamically constructed. Hence, a dynamic formulation will apply better.

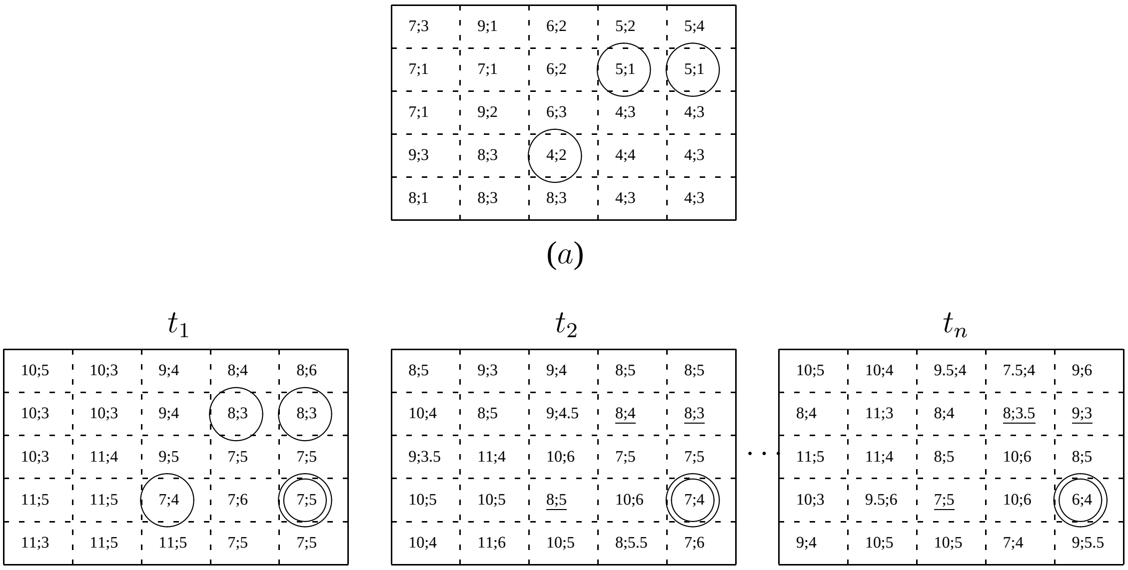
Operations on networks include (Leung, 1997): the set-theoretic operations (e.g. intersection, union, negation, inclusion), spatial and temporal distances, topological operations (e.g. connectivity, accessibility), geometric operations (e.g. length, width, shape, density), pattern, spatial interaction, and functional operations (e.g. shortest path, maximal flow). Inter-entity distances over the network or other measures of connectivity such as travel time, attractiveness, etc., can be used to determine indices of interaction in network-base applications. These operations are much used for determining the location of emergency services or for optimizing delivery routes.

## 6.3 Some illustrative examples

This section is devoted to present the characteristics of eight sub-families of problems. Firstly, it is important to notice that several didactic and hypothetical examples are discussed in the following paragraphs and the data used in all of them are artificial. We notify also that for the sake of clarity, in all these examples the decision space is schematized through a regular grided form, where punctual, linear, polygonal and network actions are represented respectively with one pixel, a set of linear pixels, a collection of adjacent non-linear pixels, and a combination of individual pixels with several pixel-based linear entities.

**Example 1: School location** Figure 1.($a$) represents a school location problem. In vector-based GIS-like tools a feasible location can completely be defined in terms of its XY-coordinates. In raster-based GIS-like tools, these coordinates are implicitly defined via the position of the cell in the grid. So, for the school location problem, each cell will represent a potential punctual action for locating the school. To each cell we associate two punctual values relative to two sitting criteria, namely implementation cost and average distance from major population centers (values in cells of Figure 1.($a$) represent respectively implementation costs and average distances). Here, the two factors are considered to be stable over time, which is convenient to all non strategic location problems in which consequences and impacts of decisions can perfectly be approached via static data. The problem comes down now to the identification of the cell(s) that optimize a certain function $f$. If we use a weighed sum (regards to its limits) as a decision rule and we consider that the two factors are of equal importance, we obtain three cells that minimize the average sum (circled cells in Figure 1.($a$)). This problem involves punctual actions and requires only static information. Thus, it belongs to the family of punctual actions-based spatio-static problems.

**Example 2: Nuclear central location** Figure 1.($b$) represents a hypothetical nuclear waste deposit location problem. Which makes the difference between the situation in Figure 1.($a$) and the situation in Figure 1.($b$) is that in the latter one, data concerning implementation costs (we suppose that costs in $t_2$ through $t_n$ are relative to operating and maintenance of the facility to be located because the implementation cost is considered to be committed in $t_1$) and impacts on environment are considered as time-varying ones and they are expressed as series of values representing measurements of the two factors in different dates. Here, we recognize that siting a nuclear waste deposit is a long-term investment decision implying several impacts on environment that vary across space and in time. For instance, the slope as well as the type of soil will have major roles in reducing or increasing impacts on environment. Taking into account these elements will reduces substantially long-term impacts on environment. As an example, the double circled cell in Figure 1.($b$) has better long-term performances than the three circled cells, which may be selected if only data available at $t_1$ are used. As the previous one, this example involves punctual actions but it requires time-varying data. Thus, it belongs to the family of punctual actions-based spatio-temporal problems.



| | | | | |
|---|---|---|---|---|
| 7;3 | 9;1 | 6;2 | 5;2 | 5;4 |
| 7;1 | 7;1 | 6;2 | 5;1 | 5;1 |
| 7;1 | 9;2 | 6;3 | 4;3 | 4;3 |
| 9;3 | 8;3 | 4;2 | 4;4 | 4;3 |
| 8;1 | 8;3 | 8;3 | 4;3 | 4;3 |

($a$)

$t_1$

| | | | | |
|---|---|---|---|---|
| 10;5 | 10;3 | 9;4 | 8;4 | 8;6 |
| 10;3 | 10;3 | 9;4 | 8;3 | 8;3 |
| 10;3 | 11;4 | 9;5 | 7;5 | 7;5 |
| 11;5 | 11;5 | 7;4 | 7;6 | 7;5 |
| 11;3 | 11;5 | 11;5 | 7;5 | 7;5 |

$t_2$

| | | | | |
|---|---|---|---|---|
| 8;5 | 9;3 | 9;4 | 8;5 | 8;5 |
| 10;4 | 8;5 | 9;4.5 | 8;4 | 8;3 |
| 9;3.5 | 11;4 | 10;6 | 7;5 | 7;5 |
| 10;5 | 10;5 | 8;5 | 10;6 | 7;4 |
| 10;4 | 11;6 | 10;5 | 8;5.5 | 7;6 |

$t_n$

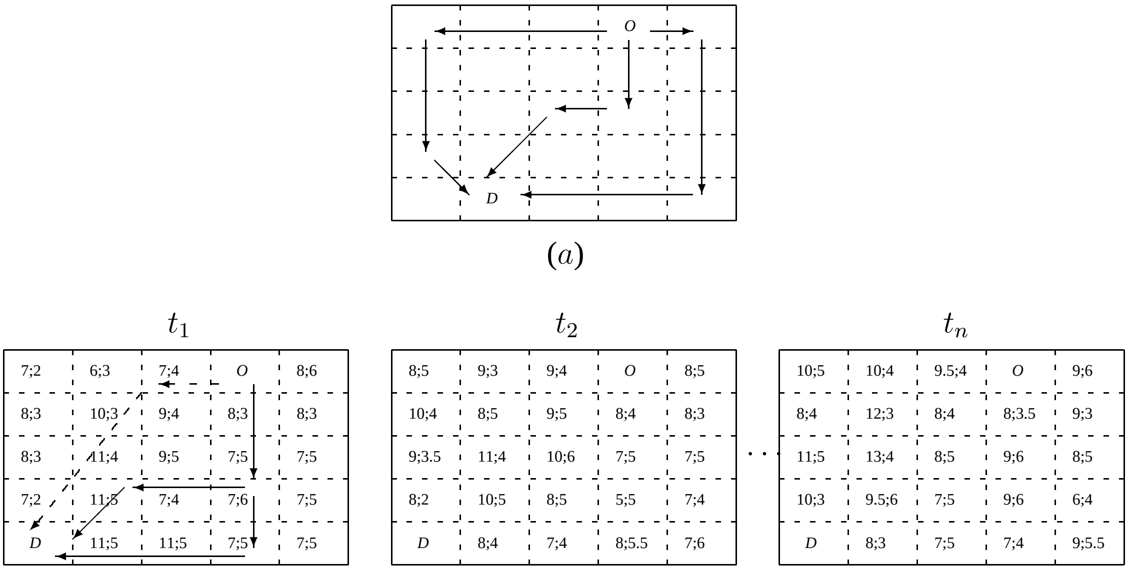
| | | | | |
|---|---|---|---|---|
| 10;5 | 10;4 | 9.5;4 | 7.5;4 | 9;6 |
| 8;4 | 11;3 | 8;4 | 8;3.5 | 9;3 |
| 11;5 | 11;4 | 8;5 | 10;6 | 8;5 |
| 10;3 | 9.5;6 | 7;5 | 10;6 | 6;4 |
| 9;4 | 10;5 | 10;5 | 7;4 | 9;5.5 |

($b$)

Figure 1: Schematic representation of school ($a$) and nuclear central ($b$) location problems

**Example 3: Route selection** In Figure 2.($a$) we present a simple trip itinerary selection problem. The objective is to select the route to follow during the trip. In most of individual spatial decision-making problems, decisions are usually tackled within ad hoc manner on the basis of simple heuristics and/or past experiences. In the route selection problem, several routes are available (in Figure 2.($a$) there are three routes; each one is represented as a collection of linear cells) and the adoption of a particular route will depend on punctual information issued mainly from past experiences. In this example, such information are sufficient to represent the decision environment because there is no need to take into account future evolution of real-world. This may be explained with the immediate nature of the consequences of decisions and the low cost of a 'poor' decision. In this example, the cost of a 'poor' decision is simply to put more time to arrive. This problem concerns the selection among several linear actions and evokes non strategic decision having immediate consequences. Accordingly, it belongs to linear actions-based spatio-static decision problems family.

**Example 4: Highway construction** Considering the problem of the selection of a corridor for implementing a new highway illustrated in Figure 2.($b$). The objective is to select the corridor that applies for future demands and respects the environment. The two values in cells of the matrix of Figure 2.($b$) represent respectively implementation/operating and maintenance costs and impacts on environment levels. Each two values are relative to the part of the corridor which is inside the cell. If we consider only the data available at $t_1$, one may have the three corridors represented in the figure. If we suppose also that the decider, basing on the data available at $t_1$, selects the corridor that is represented with dashed arrows, it may happen that in future time, this corridor supposed currently as the 'optimal' one, generates more negative impacts than the two other ones. We can not avoid a such eventuality only if we dispose of solid predictions of the sates of real-world in the future that are established by well-experienced specialists. In our example, we dispose of three matrix, the first is relative to current time, the two others are predictions of real-world in two future dates. As in the nuclear central location problem, the question that raises here is to use these predictions to select the corridor that has better long-term performances. This illustrative example requires the use of dispersed data to select line-based actions. Consequently, it belongs to linear actions-based spatio-temporal problems family.



($a$)

$t_1$

| | | | | |
|---|---|---|---|---|
| 7;2 | 6;3 | 7;4 | *O* | 8;6 |
| 8;3 | 10;3 | 9;4 | 8;3 | 8;3 |
| 8;3 | 11;4 | 9;5 | 7;5 | 7;5 |
| 7;2 | 11;5 | 7;4 | 7;6 | 7;5 |
| *D* | 11;5 | 11;5 | 7;5 | 7;5 |

$t_2$

| | | | | |
|---|---|---|---|---|
| 8;5 | 9;3 | 9;4 | *O* | 8;5 |
| 10;4 | 8;5 | 9;5 | 8;4 | 8;3 |
| 9;3.5 | 11;4 | 10;6 | 7;5 | 7;5 |
| 8;2 | 10;5 | 8;5 | 5;5 | 7;4 |
| *D* | 8;4 | 7;4 | 8;5.5 | 7;6 |

$t_n$

| | | | | |
|---|---|---|---|---|
| 10;5 | 10;4 | 9.5;4 | *O* | 9;6 |
| 8;4 | 12;3 | 8;4 | 8;3.5 | 9;3 |
| 11;5 | 13;4 | 8;5 | 9;6 | 8;5 |
| 10;3 | 9.5;6 | 7;5 | 9;6 | 6;4 |
| *D* | 8;3 | 7;5 | 7;4 | 9;5.5 |

($b$)

Figure 2: Schematic representation of route selection ($a$) and highway construction ($b$) problems

**Example 5: Historic zone restoration** Figure 3.($a$) represents the different districts of an historic zone where an ambitious project of restoration is envisaged. The project has considerable financial requirements and may have several undesirable impacts on the socio-economic activities (e.g. problem of congestion), mainly if interventions are dispersed around all the region. To avoid such situations, local authorities have defined an action plan of fifteen years divided into three periods, each of five years. The problem now is to classify the 7 districts into three groups in priority order. We suppose that the two criteria considered are: the total number of sites to be restored and the number of highly priorate sites (measurements of the two criteria are depicted in Figure 3.($a$)). Here, polygons represent potential actions which should be regrouped into three ordered classes. In the first five years, the priory districts ($d_5$ and $d_7$) are restored. Designing which are the next districts to restored may be defined in the beginning of the first period or in future time. In the first case, we may select districts $d_2$, $d_3$ and $d_4$ to be restored in period 2 and districts $d_1$ and $d_6$ to be restored in period 3 (notice that the number of priority zones may increases over time). In this problem, actions are schematized through polygonal structures. In addition, a series of decisions is required to select the different districts to handel in each period. Thus, it belongs to the polygonal actions-based spatio-sequential problems family.

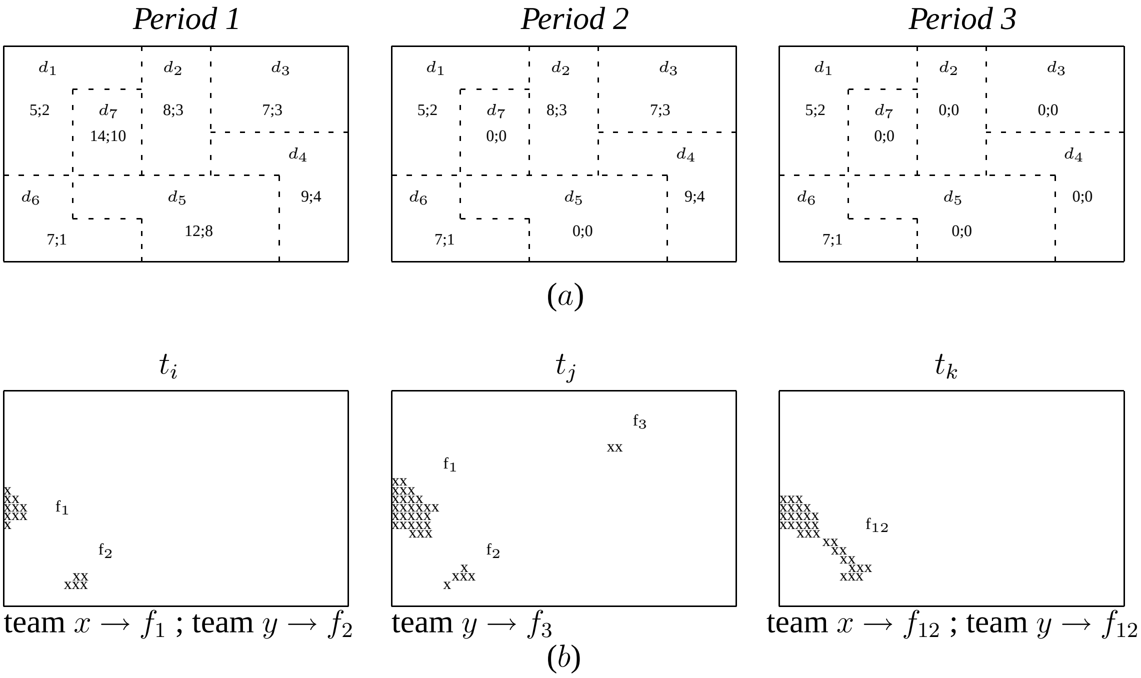


Figure 3: Schematic representation of historic zone restoration ($a$) and fire fighting ($b$) problems

**Example 6: Forest fire fighting** In fire fighting problems we are subject to several constraints related to time pressure, unpredictability of changes, and non availability of sufficient resources. Figure 3.($b$) represents evolution of the decision process in a hypothetical fire fighting problem where only two fire fighting teams ($x$ and $y$) are available. This figure schematizes the evolution of fire fronts over space and in time. The decider is called to coordinate the two teams in order to extinct fires as soon as possible and to minimize damages. He continuously receives information concerning the evolution of fronts from different controlling centers. In this problem, fronts take the form of polygons which their form and position change across space and time, and where decisions take the form of "affect team $x$ to front $f$". At time $t_i$, two fire fronts are observed ($f_1$ and $f_2$) and the decision was to affect team $x$ to front $f_1$ and team $y$ to front $f_2$. Then at time $t_j$ the decider sent team $y$ to a new fire front, $f_3$. As time progress, the timing of decisions will be more relevant for the achievement of objectives. The situation is complicated with the fact that decision taken in current time will constrain future possible decisions. In our example, affecting team $y$ to front $f_3$ had permitted to eliminate this front but a such decision will complicate the situation around front $f_2$. In fact, at time $t_k$, front $f_2$ is extended to constitutes, with front $f_1$, front $f_{12}$. The process will continues until the extinction of all fire fronts. This problem involves real-time decisions concerning the control of moving phenomena that take the form of polygon structures. Consequently it belongs to the polygonal-actions spatio-real-time problems family.

**Example 7: Track navigation** In track navigation problems, the transportation network is dynamically changing (in terms of traffic rate, climatic conditions, accidents, etc.). In such problems deciders are often subject to time pressure constraint. The specify of this type of problems is that there is not an explicit selection of a network. Instead, only one network is dynamically constructed over time. In reality, the decisions in this problem concern the selection of the route to add to the network being constructed and each of these decisions will simply create an 'instance' of the required global network. However, the ultimate objective is not select individual routes but to reach different demand points as soon as possible. In this problem attention is focalized on the dynamic definition of a transportation network and consequently it belongs to the family of network actions-based spatio-real-time decision problems.

**Example 8: Subway implementation** The construction of a subway is of a high equity. As for most strategic pubic planning problems, this one is approached sequentially in time. Accordingly, we should define an action plan of several periods. In each period, the decision concerns the implementation of a sub-network. The problem will comes down to the selection of the sub-network to implement at each period of time. This will depend on several technical, economic and social factors. For instance, sub-networks may be compared in terms of their implementation costs, their role in reducing negative effects of current congestion problems, and in terms of their coverage levels. In this example, the initial problem is decomposed into a series of sub-problems in which actions take the form of network structures. Consequently, it belongs to the family of network actions-based spatio-sequential decision problems.

The characteristics of the above-cited typical problems are summed-up in Table 4.

| *Problem* | *Characteristics* | *Family* |
|---|---|---|
| School location | Punctual potential actions<br>Short or medium-term consequences | Punctual actions-based spatio-static problem |
| Nuclear central location | Punctual potential actions<br>Long-term consequences | Punctual actions-based spatio-temporal problem |
| Route selection | Linear potential actions<br>Immediate consequences | Linear actions-based spatio-static problem |
| Highway construction | Linear potential actions<br>Long-term consequences | Linear actions-based spatio-temporal problem |
| Historical zone restoration | Polygonal potential actions<br>High equity | Polygonal actions-based spatio-sequential problem |
| Forest fire fighting | Polygonal potential actions<br>Dynamically changing environment | Polygonal actions-based spatio-real-time problem |
| Track navigation | Network potential actions<br>Dynamically changing environment | Network actions-based spatio-real-time problem |
| Subway implementation | Network potential actions<br>High equity | Network actions-based spatio-sequential problem |

Table 4: Characteristics of the illustrative examples

# 7 Problems implying complex potential actions

In many real-world applications, one may be called to represent actions with a combination of two or more atomic entities. In schools partitioning problem, for instance, decision actions can be assimilated to a combination of points and polygons where points represent schools and polygons represent zones to serve. A set of ’point-point’ composed actions may represent potential paths in a shortest path identification problem and a set of composed actions of ’point-network’ type may schematize different feasible locations, each one belongs to a different transportation network. Table 5 provides some other examples of problems where complex actions are required.

One particular composed action is the one based on a map structure. Map structures are relevant mainly in spatial problems that are related to the control of (non real) spatial phenomena. An illustrative example of representing decision spatial actions using map structures is provided in Janssen and Herwijnen (1998). The authors have proposed several transformation and aggregation methods in order to represent the performances of different policies of antipollution fights in the ’Green Heart’ region of the Netherlands. The results of the transformation and aggregation operations have been presented in performance maps, which represent the relative quality of the different policies along with their spatial patterns. These maps are then used as inputs to the evaluation step.

Another example of using map structures to represent decision actions is furnished by Sharifi et *al.* (2002), where the authors have interested to the problem of relocating the boundary between the ’Tunari National Park’ and the ’Cochabamba City’ (in Bolivia) in order to avoid spontaneous illegal settlements in between the park and the city. Four different maps, each represents a possible approach to address the problem and satisfy the objectives of stakeholders, are generated and compared with current situation.

| *Potential Action* | *Typical problem* |
|---|---|
| Point-Point | Shortest path problem: pairs of points represent different paths |
| Point-Line | Bus stops location: lines represent routes and points are candidate stations |
| Point-Polygon | School partitioning problem: points schematize schools while polygons represent zones to serve |
| Point-Network | Location in a distribution network: points represent different distribution sites (e.g. supermarkets) in the distribution network |
| Line-Line | Routes intersection: linear objects schematize the different routes |
| Line-Polygon | Agriculture preservation: rivers are represented with lines and zones to preserve with polygons |
| Line-Network | Adding a new route in a distribution network: lines are potential arcs to be included in a distribution network |
| Polygon-Polygon | Hierarchical zoning: administrative zoning where districts, departments, etc., take the form of hierarchical polygons |
| Polygon-Network | Industrial zone location: polygons schematize different potential zones in a transportation network |
| Network-Network | Correspondence between networks in public transportation: between an underground and bus networks, for instance |
| Map | Antipollution fight policy choice: each map represents the spatial pattern of a potential policy |
| Map-Point | Regional planning problem: maps represent different potential regions for implementing a new regional hospital and points represent potential sites for locating the hospital |

Table 5: Examples of complex spatial potential actions (some ones are reproduced from Malczewski (1999))

Map-based actions are also suitable for applications in which a strong spatial relation between elements of the decision space (e.g. spatial contingency and adjacency in redistricting problems, spatial compactness in land use allocation problems, composition relations in administrative partitioning problems) should be verified. An example is the redistricting problem where attention is focalized on the definition of a zoning (representing, for example, administrative, commercial or service zones) that verifies at best the spatial contingency propriety between neighbor zones and, at the same time, eliminates intersections between these zones and avoids holes. In such a problem, maps constitute an excellent support for the presentation of potential partitions and for their visual evaluation and then their comparison.

Complex actions should verify several spatial relations (e.g. proximity, appurtenance, minimum distance separation for new development from existing livestock facilities) among its atomic entities. These relations will serve as inclusion/exclusion criteria by which one atomic action is included or not to another atomic action representing the new decision space.

Generally, the generation of complex actions begins by defining more complex atomic actions (e.g. networks) on which less complex atomic actions are defined (e.g. in the school partitioning problem cited above, we should normally define polygons and then associate to each polygon a punctual location action). In some cases, the order by which actions are defined may be imposed by the nature of the problem (e.g. locating restaurants in pre-existing highways, where highways with high potential demands are selected first followed by punctual locations on these highways).

Composed actions-based spatial decision problems are not explicitly included in the typology detailed in §6. Nevertheless the typology is still adequate to describe most of them. Indeed, these last ones are usually decomposed into a series of basic problems, each one involves only one atomic action type. Considering, for instance, that our initial problem involves composed actions which are constituted of two atomic actions $e_1$ and $e_2$ that should verify a spatial relation $r$. This problem can be decomposed into two steps (see Figure 4):

- in the first step we resolve a first sub-problem involving actions of type $e_1$, and
- in the second step we resolve another sub-problem involving actions of type $e_2$.

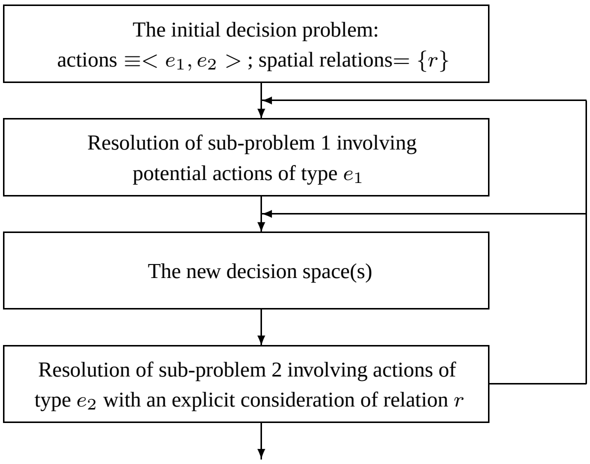


Figure 4: A process for handling complex potential actions-based spatial decision problems

The resolution of the first sub-problem permits to define the new decision space(s) over which the second sub-problem is defined and resolved. The resolution of the second

sub-problem should take into account spatial relation $r$. We remark that the process illustrated in Figure 4 is an interactive one. This enables the decider and/or analysts $(i)$ to modify the input data and $(ii)$ to repeat the process as many as necessary.
To better illustrate this idea, consider the location-allocation problem illustrated in Figure 5. In this example we look to locate $n$ service points in a given region. The initial problem involves 'point-map' composed actions where points represent the geographical position of the different service points and maps represent the different possible partitions of the study region. This problem may be decomposed into two sub-problems as follows. The first sub-problem is a partitioning one, which aims to subdivide the region into several homogenous zones. It corresponds to a map actions-based problem. The resolution of this problem permits to define the decision spaces of $n$ location sub-problems. These $n$ sub-problems correspond to $n$ punctual actions-based problems. In this example, the spatial relation $r$ may be an appurtenance relation, i.e., each service point belongs necessarily to the zone that it services. It is important to notice that map-based actions are normally of complex nature but in this example they may be considered as atomic ones because each map represents a unique manner for subdividing the study region into homogenous zones.

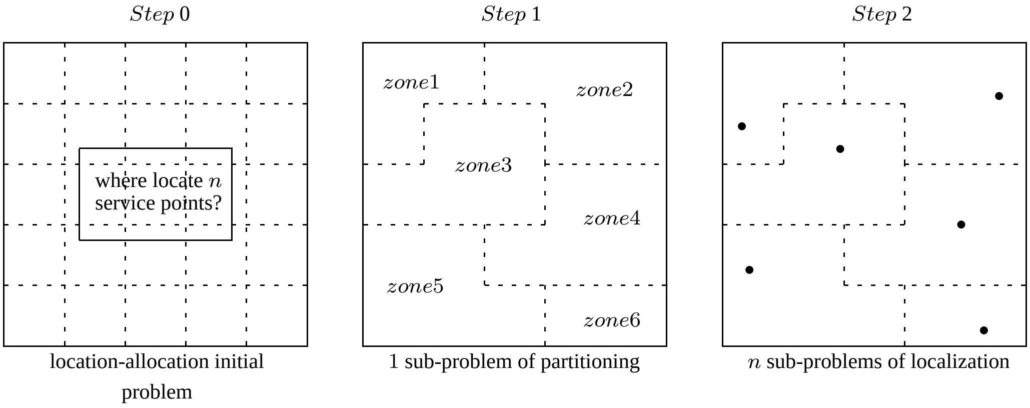


Figure 5: Location-allocation illustrative example

Finally, we notice that modes for approaching spatial decision problems detailed in §4 as well as the descriptions of spatial decision problems provided in §6.1 apply also to problems implying complex spatial actions. We particularly notice that data structures defined in §6.1 are suitable to this type of problems. They, however, require more complex modelling and resolution techniques. Equally, evaluation and comparison of complex actions require more complex operators and analysis routines. For instance, techniques as overlay[4], spatial filtering and zoning are often applied to actions based on map structures.

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[4] It refers to arithmetic and logic operations that are applied to maps representing different geographic themes. Overlapping is likely the most used operation in GIS-like tools.

# 8 Concluding remarks

This paper is a tentative for classifying spatial decision problems. Concretely, we have presented a typology obtained through a crossover of actions' types with different possible modes for approaching spatial decision problems. The proposed typology covers most of spatial decision problems that involve atomic actions. It permits also to represent and model several spatial problems that involve complex actions. The idea is to decompose the initial problem into a series of basic spatial problems that involve atomic actions. Notice, however, that it is by no means to suppose that the typology encompasses all spatial decision problems.

The proposed typology overcomes several limits of typologies of section 2. Indeed, it has at least the following merits. First, it is useful for understanding the specificities of spatial decision problems. Second, the typology facilitates the choice of spatial and temporal operators and analysis routines required to each problem type. In fact, these operators and routines are essentially determined by the type of spatial objects by which real-world spatial entities (and consequently spatial potential actions) are conceived and digitally represented. Third, it provides tools for formulating spatial problems and representing their dynamics by explicitly integrating the temporal dimension, which is necessary to convenably characterize these problems. Finally, it constitutes a suitable framework for multidisciplinary researches because it is based on simple concepts and paradigms which are devoid of any socio-economic or environmental contexts, and on which researches from different disciplines agree.

Furthermore, the typology is particularly useful to develop multicriteria evaluation-based spatial decision-aid tools. In fact, the most used practice in multicriteria spatial decision-aid consists in representing decision actions in terms of spatial entities. Practically, the typology will provide convenable framework ($a$) for generating, evaluating and comparing potential actions, and ($b$) for dealing with conceptual, methodological and technical questions related to the undertaking of the dynamics of basic elements of multicriteria evaluation models (i.e. actions, criteria and preferences) in many real-world applications.

Equally, the typology is useful to develop spatial decision support systems (or SDSS). Specifically, it helps to construct a general framework for classifying analysis, modelling and resolution techniques according to their suitability to different problem formulations. This framework will represent the first step towards the development of a model base management system to be incorporated into the SDSS. Its role is to assist analysts and deciders to select the adequate technique(s) for the problem under focus. In fact, a large variety of structured models including statistical methods, mathematical models, heuristic procedures, algorithms, and so on, are available in GIS-like tools, and usually analysts and deciders come across difficulty in selecting the relevant model to use. A well-established framework can therefore be used for a systematic organization of analysis and modelling tools through, for instance, IF-THEN rules or YES-NO questions (Leung, 1997), inside the SDSS.

Several of the topics that are mentioned in this paper require further attention. In particular, attention should be addressed towards the elaboration of an exhaustive description of spatial operators and analysis routines which are suitable to each type of actions as well as towards the identification of modelling and resolution techniques and tools that are convenable to each family of problems. Additionally, the process of decomposition of problems involving complex actions discussed in §7 requires a more elaborated study. All these elements will be dealt with in our future research where we intend to focalize on a particular family of problems, namely linear-based spatio-temporal decision problems. Our objective is to conceive and develop a multicriteria spatial decision-aid tool devoted to linear infrastructure management and planning problems.

## Acknowledgement

The authors are really thankful to *Professor* Bernard Roy for his valuable comments on an earlier version of this paper.

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