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**The Effects of Using System Dynamics-Based Decision Support Models:
Testing Policy-Makers' Boundaries in a Complex Situation**

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ABSTRACT. Systems thinking and computer-based modelling systems are widely recognised as effective for solving complex problems, particularly for the potential changes they can trigger in decision-makers' perception of where problems' boundaries lie. Surprisingly, few studies have analysed their empirical effects on decision-making. This paper explores the effects of the use of a system dynamics-based DSS by decision-makers, focusing on boundary judgements, which

indicate what issues and stakeholders are to be included in the decision analysis. The data were obtained from an experiment with 40 policy-makers, using a simulated case approach that focused on the complex biotechnology intellectual property system. They suggest that the use of such a DSS favours both the analysis of a greater range of perspectives and broader stakeholder participation, but does not strengthen either interdisciplinary integration or depth of stakeholder participation.

KEYWORDS: Decision support models, Systems thinking, System dynamics, Complex situations, Public policy making, Boundary judgements.

1. Introduction

A highly complex, increasingly interconnected and rapidly changing world (Bosch, Nguyen, Maeno, & Yasui, 2013) means that decision-making increasingly takes place in complex settings (Neumann, 2013; Qudrat-Ullah & Karakul, 2007). Such contexts, which also reflect ‘ill-structured’ problems or ‘messy’ situations, are characterised by great complexity and uncertainty (Bennet & Bennet, 2008; Petkov, Petkova, Andrew, & Nepal, 2007). According to Bennet and Bennet (2008, p. 4), a complex situation can be defined as

any issue, problem, condition, opportunity or system [...] that may be difficult to define and may significantly change in response to some solution; may not have a single “right answer”; has many interrelated causative forces; has no (or few) precedents; has many stakeholders and is often surprise prone.

In complex situations, decision outcomes often differ from the expected and desired results, even when decision-makers’ intent is to act purposively according to set objectives (Forrester, 1975). As Churchman (1979) and Ulrich (1983) have argued, all the parts of a complex situation are interconnected and, consequently, it is necessary to consider it as a whole before intending improve it. Systems thinking is one way of handling this increasing complexity. For instance, Maani and Maharaj (2004) argued that systems thinking is widely recognised as highly effective for addressing such complexity. More recently, Bosch et al. (2013) claimed that it is increasingly seen as a new way of thinking to understand and manage complex situations. Systems thinking is indeed concerned with the use of systems-based ideas in trying to understand the world’s complexity (Checkland, 1981): it involves thinking in terms of processes, relationships, and interconnections (Laszlo, 2012), and therefore treating a complex problem as a complex systemic ‘whole’ (Jackson, 2006). Yet most individuals experience difficulties in thinking systemically

(Boschetti, Hardy, Grigg, & Horwitz, 2011; Maani & Li, 2010; Sterman, 1989). Moreover, given that systems thinking posits that everything is directly or indirectly interconnected with everything else, there are inevitable limits in reaching an understanding, as the full interconnectedness of everything to everything else is impossible to grasp: individuals necessarily have ‘boundaries’ (Midgley & Richardson, 2007). In this context, the challenge of decision support systems (DSS) is not to settle on a specific solution but rather to favour more systemic thinking during the decision-making process. It involves changing the nature and quality of the thought process regarding complex situations (Doyle, 1997), and seeing things holistically and interconnectedly (Cramp & Carson, 2009; Jackson, 2006; Maani & Maharaj, 2004). In particular, given the inevitable lack of comprehensiveness, it is about creating change in regard to decision-makers’ boundaries (Midgley & Richardson, 2007).

Based on the systems thinking literature, decision support systems, which integrate system modelling, have the potential to meet this challenge (Maani & Maharaj, 2004). In fact, computer-based modelling systems are seen as useful tools for learning to understand complex systems (Forrester, 1994), and ‘to explore and make management action decisions that are more systemic’ (Bosch et al., 2013, p. 133). However, despite the widespread acceptance of the effectiveness of systems thinking and computer-based modelling systems in dealing with complex situations, many questions remain unanswered about their empirical effects on decision-making (Doyle, 1997; Maani & Maharaj, 2004). Specifically, while a change can be expected in decision-makers’ perceptions of where problems’ boundaries lie (Leischow & Milstein, 2006), little empirical evidence has been provided to document whether this is actually the case. As a narrow definition of a situation’s boundaries may lead decision-makers to restrict the multiple variables and perspectives needed to appreciate the complexity of the situation (Laszlo, 2012),

the time is opportune to empirically explore whether and how a system-modelling-based DSS can extend the formation of boundary judgements. The aim of this paper is therefore to fill in this current knowledge gap, by empirically exploring the effects of system-modelling-based DSS use, by decision-makers who must deal with a complex situation, on boundary judgements that ‘demarcate what is relevant to an analysis’ (Midgley & Richardson, 2007, p. 172). It purposely focuses on system dynamics modelling, which is one of the empirical modelling approaches that can support systems thinking and decision-making in complex situations (Caldwell, 2012; Neumann, 2013; Sterman, 2000).

The remainder of this paper is organised as follows. The next section examines the relevance of system dynamics modelling to support decision in complex situations. The research method, which involved an experiment with 40 policy-makers from different world locations and is based on a simulated decision case on the biotechnology intellectual property system, is described. The discussion of the results highlights the effects of a system dynamics-based DSS use on policy-makers’ boundary judgements. The conclusion sets out some implications, limitations and future research avenues.

2. Systems thinking and system dynamics as decision supports in complex situations

This section examines the challenges of decision-making in complex situations. The role of system dynamics modelling in such situations is discussed, and then the research framework developed to explore the potential effects of its use on individuals’ boundaries is presented.

2.1. Deciding in complex situations

In an increasingly complex world, decision-making can become problematic (Cramp & Carson, 2009): it is more likely than in the past to result in unintended consequences (Forrester,

1975; Sterman, 2000), and to be ineffective due to cognitive biases, pervasive ineffective beliefs, and poor mental models (Friedman, 2004). Complexity stems from the fact that problems ‘rarely present themselves individually but come related to other problems, in richly interconnected problem situations that are appropriately described as messes’ (Jackson, 2006, p. 648). A core characteristic of such complex problems is that they possess properties which become manifest only when examined from alternative standpoints (Paradice, 2007). Consequently, several scholars have suggested that viewing a complex decision situation from multiple perspectives can lead to better-informed choices (Hall & Davis, 2007); in particular, they have called for multidisciplinary and multi-stakeholder approaches (Beers, Boshuizen, Kirschner, and Gijsselaers, 2006).

Indeed, understanding the breadth of complex problems requires taking into account a diversity of perspectives, fields and scientific disciplines (Beers et al. 2006; Meek, De Ladurantey, & Newell, 2007). Multidisciplinary approaches are especially necessary to move beyond a single perspective when delineating problem boundaries (Beers et al. 2006). Genuine interdisciplinarity should be sought to address the multiple facets of a complex problem as a whole (Meek & Newell, 2005). As Meek et al. (2007, p. 32) pointed out, interdisciplinarity allows for ‘circling around common problems, identifying common issues, and applying resources that individual collaborators bring to the table from their respective areas of expertise and discipline’. Given the need to think holistically when facing complex situations (Cramp & Carson, 2009; Jackson, 2006; Maani & Maharaj, 2004), interdisciplinary integration is highly relevant to ‘replace the reductionist thinking of the disciplines with holistic thinking’ or, in other words, to ‘deal with interdependent variables’ (Meek & Newell, 2005, p. 330).

Solving complex problems also requires a multi-stakeholder approach so that knowledge from multiple perspectives can be integrated (Beers et al., 2006). The value of stakeholder participation in decision-making is widely recognised (Ashmos, Duchon, & McDaniel, 1998; Beers et al., 2006). For instance, Hall and Martin (2005) claimed that stakeholder participation can lead to more creative, appropriate and widely accepted solutions. However, it can also introduce more complexity (given that many more interacting components are considered) and more ambiguity (given that stakeholders with disparate and divergent goals and opinions interpret the same situation differently) (Hall & Martin, 2005). In fact, the value and challenges of multi-stakeholder approaches seem to depend on both the breadth and depth of participation. Breadth of participation captures the number and diversity of stakeholders involved, and the timing and frequency of their involvement in the decision-making process (Ashmos et al., 1998). In other words, the question is whether all concerned actors participate in each and every step of the decision-making process. Depth of participation refers to the extent to which stakeholders have the opportunity to influence outcomes in the process (Edelenbos & Klijn, 2005). This is determined by the objectives pursued by decision-makers regarding the involvement of stakeholders, but also by the ways in which they are involved, such as formal committees, informal exchanges and meetings, etc. (Ashmos et al., 1998). Thus, depth of participation is closely linked to the participatory techniques used. For instance, Green and Hunton-Clark (2003) proposed a three-level stakeholder participation ladder in corporate settings (informative, consultative, and decisional), while Edelenbos and Klijn (2005) used a five-level ladder in a public policy participatory context (informing, consulting, advising, co-producing, and co-deciding).

The fact remains that ‘much decision-making fails to account for the multiple perspectives created by complexity’ (Cramp & Carson, 2009, p. 76) and fails to be adequately holistic (Jackson, 2006). Systems thinking has the potential to overcome these challenges: it is thinking about a complex situation through the concept of ‘system’ (Checkland, 1981), which is defined as ‘a set of interconnected elements that form a whole and show properties that are properties of the whole rather than of the individual elements’ (Laszlo, 2012, p. 97).

2.2. Relevance of system dynamics-based DSS in complex situations

While systems thinking is widely recognised to be effective for addressing complex situations (Bosch et al., 2013; Cramp & Carson, 2009; Maani & Maharaj, 2004), it seems that human reasoning tends to stray from this kind of thinking (Boschetti et al., 2011; Maani & Li, 2010; Sterman, 1989). For instance, several scholars have underscored the limitations of decision-makers’ mental models in dealing with complex systems, notably bounded rationality and misperceptions of feedback loops, which stem from the dynamic nature of complex systems (Maani & Li, 2010). In this context, the main role of a DSS is to support systems thinking – to help gain an integrated, holistic understanding of a complex system (Cramp & Carson, 2009) by supporting different perspectives that are dynamic in nature (Paradice, 2007). Hence, system-modelling-based DSS are seen as particularly useful to support decision-making in complex situations (Bosch et al., 2013; Cramp & Carson, 2009).

System dynamics is a system modelling approach that supports systems thinking (Caldwell, 2012; Neumann, 2013; Sterman, 2000) and, thus, acts as a DSS in complex situations (Khataie, Bulgak, & Segovia, 2010). It has been applied to tackle many complex problems such as the development of international alliance strategies (Kumar & Nti, 2004), the innovation management process (Milling, 2002), enterprise risk management (Bharathy & McShane, 2014),

and issues related to oil refining and trading (Lane, 1997), to name a few. System dynamics provides a powerful set of concepts for understanding, modelling and simulating complex systemic behaviour, by focusing on the interconnectedness of components of the system and the underlying structures of flows, delays, information and feedback relations (Mingers & White, 2010).

Specifically, this modelling approach supports decision-making processes by providing a set of qualitative and quantitative modelling tools that are useful for understanding a complex system: a qualitative influence diagram and a quantitative level-rate model. Influence diagrams are qualitative representations, which highlight both the variables of a system and the links between these variables; embedded within reinforcing feedback loops ('positive loops' that generate exponential growth or decline behaviour over time) and balancing feedback loops ('negative loops' that generate equilibrating, or asymptotic, behaviour over time). Such a qualitative model is meant not only to represent the dynamic hypotheses and feedback loops assumed to be important, but also to create a shared mental model within a group or an organisation. Level-rate models, on the other hand, are formal quantitative simulation models, which represent a system with stock and flow variable interactions. These quantitative models aim to test and compare alternative scenarios about decision policies or actions, to foster learning and anticipate possible alternative future behaviours of the system under consideration (Sterman, 2000). As Sterman (2014, p. 91) concluded, 'simulation becomes the main – perhaps the only – way we can discover for ourselves how complex systems work'.

2.3. Towards a framework linking system dynamics with decision-makers' boundaries

If system modelling can support greater systems thinking during the decision-making process (Bosch et al., 2013; Cramp & Carson, 2009), one might conclude that using a system-

modelling-based DSS could change the formation of decision-makers' boundary judgements, that is, their beliefs, rationalities and expectations (Verweij, Van Meerkerk, Koppenjan, & Geerlings, 2014). Indeed, a more systemic way of thinking often alters the perception of what the problems are, where their boundaries lie, and who has a stake in the outcome of any change (Leischow & Milstein, 2006). In particular, it 'will eliminate externalities artificially created by a narrow definition of a system's boundaries and include as many variables and perspectives as possible in order to appreciate the complexity as well as the short and long term feedback dynamics' (Laszlo, 2012, p. 96). Boundaries can be defined as 'what' and 'who' are relevant in conducting an analysis (Midgley & Richardson, 2007); this suggests that the use of a system-modelling-based DSS, such as a system dynamics-based one, can expand the boundary judgements of decision-makers in terms of both issues and stakeholders to be included. More generally, and as explained by Verweij et al. (2014), boundary judgments are the beliefs and rationalities underlying decisions, that is, mental constructs of actors that refer to the assumptions about what should belong to the system and its environment (Ulrich, 1987).

Often, boundaries thus mark which issues are included in or excluded from the decision analysis (Midgley & Richardson, 2007). The notion of issues can refer to perspectives taken into consideration by decision-makers. When faced with complex problems, decision-makers must take a variety of fields and scientific disciplines into account (Beers et al., 2006; Meek et al., 2007). Because systems thinking may change their perception of 'what' is to be included in the decision analysis (Laszlo, 2012; Leischow & Milstein, 2006; Midgley & Richardson, 2007), using a system dynamics-based DSS may have a positive effect on the extent of the fields and scientific disciplines covered by the decision analysis. Recall, however, that genuine

interdisciplinary integration is recommended in the literature on complex systems (Meek & Newell, 2005). Therefore, the following propositions are suggested:

P1a: The use of a system dynamics-based DSS facilitates the consideration of a greater range of perspectives (in terms of fields and scientific disciplines covered by the analysis).

P1b: The use of a system dynamics-based DSS facilitates interdisciplinary integration.

Boundaries also delineate the inclusion and exclusion of stakeholders in the decision-making process (Midgley & Richardson, 2007). As pointed out by Midgley (2006), stakeholder participation in decision-making is crucial to boundary critique. The literature suggests that the many-sidedness of complex problems accentuates the need for multi-stakeholder approaches (Beers et al., 2006). Given that systems thinking may change decision-makers' perception of 'who' must be included (Midgley & Richardson, 2007; Verweij et al., 2014), a positive effect of the use of system dynamics-based DSS on the extent of stakeholders' involvement in the decision-making process may be expected. However, as noted, previous studies have highlighted the importance of distinguishing between the breadth and depth of such stakeholder participation (Ashmos et al., 1998). Hence, the following propositions are made:

P2a: The use of a system dynamics-based DSS facilitates greater breadth of stakeholder participation.

P2b: The use of a system dynamics-based DSS facilitates greater depth of stakeholder participation.

3. Research method: An experiment with practitioners in the biotechnology intellectual property system

The methodological framework included the collection of data based on an experiment conducted with 40 experienced practitioners involved in the biotechnology intellectual property system. As described below, the data collected were analysed with a content analysis technique and statistical tests.

3.1. Research context: The biotechnology intellectual property system and its modelling

The decision-making processes we investigated concern the introduction of new public policies aimed at changing the regulatory framework of intellectual property for biotechnology innovations. The choice to focus on public policies is justified by the fact these are widely viewed as embedded within complex systems (Morçöl, 2005), and are often complex to develop and implement (Lundin, 2007).

The biotechnology intellectual property system was chosen for two main reasons. First, it includes many inextricably linked components. Indeed, issues related to the protection of biotechnological innovations are not strictly characterised in terms of simple legal problems, but must also take into consideration the associated social, ethical, economic and managerial issues and concerns (Gold, Castle, Cloutier, Daar, & Smith, 2002). Second, the subject of biotechnology is highly controversial and the system's management is entangled with the goals of a wide variety of stakeholders. Thus, policy changes mainly result from negotiations between agents with conflicting interests (Helfer, 2003). In the end, intellectual property adjustments are not always adapted to challenges raised by biotechnology, and the complexity of this system calls for a reorientation of the thinking process and the use of formal models (Gold et al., 2002). Consequently, this context is highly relevant for studying the effects of the use of a system dynamics-based DSS.

A DSS for the biotechnology intellectual property system was designed and modelled based on system dynamics principles. These modelling tasks were part of an on-going research project conducted by the Intellectual Property Modelling Group (IPMG), which involved some 20 researchers from several disciplines, including law, management, economics, bioethics, philosophy, political science and health policy. The group modelling process resulted in both qualitative and quantitative system dynamics models.

The qualitative model, which takes the form of an influence diagram, was developed to highlight all the variables included in this complex system, causal relationships between these variables, and the reinforcing and balancing feedback loops deemed to be important (see an excerpt in Figure 1). To develop the influence diagram, the members of IPMG identified eight overarching areas of inquiry to target the 'object' of biotechnology intellectual property system: (1) intellectual property rights; (2) economic efficiency; (3) innovation management; (4) knowledge management; (5) risk management; (6) integrity of living things; (7) sovereignty; and (8) distributive justice. Then, they collectively identified some key variables for each area, which allowed the entire team to represent the system of the underlying problem under study. It was followed by group modelling activities conducted in three steps: elaboration of an influence diagram for each of the eight areas; the integration of these eight sub-models into a unique diagram; adjustments on an iterative basis and validation of the global influence diagram. These activities were conducted during structured group and sub-group sessions, during which the authors shared the combined roles of facilitator, coach and recorder (see Richardson & Andersen, 1995). Overall, twelve modelling sessions were held over a two-year period with IPMG members. At the end of the modelling process, the influence diagram, which represents a

systemic ‘big picture’ of the biotechnology intellectual property system, includes 117 variables and 361 causal links.

INSERT FIGURE 1 ABOUT HERE

From this influence diagram, a quantitative simulation model was conceptualised and designed to enable the testing and comparison of alternative decision scenarios. While the development of this simulation model relied on dedicated software (PowerSim), an Excel-based interface was created to facilitate its use by decision-makers. This interface includes two main spreadsheets. The first one allows the user to specify a scenario to be simulated by modifying one or more parameters (see excerpts in Figure 2). On this Excel spreadsheet, each area of inquiry lists the possible variables that can be modified during the simulation. An interactive menu enables a user to browse from one area to another, using an interactive dictionary to find the meaning of a variable if needed. After running the simulation from the PowerSim software, a user can access simulated results on the second Excel spreadsheet (see excerpts in Figure 3), and may observe the impact over time on the variables of interest. The latter are once again classified by area and the underlying results may be consulted within a table or graph by using an interactive menu.

INSERT FIGURE 2 ABOUT HERE

INSERT FIGURE 3 ABOUT HERE

3.2. Data collection through an experiment conducted with policy-makers

An experiment based on the simulated case approach was conducted with policy-makers affiliated with administrative departments concerned with intellectual property policy. A simulated case approach allows one to ‘exercise a degree of control over the decision and the environment, while using knowledgeable decision-makers’ (Henderson & Nutt, 1980, p. 374).

Forty decision-makers in different world locations were interviewed at government ministries and national intellectual property offices in five different countries (Belgium, Canada, France, the United Kingdom, and Switzerland), two European intergovernmental organisations (European Patent Organisation, European Commission), and five international intergovernmental organisations (World Intellectual Property Organization, Organisation for Economic Co-operation and Development, World Trade Organization, World Health Organization, Food and Agriculture Organization of the United Nations).

During individual in-depth interviews (duration ranging from one to three hours each), conducted with an interview guide, policy-makers were encouraged to explain in detail the decision-making process they would follow to solve a decision case (see Appendix). As part of the experiment, the decision case focused on the development of intellectual property policies that could be introduced to encourage biotechnology innovations and facilitate access to new technologies. To address external validity, namely the realism of the simulated case (Lilien, Rangaswamy, Van Bruggen, & Starke, 2004), two sets of meetings were held to pre-test the case decision script (one meeting with two representatives from Health Canada, and another one with a representative from the Ministry of Economy in France).

The experimental (Exp) and control (Ctrl) subsamples were of equal size and evenly distributed across each geographical area (see Table 1): unlike the 20 respondents in the ‘control’ subsample, the 20 participants in the ‘experimental’ subsample used the system dynamics-based DSS developed by the authors. During interviews, then, members of the experimental subsample were exposed to the qualitative and quantitative counterparts of the model, and were prompted to simulate and evaluate their own potential policy alternatives using the DSS’s Excel interface.

Interviews with the experimental subsample started with a presentation of the influence diagram and a ‘training’ session on the use of the simulation model.

INSERT TABLE 1 ABOUT HERE

3.3. Data analysis method

A thematic content analysis was carried out, based on the coding of interview transcripts using NVivo software. Following Miles and Huberman (1994), a coding scheme had been predefined and was then further refined following the analysis of the first interviews. While the initial coding was established to investigate various dimensions of the decision-making process, the relevant coding categories employed herein are those encompassed within the following two themes: first, the theme related to the decision analysis approach described by respondents (including ‘elements on which the analysis is based’, ‘scientific disciplines involved’, and ‘interdisciplinary integration’); and second, the theme focusing on stakeholders (‘identity of the stakeholders involved’, ‘the ways in which stakeholders are involved (when and how)’, ‘forms of influence that stakeholders exercise’, and ‘stakeholders excluded from the decision-making process’). Taking reliability concerns into consideration, a double-coding procedure was conducted: three interview transcripts underwent internal double-coding, while an external double-coding process was applied to three others.

Based on the thematic content analysis, a comparative qualitative analysis was conducted to question commonalities, contrasts and differences between the control and experimental subsamples. This qualitative approach was supplemented with statistical inference using SPSS software, to identify significant effects associated with the use of the system dynamics-based DSS, that is, to test the propositions (*P1a*, *P1b*, *P2a* and *P2b*). To this end, the encoded qualitative data was converted into variables for quantitative processing, and a database was

created following specific rules. The encoded data within the ‘decision analysis approach’ theme resulted in two numerical variables (number of fields and number of scientific disciplines) and one nominal variable (whether an interdisciplinary approach was pursued or not). Concerning variables within the ‘stakeholders’ theme, breadth of participation was also converted into two numerical variables (number of diversified stakeholders involved and number of specific phases in which they were involved) and one nominal variable (list of phase(s) concerned), while depth of participation resulted in one numerical variable (number of diversified participatory techniques used) and one nominal variable (participation ladder regarding the participatory techniques used). Finally, the relationships between the respondents’ subsample (control or experimental) and each of these variables were examined using the non-parametric Kruskal-Wallis test or Fisher’s exact test for small samples (depending upon the type of dependent variables) (Huizingh, 2007).

4. Results and discussion

This section presents research findings which explore the effects of DSS use by policy-makers on where their boundaries lie regarding both issues covered and stakeholder involvement (test results are in Table 2). A discussion examines policy-makers’ reactions to their interaction with the DSS, in order to further document the implications of these results.

INSERT TABLE 2 ABOUT HERE

4.1. The effects of DSS on boundary judgements about the system’s issues

Issues related to the protection of biotechnological innovations must be addressed through different fields and scientific disciplines. The interviews conducted with respondents led to the identification of many fields, including legal, economic, ethical, technological, political,

financial and cultural aspects, and reveal that diverse disciplines can be involved, such as law, economics, social sciences, life or health sciences, management, engineering and political sciences. The fact remains that the scope of the decision analysis, in terms of the fields and scientific disciplines covered, varies amongst policy-makers (see Figure 4): the number of fields that a policy-maker takes into account ranges from three to six depending on respondents, and the number of disciplines ranges from two to six.

INSERT FIGURE 4 ABOUT HERE

Respondents tended to analyse problems from a multi-perspective approach. For instance, one respondent explained that *'you develop options regarding legal, economic and social aspects'* (Exp_11). However, none of the respondents took all the identified fields or disciplines into account. Most importantly, it appears that the extent of fields and scientific disciplines covered differed between the experimental and control subsamples. Indeed, the number of fields and disciplines covered was significantly greater for respondents in the experimental subsample than for respondents in the control subsample (see Table 2, $p = .009$ and $.039$, respectively). This might suggest that the use of the system dynamics-based DSS had a positive effect on the number of fields and scientific disciplines taken into account: proposition 1a appears to be empirically supported.

All respondents were aware of the interconnectedness of systemic issues. For instance, one policy-maker insisted *'Always keep in mind that there are several topics that are interconnected. It is true that with biotechnological innovations, the problem is that they touch many aspects.'* (Exp_20). Nevertheless, whereas several policy-makers favoured an interdisciplinary approach (*'It is difficult to talk about disciplines because here, concerning intellectual property and biotechnology, it is a mix'*, Exp_11), others described a more fragmented approach (*'In fact,*

there are no real relationships between our economists and lawyers', Ctrl_3; *'It is approached from quite different perspectives, but the concerns of lawyers, even when they are interested in economic aspects, are not economic concerns. [...] So it is difficult and, in fact, we cannot speak of centralised work*', Ctrl_18). Some decision-makers deliberately tried to achieve interdisciplinary integration, while others did not, regardless of subsample (see Figure 5). Thus, the use of the DSS had no effect on interdisciplinary integration: no significant difference was found between the two subsamples regarding interdisciplinarity (see Table 2, $p = .733$). Thus, Proposition 1b is not supported.

INSERT FIGURE 5 ABOUT HERE

To sum up, when policy-makers used the system dynamics-based DSS, they covered more perspectives in their analysis (*P1a supported*) but did not strengthen interdisciplinary integration (*P1b not supported*). On the one hand, this finding reveals that such a DSS is able to support a broader reflection process by encouraging the consideration of more fields and scientific disciplines, as is recommended in the literature on complex systems (Beers et al., 2006; Flood, 2000; Meek et al., 2007). This may suggest that the use of a system dynamics-based DSS may contribute to changed perceptions of issues' boundaries. On the other hand, contrary to what might be expected, the use of such a DSS did not emphasise the holistic and interdisciplinary nature of the decision-making process, even though this is necessary in complex systems (Jackson, 2006; Meek & Newell, 2005).

4.2. The DSS's effects on boundary judgements about the system's stakeholders

The content analysis of interviews led to the identification of diversified stakeholder profiles, including industry players, intergovernmental organisations, research laboratories, independent inventors, nongovernmental organisations, citizens, international commercial actors,

and press and media. Although policy-makers may be influenced by all these interested parties, the stakeholders involved in the decision-making process varied from one respondent to another, except for industry players, who were consistently involved (see Figure 6). While policy-makers may have to answer to pressures from many stakeholders, this research focuses on those who are ‘proactively’ involved. It is interesting to note that, although some actors may be deliberately excluded from the decision-making process (because of the costs that would result from their participation, for instance), others may be omitted unintentionally because they are unidentified, as one respondent explained: *‘The problem is that there are some that we know, but I do not know if all are really identified. Well, we discovered some actors a few times.’* (Ctrl_4).

INSERT FIGURE 6 ABOUT HERE

Thus, policy-makers do not all seek to involve all possible groups of stakeholders in their decision-making process. In fact, only one respondent adopted a participatory approach that included all identified stakeholders without exception. By contrast, only one respondent called on only one stakeholder group (in this case, industry players). It is interesting to note that policy-makers in the experimental subsample tended to involve significantly more diversified stakeholders than those in the control subsample (see Table 2, $p = .016$). In other words, the use of the system dynamics-based DSS had a positive effect on participation breadth.

Regarding the phase when stakeholders get involved, four key phases were identified from the content analysis of the respondents’ discourse: (1) during policy pre-development activities to diagnose the problem or appraise an idea; (2) upstream from potential policy formulation, that is to say, in the identification of possible solutions; (3) downstream from the potential policy formulation or during the refinement of the solution; or (4) during the implementation or introduction of the new policy. Note, however, that none of the policy-makers maintained a

participatory approach throughout the entire process: at most, stakeholders were involved in three of the four phases identified. For both subsamples of respondents, it seems stakeholders were mainly involved in activities upstream from policy development (see Figure 7). In short, no significant difference is noted between subsamples regarding the phases and frequency of involvement by stakeholders (see Table 2, $p = .673$ and $.510$, respectively). Ultimately, if DSS use had an effect on the breadth of participation, this was true only for the number of diversified actors involved, and not for the phases and frequency of their involvement. Therefore, Proposition 2a is only partially supported.

INSERT FIGURE 7 ABOUT HERE

Obviously, the objectives of the participatory approach differ depending on the involvement phase. For instance, when stakeholders' participation occurs early in the process, it aims to foster a better understanding of the current situation and the issues raised, but when they are involved downstream from the potential policy formulation, it is mainly to test the solution with them, and allow them to react, comment, and possibly refine and readjust the solution. Nevertheless, the objectives of stakeholder participation are closely linked to techniques used to involve them. While many and varied participatory techniques can be used, the content analysis of interviews enabled their classification into three broad categories: consultation of stakeholders (including surveys, as well as consultations on the Internet); interactions with stakeholders (including more or less formal meetings); and establishment of working groups with stakeholders. These three categories, obtained from the interview content analysis transcripts, suggest a three-level ladder of stakeholder participation: while some techniques seek strictly to consult stakeholders (to enable them to respond and make or offer comments, test and/or readjust the thinking), others favour more interactions, or even true co-participation through working groups. Although

respondents tend to combine different techniques, policy-makers do not all favour the same ones (see Figure 8). The trend, however, is to favour direct interactions with stakeholders. By contrast, working groups were used by less than half of the policy-makers. In fact, the choice of participatory techniques seems to be mainly driven by the process step at which they occur. For instance, working groups are more frequent downstream from policy formulation: *‘When you ask people to work together, each with different interests, like people in the industry, researchers who think completely differently, representatives of NGOs, etc., you do not end up with much. Thus, you should have already submitted a proposal.’* (Ctrl_12). Hence, no significant difference was found between the two subsamples regarding the number of diversified participatory techniques used and the participation ladder concerning the broad spectrum of available techniques (see Table 2, $p = .931$ and $.523$, respectively). Proposition 2b, which suggests that DSS use would have a positive effect on the depth of stakeholder participation, is thus rejected.

INSERT FIGURE 8 ABOUT HERE

In short, while policy-makers’ use of the system dynamics-based DSS had an effect on which stakeholders were involved, it had no impact on when and how they were integrated into the decision-making process. In other words, it favoured broader participation in terms of the number of diversified stakeholders involved (*P2a partially supported*) but did not strengthen the depth of stakeholder participation (*P2b not supported*). Although proposition 2 is only partially supported, the observation that DSS use leads to a more diversified set of stakeholders becoming involved is crucial. Indeed, many authors have stressed the importance of expanding stakeholders’ participation in decision-making processes in complex systems, to reduce conflicts, increase informational social exchanges (Ashmos et al., 1998), and take multiple perspectives

into account (Beers et al., 2006; Flood, 2000). Admittedly, stakeholder participation is seen as a managerial response to complex strategic issues (Ashmos et al., 1998).

4.3. The reactions of users of the system dynamics-based DSS

This research also captured policy-makers' reactions (those in the experimental subsample) to their experience with the proposed DSS. A large majority of them reacted very positively, greatly appreciated the opportunity, and saw great value in the possibility of simulating their own decision-making scenarios. For instance, one respondent simulated the effects of increasing the parameter "patent eligible invention" (see the specification scenario and simulated results displayed in Figures 2 and 3), while others explored scenarios associated to the practice of compulsory licences, the duration of patent protection, the expenditure on research and development, etc. Some of their reactions were expressed as follows: *'One day, you will give me everything we need to use this model in-house. Because it is extremely useful. This is very interesting. [...] Oh, and now, if we increase the duration of patent protection even more, can we see what happens?'* (Exp_9); *'This model is really interesting; it is interesting to see all the interdependencies, but also to see that the effects of a new policy are always very slow.'* (Exp_20).

In addition, users' reactions suggested that the system dynamics-based DSS was capable of supporting reflection and challenging thought: *'Because, to tell you the truth, we do not actually know very well what impact it may have, so I'm interested to see... Ah, but in fact, it does not change much. That's interesting. I did not think that... Actually... no, actually, it all makes sense, but one must see all these impacts, in fact, these impacts are everywhere. I had not thought of that.'* (Exp_16). More generally, the literature suggests that the use of computerised decision support systems may support reflection. For instance, Chang (2014) recently showed that the

visualised outputs of a DSS can help decision-makers develop a more detailed understanding of a complex situation. In the same vein, it has been suggested that decision-makers should explore ‘the outputs of computer based solutions in the context of their own intuitions until such point that no new insights are found’ (Maule, 2010, p. 112).

Nevertheless, while the experimental protocol followed to introduce the DSS was the same for all policy-makers in the experimental subsample, five respondents showed little interest in it, or even had a negative reaction against it. Four of these five respondents argued that such a simulation model is useless (*‘I think that it is possible to think without that’, Exp_4; ‘To my knowledge, we do not have tools like this. But in fact, we do not have the need’, Exp_13*). Some of them, however, found the influence diagram very interesting, although they were not interested in the simulation model’s numerical results per se (*‘However, your diagram is superb. Can I keep it? I would like to show it to my colleagues’, Exp_3*). On the other hand, one of the five respondents completely rejected the approach that was presented to him: he questioned the validity of the model and had no confidence in the simulated output (*‘You will have a hard time convincing me. I’m very sceptical’, Exp_6*). Indeed, ‘if users do not recognise the intrinsic quality of the DSS or the value of the outcomes it helps generate, they may not be satisfied’ (Lilien et al., 2004, p. 220). Obviously, the fact that not all respondents appreciated the DSS is not surprising: for instance, Gettinger, Kielsing, Stummer, and Vetschera (2013) argued that user satisfaction with a DSS might depend greatly on the characteristics of the users themselves, such as their decision-making styles.

5. Conclusion

Decision support technologies are usually designed to extend the decision-makers’ bounds of rationality (Lilien et al., 2004). In complex situations, the challenge is to favour more systemic

thinking to create change in regard to ‘what’ and ‘who’ are relevant in conducting an analysis from the decision-makers’ standpoint (Midgley & Richardson, 2007). This paper therefore aimed to explore the effects of a system dynamics-based DSS use on policy-makers’ boundary judgements in terms of both the issues and the stakeholders to be included in decision-making.

The results confirm that the use of such a DSS leads to consideration of a greater range of perspectives (in terms of fields and scientific disciplines covered by the analysis) and of a greater breadth of stakeholder participation regarding the number of diversified stakeholders involved. However, contrary to what might be expected, the results also indicate that the use of such a DSS had no effect on either the depth of participation (i.e., the ways in which stakeholders are involved) or interdisciplinary integration during the analysis. Thus, this research suggests that use of a system-modelling-based DSS by decision-makers may lead to a broadening of their decision space, in terms of the multiplicity of both perspectives (the ‘what’) and stakeholders (the ‘who’) taken into account, but it does not affect ‘how’ the decision analysis is conducted.

Nevertheless, these findings cannot be taken as definitive, due to the experimental method followed in this study. In particular, one might suppose that the use of a system dynamics-based DSS might have had significant effects on the ‘how’ if learning processes had been taken into account over time. Indeed, decision-makers may need an appropriation delay in adopting such a DSS (Lilien et al., 2004), if they are to effectively integrate a systemic perspective into their decision-making process and learn how to cope with complex and dynamic tasks (Quadrat-Ullah & Karakul, 2007). Other limitations, which suggest avenues for further research, must also be mentioned. Given that some respondents (however few) showed little interest in the DSS, it would be interesting to further investigate the characteristics of decision-makers that could moderate the effects of DSS use (Carlsson & Turban, 2002), as well as the organisational culture

in which decisions occur (Gray & El Sawy, 2010). It would also be useful to compare the benefits of different types of system-modelling-based DSS, without limiting the study to system dynamics models. Similarly, as the experiment focused on a single complex system, it would be interesting to replicate it in business decision-making environments. As the DSS used by the policy-makers interviewed in this study was developed by the IPMG members, it remains that the respondents' boundary judgments were limited by the view of the IPMG, however large and interdisciplinary, but yet bounded.

These results have important implications for decision-makers who face complex situations. The recent growth in web-based systems simulation (Sterman, 2014) and in business intelligence and analytics technologies is likely to exert some influence on problem boundary judgement by reducing the cost implications of 'depth' and 'breadth' considerations in decision-making processes. Even in this emerging technological context, the effects of the 'what' and the 'who' on decision-making processes will remain key problems to be addressed. There are considerable decision-making hazards associated with a narrow definition of a situation's boundaries. However, these technological capabilities may also help alleviate the experimental constraints that now limit a deeper understanding of the 'how' in problem boundary judgement.

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Appendix. Script of the simulated decision case

Preamble

The development of commercial applications of biotechnology has grown rapidly, as shown by an increase in the number of biotechnology patents. Generally, it is recognized that the intellectual property rights constitute a legal and economic development tool, which supplies required incentives for innovation. However, some argue that some questions remain regarding the application of intellectual property to the biotechnology sector and its effects on legal, economic, managerial and ethical aspects.

Mandate

You have the mandate to design and introduce new intellectual property policies, to improve the intellectual property management, in order to increase incentives for innovation and access to technology.

Question

How will you proceed, in other words, what will be the decision-making process underlying the design and introduction of new policies?

For example: What will be the essential stages? What elements will the analysis concern? Who will you involve and why? What actors will you try to convince and how? Etc.

Table 1. Interviews conducted

Geographical breakdown	Number of interviews		Total number of interviews
	Control subsample	Experimental subsample	
Belgium	1	0	1
Canada	4	3	7
France	5	5	10
Switzerland	0	1	1
United Kingdom	3	4	7
European level	3	3	6
World level	4	4	8
TOTAL	20	20	40
<i>ID *</i>	<i>Interviews from Ctrl_1 to Ctrl_20</i>	<i>Interviews from Exp_1 to Exp_20</i>	

* For the sake of anonymity, the respondents are only identified as a function of their subsample.

Table 2. Statistical significance of the effects of the use of the system dynamics-based DSS

<i>Dependent variables</i>	<i>Independent variable: Subsample affiliation</i>	
	Kruskal-Wallis test	Fisher's exact test
<i>Issue boundaries</i>		
Number of fields covered in the analysis	.009**	
Number of scientific disciplines covered	.039*	
Interdisciplinary approach vs. non-interdisciplinary approach		.733
<i>Stakeholder boundaries</i>		
Number of diversified stakeholders involved	.016**	
Phases of stakeholders' involvement		.673
Frequency of stakeholders' involvement (number of phases)	.510	
Number of diversified participatory techniques used	.931	
Participation ladder regarding techniques used (only consultation, at least interaction, at least working groups)		.523

* $p < .05$; ** $p < .01$

Figure 1. Excerpt of the influence diagram

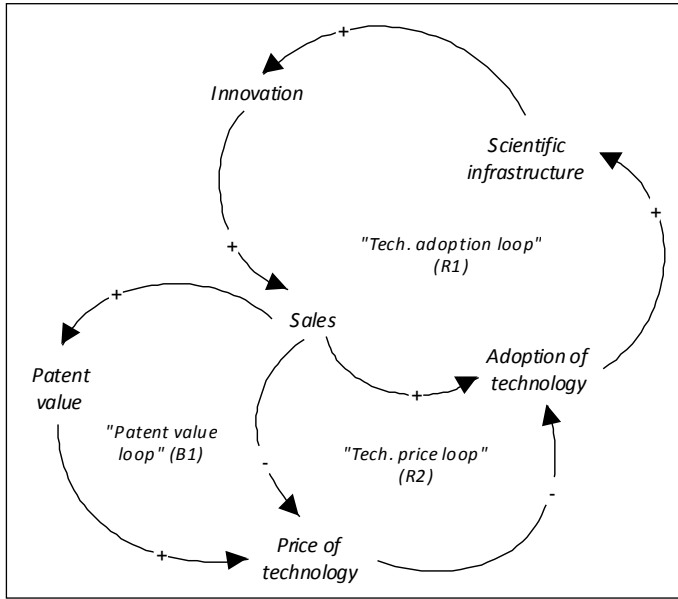


Figure 2. Excerpts of the simulation interface through Excel: Scenario specification

Click on the theme of your choice to go there			
▶ Intellectual property box			
▶ Innovation management			
▶ Knowledge management			
▶ Economic efficiency			
▶ Distributive justice			
▶ Integrity of living things			
▶ Risk management			
▶ Sovereignty			

▶ RETURN TO MENU	Intellectual property box	Statu quo	Scenario	
	Number of biotechnology issued patents (Number)	2733	2733	▶ Dictionary
	Number of biotechnology patent applications filed (Number)	10766	10766	▶ Dictionary
	Patent eligible invention (Scale 1 to 3, with 1=low and 3=high)	2	3	▶ Dictionary

Figure 3. Excerpts of the simulation interface through Excel: Simulated results

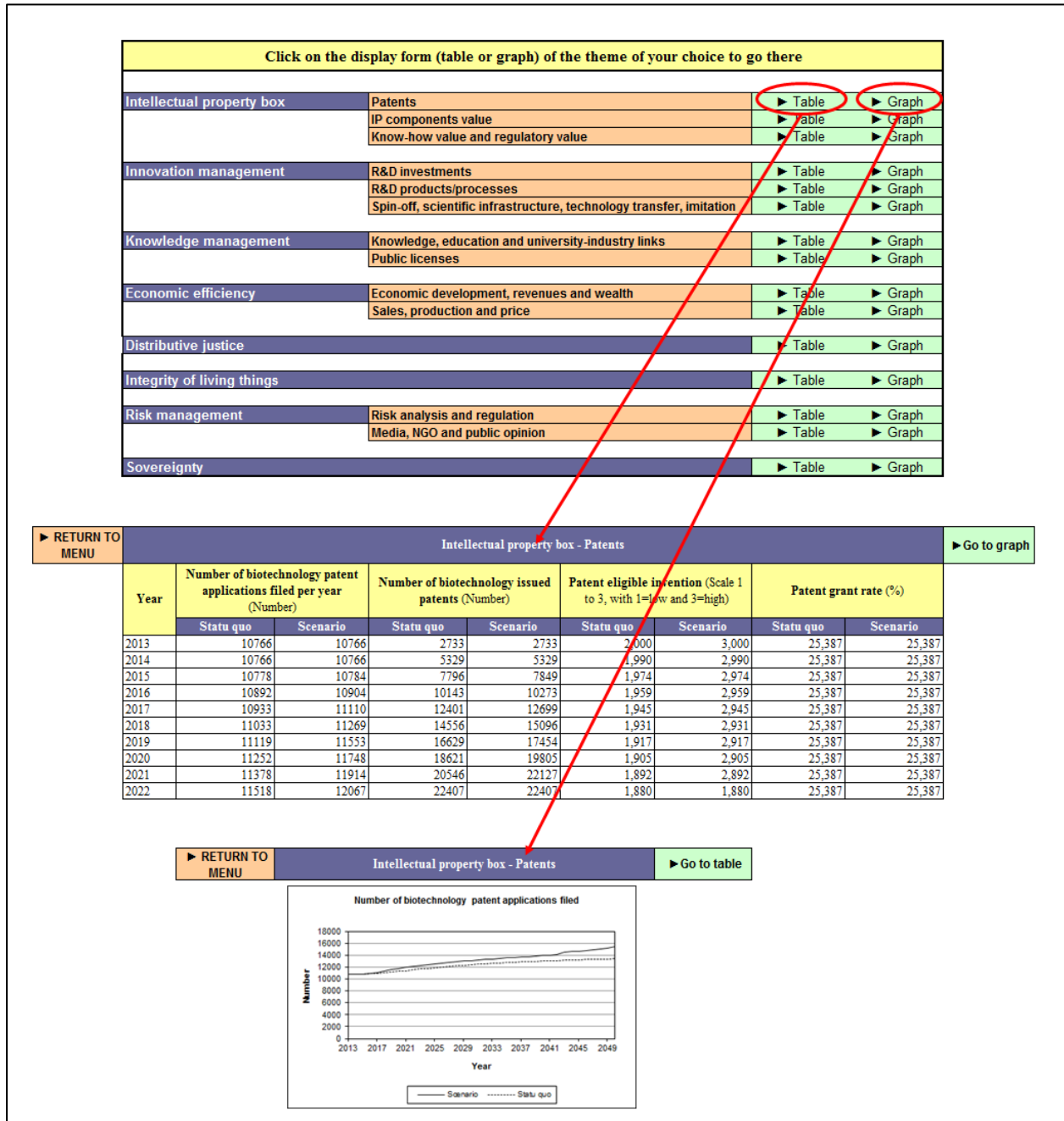


Figure 4. Perspectives covered by the analysis

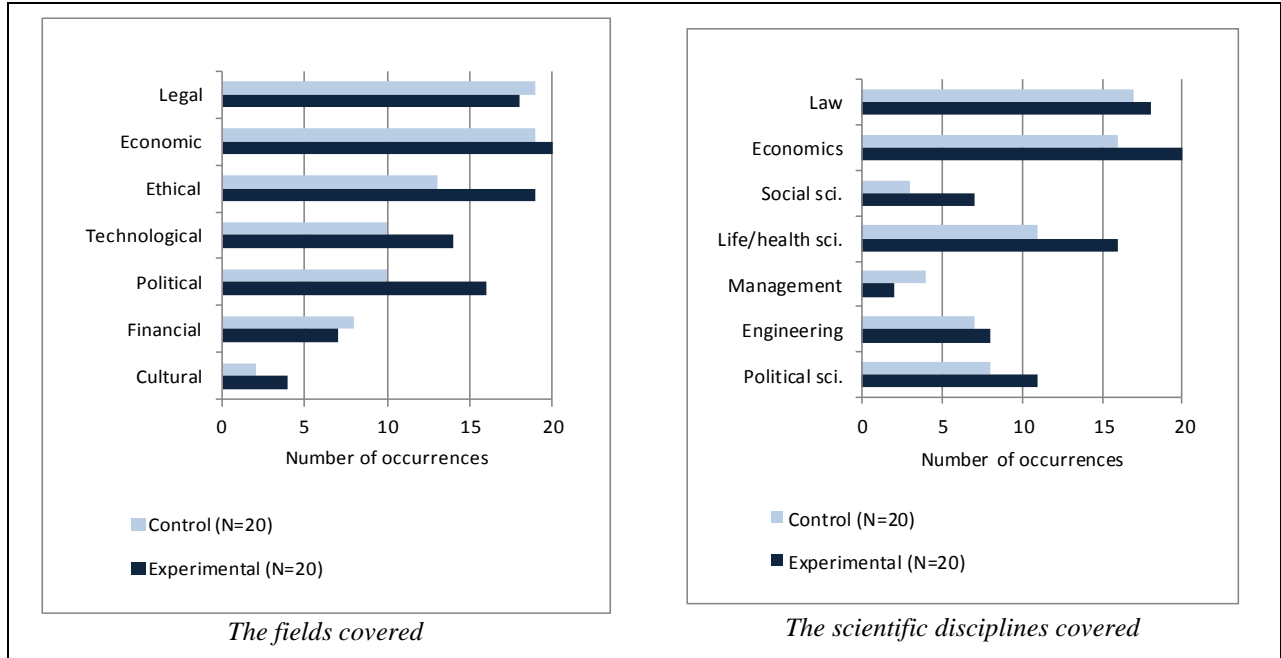


Figure 5. Interdisciplinary vs. non-interdisciplinary approach

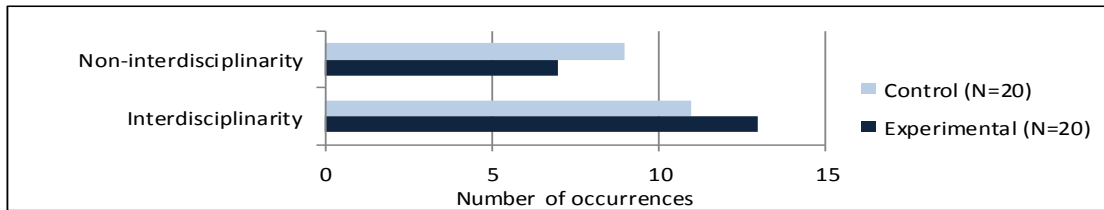


Figure 6. Stakeholders called on by policy-makers

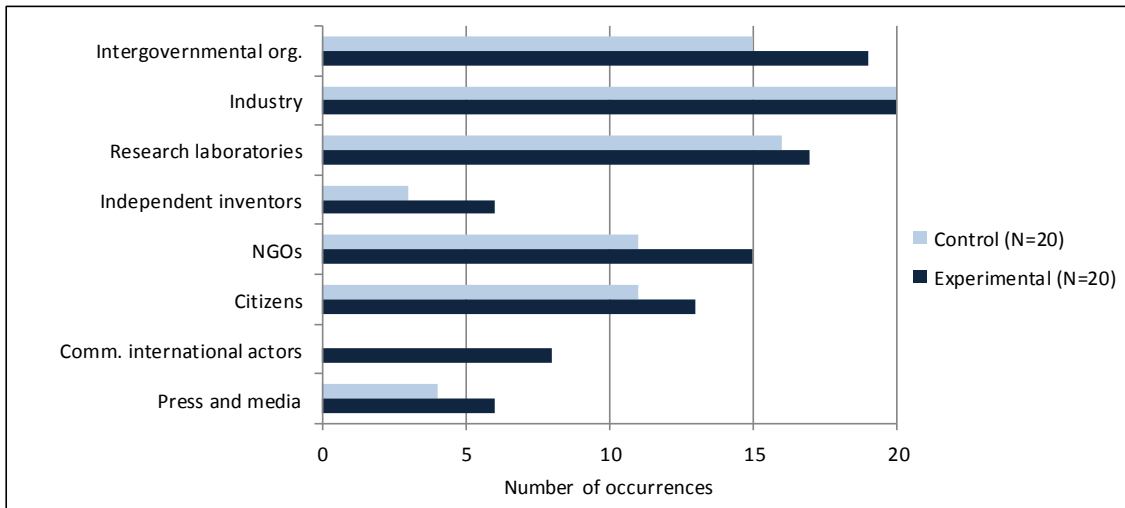


Figure 7. Phases of stakeholders' involvement

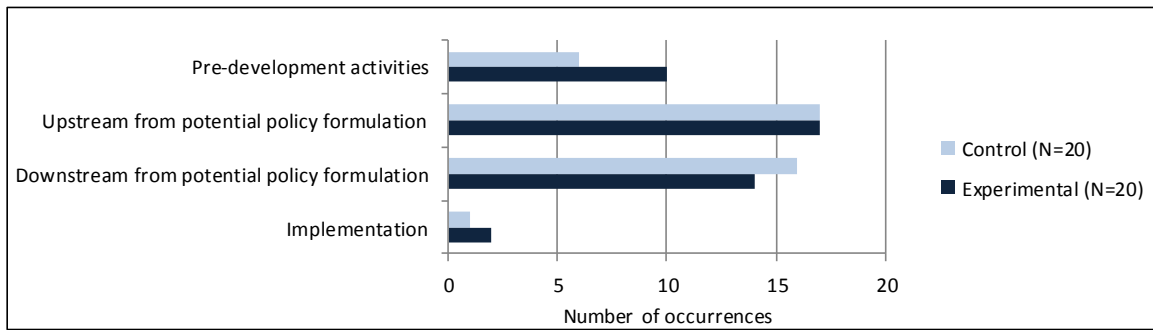


Figure 8. Broad categories of participatory techniques used by policy-makers

