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An integrated conceptual framework for SDI research: experiences from French case studies*

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Abstract. Understanding the contribution of a Spatial Data Infrastructures (SDI) to society through improved economic, social and environmental outcomes implies an integrated and dynamic approach. To address this challenge, we propose a research framework that gathers theories and findings from a study concerning 45 French institutional SDIs. Its goal is to provide a logical structure for a holistic analysis of the complex components that affect the production and use of geographical information, their relationships, the dynamics of these relationships and the resulting outcomes. Two published frameworks, the Press-Pulse Dynamics and the Institutional Analysis and Development, are used as boundary objects during a three-workshop process gathering the research team. The result of this collective process leads to the design of an integrated conceptual framework for SDI research. It describes five main components of SDI (external drivers, a social component, patterns of interactions, a technical and informational component and outcomes), their relationships and research hypotheses. Guided by external press and internal pulse dynamics, the iterative framework redresses

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the balance of SDI components in favor of the social block and links this block to the technical and informational component through two bridges: patterns of interactions and outcomes. It shows how social norms and representations of different types of actors affect collective and individual actions, which then impact the technical and informational component of SDIs. In turn, technical and informational artifacts influence outcomes, thereby modifying human actions and initiating feedback that impacts the original dynamics and processes. We provide such a type of conceptual activity for assimilating large amounts of social and technical knowledge to strengthen our understanding of SDIs functioning and dynamics.

Keywords: Spatial Data Infrastructure (SDI), conceptual framework, French institutional SDIs

1. INTRODUCTION: SDIS AS COMPLEX SOCIO-TECHNICAL ASSEMBLIES STUDIED FROM A SECTORIAL PERSPECTIVE; THE NEED FOR A "MULTI-VIEW" APPROACH

With the potential of geospatial information now reached, SDIs have emerged since the mid-1990s as an enabling platform for evidence-based decision and policy making applied to sustainable development challenges (Scott and Rajabifard, 2017). By facilitating spatial data sharing through SDIs (Maguire and Longley, 2005), the aim is to support economic development, social stability, good governance and sustainable management of the environment at multiple institutional levels (Williamson et al., 2003). This general goal provides benefits for the geographical information community while reducing production and management costs (Crompvoets et al., 2004).

1.1. The state of the art

The SDI concept is challenged by its ambiguity (Bregt et al. 2009), despite the definition proposed by Rajabifard et al. (2002), who identify five core components including policy, access networks, technical standards, people (including partnerships) and data. Some authors (Hendricks et al., 2012; Coetzee and Wolff-Piggott, 2015) show that the definition of SDI and the majority of research on this topic still put a greater emphasis on its technological components, thereby minimizing its structural and human resource components. However, SDIs are thus regarded as socio-technical assemblies (Harvey, 2000), which can be viewed as self-organizing, complex adaptive systems (Amin, 2000; Bregt et al., 2009) emerging from a continuous process of negotiations between human and non-

human actors in the actor-network theory (Callon, 1985). Bringing Sciences and Technologies Studies (STS) approaches into Geospatial Information (GI) Science is a worthy enterprise already experimented in the context of public administration GIS deployment. For example, Roche and Caron (2004) study organizational facets of GIS. Harvey and Chrisman (1998) and Martin (1998) work on spatial data sharing in a sociological perspective. More recently, many researchers in social sciences investigate various non-technological components of SDIs. For example, Rodriguez-Pabon (2006) presents an assessment framework of national SDIs that highlights the non-technological benefits of these platforms. Delgado-Fernandez et al. (2005) propose an index of SDI readiness that takes into account the socio-political contexts of their deployment. Other studies on assessment-related issues of SDIs have also been undertaken over the last decade (Crompvoets et al., 2008), with a focus on economic impacts (Craglia and Campagna, 2010) or their governance systems at a national level (Georgiadou et al., 2006; Crompvoets et al., 2018) or at a local level (Harvey et Tulloch, 2006). The literature review also reveals a few studies which focused on the content of SDIs in terms of data or uses. Concerning data, Reznik et al. (2016) present a standardized evaluation of the performance, capacity, and availability of catalogue services. Concerning uses, Georis-Creuseveau et al. (2017) propose a methodological approach, oriented towards the study of the relationship between SDIs and the users interacting with them as part of their professional practices. Nedović-Budić et al. (2008) also study the user aspect of SDIs in its role as a key factor of effectiveness in terms of management and planning of environmental policies.

1.2. Open research questions

Two gaps can be identified in relation to this state of the art. On the one hand, the fact that most of these studies are based only on one case study or on SDIs positioned at the same administrative level – most often at the national level, sometimes at the local level. We notice that the intermediate level (e.g., the regional level) is rarely taken into account and that the multiscale analysis of the SDI ecosystem is poorly studied. On the other hand, the fact that most of these studies focus on one SDI component restricts our understanding of the functioning of SDIs as the relationships between components. According to Noucher et al. (2017) studies tend to focus on a single aspect of SDIs because of three main difficulties: (1) the acquisition of a comprehensive view of all the information that flows through these decentralized platforms, (2) the identification of SDI users

(producers, users or produsers), and (3) the description of their uses and their relationships.

To fill these gaps, some research aims to develop research frameworks on SDIs (Dessert et al., 2012; Crompvoets et al., 2008). Our contribution takes this perspective. In particular, we propose A vision (not THE vision) through a systemic approach of the SDIs ecosystem and answering several questions, for example, How and why do their components interact? What are the main factors in their dynamics? Do they really improve environmental and development sustainability? What are the outcomes for societies?

Due to the contexts in which spatial data is produced, analyzed, circulated and used, SDIs contribute to the complexity of the "spatial information universe" (Ballatore, 2014) and meet the goal of critical data studies (Kitchin and Lauriault, 2014). They can be seen as complex adaptive systems which adjust their structure, behavior and objectives to changing external circumstances (Grus et al., 2010). Some authors (Crompvoets et al., 2008; Bregt et al., 2009; Nedović-Budić et al., 2011; Noucher et al., 2017) have highlighted the need for a multi-view framework adapted to an interdisciplinary or even transdisciplinary approach to assessing SDIs, which should enable its complex socio-technical nature to be considered. To address this challenge, we propose a conceptual framework that gathers theories and findings from a recent study concerning the French institutional SDIs (Noucher et al., 2017). It aims to help future research on SDIs by highlighting the data to be collected, the processes to be analyzed and the disciplinary knowledge to be mobilized.

This paper is organized as follows. In Section 2, we explain why a conceptual framework is needed to improve SDI research and give reasons for our choice of two scientific frameworks to guide our thinking and we present the empiric study that feeds the framework and methods for producing our conceptual framework for SDI research (detailed in Section 3). The key elements resulting from this are discussed and suggestions for further research are outlined in Section 4.

2. METHODOLOGY: FROM PIECES OF KNOWLEDGE TO INTEGRATED SYNTHESIS

We agree with Nedović-Budić et al. (2011) that research frameworks and methodologies concerning SDI phenomena insufficiently reflect their interdisciplinary nature. From this point of view, the complexity of SDIs justifies the

development of a conceptual analytical framework inspired by empirical studies and useful for shedding light on components and their interactions. This conceptual framework could provide a logical structure for a holistic analysis (Simon, 1990) of the multiple and complex components that affect the production and use of geographical information, their relationships, the dynamics of these relationships and the resulting outcomes. As other conceptual frameworks, it could cut across spatial dimensions, temporal dimensions and various scales as well as highlight important assumptions and gaps in understanding (Leemans and de Groot, 2003).

2.1. The "Press-Pulse dynamics" framework as a guide

Scientific literature contains numerous examples of conceptual frameworks for analyzing different types of situation where humans interact with humans or non-humans (Latour, 2005). In social-ecological research, scientists have developed several frameworks which bring together theories and findings from multiple disciplines (Binder et al., 2013), with various degrees of equal representation of social and ecological systems. By example the general framework for analyzing the sustainability of social-ecological systems proposed by E. Ostrom (2009) is developed from anthropocentric and dynamic perspectives.

In the same way, the iterative "press-pulse dynamics" (PPD) conceptual framework designed by Collins et al. (2011) aims to guide long-term interdisciplinary social-ecological research which integrates the internal and interactive dynamics of social and natural systems. This "PPD" framework is designed to be generalizable, scalar, mechanistic driven (Collins et al., 2011). It combines interacting sociological and ecological complex dynamics through cross scale interactions and feedbacks between human and natural components (Holling, 2001). This framework is built on two main components of social-ecological systems (social and biophysical) linked by two critical linkages (press-pulse dynamics and ecosystem services). Pulse dynamics (sudden events) and press dynamics (extensive and subtle changes) interact and are submit to external drivers. "*The model assumes a continuous cycle of human decision making which affect the biophysical template via changes in 1) the intensity of press events and 2) the frequency, intensity and scale of pulse events. These press and pulse events have quantifiable implications for and impacts on ecosystem services which form the second link between the two main components. Changes in these services feed back to alter human behaviors and outcomes"* (Collins et al., 2011).

Our thinking has been also inspired by the Institutional Analysis and Development (IAD) framework adapted to knowledge commons by Hess and Ostrom (2005). According to these authors "*it provides a causal schema of structured independent variables which is well suited to the analysis of a complex, rapidly evolving common-pool resource: the underlying factors (physical/material characteristics, the attributes of the community, rules-in-use), action arena, patterns of interactions, outcomes and evaluative criteria"*. The focus of the IAD framework adapted by Hess and Ostrom (2005) is to explore the concerns for knowledge sharing in the era of Web.

We consider the geographical information of the SDIs as a type of knowledge commons. They allow the production, management and sharing of information considered as a social phenomenon where communities interact with informational resources, technologies, rules and norms. These social interactions take place over a wide range of scales and within a complex, overlapping variety of formal and informal structures.

In agreement with other authors (Bregt et al., 2009) who show the need of a genuine socio-technical and praxis-focused research paradigm for SDI, we argue that a "press-pulse dynamics" conceptual framework can be used as a guide enriched by some pieces of the IAD framework to design an integrated conceptual framework for SDI research.

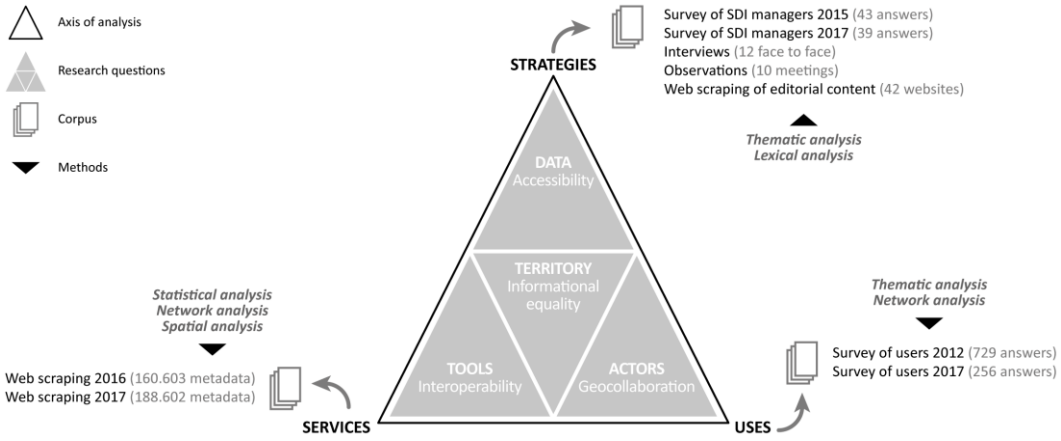
2.2. The empirical data used in the design of the framework

We studied 45 French institutional SDIs (16 national and 29 regional) with the objective to provide knowledge relating to spatial data sharing based on three dimensions: 1. the strategic orientation (what the managers say and show through the SDI websites), 2. the content of SDIs in terms of technical services and data, and 3. the uses of SDIs for planning and management. For details on the context of this study and previous results, readers can refer to Noucher et al. (2017).

A mixed method for capturing large and diversified datasets (metadata, website display and results of online surveys and interviews) was implemented to analyze the 45 national and regional French SDIs (Figure 1) by a research team made of geographers, data and computer scientists. The qualitative approach was based on lexical analysis of the editorial components of websites and verbatim reports of interviews with several SDI managers to clarify their objectives and strategies. A quantitative approach, based on statistics and network analyses, was applied to

data from surveys of managers and users of the 45 SDIs, and to the content of metadata catalogues. A spatial analysis of the catalogue data was performed. The qualitative data on uses and the contribution of SDIs to management and planning was analyzed.

Figure 1: Analysis framework, data and methods applied to 45 French institutional SDIs



This overall approach produced a lot of qualitative and quantitative data which have been analyzed through different perspectives and topics: 1. how SDIs participate in database dissemination, 2. their territorial coverage (spatial, thematic, temporal, organizational) and 3. their role in management practices.

Performed over 5 years (2012-2017), diachronic analyses revealed the dynamics behind the evolution of these different dimensions. For example, this multi-viewed approach to French institutional SDIs through data, information systems, actors and land provided a critical analysis of the French context by comparing theoretical assertions with part of the national SDIs network (Noucher et al., 2017). Thus, regardless of all the work put into indexing data in geocatalogues, our analyses showed that a very small amount of data was open access. Furthermore, despite numerous awareness-raising efforts (training, work group focusing on the co-production of data, etc.), the communities of practice involved were not diverse, with more than 70% of contributors originating from public authorities. Lastly, in spite of investment in the production of data repositories, the spatial coverage of data remained heterogeneous, with informational hotspots in stark contrast with

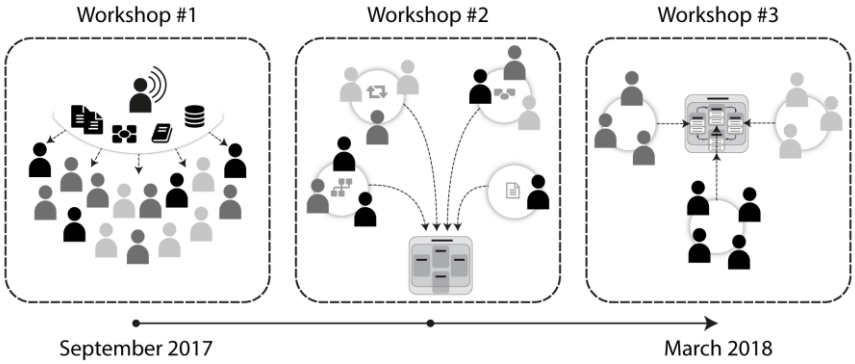
the predominant “dead zones”. Another interesting result of the study showed the changes in uses from 2012 to 2017 (Georis-Creuseveau et al., 2018). Despite the development of regional SDIs, the emerging role of national SDIs in France is probably due to the fact that they are open to the general public and provide data related to territorial issues.
In this paper, we specify that most French users’ professional practices were based on multiple SDIs. The main knowledge resulting from the study of the 45 French institutional SDIs coupling with the GI Science expertise of the research team have been mobilized to feed the framework in its various components.

2.3. The main steps in developing the framework

Beyond our sectorial analyses, a transversal vision was required in order to cross the three dimensions of our study, i.e., 1. the strategic orientation (what the managers say and show through the SDI websites), 2. the content in terms of technical services and data, and 3. the uses for planning and management. In this prospect, the objective was to build a conceptual framework based on the main results concerning the 45 French institutional SDIs, in terms of knowledge gained and gaps to be filled.

Three workshops were organized during the last six months of the study (Figure 2). They gathered the research team according to a collegiate participation mode where “*the participants work together as partners i.e. the “Ownership” and responsibility are equally distributed among them, and decisions are made by agreement or consensus among all the partners”* (Barreteau et al., 2010). In this arena, we used the template by Collins et al. (2011) as a boundary object (Callon, 1985; Star and Griesemer, 1989). This social-constructivist concept has been defined by the STS field (Callon, 1985; Latour, 2005) and applied among others to GI Science (Harvey and Chrisman, 1998). According to these authors, boundary objects stabilize relationships through the negotiation between different points of view.

Figure 2: The three-workshop process



The first workshop was led by one member of the research team who presents the objectives, the schedule, the methodology, and the available materials: empirical fieldwork concerning strategies, services and uses of French institutional SDIs, academic literature including Collins et al. (2011) and Hess and Ostrom (2005). Between the first and the second workshop, the participants have worked alone or in small groups. Each proposal was presented and discussed during the second workshop. It led to an agreement on the outline for a common framework consisting of:

1. the five main SDI components (external drivers, outcomes, a social component, a technical and informational component, patterns of interactions),
2. the symbol representations (box, arrows, etc.), and
3. a first draft of the literature-based description of the sub-components.

Depending on their skills, groups were then formed to describe the components. One month later a third workshop was organized. It aimed to collectively stabilize the description of the five components, to draw up a list of research hypotheses and to identify knowledge gaps.

3. RESULTS: A SDI FRAMEWORK BASED ON FIVE COMPONENTS

Figure 3 presents the proposed conceptual framework for SDI research. It contains five main components: 1. the external drivers, 2. a social component, 3. a block of patterns of interactions which introduce pulses, 4. a technical and informational component, and 5. the outcomes.

H1 to H4 refer to integrating hypotheses as follows:

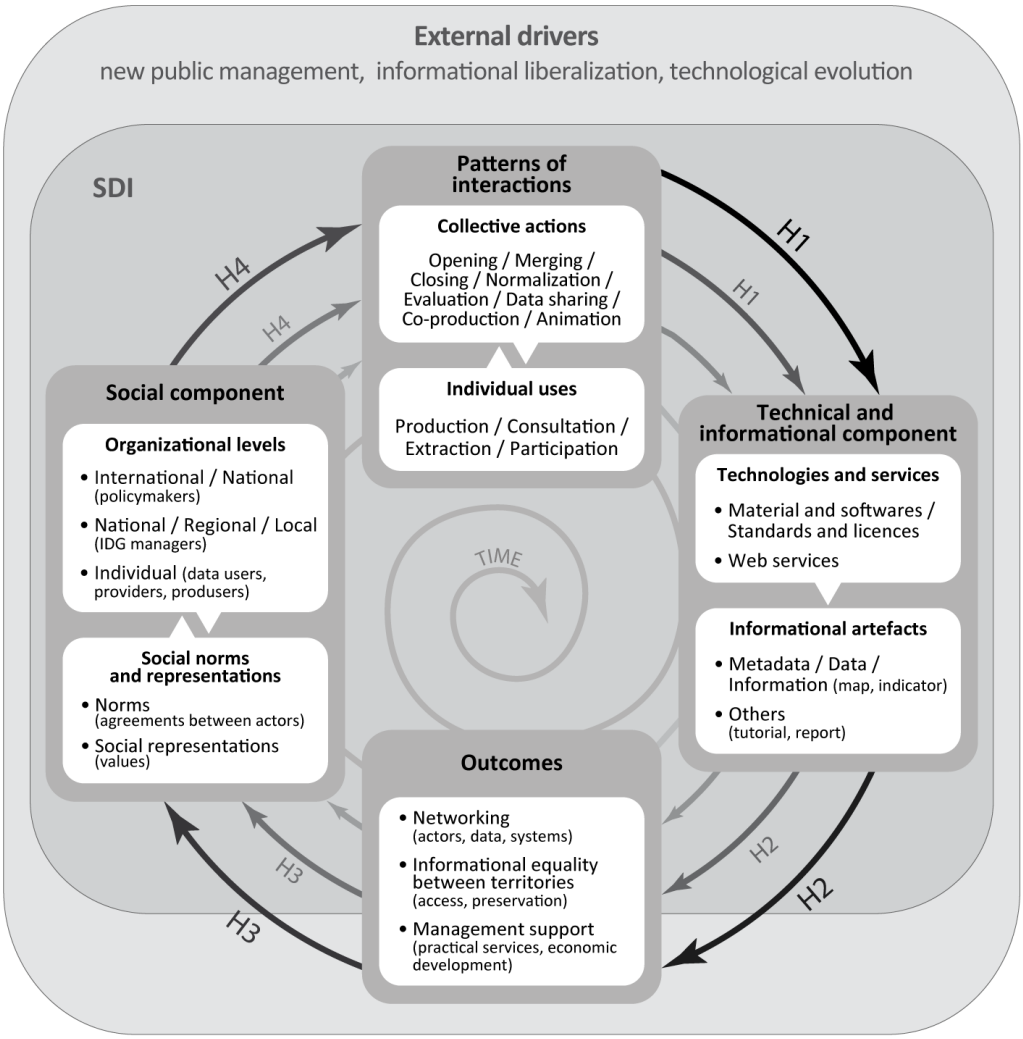
H1 – Individual and collective actions modify the technical and informational component of SDIs.

H2 – High-performance SDIs, which produce a diversity of deliverables, offer different types of services to territories and society.

H3 – Different social norms and representations contribute to varying opinions on the services provided by SDIs to territories and society.

H4 – The factors triggering action and use are linked to social norms and representations as well as a multi-level governance of SDIs.

Figure 3: The conceptual framework for SDI research.



3.1. External drivers

Press events are considered as external drivers acting at a global level and impacting Digital Earth (details below). The interviews and surveys with managers of the French institutional SDIs and the lexical analyses of the editorial content of their websites enabled to highlight three main types of external drivers, which can exclude each other, be juxtaposed or mutually support each other (outer box in Figure 3).

First, public policies (i.e., territorial planning and management policies, policies for preserving biodiversity, economic development policies) create a "meta regulatory framework" that influences the strategies of managers and users of SDIs. In France, in 2015, the NOTRe (New Territorial Organization of the Republic) law approved the transition from 22 to 13 metropolitan regions and consequently led to the merger of several regional SDIs or the transfer of data to open data portals, as shown by the online survey performed in 2017 towards the managers of French institutional SDIs. The data aspect of these policy frameworks has enabled the theories developed in the context of the information society paradigm and the rolling out of a "new public management" (Hood, 1995). In this context, information is presented by the managers of French institutional SDIs as a resource for optimizing spatial management and planning and as a tool for modernizing society from an ecological perspective. Our study concerning the French institutional SDIs underlines the importance of the economic argument in justifying their deployment. This shift is an extension of the theories, which link the broadening of access to information and the social and economic innovation developed at the beginning of the 2000s.

Second, another group of external socio-political factors likely to impact SDIs stems from democratic requirements that turn information into a social right that needs to be defended. The fact that disputes are increasingly judicialized, especially in the environmental domain, has prompted a renewal of laws and the activation of legal measures in favor of better access to information (Gautreau and Vélez, 2011). The growing number of participatory bodies built on discussion or the co-building of information also illustrates the new role that the civil society plays in producing and disseminating knowledge. Principle 10 of the famous Rio Declaration on Environment and Development (1992) points these aspects out[1].

[1] "*Environmental issues are best handled with the participation of all concerned citizens, at the relevant level. At the national level, each individual shall have appropriate access to information concerning the environment that is held by public authorities, including information on hazardous materials and activities in their communities, and the opportunity to participate in decision-making*

Promises made relating to transparency and participation are thus key elements in the position held by managers, as highlighted by the interviews or the analysis made of the arguments put forward in the editorial content of analyzed websites (Gautreau and Noucher, 2016). They justify the creation of SDIs to facilitate access to data in keeping with informational liberalism (Loveluck, 2015), which makes the circulation of standardized data a carrier of democracy[2].

A third type of external driver emerges from factors associated with technological evolutions and the transformation of the Internet into a media space. A first set of factors stems from technological evolutions that have appeared over the last twenty years. Some speak of a "geospatial revolution"[3] to describe both the increasing geo-digitalization of the world and the democratization of digital use. The expression "digital society" (Lindgren, 2017) underlines the power of digital technologies that now permeates all of society and is most spectacularly embodied by the Internet. Similarly, the expression "the cartographic turn of the Web"[4] bears witness to the renewal of techniques and uses of the Internet, which views localized data as an indispensable web-based information resource. The lexical analysis of the websites of the 45 French institutional SDIs highlights that more than a third of them put an emphasis on their technical capacities i.e., downloading services, viewing services, data interoperability. The notion of *Digital Earth*, put forward by Al Gore, in 1998[5], can be taken as a political vision which brings these factors together and influences the imagination of actors involved in the "SDI" system. The question of digital commons and open data seems to be ever more present in the principles that the managers of institutional SDI seek to defend. This context has already imposed changes as the majority of French SDIs deployed in the 2000s were only accessible to a few institutional partners. For the majority of the 45 French SDI managers included in the study, the issue of data accessibility is, therefore, at the heart of these dynamics and one of the priority objectives is to

processes. States shall facilitate and encourage public awareness and participation by making information widely available. Effective access to judicial and administrative proceedings, including redress and remedy, shall be provided"

[2] Such as the Open Data Charter signed by the heads of the G8 states during the Lough Erne summit in Northern Ireland in June 2013: https://www.gov.uk/government/publications/open-data-charter

[3] This refers to a Penn State University (USA) web documentary, whose title and content are good illustration of the change in perspective which accompanies these technological developments: http://geospatialrevolution.psu.edu/

[4] Without focusing on the Web, Lévy (2015) proposes this expression to describe the evolution of cartographic practices at the heart of and beyond the geographic discipline, with the emergence of community, militant or artistic projects based on maps.

[5] http://portal.opengeospatial.org/files/?artifact_id=6210

promote the wider use of spatial information (Noucher et al., 2017). This positioning was probably the result of national injunctions, e.g., the French Law for a Digital Republic (2016) and the announcement of substantive national initiatives such as the report on sovereign geographical data (2018) or the national plan for Open Sciences (2018).

3.2. Social component

In the proposed framework, the social component of SDIs is characterized by two interacting sub-components (box in the left part of Figure 3). The first one comprises the different organizational levels of the community of interest (individual or collective actors). Actors relate to each other through networking. Institutional decision makers are groups of individuals commissioned by the state or states to establish and implement active policies on geographic information. For example at a European level, DG ENV (Directorate-General for Environment) worked towards establishing the INSPIRE Directive (2007), which then translated into national institutions such as the National Council for Geographic Information in France. These groups raise awareness about the directives and provide advice to managers of SDIs implemented at all institutional levels. The managers of institutional SDIs are present from national to local levels. In France, the regional level is the strongest link in the chain for implementing general-interest SDIs over national territory (Noucher et al., 2015). National thematic SDIs managed by specialist organizations, such as Ifremer and SHOM (national hydrographic service) in the maritime domain and institutional SDIs relating to more local entities such as the towns, complete the system. An analysis of the interconnection of French institutional SDIs, through the geo-catalogue harvesting network[6] for example, highlights this center-to-peripheral organizational structure based on territorial levels. The individual level of the community of interest refers to data users, data providers and data producers (Budhatodki et al., 2008), as well as, the different contributors at technical and decisional levels. They can be internal (e.g., technicians, SDI managers) or external (e.g., scientists, companies that provide/search for information, etc.) to an SDI system at different territorial levels. Our survey, conducted in 2017 on 256 users, reveals that the majority of professionals concerned are involved on a sub-national scale (24% at a regional level, 22% at a sub-regional level, 35% at an inter-municipal level), and very few

[6] http://geobs.cnrs.fr

show an interest for national and supranational scales (12% at a national level, 6% work at a European and international level) (Georis-Creuseveau et al., 2018).

The above sub-component acts and reacts according to social norms and representations that we have gathered into a second sub-component. According to Di Méo (2008), social representations reflect the system of values common to members of the same group and are built on core-based learning, where the core comprises a few guiding principles. These representations are based on visions, trust and promises that provide productive outcomes. The development of communities of practice associated with French institutional SDIs (132 in 2015 and 150 in 2017) demonstrates the importance of organizational dynamics, which contribute to enhancing social representations, in addition to technical infrastructures. As maintained by Abric (1984), these representations have four main functions which we identified through the surveys and interviews concerning the 45 French institutional SDIs. The knowledge function enables reality to be understood and explained, thus providing a framework for action. For example, in France, understanding and integrating the different European or national standards (INSPIRE, and others) provides a framework for individual actions regarding SDIs. The identity function defines the social identity of each individual, thus preserving the specificity of different social groups. For example, the importance of moving towards open access or open data characterizes some SDI members. The guidance function of social representations enables each individual to anticipate and generate expectations and decide what is possible in a particular social context, for instance, deciding what services can be provided by SDIs. As Harvey (1997) has demonstrated, the national influence culture on the design of information systems must also be taken into consideration because cultural norms do not always and everywhere lead to identical results. Social representations can also come into play in hindsight, through its justificatory function. In the context of the SDIs we studied, social representation can impact effectiveness, which is related to how the value of an act is judged, e.g., the services provided by an SDI, and wisdom which is the process by which we discern or judge between right and wrong, good and bad (Ackoff, 1989). It relies on moral and ethical codes and can concern open access/data, for example. As Leonard-Barton (1988) reminds us, value misalignments can appear between technology and user environment, i.e., benefits on performance criteria applied at the SDI level but a negative individual impact for data users and technical staff.

3.3. Patterns of interactions

We envisage the interaction of social and technical components through a series of processes that can take place at different levels and that we group together in the « patterns of interactions ». Thus, in the continuity of the framework proposed by Chrisman on GIS (2002), a SDI must be seen as the articulation of components (which have a certain proximity to Chrisman's *circles* without being exactly the same items) that are as many levels of coherence and specific constraints of the system: "*The organized activity by which people – measure aspects of geographic phenomena and processes; – represent these measurements, usually in the form of a computer database, to emphasize spatial themes, entities, and relationships; – operate upon these representations to produce more measurements and to discover new relationships by integrating disparate sources; and – transform these representations to conform to other frameworks of entities and relationships. These activities reflect the larger context (institutions and cultures) in which these people carry out their work. In turn, the GIS may influence these structures*" (Chrisman, 2002). The spiral representation of these multiple processes highlights their dynamics and possible feedback.

The social component of SDIs is key to the transaction processing described in the patterns of interactions of two types: individual and collective actions (box in the upper part of Figure 3). *Individual people* at the different organizational levels are a key factor in the different types of SDI uses, e.g., providing information, using the resources, participating in collaborative actions. Our study of French institutional SDIs highlighted that individual contributions cover a broad range of different actions, which do not amount to simply using the tools. The combination of multiple SDIs across various institutional levels reflects the different data levels and scales associated the professional practices of users (Georis-Creuseveau et al., 2018). In term of data production, the exploration of the 45 geocatalogues reveals the very low diversity of contributors to French institutional SDIs. 70% of the metadata come from public authorities and only 3% from the private sector. In national and regional French SDIs, research data have been increasing since 2012, probably due to the growth of regional funds dedicated to the research sector, the growing demand for the opening of research data and the lack of success in the implementation of SDIs in academic institutions. The individual uses of SDIs interact with collective actions, thus generating different types of pulses which impact individual uses and change the technical and informational components. Alongside technical and data input developments, training and communication as well as substantial work on standardization and organizational set-up are carried out. These individual actions

interact to become collective actions through networking, e.g., individual participation to data sharing or co-production activities. As the projects associated with the SDI (training, co-production, etc.) are developed, the commitment to their implementation increases, and the actors then enter a phase of collective learning. After a while, this collective learning produces practices. Real communities of practices (Wenger, 1995) then emerge. They articulate individual objectives and commitment to the collective.
These *collective actions* can be witnessed, especially on a local and regional scale, through the emergence of communities of practices which favor different forms of geo-collaboration, such as the co-designing of models, or the co-production and collaborative data quality assessment of data (Noucher, 2011). In France, the number of SDIs managing communities of practices has been evolving since 2012; the latter are interested in less technical and more thematic subjects (e.g. landcover, urbanization, etc.). Collective actions also involve decision-making or, more broadly, discussion, which can be explicit or implicit, political or technical, formal or informal (Rosenberg, 2007). For example, pulse events decided at a high organizational level of SDIs can be: opening, merging or closing an SDI, opening access to data, developing a service (interoperability), reporting and evaluation, etc.

These individual and collective actions, considered as patterns of interactions, are motivated by the social representations of the system and its development. They lead to adjustments within the technical and informational component of an SDI.

3.4. Technical and informational component

Collective strategic choices and decisions affect the technical and informational template on two main levels (box in the right part of Figure 3). First, the "technologies and services" sub-component comprises two types of facilities as defined by Hess and Ostrom (2005), which are mechanisms for data access and data searching, data and metadata submission functionalities, and mechanisms for added-value data processing. All the technical infrastructures are needed for SDIs to function properly (hardware, software, server, networks and telecommunication equipment) and also need to meet interoperability standards developed to enable web services to operate. They facilitate both the publication and exchange of geographic information and metadata, and also enable geographic information to be combined as well as services to interact for providing coherent outcomes. The general functioning of SDIs relies on web services which offer different functionalities: information searches via a catalogue (e.g., Catalogue

Services for the Web – CSW), data viewing through a viewer (e.g., Web Map Service – WMS), data downloads from the catalogue or the viewer (e.g., Web Feature Service – WFS). Thus, 40 out of the 45 SDI managers surveyed reported that they used web services to access remote metadata (CSW) or data (WMS, WFS) potentially distributed on several servers. These interconnection issues are at the heart of national spatial data infrastructure implementation strategy. The recent reorganisation of the geoportal/geocatalogue has been implemented in the context of the emergence of the platform-state and is aimed at reinforcing the mechanisms for aggregating regionally- or locally-produced data on a national level, to develop chained geoprocessing with heterogeneous sources or even to improve harvesting/caching mechanisms. The platform-state is a national strategy to promote the emergence of new digital public services, based on improved data circulation. This concern with improving the circulation of information is also perceptible on a regional level, with SDIs that set themselves the objective of developing new functions (web services) to promote the interoperability of different systems, reduce public spending and save time (Noucher et al., 2017). Other services also ensure geographic data transformation, metadata management, the coordination of interacting services, etc. Sophisticated services are sometimes proposed to create online maps, extract geographic information corresponding to a specific area, etc. All these facilities make artifacts available.

Second, the information sub-component of SDIs can be broken down into two main artifacts. The first consists of geographic data available in different formats, the metadata describing the data in a standardized manner to make it usable and the information (map, geo-visualization, indicator) resulting from specific data processing for a given purpose. The indicators produced by processing of a set of information to gain a brief insight are essentially used for diagnostics, communication, policy evaluation and decision-making functions. All the other resources such as tutorials and contextual information (reports, editorial site content, etc.), make up the second type of artifact provided by the information sub-component of SDIs.

The facilities and the artifacts are often the only visible aspect of SDIs. The cumulative dynamic of SDIs which we observed in France reinforces the importance accorded to this component. Benchmarking reports for the INSPIRE Directive[7] concentrate on this aspect by proposing quantitative evaluations of

[7] https://inspire.ec.europa.eu/monitoring-and-reporting/69

databases, services and metadata that have been accumulated. However, as our conceptual framework shows, this component is only one part of a complex integrated system.

3.5. Outcomes

Facilities and artifacts within the technical and informational component of SDIs determine the services provided, i.e., the outcomes, by SDIs to territories and society at large (box in the lower part of Figure 3). The outcomes block is the second set of interactions linking the technical/informational and social components of the SDI framework. Outcomes are as much about what SDIs produce (i.e., the tangible aspects of their implementation) as the virtues they are endowed with (i.e., the performance of positions held and promises made in relation to these). We identify three main types of SDI outcomes.

The first one is dealing with the different forms of networking. From an actor perspective, it is expressed through geo-collaboration (skills cluster, co-production) or disintermediation (diffusion without an intermediary). Individual benefits through networking include time savings, accessibility of information, training opportunities and involvement within the organization. In France, 150 communities of practices, as a result of the 45 institutional SDIs, are potential places of cooperation and reciprocity (social capital). In France however, these geo-collaboration dynamics are currently observed in an inward-looking system without diversification: government administrations and research act separately, the private sector is not represented, and associations are still only marginally involved (Noucher et al., 2017). Data networking takes place through improved access to data (open data) or more restricted access using an informational enclosure based on charters and protocols (Gautreau and Noucher, 2016). System networking relies on interoperability, which makes it easier for an inexperienced user to access information.

The second outcome of SDIs that we identified is the goal to provide all territories with equal access to information by opening access to databases for example. It is considered by the majority of SDIs policy makers and managers we surveyed as a key objective. But despite the many actions implemented (animation, training, involvement of field actors in the governance of SDIs), this aim is far from being achieved in France, where informational imbalances clearly exist between those territories with a huge amount of notably free access data at hand and those that have hardly any data at all (Noucher et al., 2017). This situation may reveal local

problems and power struggles between public administrations with varying geographical or thematic perimeters. This second outcome includes the goal to create a form of “digital knowledge commons” (Hess and Ostrom, 2005) around a given theme or territory which can lead to generate economic and civic values.

As a third outcome, SDIs can provide help with managing territories through the development of specific applications that transform data into practical services. 77% of the users surveyed in 2017 stated that the SDIs contribute to the management of territories due to the accessibility of geographical information and the appropriate nature of the information. In terms of benefit, access to geographical data is highlighted before geo-collaboration and the pooling of resources benefits. SDI artifacts can contribute to governance and economic development by creating wealth and avoiding costs incurred by intensive use, however, non-use also leads to hidden costs. This efficiency of SDIs can be associated to the goal of the core infrastructure which supports economic development, social stability, good governance and sustainable management of the environment at all levels, as described by Williamson et al. (2003).

Nevertheless, the outcomes of the services provided by SDIs at a local, regional and national levels do not always meet the objectives of all the actors who do not share the same points of view (Table 1), as shown by the interviews and surveys addressed to the French institutional SDIs managers and users.

Table 1: Potential outcomes of SDIs deduced from surveys and interviews conducted on French SDIs (keeping with Hess and Ostrom (2005) but adapted to SDIs).

POTENTIAL OUTCOMES (FRONT SIDE)	***POTENTIAL OUTCOMES (BACK SIDE)***
NETWORKING	**NETWORKING**
Actor networking (geocollaboration, cooperation, reciprocity)	**Competition between actors** (leadership conflicts)
Data networking (open data)	**Segmentation of data access rights** (new informational enclosure)
System networking (interoperability)	**Cohabitation of heterogeneous systems** (lack of standards)
INFORMATIONAL EQUALITY/INEQUALITY	**INFORMATIONAL EQUALITY/INEQUALITY**
Informational equality between territories (base map production, global use)	**Informational inequality between territories** (spatial injustice – data hotspot or hole)

Preservation of information (spatial data memories)	**Accumulation of information** (data deluge)
MANAGEMENT SUPPORT	**MANAGEMENT SUPPORT**
Economic development (avoided costs, use of innovative services)	**Economic development** (hidden costs, non-use)
Services (governance, sustainable development)	/

4. CONCLUSION AND OUTLOOK

The integrated conceptual framework for SDI research we propose is the final result of a study concerning 45 French institutional SDIs. It was built by consensus of the research team over three workshops and follow-up discussions. As the framework developed, there were topics that led to agreement or sometimes disagreement between the members of the research team. At the start, some participants considered the approach too simplistic and superficial. However, the writing process clarified things and harmonized the modeling exercise by describing the content of components in detail. Participants also seemed to have difficulties in grasping the dynamic dimension of SDIs, which was not always helped by the static representation of the framework of Collins et al. (2011). Most of the discussions held by the group focused on the social component, the outcomes and the interaction factors, whereas the external factors and the technical and informational component were relatively easy to justify and describe. This is probably due to the area of expertise of the participants (geography, data and computer sciences) and the knowledge they had gained from the study of the 45 French SDIs.

The two frameworks used (Collins et al., 2011; Hess and Ostrom, 2005) have been discussed, deconstructed, reassembled and adapted to the SDI system. They acted as boundary objects that stabilize knowledge shared by the research team and have proved their mediating effect in this type of collective process. We agree with Barreteau et al. (2010) that the intuitive and visual nature of the conceptual models and templates is suitable to innovative and creative interdisciplinary collaborations. Several adaptations of the “PPD” framework have been made. In our framework, press events are considered as external drivers and the outcomes are also partially external to SDIs. Pulse dynamics are replaced by the patterns of interactions considered as short-term processes, and the ecosystem services are replaced by the notion of outcomes herited from the IAD framework well adapted to SDIs. So the dynamics of the SDI system are driven by processes on two

different scales. In the footsteps of Masser (2005), we distinguish between internal short-term processes (patterns of interactions) which lead to the adjustment of a SDI to a specific context and external long-term processes (press events/external drivers) which occur in response to "global" changes.

In terms of results, firstly, our proposal brings the SDI model of Rajabifard et al. (2002) into focus by qualifying the main components. It redresses the balance of components in favor of the social block and links this block to the technical and informational component through two bridges: the patterns of interactions and the outcomes. These bridges can be view as the "*included middle where interdisciplinary paradoxes and dilemmas are reconciled"* (Bregt et al., 2009). Dynamics are also shown to be explicitly due to external drivers which we have described. Improving knowledge of the social mechanisms which influence the functioning and evolution of SDIs could feed current reflection in Europe on evaluation criteria. INSPIRE reporting, which has predominantly focused on the technical and informational component (i.e., quantity of metadata, number of services, etc.) in the past, currently appears to be evolving towards including all aspects of use (economic efficiency, partaking in knowledge commons, contribution to informational governance, etc.). Secondly, this integrated conceptual framework can serve as a guide for any future research tackling the SDI system in all its complexity, by emphasizing not only the technical, informational and social components but also, and above all, the drivers behind SDI dynamics (the outcomes, uses, governance, etc.) at international, national, regional and local levels. It sets hypotheses to be tested in different contexts, and is scalable, i.e., adapted to a set of SDIs or to one SDI as an Annexe to this article.

Integrating social and technological/informational components and feedback is crucial in this framework. However, the components give rise to research questions that still require field-related expertise. For instance, in terms of the social component, existing governance modes could be studied in reference with scale approaches proposed by Termeer et al. (2010). As for uses, light still needs to be shed on the individual determinants both of action and the appropriation of SDIs by the different types of actors, particularly in relation to norms and social representations as well as sociological characteristics (Venkatesh et al., 2003). Similarly, the impacts of different types of positive or negative governance actions on users could be analyzed from a historical perspective specific to each SDI (Sjoukema et al., 2017). It is quite clear that competencies from multiple disciplines alongside practical knowledge are needed to understand how SDIs function and

evolve. For example, the processes involved in the social component benefit from ethnographic, social and political expertise on the governance of SDIs. An analysis of the discrepancies between the discourse of policy makers on the one hand and user practices, contents (facilities and artifacts) and outcomes on the other, constitute an interdisciplinary field of research, drawing extensively on Humanities and Social Sciences and Computer Sciences (Noucher et al., 2017). Economics are of interest in the field of outcomes, particularly in terms of the economic efficiency of SDIs (Craglia and Campagna, 2010). On another level, management sciences could throw light on the individual acceptance process of the technical component of SDIs (Venkatesh et al., 2003). All these disciplines could bring their expertise to various parts of the system and improve the understanding of the complex functioning and dynamics of the whole. This process could also integrate a non-academic public, i.e., SDI practitioners (users, stakeholders, decision-makers). Researchers and practitioners could work together over extended periods to develop novel conceptual and methodological frameworks with the potential of producing transcendent theoretical approaches (Klein, 2008).

This proposal of an integrated conceptual framework can also contribute to scientific issues concerning the adaptability and resilience of SDIs. In our approach, we considered that the dynamics of the system were subject to external drivers, some of which could lead to its disappearance. The external drivers are combined with internal pulses to which the system continuously adapts itself. As shown by Leonard-Barton (1988) for technical innovations, SDIs can be viewed as a process of mutual adaptation between the technological and informational component and the social component. According to this author, "*technical and values misalignments imply adaptive responses conceived as recursive cycles where the system never returns to the same situation from which the cycle of adaptation started"*. External drivers and internal pulses through collective actions and individual uses continuously alter the original situation. We agree with Grus et al. (2010) that SDIs may be considered as adaptive systems. They adjust their design, content, production and governance not only according to external drivers but also internal dynamics linked to individual and collective actions. It shows that a SDI system considered at a national level by example, as well as its individual SDIs, are characterized by high instability and resilient capacity. Sjoukema et al. (2017) have discussed the adaptive nature of SDI governance for meeting goals, satisfying all actors and being in alignment with new visions and ideas. They demonstrated that success came after 20 years of repeated false starts which seemed to have stimulatory effects. The governance of these systems and their

capacity to adapt to changes occurring at different levels (international directives, administrative reshuffling at a national level, social requirements, etc.) is undoubtedly worth studying to understand the dynamics of these socio-technical assemblies over the medium term.

In addition to the prospective improvement of the conceptual framework of SDIs thanks to inter-/transdisciplinary approaches and testing in different contexts, a future step would be to counterbalance the inward-oriented research. SDIs are actually only one part of digital earth as a whole. Its relationships with VGI, Open data, GeoWeb and non-institutional SDIs, considered as external drivers in our framework, also need to be studied. This sizeable challenge implies monitoring programs and geographic information observatories for supporting sciences (Adams et al., 2014). Their implementation is essential to the knowledge of the dynamics affecting these complex systems at different spatial and temporal scales. From this perspective, the development of techniques for capturing and processing large volumes of heterogeneous data is a challenge. Simultaneously conceptual activity aimed at the SDI community can provide explicit roadmaps for guiding future research. As in other fields of science, conceptual models and frameworks may be valuable tools for assimilating large amounts of social and technical knowledge to strengthen our understanding of SDI functioning and dynamics.

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Disclosure statement

No potential conflict of interest was reported by the authors.

Supplementary materials

The website geobs.cnrs.fr provides access to technical reports, geovisualizations, open access articles, open data corpora and open source scripts from the research project.