Introduction

"Men decide far more problems by hate, love, lust, rage, sorrow, joy, hope, fear, illusion, or some other inward emotion, than by reality, authority, any legal standard, judicial precedent, or statute."

Attributed to Marcus Tullius CICERO (106–43 B.C.)

This introduction will attempt to define the context in which this doctoral thesis was initiated. To start with, the general context will be outlined through the definition of the background whether related to the personal or scientific settings. After a few words on the general context, the focus will be placed on the specific context through an essay defining the research trends at the beginning of the investigation[1]. This part will justify the need for initiating such a research from a *spatial information science* perspective (see Box 1 on the topic). Then, the research focus will be set and the structure of the thesis will be exposed. The reader should then better understand the options selected, the path followed and the results obtained.

[1] In conformity to the publication-based thesis regulations as stated in the *ULg Geography February 2002 dissertations' regulation addendum* (§C.1).

Basic settings and first choice

The research theme agreed on – '*errors and uncertainties in spatial decision support systems*' – frames this doctoral investigation. The preface gives an insight on where the investigation was started from, on how it was defined and on the actions taken in order to clarify the ideas and fill the lag. This doctoral investigation has originally no link to any project; it was initiated as a lonely, self-supported, and after-hours research. After its completion, its robustness has been challenged within different national and international research projects for which its results proved to be helpful.

For this research, no data, no data management system, no models management system and no decision support systems were available, only image processing and geographical information system software were. The disadvantages of not being linked to a specific project were counterbalanced by the advantages of the freedom of thoughts. So, the research was reoriented towards a conceptual approach of the issues under considerations. It is only in the late stage of the research that several great opportunities arose to confront the concepts developed with reality or with different realities. But let's not anticipate with the later chapters and let's start sketching the research trends in geographic information at the beginning of the thesis.

Box 1. Spatial information science and geographic information science

The expressions spatial information science and geographic information science (GISc) are very close in terms of concepts compared to other expressions sharing the same meaning such as geomatics, geoinformatics, geocomputation, geo-information engineering (Chrisman N.R., 1999; Gahegan M., 1999). The latter differ in their roots and, as a result, in their ways of apprehending the problems at stake. The difference between geographic and spatial ISc comes from the fact that the information they refer to are characterising phenomena respectively at geographic scales and at any scale, from sub-molecular to intergalactic.[2]

For Mark D.M. (1999, p. 7), GISc is "the basic research field that seeks to redefine geographic concepts and their use in the context of geographic information systems. GIScience also examines the impacts of GIS on individuals and society, and the influences of society on GIS. GIScience re-examines some of the most fundamental themes in traditional spatially oriented fields such as geography, cartography, and geodesy, while incorporating more recent developments in cognitive and information science. It also overlaps with and draws from more specialized research fields such as computer science, statistics, mathematics, and psychology, and contributes to progress in those fields. It supports research in political science and anthropology, and draws on those fields in studies of geographic information and society." (See also Table 2)

Research trends

In a reflection on his field of investigation, Goodchild M.F. (1992, p. 32) argues that the GIS community needs "to ensure that GIS, and spatial data handling technology, play their legitimate role in supporting those sciences for which geography is a significant key, or a significant source of insight, explanation and understanding". Following his article, part of the scientific community involved in the development of computerised geographic information systems (GIS) has taken a few steps back to consider the place and role of those systems in society and in research. Under the umbrella of the University Consortium for Geographic Information Science (UCGIS), leading scientists have defined the research priorities for geographic information science doing abstraction of the underlying geographic information technology framework. Those North American oriented priorities cover a wide range of aspects and seven out of ten are partially justified for improving spatial decision-making or at least to lessen the likelihood that inappropriate decisions be made based on geographic information

[2] Note that within this manuscript and research the term 'spatial' has a slightly reduced meaning since only the scales relevant to human decision-making are taken into account.

technologies' products (UCGIS, 1996a). Table 1 shows those priorities and their expressed relations to spatial decision or decision-making.

Table 1: Decision related priorities in GISc (page in UCGIS, 1996a)

1996 UCGIS Priorities expressed relations to spatial decision or decision-making
distributed computing (see p. 119)
- geographic and social distribution of stakeholder groups
extensions to geographic representation (see p. 120)
- increase in use of GIS for policy analysis - data with different quality level
cognition of geographic information (see p. 121)
- fully mature GI technology as tools in the service of mankind - user-friendly technology in the hand of lay people - comprehension of complex GI - multi-disciplinarity
scale (see p. 123)
- interactions and influence of the different levels on each other - systematic understanding of spatial and temporal variations
the future of the spatial information infrastructure (see p. 125)
- public access to GI - efficiency of governmental agencies - policy analysis support - use of local information and knowledge
uncertainty in spatial data and GIS-based activities (see p. 127)
- avoiding misleading information - impact of GI technology on DM - identification and follow up of uncertainty
GIS and society (see p. 127)
- impact on the people (e.g. privacy) - media to increase public participation - impact of GI technology on the DM processes

The three remaining priorities ('spatial data acquisition and integration', 'interoperability of geographic information', 'spatial analysis in a GIS environment') were not specifically addressed in terms of decision-related issues. Nevertheless, it could easily have been the case since having no relevant data, or not being able to access them straightforwardly, or not being able to analyse them properly would directly or indirectly affect the capabilities of decision-makers resorting to GI technologies.

In particular, for the research topics in immediate connection to the thesis theme, the priority of a better understanding of **cognition of geographic information** finds its justification in the following sentences. "In the past decade it has become clear that an understanding of certain aspects of human cognition is essential if future geographic information technologies are to realize their full potential as tools in the service of human decision making. If geographic information systems are to be made easier to use, by people who must make geographic decisions but are not willing to undertake the extensive and lengthy training required by today's systems, then GIS interfaces must be made more intuitive, and users must be able to interact with them in ways that reflect their natural thought processes. […] How can complex geographic information be presented to the user in ways that promote comprehension and effective decision making? […] Research into the cognitive aspects of geographic information technologies is part of a research tradition begun primarily in the 1960s by urban planners, behavioral geographers, cartographers, and environmental psychologists. Planners study how humans perceive and learn about places and environments. Behavioral geographers develop theories and models of the human decision making processes that lead to behavior in geographic space, such as shopping, migration, and the journey to work. Cartographers study how maps are perceived and understood by users with varying levels of expertise. Environmental psychologists have refocused traditional questions about psychological processes and structures, to examine how they operate in the contexts of built and natural environments. All of these disciplines will need to work together to address the cognitive aspects of geographic information technologies" (UCGIS, 1996a, p. 121).

The priority of **uncertainty in spatial data and GIS-based activities** is a major issue since "error-laden data, used without consideration of its intrinsic uncertainty, has a high probability of leading to inappropriate decisions" (p. 127). Furthermore, "at this time, our understanding of uncertainty in geographic data and its consequences for decisions made using geographic information technologies is very incomplete" (p. 127). So, "intensive research is needed [… for] implementing strategies and methodologies for reducing, quantifying, tracking, and reporting uncertainty in GIS implementation, in geographic data collection and generation, and in spatial data standards and decision making processes" (UCGIS, 1996a, p. 127).

The coordination of different decision levels with their own spatial and temporal contexts and variations points to **scale** as a research priority. "Despite longstanding recognition of the implications of scale for geographic inference and decision making, many questions remain unanswered" (UCGIS, 1996a, p. 123).

The priority of an open **spatial information infrastructure** is justified for true democratic decision-making. Although, "developing the technical and institutional means to support creation and contribution of local knowledge presents a novel challenge to technologists and decision makers alike" (UCGIS, 1996a, p. 125).

Finally, the priority **GIS and society** should not be forgotten since "the geographic information technologies seem to have certain unique characteristics that will affect their eventual impact […] and relevance to community-based decision making and political processes" (p. 126). So the question "Can GIS be used to increase participation in public decision making?" (UCGIS, 1996a, p. 127) is raised.

The same year, looking at the geographical information technology, Karimi and Blais (1996) identified the current and future directions in GIS research given the fact that "a survey of existing GISs [for example see GIS World Sourcebook (1995)], and reported experiences with some GIS products indicate that current GISs are suitable to be employed as a base for building spatial problem-solving environments, known as Spatial Decision Support Systems (SDSSs)" (p. 85). Nevertheless, they recognise that "current GISs have shortcomings that clearly make them limited SDSSs" (p. 86). So, in order to define future GIS as being excellent SDSS, they identify within four types of considerations a number of technical deficiencies and their counterparts in terms of aims to be reached. The issues related to '**data**' include 'data conversion', 'data analysis and processing', 'data format', 'data model', and 'data volume'. Those of '**software**' cover 'design', 'application development', 'interfacing with external systems for real-time processing', 'integration strategies', 'user interfaces', and 'online access'. The failures of '**spatial analysis and modelling**' originate from 'processing strategies', 'simulations', 'functionality', 'inferencing for decision support', and 'uncertainty management'. Finally, in terms of '**computing**', the 'architecture', the 'platforms', the 'processing', the 'computations', and the 'problem-solving environment' should be improved.

The following years, the UCGIS kept itself busy with the definition of educational priorities for their national GI community (Kemp K. & Wright R., 1997a 1997b; Macey S.M., Dean G., *et al.*, 1997; Miller H., Kemp K., *et al.*, 1997; Obermeyer N.J. & Onsrud H.J., 1997; Saalfeld A., Aggarwala R.K., *et al.*, 1997; Thompson D., Buttenfield B.P., *et al.*, 1997; Ventura S.J., Craig W.J., *et al.*, 1997; Wright D., Elmes G., *et al.*, 1997; Wright R. & Kemp K., 1997) and with the refinement of their research priorities (Jensen J., Saalfeld A., *et al.*, 1998; Montello D.R., Freundschuh S.M., *et al.*, 1998; Onsrud H.J., Lopez X., *et al.*, 1998; UCGIS, 1996b; 1998a; 1998b; 1998c; 1998d; 1998e; 1998f; 1998g), the identification of research application topics related to the emerging GISc ('crime analysis', 'risk

assessment and response', 'transportation planning and monitoring', 'urban and regional planning', 'water resources', 'involving the public in solving community problems', and 'public health and human services') (UCGIS, 1999), and the identification of critical and promising research issues for the cross-disciplinary domain of GISc (Buckley A.R., Gahegan M., *et al.*, 2000; Buttenfield B.P., Gahegan M., *et al.*, 2000; Mark D.M., 1999; Mark D.M., Egenhofer M.J., *et al.*, 2000; Merry C., Wright D.J., *et al.*, 2000). In particular, within the critical and promising research issues, let's point to 'scale and resolution', 'uncertainty and spatial dependence', 'cognition', 'geospatial data mining and knowledge discovery', and to the 'ontological foundations for geographic information science'. These research themes are in one way or another related to the crosscutting challenge of this thesis.

A couple of years after the creation of UCGIS, the Association of Geographic Information Laboratories in Europe (AGILE) was established with the mission to promote academic research and teaching on geographic information science in Europe and to facilitate networking activities between geographic information laboratories at the European level. One of the actions taken by AGILE was to established working groups on 'data policy', 'environmental modelling and planning', 'interoperability', and on 'education'. Based on the European context (spatial dimension of EU policies and European research area), this association worked on a research agenda. The following five challenges have been put forward as priorities: '**GI policy and society**', '**theory of spatio-temporal information systems**', '**dynamic modelling of environmental and social processes**', '**semantic interoperability of spatial data and services**', and '**integration of social and physical sciences in their contribution to space**' while a survey of research activities listed 28 themes partially based on UCGIS's research agenda (AGILE, 2001a 2001b 2001c).

Out of the academic circles, the umbrella organisation for geographic information in Europe also identified its priorities assuming that "the main problems to be tackled are primarily political and institutional rather than technical in nature" (EUROGI, 2000, p. 4). The objectives identified for a GI strategy at the European level are: 'encouraging greater use of geographic information in Europe', 'raising awareness of geographic information and its associated technologies', 'improving the European GI infrastructure', 'promoting the development of strong national GI associations', and 'representing European interests in the global spatial infrastructure debate'. This research is somehow related to the three first objectives. This ends up the description of the general context in which the doctoral research has taken place. The next section goes a step further through a focus on the specific context and through the definition of the thesis objectives.

Setting the research focus

The research theme '*errors and uncertainties in spatial decision support systems*' opens to a wide variety of potential investigations. Not only does it combine a high priority research topic in the GIS community (uncertainty) with what is seen as being tomorrows' computer systems for dealing with spatial phenomena (SDSS) (Figure 1), but also, as will be exposed in the prerequisites, because the meanings attached to the different words and expressions of this theme are numerous and can lead to various interpretations and combinations. For example, in 'spatial decision support systems' (or 'système d'aide à la décision à référence spatiale' in French), what does the term 'spatial' refers to ? Should it be understood as being a 'spatial <decision support system>', or as being a '<spatial [computer] system> for supporting decision' (Goodchild's point of view)[3], or as being a '<spatial support> for decision system', or as being a 'system supporting <spatial decision>'? Similarly, do the terms 'errors and uncertainties' apply to the term 'spatial' or is it to 'decision' or 'support' or 'system' or to one of their combinations ?

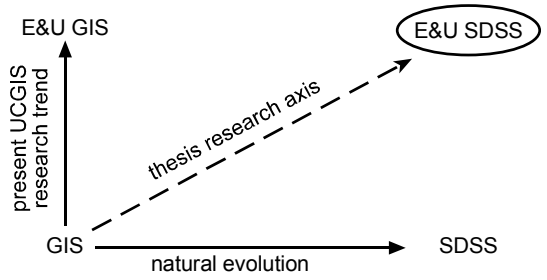

Figure 1: Research topic as seen at the time of defining the investigation.
E&U stands for errors and uncertainties.

Based on Heywood I., Oliver J., *et al.* (1994, p. 638) statements that "there appears to be insufficient research by the GIS community into how decision makers actually make decisions", that "more attention must be focused on understanding the role of spatial information in the decision making culture as a whole", and that "a complex problem is the need to fit GIS into the context of the whole decision making process rather than fit decision making into GIS", the research objectives were set to:

- to apprehend how decision-makers take decisions,

[3] Personal communication at ISSDQ'99

- to understand the role of spatial information in the decision making process,
- to fill the gap between decision-makers and the GIS community.

So, in order to refine the investigation theme and to fulfil the general objectives, it was decided to look at the errors and uncertainties in spatial decision support systems, not from the GIS community standpoint but from the decision-makers' one (DM) (Figure 2). In that perspective, a model had to be elaborated not only to serve as a common platform between the different ontologies, but also to structure the whole process. With this model, it should be possible to position the numerous approaches claiming to be related to decision-making and in particular GI, as well as to study errors and uncertainties from a decision-maker's standpoint. As will be explained in the next chapters, based on the elaborated model, the study of errors was identified as being not relevant from this point of view.

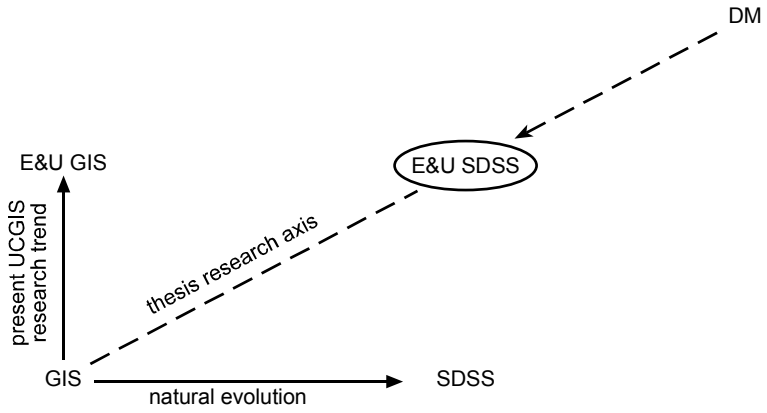

Figure 2: Standpoint taken, from the beginning, on the thesis topic.

The underlying idea with the understanding of the role of spatial information, was that, at a local level, spatial characteristics play an important role in decision-making while at the national and internal level, they are ignored. This hypothesis requires not only to have a clear view of what is meant by spatial information, but also to understand the process of decision-making as a whole and not as being a black box. Here again the elaborated model is used to apprehend the role of space in decisions and to identify the various types of spatial decisions. Out of the different potential meanings attached to SDSS, this investigation favours the 'system supporting <spatial decision>'. This original approach points to a major deficiency: the lack of definition for the concept of 'spatial decision'. The thesis proposes several ways to overcome this shortcoming, each having distinct implications for the development of computer-based support systems. The issue of drought was initially identified as application topic for the multi-scale study from the farm level to the European one. It turned out that the scientific knowledge on this topic is

still relatively scarce. It was anyhow kept, even after the restructuring of the SAI (see in the preface), for illustration purposes and was used as a pretext during the major fieldwork for apprehending the spatial dimension(s) of decisions.

This conceptual work was confronted to reality through some fieldwork, some internship and lately through some European and national research projects. This confrontation to different realities allowed to test the robustness of the concepts and to fulfil the third objective which runs on the long term. It is, of course, a modest contribution to the advancement of spatial science compared to recent research projects such as INSPIRE (Carlyle S., Zirm K.L., *et al.*, 2002; European Commission, 2001; Lillethun A., Weber J.-L., *et al.*, 2002; Rase D., Björnsson A., *et al.*, 2002; Smits P.C., Düren U., *et al.*, 2002; Wiberg H.-E., Engberg A., *et al.*, 2002) or GINIE (Craglia M., 2003; Craglia M., Annoni A., *et al.*, 2003b; Smits P., Poulit J., *et al.*, 2003) and to the lobbying activity of private companies (data, software and service providers) and of GI associations which lead to the recognition at different levels of the specificity of spatial industry (Craglia M., Annoni A., *et al.*, 2003a; Probert M. & Wolfkamp A., 2003). Besides, this thesis also contributed to the spatial awareness of decision-makers. This aspect is not as such described in the text although it needed specific time to achieve it. The education of end-users has indeed been identified as important by several authors especially since the GIS field widened to the one of GIScience (Diduck A., 1999; Forer P. & Unwin D.J., 1999; Ormeling F., 2004; Weir M.J.C., 1989).

This paragraph attempts to circumscribe the manuscript's content by stating what the thesis is not about. As was mentioned earlier, the research was started *ex-nihilo*, out of an organisation and its decisions activity, only having some software and no data. So, the description of a decision process such as Barouch G. (1989) or Faludi A. & Waterhout B. (2002) was not possible. Neither was the development of an SDSS component such as a data-mining module (Clementini E., Di Felice P., *et al.*, 2000; Eklund P.W., Kirkby S.D., *et al.*, 1998; Koperski K., Han J., *et al.*, 1998; Lefébure R. & Venturi G., 1998) or a visualization module (Davis T.J. & Keller C.P., 1997; Douven W.J.A.M. & Scholten H.J., 1994; Drecki I., 1999 2002; Husdal J., 2001; Kraak M.-J., 2000; Malczewski J., 1999b; Malczewski J., Pazner M., *et al.*, 1997; Morency J. & Chevallier J.-J., 1996; Smith A., Dodge M., *et al.*, 1998) or a decision module (Laaribi A., 1995a 1995b; Laaribi A., Chevallier J.-J., *et al.*, 1993 1996; Wu F., 1998). The research focus has not been set on the human factors determining the individual decisions of adopting GIS technology by public authorities (like in Budič Z.D. & Godschalk D.R., 1994; Morin D.M., 1999; Nedovic-Budič Z.D. & Godschalk D.R., 1996). Neither was it set on the influence of map design or of visualization techniques on decision-making (such as in MacEachren A.M. & Kraak M.-J., 1997; McKendry J.E., 2000). The research did not aim at developing a SDSS since not a single specific problem had to be solved (Frank W.C., Thill J.-C., *et al.*, 2000; Ji W. & Jeske C., 2000; MacLean D.A., Porter K.B., *et al.*, 2000; Nath S.S., Bolte J.P., *et al.*, 2000). The investigation is not about the analysis of a policy with or without computer support

(Acks K., 1998; Ballas D. & Clarke G.P., 2000; Loomis J. & Helfand G., 2001; Walker P.A. & Young M.D., 1997).

Based on the identified deficiencies (see next chapter for more details) – lack of a specific spatial decision theory and of concept definition; conflicting concepts within the field of GIS and with the fields falling in GISc; little or no attention given to space in the decision literature; misconception of many IT specialists with regard to what decision-makers need and on how they decide; lack of a unifying model to position the fields of decision science –, this investigation proposes:

- a generic model of the decision-making process,
- definitions of the 'spatial decision' concept,
- description of uncertainties in spatial decisions,
- a clear vision of the role of spatial information in decision-making,
- several research opportunities based on the concepts developed.

The concepts are illustrated with many examples at different scales. The standpoint taken (decision-maker's view) proved to be very valuable, not only because it avoided the bias of a cartographic vision on the issue found in most GIS researches (Aronoff S., 1995; Berry J.K., 1995; Birkin M., Clarke G.P., *et al.*, 1996; Bonham-Carter G.F., 1994; Chung C.-J.F., 1995; Cornélis B. & Garuti D., 1995; Haines-Young R., Green D.R., *et al.*, 1993; Heuvelink G.B.M., 1998; Longley P. & Batty M., 1996; Maathuis B., 1995; Malczewski J., 1999a; Marble D.F., 1984; Meijerink A.M.J., de Brouwer H.A.M., *et al.*, 1994; Pantazis D.N., 1994; Pantazis D.N. & Donnay J.-P., 1996; Ripple W.J., 1987; Thill J.-C., 2000; Valenzuela C.R., 1992; van Westen C.J., 1995; van Westen C.J., van Duren I., *et al.*, 1993), but also because it helped ponder the importance of space in the decision process. In other words and as can be seen on Figure 2, this investigation inscribes itself in the geographic information science (GISc) approach and not in the GIS tradition.

As can be seen in table 2, the disciplines involved in the development of GISc are many and each is busy with some particular aspects of the science while bringing in its own views and methods. Similarly, the decision science covers a wide range of disciplines such as statistics, psychology, operations research (OR), cognition, policy analysis, computer science, artificial intelligence (AI), political science, economy, planning,…. From table 2, it is clear that this doctoral research has been working on making links between two interdisciplinary sciences both at the level of developing concepts and at the level of establishing formal and theoretical foundations for the intersection science. Hence, to conclude, it can be said that, while opening a brand-new way to the understanding of decision-making processes in GISc, this doctoral research contributes to the present philosophical debate between neo-positivism and post modernism (see Raper J., 2000, for a more detailed discussion).

Table 2: Some GISc disciplines (after de By R.A., 2000) in relation to some decision science disciplines (in italic)

Activity in GISc	Sample disciplines
Development of spatial concepts	Geography *Cognitive science* Linguistics *Psychology*
Means for capturing and processing spatial data	Remote sensing Surveying engineering Cartography Photogrammetry
Formal and theoretical foundation	*Computer science* *Expert systems* *Mathematics* *Statistics*
Applications	Archeology Architecture Forestry Earth Sciences *Regional planning* *Urban planning* Surveying
Support	*Legal sciences* *Economy*

Structure of the manuscript

The manuscript is structured in chapters, parts, sections and sub-sections. Chapters are almost always divided into fours parts. The present introduction is followed by a chapter presenting the prerequisites which were found necessary to get to a spatial decision theory. According to her background and knowledge, the reader could easily skip what is not new to her. It is not advised to do so, because the core of the work (model and concepts developed) is based on the reframing of many elementary concepts. The theory development chapter is followed by several confrontations with 'reality' exposing some experimental results. Some research perspectives conclude the manuscript.