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Proposed taxonomy and framework to support the decision-making of investments in Big Science

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Thèse présentée en vue de l'obtention du diplôme de *Philosophiæ Doctor*

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Proposed taxonomy and framework to support the decision-making of investments in Big Science

présentée par **Cintia Maria RODRIGUES BLANCO**

en vue de l'obtention du diplôme de *Philosophiæ Doctor*

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DEDICATION

For my beloved daughter: Yedda

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RÉSUMÉ

Au cours des sept dernières décennies, les projets de Mégascience (*Big Science*) ont adopté une dimension internationale, sont devenus plus complexes et plus coûteux, rendant ainsi plus difficile la prise de décision des gouvernements en matière d'investissement. Combinant des méthodes de recherche qualitatives et quantitatives, l'objectif principal de cette recherche est d'aider les gouvernements nationaux à améliorer leur capacité à prendre des décisions éclairées et structurées en matière d'investissement en Mégascience, avec la participation de la communauté scientifique et de l'industrie. Pour atteindre cet objectif, deux objectifs spécifiques sont poursuivis. Le premier vise à construire une taxonomie générale de la Mégascience qui offre une compréhension globale allant au-delà de la vision traditionnelle du terme, c'est-à-dire de gros projets d'infrastructure pour la physique de haute énergie. Cette taxonomie est construite sur la base de domaines de recherche qui, en combinaison avec des définitions pratiques et complètes, peut être utilisée pour présélectionner des projets qui, s'ils répondent à des exigences spécifiques, seront éligibles à recevoir des financements importants. Le deuxième objectif spécifique est la structuration du problème de l'investissement gouvernemental en Mégascience. À cet effet, une série de 50 entretiens avec des parties prenantes de haut niveau de la Mégascience trace un portrait détaillé de la complexité de la prise de décision de financement. Les résultats ont révélé qu'il existe une seule cause principale du problème de décision d'investissement en Mégascience qui est la nature même de la Mégascience, dont le but est d'explorer la frontière de la connaissance, plutôt que le montant astronomique du financement en lui-même. La structuration du problème a également révélé que pour résoudre le problème, il est nécessaire de promouvoir un processus décisionnel qui soit objectif, et donc fondé sur des critères qualitatifs et / ou quantitatifs. Au final, cette recherche propose un cadre systématique et personnalisable afin de faciliter la prise de décision en matière d'investissements dans le domaine de la Mégascience. Le système propose un index de la Mégascience (« BigSci Index »), compatible avec toutes les initiatives en Mégascience de façon à fournir un cadre transparent, éclairé et fondé sur des données probantes pour le processus décisionnel et la reddition de comptes. La communauté scientifique, les représentants de l'industrie et les analystes gouvernementaux sont des éléments centraux de cette cadre. Les résultats de cette recherche offrent une double perspective par l'intermédiaire d'une contribution à une meilleure compréhension du phénomène de la Mégascience et également par l'introduction d'une nouvelle

approche du problème de la prise de décision dans le financement des projets. L'adoption du cadre proposé permettrait de garantir aux gouvernements une prise de décision éclairée dans les investissements en Mégascience tout en adoptant les meilleures pratiques dans un processus rationnel, structuré et objectif. Ces avantages comprennent également une utilisation plus efficace des fonds publics et une plus grande transparence dans la prise de décision. Cela se traduirait en effet par une augmentation des avantages sociaux, économiques, politiques et scientifiques des investissements dans des projets de Mégascience.

ABSTRACT

Over the past 70 years, Big Science projects have adopted an international dimension, which has become more complex, costly, and challenging regarding governments' decision-making in investments. Combining qualitative and quantitative research methods, this research's primary goal is to support national governments to improve their capacity to make informed and structured decisions on Big Science investments, with the participation of the scientific community and the industry. To reach this goal, two specific objectives are pursued. The first specific objective is to build a taxonomy of Big Science that provides a comprehensive understanding of the term beyond the traditional view of BigSci as high-energy physics infrastructure projects. This taxonomy is built based on research fields that, along with a proposed workable and comprehensive definition of Big Science, may be used to pre-select candidate project proposals to receive significant investments if they meet specific requirements. The second specific objective is to structure the problem of government investments in Big Science. To that effect, a set of 50 interviews with high-level Big Science stakeholders provided an in-depth portrait of the complex situation of the funding decision. The results revealed a single prime cause of the Big Science investment decision problem, which is the inherent nature of Big Science of exploring the frontier of knowledge, rather than the exorbitant amount of funding it demands. The problem structuring also revealed that to solve the problem, it is necessary to promote a decision-making process that should be objective, i.e., grounded on qualitative and/or quantitative criteria. In the end, this research proposes a systematic and customizable framework for supporting the decision-making of Big Science investments. The framework introduces the BigSci Index, which addresses any Big Science initiative and provides measures to ensure transparent, informed, and evidence-based decision-making and accountability. The scientific community, industry representatives, and government analysts are central components of the framework. The results provide a two-fold perspective: they contribute to a new understanding of the phenomenon of Big Science and offer a new approach to its funding decision problem. Adopting the proposed framework for the government decision-making of Big Science investments would ensure that decisions are well informed, follow best practices, and involve a rational, structured, and objective process. The benefits also include more effective use of public funds and greater clarity and transparency in decision-making. These, in turn, would translate into

increased social, economic, political, and scientific benefits from investments in Big Science projects.

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LIST OF SYMBOLS AND ABBREVIATIONS

ATLAS	A Toroidal LHC ApparatuS
ATTO	Amazon Tall Tower Observatory
BBMRI	BioBanking and Molecular Resource Infrastructure
BigSci	Big Science
BiS	Big Science
BRAIN	Brain Research through Advancing Innovative Neurotechnologies
Brexit	'British' + 'exit'
BSBF	Big Science Business Forum
C4	four-carbon compound
CEO	Chief Executive Officer
CEPC	Circular Electron Positron Collider
CER	Comité d'Étique de la Recherche avec des êtres humains (Polytechnique Montréal)
CERN	European Organization for Nuclear Research (French: Organisation Européenne pour la Recherche Nucléaire), derived from the name Conseil Européen pour la Recherche Nucléaire
CNAO	National Center for Oncological Hadron Therapy
COO	Chief Operating/Operations Officer
COVID-19	CoronaVirus Disease 2019
CSPC	Canadian Science Policy Conference
CyVERSE	Cyberinfrastructure for Data Management and Analysis
DestinE	Destination Earth
DMP	Planning for Data Management and Preservation
DNA	DeoxyriboNucleic Acid
€	Euro (sign)
EC	European Commission
ELSI	Ethical, Legal, and Social Implications
EMBL	European Molecular Biology Laboratory
EncoDE	Encyclopedia of DNA Elements

Eng&Tech	Engineering and Technology
ERIC	European Research Infrastructure Consortium
ESRF	European Synchrotron Radiation Facility
ESS	European Spallation Source
E.U.	European Union
FAIR	Facility for Antiproton and Ion Research
FAST	Five-hundred-meter Aperture Spherical radio Telescope
FCC	Future Circular Collider
FORD	Fields of Research and Development
GDP	Gross Domestic Product
GOV	government
HapMap	Haplotype Map
HGP	Human Genome Project
HDI	Human Development Index
HI	High Impact
HR	Human Resources
Human.	Humanities
ICT	Information and Communication Technology
ID	identity
ILC	International Linear Collider
ILL	Institut Laue-Langevin
ILO	Industrial Liaison Officer
IND	private sector (industry)
intl	international
IP	Intellectual Property
IPR	Intellectual Property Rights
ISS	International Space Station
ITER	International Thermonuclear Experimental Reactor
JET	Joint European Torus
JLab	Thomas Jefferson National Accelerator Facility

JWST	James Webb Space Telescope
LBL	Lawrence Berkeley Laboratory
LHC	Large Hadron Collider
LiS	Little Science
LLAMA	Large Latin American Millimeter Array
LNLS	Brazilian Synchrotron Light Laboratory (Portuguese: Laboratório Nacional de Luz Síncrotron)
LRDC	Learning Research and Development Center
Ltd.	Limited (company)
LTER	Long Term Ecological Research Network
MAVT	Multi-Attribute Value Theory
MCDA	Multi-Criteria Decision Analysis
MCTI	Ministry of Science, Technology and Innovation (Portuguese: Ministério da Ciência, Tecnologia e Inovações)
MSc	Master of Science
NASA	National Aeronautics and Space Administration (U.S.)
NCFI	National Cold Fusion Institute (U.S.)
NGO	Non-Governmental Organization
NIH	National Institutes of Health (U.S.)
OECD	Organisation for Economic Co-operation and Development
O.S.	Open Science
PhD	Philosophy Doctor
PI	Principal Investigator
PSM	Problem Structuring Method
Q1	First Quartile
R&D	Research and Development
RI	Research Infrastructure
$	dollar or peso sign, indicating the units of various currencies all over the world
SCI	scientists
Sci.	Sciences

S&T	Science and Technology
SIBiUSP	Integrated Library System of the University of São Paulo, Brazil (Portuguese: Sistema Integrado de Bibliotecas da Universidade de São Paulo)
SKA	Square Kilometre Array
SNN	Spiking Neuronal Network
SNOLAB	Sudbury Neutrino Observatory Laboratory
SODA	Strategic Options Development and Analysis
SSC	Superconducting Super Collider
SSH	Social Sciences and Humanities
STEM	Science, Technology, Engineering, and Mathematics
STI	Science, Technology and Innovation
Tech	Technology
TMT	Thirty Meters Telescope
TRL	Technology Readiness Level
UN	United Nations
U.S.	United States
USA	United States of America
USD	United States Dollar
VLT	Very Large Telescope
VPN	Virtual Private Network
WoS	Web of Science
WWII	World War II
X	undefined number

LIST OF APPENDICES

CHAPTER 1 INTRODUCTION

Big Science has always attracted society's attention and triggered people's imagination. Scientists, politicians, military, prominent businesspeople, or small entrepreneurs, even artists get thrilled by its size, complexity, multidisciplinary high-level teams, duration, promises, potential and achieved outputs, inventions, innovations, advancements, and costs. Big Science, henceforth known as BigSci, is scientists' dreams come true, but also politicians' nightmares. More current in people's life since the 1940s, BigSci has scared and delighted; some of its achievements brought regret, others, hope. Nowadays, world expectations turn to BigSci as an option to achieve unlimited, safe, and non-carbon emitting energy, that could be useful in the fight against climate change, in initiatives such as the Joint European Torus (JET) and the International Thermonuclear Experimental Reactor (ITER) programs (Woodall, 2019).

The title suggests going 'Beyond traditional Big Science', an exciting and challenging endeavor. Many people, inside and outside of the academic study of science and politics, have used the term 'Big Science' in a variety of ways (Barker & Halliwell, 2018; Capshew & Rader, 1992; Crease & Westfall, 2016; Hallonsten, 2016a; OECD, 1993), and so it has become diluted over the years and analytically useless. Nonetheless, since it has become so well-known and has a rhetorical appeal to it, it is almost impossible to avoid it. The best option is to stick with it and nuance it with more analysis and discussion. We chose to go 'Beyond traditional Big Science', featuring an expanded version of its conventional prominent attributes and aspects linked to high-energy physics and its colossal laboratories (A. M. Weinberg, 1961). Present-day BigSci is not limited by sophisticated facilities (Aronova, Baker, & Oreskes, 2010), a floor or a ceiling, but it has grown beyond and cannot go in its traditional style. More than this, science must call the BigSci primary funder's attention, the government, to this 'expanded condition' and allow other research domains to go further and deeper, seeking answers to fundamental questions and pushing the limits of knowledge in all fields.

Contemporary BigSci is a phenomenon that started in the twentieth century due to the evolution of scientific research because of the need to find answers to increasingly complex scientific questions (Capshew & Rader, 1992; Hallonsten, 2016a; Price, 1986). BigSci search for new knowledge/answers to complex scientific questions demands much time and patience. In this sense, it is impossible to have a fast track mode in BigSci projects, as Berkley (2020) suggested, even if they aim to save lives, develop vaccines, and bring the cure to new diseases such as the coronavirus disease 2019 (COVID-19). The COVID-19 vaccine research has been improving/adapting/applying very well-known immunization methods to produce a vaccine under an international emergency state (J. Cohen, 2020). Those initiatives have a clear technological purpose, rather than studying/developing new methods/solutions, pushing the frontier of knowledge, an undated scientific purpose. So, those efforts related to COVID-19 cannot be framed as BigSci projects.

Most recently, in a panoramic view of the world's science, technology and innovation (STI) activities landscape, BigSci projects appear as a remarkable example of integrated multidisciplinary research, international collaboration initiatives, and multifaceted relationships between government, scientists and industrial sectors (Choudhury, Fishman, McGowan, & Juengst, 2014; Lambright, 2002; Peacock, 2009; Purton, 2015).

From the scientific and industry perspective, the lack of a clear policy and the attractive status/label of 'Big Science' creates a possible conflicting relation between actors and the government (CSPC, 2017). Moreover, scientists, "in their envy of the support afforded 'Big Science' in the field of physics" (Aronova, Baker, & Oreskes, 2010, p.203), may have the temptation, when writing a project proposal for submission to the government, to point out some ways in which the proposal fulfill all the requirements of a BigSci project and should, therefore, be funded (Westfall, 2003). This situation could lead to avoidable and unnecessary internal conflicts and misunderstandings within the scientific community as scientists fight for the same funding. Besides, the alleged potential scientific, economic, social, and even political benefits of these endeavors, enthusiastically advocated by interested scientists and sometimes industry, may fail to convince skeptical decision-makers. The latter still faces varying pressures from all those who do not directly benefit from the investment, that is, those who feel disadvantaged, such as scientists from other less prominent scientific areas, the industry, or even society. (Aronova et al., 2010)

From the government's perspective, BigSci projects are a source of complex public decisions in science policy, funding, and evaluation. One of the reasons for the interest in BigSci is that it is widely assumed to perform cutting-edge research that usually leads to innovation and should be encouraged (Lamy et al., 2017; MCTIC, 2016; Naylor et al., 2017). Furthermore, the participation of a country in BigSci projects ensures that it is active in leading-edge research fields, brings considerable prestige in the international arena, as well as potential cost savings and other benefits, but also comes with complex risks (Elzinga, 2012; Hallonsten, 2015).

However, public financial support is inevitable for BigSci due to its size, costs, and complexity. Projects such as the Artemis program (NASA, 2020), the European Molecular Biology Laboratory (EMBL)[1], the Sudbury Neutrino Observatory Laboratory (SNOLAB)[2], and the Amazon Tall Tower Observatory (ATTO)[3], which costs varying from hundreds of millions to dozens of billions of dollars, well represent the complexity of the BigSci funding decision. Nations are increasing their STI expenditures over the years, actively fostering BigSci projects and related science policies (A. Abbott, 2017; Canada, 2018; ECOM, 2018; Katsnelson, 2016; Theil, 2015; Xin & Yidong, 2006). Implicit in this growing trend for BigSci initiatives are several aspects of decision-making and science-policy challenges. After all, the main feature of these initiatives in the government's eyes is that big money is involved, as well as long-term investments, huge researchers' teams, and eventually other countries, human and international relations, and management, all of which have a tremendous political impact.

Regardless of this, BigSci figures on investments, outcomes, or innovations are impressive (Purton, 2015). It is a relevant government matter that demands more effectiveness and transparency in the approval and funding process "in an era where cost efficiency and the contribution of science to innovation and economic development appear to be the dominant rationale for investment" (Jacob and Hallonsten, 2012, p.411).

1.1 Motivation

Recent examples (Berkley, 2020; J. Cohen, 2020; Sun, 2020) show that scientific and industrial communities and government do not agree in proposing a BigSci initiative in a similar approach adopted by the Human Genome Project (HGP) to allow a quicker and more efficient answer to the

[1] https://www.embl.de/

[2] https://www.snolab.ca/

[3] https://www.attoproject.org/

actual global coronavirus emergency issue. Ironically, HGP was the source of one of the emblematic examples of a very expensive clashing between scientists, government, and industry (F. S. Collins, Morgan, & Patrinos, 2003; Lambright, 2002), culminating with international principles for data sharing, the Bermuda Principles (Maxson Jones, Ankeny, & Cook-Deegan, 2018), and the biotechnology sector loss of about USD 50 billion in market capitalization in two days (Herper, 2017).

Similar conflicting situations between BigSci stakeholders are not rare or exclusivity of medical and health sciences. More than that, BigSci is a sensitive topic, and many authors already showed in real case studies that the government decision-making is a source of relational problems (Gingras & Trepanier, 1993; Leach, 1973; Linton, 2008; Richardson, 2016; Thomasson & Carlile, 2017; A. M. Weinberg, 1961; S. Weinberg, 2012). Lately, scientific discussion forums such as the Canadian Science Policy Conference (CSPC), among others, emphasized conflicts between scientists and public decision-makers on BigSci matters, as well as similar ones with the media and the society, impacting directly and negatively in valuing science and BigSci, related policies and funding practices (CSPC, 2015, 2016; Finnegan, 2016).

Apart from the conflicts observed by the literature and forums, one constant factor is that scientific and industrial communities' claim about a more transparent, informed, structured, evidence-based decision-making process on BigSci projects investments. Thus, our motivation responds to a generally perceived need mainly expressed by the scientific and industrial communities as well as government technical analysts for a systematic and transparent decision-making framework for the government's investments in BigSci.

In short, this research addresses the single, complex, conflicting problem of the government's decision to fund or not BigSci projects.

1.2 Objectives

The development of this research has the primary goal of supporting national governments to improve their capacity in making informed and structured decisions on Big Science investments, with the participation of the scientific community and the industry by proposing a decision aid framework. Furthermore, it is essential to highlight the innovative aspects of this proposed framework:

- customizable, that is, flexible and adaptable to any high-level government decision-maker or group of top decision-makers demanding an informed, structured and more transparent decision process of BigSci investments;
- participative, that is, ensure active participation of the scientific and industrial communities;
- robust, that is, can assess any civil BigSci project proposal from all research fields.

Other elements or secondary goals are required to reach this primary objective:

- build a taxonomy of BigSci based on research fields;
- build a workable and comprehensive definition of BigSci;
- structure the problem of government BigSci investments;
- identify (elicit) government decision-makers' values, preferences, judgments, and criteria related to BigSci investments.

1.3 Approach and contribution

We conducted this exploratory research based on literature and empirical observations. Literature consisted of white literature or "high-quality, relevant, peer-reviewed articles" (Adams, Smart, & Huff, 2017, p. 432) as well as grey literature or "not subject to traditional academic peer-review processes" (Adams et al., 2017, p. 432). Empirical observations were represented by exclusive interviews with a selected group of BigSci high-level stakeholders. We employed a multi-methodology approach encompassing qualitative and quantitative methods: the qualitative metasynthesis (Cooper, 2015; Erwin, Brotherson, & Summers, 2011), the systematic inductive approach analysis (Gioia, Corley, & Hamilton, 2012), the Strategic Options Development and Analysis – SODA (Eden, 2004; Eden & Ackermann, 2001), and the Multi-Criteria Decision Analysis – MCDA (Belton & Stewart, 2002; Franco & Montibeller, 2010b; Montibeller & Franco, 2010).

We recognize that this research contributes to shed light on present-day BigSci as a phenomenon in all research fields and categorize it in a new taxonomy. It also contributed to show that before complex and relevant decisions, especially related to huge investments, tools based on a scientific approach can help top decision-makers: structure the problem, understand it better, plan their decision or alternatives, and minimize conflicts between stakeholders. A framework to support government decision-making on BigSci investments would help document/track the decision process and make it transparent and rational. Furthermore, this thesis aims to bridge decision-makers, scientists, and industry, transitioning scientific knowledge to practical use in a real-world situation where there are significant opportunities for stakeholders to learn from each other and the process.

1.4 Thesis outline

The remainder of the thesis is organized as follows. Chapter 2 provides a critical overview of the relevant literature on central themes in the BigSci context. Chapter 3 describes the adopted methodology and the primary and secondary data used. Then comes the first part of our results and discussion with the proposed taxonomy and definition of BigSci in Chapter 4. An in-depth problem structure follows in Chapter 5, offering a rational analysis of the complex BigSci investment issue. Chapter 6 presents the subsequent development of a multi-criteria model, the principal constituent of the following framework. At the same time, our proposed framework as a decision aid tool for the government decision-making of BigSci investments is the central topic of Chapter 7. Finally, Chapter 8 summarizes the main conclusions and future recommendations.

CHAPTER 2 CRITICAL LITERATURE OVERVIEW

This research work is at the crossroad of six domains in the context of BigSci: collaboration, innovation, Big Data, Open Science, government issues, and decision analysis. These correspond to the six key Sections themes of this research project. This chapter presents a critical overview of the relevant white and grey literature about BigSci, highlighting recent advances and identifying the gaps that this research will aim to fill as well as the links between this research work and past studies.

Big science is a term used by the scientific community in the literature over the past 70 years, in particular by historians of science, researchers from medical sciences and private organizations. BigSci, as a topic in the literature, still maintains its characteristic of being “remarkably heterogeneous” as pointed out by Capshew & Rader (1992, p. 5). Before that, in a science-led economy scenario, but already under budgetary constraints, BigSci has been a topic of discussion and concerns by scholars, governments, funding agencies, and policymakers all over the world (Catalano, Florio, & Giffoni, 2016; Hallonsten, 2015; Mallory et al., 2018; Patry, Ewart, Heuer, & Lockyer, 2015; Richardson, 2016; S. Weinberg, 2012). On the one hand, studies have identified positive aspects of BigSci such as substantial knowledge advances and technology push (S. Weinberg, 2011), multidisciplinary collaboration and open science (Koch & Jones, 2016) or the benefits of accessing and sharing big databases (Borgman et al., 2015; Saez-Rodriguez, Rinschen, Floege, & Kramann, 2019; Samet, 2009). On the other hand, investigations have studied its negative aspects such as the potential threat to scientists’ creativity and individual reward (Heilbron, 1992; Stanford, 2019), constraints to academic freedom (Aronova et al., 2010; Dahn, 2019; Stanford, 2019; A. M. Weinberg, 1961), the unbalanced power struggles in collaborations (Leonelli, 2007; Ness, 2007) or findings' reproducibility and scientific method issues (Longino, 2016; Schatz, 2014).

Case studies constitute the bulk of the literature on BigSci and focus mostly on history, collaboration, performance, management, policies, impacts, innovation, and evaluation of specific projects; few documents, usually books and reports, are dedicated to a general view of the phenomenon. For example, Larsson (2020) worked on a comparative organizational failure case study between the U.S. National Cold Fusion Institute (NCFI) and the Swedish node of the BioBanking and Molecular Resource Infrastructure (BBMRI), finding ten types of organizational failure present in at least one of the organizations. D'Ippolito & Rüling (2019) studied collaboration at the Institut Laue-Langevin (ILL), identifying four typical collaboration patterns between scientists and users. Kim, Hong & Jung (2019) proposed a quantitative approach to support strategic policies related to BigSci projects and successfully applied it to nuclear fusion research in 14 countries. Castelnovo, Florio, Forte, Rossi & Sirtori (2018) quantitatively measured the positive economic impact of high-tech procurements for the Large Hadron Collider (LHC), suggesting a systematic cost-benefit analysis. Among the many historical studies, Westfall (2016, 2018, 2019) chronicled the history of the experimental program at the Thomas Jefferson National Accelerator Facility (JLab), highlighting the challenges and the rise of the New Big Science era. Regarding the evaluation of such BigSci projects, the European Synchrotron Radiation Facility (ESRF) and other two similar facilities were the focus of Hallonsten's (2013) assessment analysis. The author reached convincing conclusions using a combination of varied elements to build a fairly adequate performance measure. ESRF was also the target of Simoulin's in-depth sociological and historical studies derived from observations and interviews over 14 years (from construction to full operation), highlighting aspects of the ecosystem/interactions of users and instrument scientists/engineers (Simoulin, 2007), organization and management of science issues (Simoulin, 2012b), and the 'evolutionary' paths of increasing multidisciplinarity (Simoulin, 2012a) and internationalization (Simoulin, 2016) trends of light sources facilities.

BigSci, as a phenomenon, was thoroughly studied in books such as Galison and Hevly (1992), Hallonsten (2016a), and Cramer & Hallonsten (2020), explored BigSci comprehensively as a phenomenon.

2.1 Historical overview

Throughout the history of humanity, it is noticeable that STI plays a fundamental role in countries' progress. It is also noticeable that wars, natural hazards, lack of natural resources or competitive disadvantages drive these advances. Thus, necessity forced astronomy along the BigSci path long before physics and other sciences. Astronomic knowledge and useful applications in geodesy, navigation, and measurement of time aroused interest and the financing of governments that created real research institutes (Dreyer, 1953; North, 1994). Sixteenth-century astronomical observatories (S. Weinberg, 2012); sixteenth and seventeenth centuries "stellar and planetary astronomy, cartography, mathematical and descriptive geography (including…anthropology and ethnography), natural history, meteorology … , pharmacy and medical botany, and some parts of mixed mathematics" (Harris, 1998, p. 295); eighteenth-century Pacific exploration voyages (Raj, 2008); and nineteenth-century large-scale scientific expeditions (Smith, 1996) exemplify some expensive practical-driven enterprises nominated as BigSci. In any case, a significant part of the BigSci studies has focused on the twentieth-century phenomenon onwards.

According to Kojevnikov (2002), the Russian research institutes system implemented in 1921, in response to the economic and scientific crises after World War I and dedicated to national, practical, military and industrial needs, was the first case of BigSci in the twentieth century. On the other hand, other authors pointed out that the need to implement its nationalist strategy made Germany the first country to perform BigSci in the last century (Ciesla, 2000; Ciesla & Trischler, 2003; Dahn, 2019; Nye, 1999; Rezende, 2012). In the early 1930s, Germans started to build unmatched infrastructure in preparation for World War II (WWII), developing jet engines, guided missiles, submarines, rockets, and chemical weapons (Ciesla & Trischler, 2003; Cornwell, 2004; Dahn, 2019; Rezende, 2012).

At the same time, but initially, for scientific purposes only, the USA built its first cyclotron, the Lawrence Berkeley Laboratory (LBL), inaugurating the BigSci era in America and taking the first step to the multipurpose national research laboratory system and the military-industrial complex or the Pentagon system (Dennis, 2016; Heilbron & Seidel, 1989; Hiltzik, 2015). When LBL was later mobilized for war in 1940/41 as one of the contributors to the creation of the atomic bomb, known as the Manhattan Project (Heilbron & Seidel, 1989), USA BigSci settled the national security rationale that dominated until the end of the Cold War (Capshew & Rader, 1992). Other historians of science accepted as a standard beginning for BigSci in America the radar and atomic bomb projects during WWII (Westfall, 2003).

Therefore, this warfare period led to increasing science funding, collaboration among scientists, major industries, and government, and to adopting a new modus operandi for research in countries directly involved in WWII, especially Germany and the USA (Ciesla & Trischler, 2003).

Since 1941, biomedical sciences had followed physics in turning into BigSci when the U.S. government fostered large medical projects for penicillin, steroid hormones, and blood derivatives

(Rasmussen, 2002). Later, the International Geophysical Year (1957-58) was the first BigSci initiative in earth sciences (Aronova et al., 2010), emphasizing the creation of Big Data centers to keep and organize the data for future comparisons and developing global environmentalism (Goossen, 2020). Then, in the 1970s, social sciences (Holzner & Salmon-Cox, 1977) and humanities (*Palaeoanthropology*, 1970) claimed to follow the BigSci model with the Learning Research and Development Center (LRDC) and the Swartkrans and Sterkfontein archeological excavation projects, respectively. In opposition to the dominant idea that points out the Human Genome Project (HGP) as the first BigSci in biological sciences (F. S. Collins et al., 2003; Lambright, 2002), Aronova et al. (2010) also advocated that the International Biological Program (1964-74) was the first BigSci initiative in biology with large-scale collaborative experiments.

Some authors (Crease & Westfall, 2016; Hallonsten, 2016a) recognized two different periods in BigSci evolution grounded in science policy priorities: the first, Old BigSci, being towards basic research after WWII; and the second, New or Transformed BigSci, progressively moving towards applied research (materials, biomedical sciences and nanotechnology) in the post-Cold War period. The authors also mentioned other characterizing features of the current era, such as government-industry partnerships, consortia of countries, excessive bureaucracy, pressure for accountability and economic benefits, as well as intellectual property and ethical issues.

To summarize, the literature shows that BigSci has evolved since the 1920s encompassing new disciplines, new stakeholders, new facilities, new concerns, and discussions, but one main problem remains: its financial sustainability.

2.2 Big Science concepts

The definition of Big Science is something that evades a simple answer. Therefore, it is necessary to access the relevant literature, where the discussion has been most vivid and most helpful, to understand how complex BigSci is. It is feasible to find proposed definitions providing information background to clarify ideas about BigSci using tertiary sources such as encyclopedias and dictionaries. Table 2.1 shows examples of the definition of BigSci given by tertiary sources. It is possible to capture the common aspects of building a general first concept, but this is still insufficient and blurry. The following Subsections present what white and grey literature have about the origin and definition of BigSci.

Table 2.1 BigSci definition in tertiary sources[4]

Source	Definition
TERMIUM Plus[5]	"large-scale scientific research consisting of projects funded usually by a national government or group of governments" or "megascience"
Encyclopædia Britannica (https://www.britannica.com/science/Big-Science-science)	"style of scientific research developed during and after World War II that defined the organization and character of much research in physics and astronomy and later in the biological sciences"
Wikipedia (https://en.wikipedia.org/wiki/Big_Science)	"is a term used by scientists and historians of science to describe a series of changes in science which occurred in industrial nations during and after World War II, as scientific progress increasingly came to rely on large-scale projects usually funded by national governments or groups of governments"

2.2.1 Origin of the term

According to Capshew and Rader (1992), who thoroughly studied the term, the first known use of Big Science is almost impossible to determine. The authors suggested that it was first introduced in a 1958 review published in the Bulletin of the Atomic Scientists. In 1947 however, amid the tense atmosphere of the early Cold War, the physicist Louis Ridenour used the term "big science" in the meaning defined above in a scientific journal for the first time (Ridenour, 1947a). In The American Scholar, republished months later in the Bulletin of the Atomic Scientists (Ridenour, 1947b), Ridenour exposed the concerns about a core problem related to BigSci:

> The conclusion here is that big science needs big money; and that, while big science is not the only part of science, nor even, perhaps, the most important part of science, it is sufficiently important to justify the availability of a certain amount of big money during the years to come. (Ridenour, 1947a, p. 215)

[4] All websites accessed on 30 April 2020.

[5] https://www.btb.termiumplus.gc.ca/tpv2alpha/alpha-eng.html?lang=eng&i=1&srchtxt=BIG+SCIENCE&index=alt&codom2nd_wet=1#resultrecs

Albert Einstein, Robert Merton, Vannevar Bush, among other 11 scientists and military researchers, took Ridenour's argument further and replied to it (Ridenour, 1947b). At that moment, BigSci and defense activities were closely linked, and science funding for military purposes represented an unprecedented scale in history, physics being the central research field (Almeida, 2007; Hallonsten, 2016a).

The term 'Big Science' is also frequently attributed to Alvin Weinberg, physicist and U.S. chief science advisor, who published in 1961 a commentary for Science exposing negative considerations about large-scale scientific enterprises (A. M. Weinberg, 1961). Weinberg's article undoubtedly popularized the term, yet "he used it like we might use 'Big Pharma' or 'Big Oil'—as a slur" (Crease, Martin, & Pesic, 2016, p. 356). In his 1986 book Little Science, Big Science…and Beyond (Price, 1986), even Solla Price mentioned that Weinberg first coined and described the term. As a high-level influencer, Alvin Weinberg played a much more significant role than solely popularizing the term. He proposed to confine BigSci to national laboratories as an alternative to contain BigSci disease contagion; and indirectly restricted its rapid expansion towards other disciplines (Aronova et al., 2010).

2.2.2 Concepts of the term

Examples of BigSci in the white and grey literature reflect contemporary usage of the word. Numerous authors have studied the BigSci phenomenon (Almeida, 2006, 2015; Autio, Hameri, & Vuola, 2004; Beise & Stahl, 1999; Crease & Westfall, 2016; Dahn, 2019; Georghiou, 1998; Hallonsten, 2013, 2018; Hallonsten & Heinze, 2012; Johnston, 2018; Stanford, 2019; Vermeulen, 2013, 2016; Vermeulen, Parker, & Penders, 2013; Vuola & Hameri, 2006; Westfall, 2003). Furthermore, many studies provide evidence that several stakeholders, inside and outside of the academic environment, have used the term 'Big Science' in various ways (Capshew & Rader, 1992; Galison & Hevly, 1992; Hallonsten, 2016a). The term is not solely used for expensive large-scale scientific research that involves large teams of scientists, multidisciplinary collaborations, or consortia of countries, but also for a type of project or facility, an organizational model of science, a label for different organizations, a new form of scientific production, research approach or method, or as a new scientific era. As the term has become so well-known, popular, and even fashionable, it is almost impossible to avoid it. In other words, BigSci is a buzzword and has its accompanying buzzword problems, as pointed out by Scudellari (2017).

Besides tertiary sources (Table 2.1), previous authors also proposed definitions and concepts of BigSci (Table 2.2). Among those, TERMIUM Plus (Table 2.1), the Government of Canada's terminology and linguistic data bank also indicated "megascience" as a BigSci synonym. Regarding this interchangeability, Hoddeson, Kolb, & Westfall (2008) exposed it is quite common to find documents using the terms megascience and BigSci indistinctly to refer to costly scientific research projects. However, they declared that for their purposes, megascience is not a BigSci synonymous but “a bigger Big Science shaped by restricted funding for physics after about 1970” (p. 262), whose “most striking feature…is that its experiments seem no longer to ‘end’” (p. 3).

Table 2.2 Some examples of proposed definitions and concepts of BigSci by previous authors

Author	**Comment**
Weinberg (1961, p. 162)	replaced ‘large-scale science’ by ‘Big Science’ and declared: “Big Science is an inevitable stage in the development of science and, for better or for worse, it is here to stay.”
Price (1986, p. 2)	was enthusiastic about the growth of science and announced: “The large-scale character of modern science, new and shining and all-powerful, is so apparent that the happy term ‘Big Science’ has been coined to describe it.”
Galison & Hevly (1992, p. 355)	showed that conceptualizing BigSci is a relatively long-term challenge. In the concluding chapter, they stated outstandingly: “With an adjective combining quantitative and qualitative senses, the phrase [BigSci] is conveniently murky, appropriate for an activity that few can define or describe precisely but many feel able to recognize on sight.”
Capshew & Rader (1992, p. 4)	made a detailed historical description of the subject and a somewhat philosophically oriented analysis of what the concept of BigSci might mean considering various perspectives regarding scale, complexity, scope, impact, and significance. They stated: “Thus Big Science has come to be identified almost entirely as a contemporary phenomenon, with the singularity of current large-scale research enterprises taken for granted.”
Smith (1996, p. 739)	described as a large-scale scientific enterprise and warned that: “Science on such a grand scale helps to underline that the usual equation of Big Science – Big Bucks plus a Big Machine equals Big Science – is too limiting.”
Westfall (2003, p. 56)	argued that BigSci, in analytical terms, is not especially useful because anyone has used it for his/her own political or academic purposes. She concluded with one possible perspective: “Thinking in terms of ‘expensive science’ might allow us to focus more precisely on the important issue of how much large-scale science of various kinds costs taxpayers, not only in construction costs but in continuing yearly expenses.”
Almeida (2006, p. 266)	advocated BigSci has always been linked to national security and hegemony: “Big Science is an expression that lies in the political-military dimension of science, and its purpose is to elaborate and carry out research projects aimed at preparing for war and maintaining world scientific leadership.”
Hallonsten (2016a, p. 4)	strived to explore all aspects of BigSci to promote a better understanding of the phenomenon: “Big Science is understood as science made big in three dimensions: big machines, big organizations, and big politics.”
Saez-Rodriguez et al. (2019, p. 1327)	summarized that BigSci is “the joint effort of large consortia to generate big data to help reach a common goal”.

In fact, with the end of the Cold War in 1991, "'big science' was partly overlaid with megascience" (Elzinga, 2012, p. 421). The megascience concept was coined by the Organisation for Economic Co-operation and Development (OECD, 1993, p.42):

> …a megascience project, or megaproject, is one that addresses a set of scientific problems of such significance, scope, and complexity as to require an unusually large-scale collaborative effort, along with the facilities, instruments, human resources, and logistic support needed to carry it out.

Since then, the OECD increasingly adopted 'megascience' instead of 'Big Science' and, in 1999, definitely updated it to 'global science', consolidating and expanding the concept to encompass real global issues of basic research such as global societal challenges or global impact of research in many areas (OECD 2012, 2019b).

Hallonsten (2016a) made a thorough analysis of the various uses of the term BigSci in the introductory chapter to his book, arriving at a separation between a "wide" and a "narrow" interpretation of the term. The author stated that the "wide" means that anyone is free to use the term BigSci in any way s/he likes. However, for the concept to be analytically useful, a "narrow" interpretation is necessary. He provided this "narrow" interpretation that works for his book and articles, but certain things fall outside it, for example, the HGP.

Even though the definitions and concepts (Tables 2.1 and 2.2) may share many aspects, they still narrow the subject in regularly associate it with large equipment (Smith, 1996), while it must have a more comprehensive feature for a government perspective. Moreover, there is no unique, definitive or absolute definition of BigSci, and there may exist at least as many concepts as there are individuals involved in BigSci. As shown above, these insights captured a trend from most social sciences and humanities scholars to restrict the term to high-energy physics facilities such as synchrotron light sources or X-ray sources (Aronova et al., 2010), while expert advice organizations tend to extend the concept (Elzinga, 2012) to a broader application. In any case, each one has its reasons for using and defining the term BigSci. In the end, the term may still be considered a buzzword among so many (Scudellari, 2017).

2.3 Big Science classifications

To the best of our knowledge, only 11 documents propose a classification of BigSci in the literature. Each classification has a defined character suitable for a specific purpose. Table 2.3 summarizes those perspectives categorizing BigSci based on:

- institutional arrangements (Ayabe, 1999; Kevles & Hood, 1992; Leonelli, 2007; OECD, 1993);
- collaborations (OECD, 1993);
- historical periods (Crease & Westfall, 2016; Galison, 1997; Hallonsten, 2016a; Lillian Hoddeson et al., 2008);
- research approaches (Aronova et al., 2010; Quinlan, Kane, & Trochim, 2008; Smith, 1996).

Table 2.3 Classification of BigSci in the literature

Criterion	Categories	Reference
Institutional arrangement	"centralized form": big technological mission under centralized control and direction of a big team to produce and operate a major technological system. "federal form": big subjects research program under decentralized efforts to develop the task and integrate information into a systematic database. "mixed form": big facility research program under centralized control and federal uses of the facility by various research groups and institutions.	Kevles & Hood (1992)
	"central-facility": requires a central facility that demands big-budget and innovative engineering development, including "fixed-site projects" (like telescopes) or "mobile-facility projects" (like ships). "distributed-facility": does not require a central facility, including "intrinsically distributed projects" (geographically dispersed sites) or "optionally distributed projects" (operated in a centralized or distributed mode).	OECD (1993)
	"Big science" or "capital-intensive": requires extensive facilities and big budgets to accomplish project goals; otherwise, it does not start. "mass science" or "labor-intensive": does not require big infrastructure or budget to start, can be implemented and executed at a slower pace under financial constraints without compromising the project.	Ayabe (1999)
	"centralised big science": highly centralized, large-scale scientific collaboration with a leading institution ruling the scientific, financial and administrative issues. "decentralised big science": large-scale scientific collaboration in which all participants agree on the set of objectives, but each one carries their research with not necessarily standardization of methods.	Leonelli (2007)
Collaboration	"first type": big Research and Development (R&D) collaboration program encompasses industrialized countries using huge high-performance facilities in one or more locations. "second type": global-scale R&D collaboration program encompassing any country and focusing on politically sensitive objectives.	OECD (1993)

Table 2.3 Classification of BigSci in the literature (cont'd)

Historical period	"microintegrated big science": typical power/governance structure and conflicting work relation/practice between physicists and engineers in U.S. BigSci projects in the 1950s. "macrointegrated big science": same structure and conflict between physicists and engineers but in U.S. BigSci projects in the 1970s.	Galison (1997)
	"big science": U.S. large-scale physics research conducted during the first two decades after WWII with almost unlimited funding. "megascience": more extensive large-scale physics research in the U.S. conducted after 1970 under restricted funding.	Hoddeson et al. (2008)
	"Old Big Science": large-scale research at major facilities dominated by high-energy physics during the Cold War; "New or Ecologic Big Science": large-scale research at big facilities dominated by materials science after the Cold War.	Crease and Westfall (2016)
	"Old Big Science": Cold War phenomenon characterized by using big machines, huge telescopes, and space programs. "Transformed Big Science": post-Cold War phenomenon characterized by using big machines in a multidisciplinary Pasteur's Quadrant (Stokes, 1997) orientation.	Hallonsten (2016a)
Research approach	"machine centered": large-scale scientific enterprise involving costly equipment and major research facilities. "expedition driven": large-scale expedition whose one of the objectives is scientific. "coordinated": large-scale coordinated scientific project spread among various sites. "mixed": large-scale scientific enterprise that encompasses machine-centered and coordinated approaches in multidisciplinary research and objectives.	Smith (1996)
	"centers of excellence programs": multidisciplinary team in health sciences focused on direct interaction between basic and clinical researchers to develop a set of goals including prevention, diagnosis, and treatment techniques. "clinical research networks": the same but focused on conducting clinical trials, requiring coordination between multiple clinical centers.	Quinlan et al. (2008)

Table 2.3 Classification of BigSci in the literature (cont'd)

Research approach	"data-driven": international large-scale scientific collaboration focused primarily on collecting observational data around the world. "hypothesis-driven": international large-scale scientific collaboration focused on testing any hypotheses or theories. "instrument-driven": international large-scale scientific collaboration focused on developing sophisticated instrumentation, in particular, for physics experiments. "platform-driven": large-scale collaboration focused on developing complex platforms, in particular, for upper-level atmospheric and astronomical observations.	Aronova et al. (2010)

2.4 Big Science, Big Data and Open Science

The Nobel Prize laureate Sir John Sulston's "vision for open science guided the public Human Genome Project, based on science to benefit society" (Maxson Jones et al., 2018, p. 693). But Big Data and Open Science (open access) have an older origin: the World Data Center system that archived and distributed observational data from sites of the 1957–1958 International Geophysical Year (Borgman, 2015). And just as BigSci, the definitions of Big Data and Open Science do not make consensus among scientists, industry and public sectors, but a source of conflicting relations (Borgman, 2015; Leonelli, 2013; Levin & Leonelli, 2017; Maxson Jones et al., 2018). While some authors like Koch & Jones (2016) strongly encourage them, others like Levin & Leonelli (2017) ask for more reflection on the subject, and the HGP leader group advises on how to embrace them (Green, Watson, & Collins, 2015). Moreover, all three are considered buzzwords due to the lack of consensus around their meaning and core features as bigness and openness (Borgman, 2015; Maxson Jones et al., 2018).

For library and information sciences, Open Science (O.S.) is the term used to designate a new model of construction and organization of scientific knowledge, which arose mainly with the 1990s digital era. Computer science was a pioneer in that its researchers have deposited their articles in FTP servers since the 1970s (Larivière, personal communication, December 9th, 2016).

Other authors (Bartling & Friesike, 2014; Nielsen, 2011) declared that O.S. is an umbrella term related to the second scientific revolution, or enthusiastically called 'Second Open Science Revolution', considering the 'First' one as a movement to disseminate scientific knowledge through scientific journals from 1665, based on the available technology, the press. Thus, using the World Wide Web as the most recent available technological tool, physicists started the Second O.S. Revolution depositing their articles in arXiv since 1991, especially the publications in particle physics and astronomy related to BigSci projects. Those authors also advocated that O.S. is the movement that is opening, at all levels of society, the scientific process of creating knowledge, from its initial idea to its final publication, particularly the one financed by public resources, stimulating the practice of co-creation of knowledge.

From a more formal point of view, the four central components of O.S. to ensure unrestricted openness of the scientific process (Kraker, Leony, Reinhardt & Beham, 2011, p. 645) are:

- “open access as a way to make research results available”;
- “open data as a way to publish the raw data”;
- “open source as a way to give access to research prototypes”;
- open methodology or open reproducible research as a way to “sharing the methodological details of the study provided, and the tools used for data collection and analysis”.

Besides those components, Pontika, Knoth, Cancellieri, & Pearce (2015) studied the subject thoroughly, advocating O.S. has been increasingly incorporated into research practices, yet little understood or enough discussed by research stakeholders involved. The authors also proposed a detailed O.S. taxonomy (Figure 2.1), exposing the topic’s complexity and coverage, increasingly present in BigSci projects in all research fields.

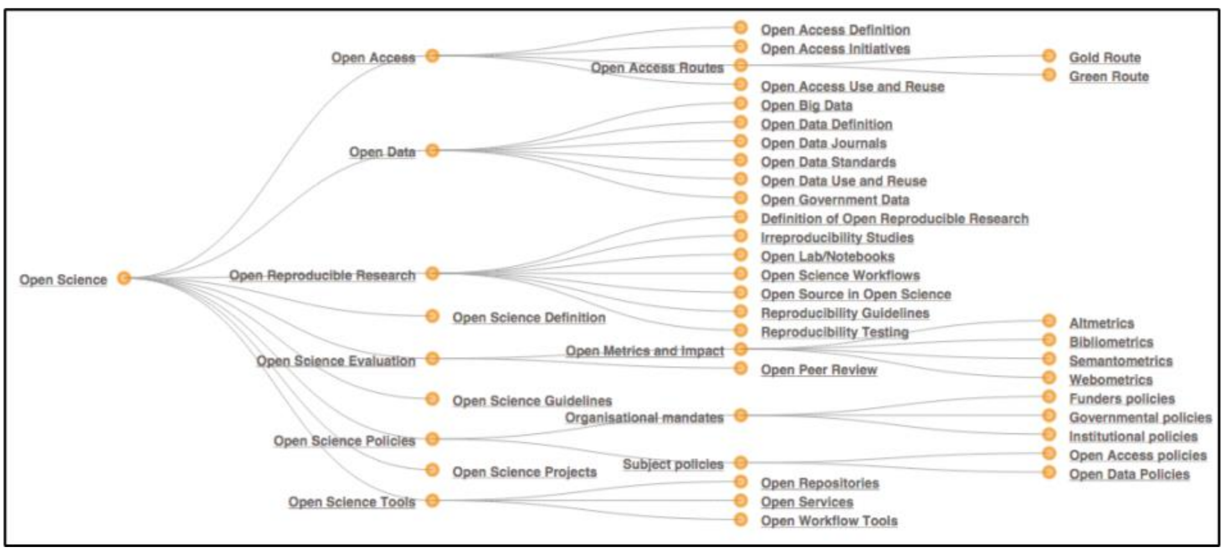

Figure 2.1 Open Science Taxonomy. © Pontika et al., 2015. Reproduced with permission.

It is important to note that such a complex subject is out of this research scope, except the data-sharing issues, increasingly discussed in the BigSci context since the HGP (Green et al., 2015; Koch & Jones, 2016). Before that, topics like intellectual property rights claims were rarely considered because observational data and subsequent discoveries from projects in “physics, astronomy, atmospheric and molecular chemistry, and the mathematical sciences” were traditionally in the public domain (David, 2014, p. 27) and made use of O.S. advantages. Moreover, those research fields’ concerns were demands on e-infrastructure, not only physical but also related to data management and preservation planning, and systems to support their activities (Bicarregui et al., 2013; Schroeder, 2007).

One of the HGP's major legacies is the mandatory research component of Ethical, Legal, and Social Implications, ELSI, in biomedical works, in particular BigSci initiatives (Green et al., 2015). In addition to those already sensitive aspects, some authors highlighted that economic (commodification of science), scientific (discoveries), cultural (personal unrewarding), and political (data policies) considerations are necessary to analyze the openness of research practices and data sharing for each individual BigSci project (Leonelli, 2013; Levin & Leonelli, 2017; Papadopoulos, 2015).

O.S. collaborations are fully open short-term groups formed by “[a]nyone in the world [who] could follow along and, if they wished, make a contribution” (Gowers & Nielsen, 2009). Even “non-scientists and amateurs in research” – citizen science (Fecher & Friesike, 2014) contributes to the solution of a complex research problem (theoretical or experimental). The participation can work under “a preliminary list of rules... These rules helped create a polite, respectful atmosphere, and encouraged people to share” (Gowers & Nielsen, 2009). Contributors interact through the Internet using blogs or wiki tools.

O.S. collaborations can be the best solution in a situation of humanitarian disaster or large-scale epidemic because they self-organize without formal agreements. Under these situations, two main reasons facilitate collaboration:

- the emergence and severity of the situation (large-scale epidemic or fast-growing pandemic, for example).
- rapid mobilization of scientists and public health agents around the world. Various examples such as COVID-19, Ebola or Zika virus epidemics showed that the urgent need and the opportunity of available Information and Communication Technologies (ICTs) had given medicine the know-how to organize itself quickly in successful O.S. collaborations.

Salmi (2015) enhances that “scientists and public health officials around the world have worked to rapidly coordinate studies and emphasize the need to share information with colleagues at the start of infectious disease outbreaks”. BigSci would not be such an efficient solution because all formality associated with international arrangements for data and technology sharing, as well as collaboration conditions, usually take years to happen. In outbreaks or pandemic such as the COVID-19 one, scientists need and respond in a few weeks (J. Cohen, 2020). According to Carillo & Papagani (2014), BigSci and O.S. have a complex relationship, sometimes conflicting, which regulates their action in the political arena where they seek to influence others in order to reach their interests; also, this relation passes through intellectual property rights.

Knoppers et al. (2011) propose a Code of Conduct for international data sharing that could also be applied to other disciplines in BigSci, incorporating "seven principles: quality, accessibility, responsibility, security, transparency, accountability and integrity".

2.5 Big Science and collaboration

The reality is that "Big science has prompted scientific collaboration, ultimately leading to multidisciplinary, co-operative science" (Larsson, 2020, p. 57). Other authors also explored this observed fact strongly relating BigSci and collaboration, in particular in Europe (Canals, Ortoll, & Nordberg, 2017; D'Ippolito & Rüling, 2019; Dai & Boos, 2019; Hallonsten, 2012; Hoekman, Frenken, & Tijssen, 2010; Rekers & Sandell, 2016). Scientific collaboration is a broad research topic explored by several disciplines that approach the subject from different perspectives. The high interest in the subject reflects the current landscape of global scientific research, which faces scientific problems that are increasingly complex and impossible to be investigated and solved by a single person (Price, 1986). It is also acknowledged that "participation in Big Science projects…and the exchange of technology and knowledge with science-based partners are fruitful environments for industry" (Puliga, Manzini, & Batistoni, 2019, p. 187). Technological collaboration is another research topic increasingly studied in the literature, in particular through case studies, where the industry is an essential actor that builds the facilities, pushes the technology frontier, and makes scientists dreams come true (Autio et al., 2004; Castelnovo et al., 2018; Eerme & Nummela, 2019; Hameri, 1997; Puliga, Manzini, & Batistoni, 2019; Vuola & Boisot, 2011).

2.5.1 Scientific collaboration

Few people have comprehensively tackled the research matter of defining 'scientific collaboration'. One of the most remarkable articles that expressed this concern and proposed a taxonomy was Katz & Martin (1997). The authors identified the need for conceptualization without performing it, concluding that the definition of collaboration varies over time and depends on factors like the scientific field and country. Later, Sonnenwald (2007) proposed a comprehensive definition; however, it seems that most authors who investigated scientific collaboration treat it as a universally known and accepted term a little like what we noticed with BigSci. Furthermore, the author declared BigSci as a category of scientific collaboration that is a synonym of large-scale collaboration. Recently, Autio (2014, p. 13) also defined BigSci in details as a type of collaboration: "large-scale, often capital-intensive scientific collaborations that are underpinned by shared scientific resources, such as measurement and observation facilities, experimentation and research facilities, shared data resources, and supporting infrastructure".

The main characteristics and typologies of scientific collaboration depend on the context in which it is being analyzed. According to Sonnenwald (2007), the most commonly used classification is disciplinary, geographic, and organizational, but Katz & Martin (1997) pointed out that categorization criteria are not exclusive and can be combined. Literature documented and studied many forms of scientific collaboration. For instance, D'Ippolito & Rüling (2019) proposed four types of collaboration for BigSci organizations in physics, based on interactions between instrument scientists and users. The authors identified four collaboration patterns at Institut Laue-Langevin (ILL), a European neutron source: "full service" with high expertise-gap between scientists and users and low co-development focus, "complementary collaboration" with high expertise gap and high co-development focus, "instrument service" with low expertise gap and low co-development focus, and "peer collaboration" with low expertise gap between instrument scientists and users and high co-development focus.

Regarding the disciplinary dimension, Sonnenwald (2007) stated that scientific collaboration is characterized primarily by being intra-, inter-, or transdisciplinary:

- Intra-disciplinary, or only disciplinary, collaboration is that in which the participants are of the same discipline as well as the knowledge produced.
- Interdisciplinary or multidisciplinary collaboration, in which participants are from different disciplines, is often associated with applied, experimental and quantitative research more than theoretical research, more common in natural sciences and medicine than in social sciences and occasional in arts and humanities (Katz & Martin, 1997; Larivière, Gingras,

& Archambault, 2006; Price, 1986). Literature shows that traditional BigSci projects are multidisciplinary collaborations, mainly in the natural sciences (Crease & Westfall, 2016; Hallonsten, 2016a; Saez-Rodriguez et al., 2019).

- Transdisciplinary collaboration is the interdisciplinary collaboration characterized by "the integration of natural sciences, social sciences, and the humanities and the involvement of multiple stakeholders from all aspects of society" (Sonnenwald, 2007, p. 647) to solve wide-ranging scientific problems related to contexts rather than disciplines. Transdisciplinarity is a relatively recent trend in BigSci, in particular in medical and environmental sciences projects, where collaborations can be categorized as transdisciplinary with research teams representatives not only from natural sciences and medicine but also from social sciences and humanities (F. S. Collins et al., 2003; Lambright, 2002; Mauz, Peltola, Granjou, van Bommel, & Buijs, 2012; Peters & Okin, 2017; Schimel & Keller, 2015; Tschakert, 2012; Vermeulen et al., 2013).

Several spatial scales can characterize the geographical dimension of scientific collaboration. On a large scale or country level, collaboration may be national or international (Katz & Martin, 1997; Sonnenwald, 2007):

- National or intra-national collaboration is when the participants work in the same country, regardless of their institutional affiliation. Few nations prefer to develop some BigSci projects based only on national collaborations such as the U.S. or China, among others (Hallonsten, 2011; Mendoza & Vara, 2006; Morelle, 2016; Westfall, 2016, 2018, 2019).
- International collaboration is when the participants work in different countries, regardless of the cultural, economic, political, or social issues involved. BigSci projects often encompass all geographical categories of collaboration on the same project (Aronova et al., 2010; F. S. Collins et al., 2003; H. M. Collins, 2003; Ponjaert & Béclard, 2010; B. Wu & MacDonald, 2019).

International collaborations turned relevant to BigSci, particularly for European countries (Olivotto, 2009) and environmental sciences (Aronova et al., 2010) after WWII, and since then, have considerably risen and proliferated together with BigSci initiatives (Crew, 2019; B. Wu & MacDonald, 2019). Apart from promoting the international prestige and visibility of the BigSci projects, those partnerships have been increasingly responsible for successful research strategies and positive impact in their productivity (Alvarez, Vanz, & Barbosa, 2017; González-Albo, Gorria, & Bordons, 2010; Jang & Ko, 2019; Kahn, 2016). The dominant role of leader countries in science and technology usually marks the management and coordination of BigSci projects and their respective international collaboration (Lambright, 1998; Robinson, 2020). Individual leadership and vision are also always crucial in governing those international endeavors (L Hoddeson & Kolb, 2003; Lambright, 2002; Schwing et al., 2020). The choice of collaborators among countries in BigSci projects can be linked to potential cost savings, other benefits, and complex risks (Elzinga, 2012; Hallonsten, 2015). The initiation, maintenance and delivery of international BigSci collaborations is a complex process with a strong political bias that has been the topic of recent studies (Robinson, 2019, 2020), pointing to specific conditions like innovative leadership and funding.

In addition to these two large geographical groups of scientific collaboration, Sonnenwald (2007, p. 647) also mentioned "scientific collaboratory" or "a laboratory without walls". This type of collaboration is a common practice in astronomy and space sciences, especially that associated with BigSci projects, in which the researcher has remote access to the scientific instrument or laboratory facility like the International Space Station (ISS) or the Very Large Telescopes (VLTs).

It is worth mentioning that, recently, significant incidents became a threat to international collaboration in BigSci: (a) U.S. National Institutes of Health (NIH) warnings about foreign scientists' conduct, in particular Chinese, regarding the potential theft of data (Woolston, 2019), and (b) Brexit impacts on the European Union (E.U.) science and BigSci projects (Peplow, 2019).

From an organizational perspective, scientific collaboration can also be characterized by scales, the most common being, in ascending order, the group, the department, the institution, and the sector (Katz & Martin, 1997):

- Group: (a) intragroup – between individuals in the same research group, (b) intergroup – between groups (e.g., in the same department);
- Department: (a) intra-department – between individuals or groups in the same department, (b) inter-department – between departments (in the same institution);

- Institution: (a) intra-institution – between individuals or departments in the same institution, (b) inter-institution – between institutions;
- Sector: (a) intra-sector – between institutions in the same sector, (b) inter-sector – between institutions in different sectors.

From an organizational perspective, BigSci projects encompass all types of collaborations. Furthermore, one relevant theme is leadership, closely linked to political actors and decision-makers, and usually considered responsible for the success or the failure of BigSci initiatives (Lambright, 1998, 2002; Larsson, 2020). The literature also institutionally explores and analyzes BigSci collaborations, including their ecosystems (Crease & Westfall, 2016; Westfall, 2010), managerial, historical and political aspects (H. M. Collins, 2003; Hallonsten, 2012; Kevles, 1997; Maxson Jones et al., 2018; Ponjaert & Béclard, 2010), and performance (Carrazza, Ferrara, & Salini, 2014; Leeming, 2019; Zhang, Vogeley, & Chen, 2011).

2.5.2 Technological collaboration

Regarding BigSci inter-sectoral collaborations, the literature focuses on technological collaboration between industry and BigSci organizations and subsequent radical and incremental innovations. Nevertheless, it is essential to note that we adopted the traditional inter-sectoral collaboration concept by Katz & Martin (1997). Thus, in this research, inter-sectoral collaboration refers to the collaboration between institutions in different sectors, for example, between BigSci organizations and industry.

Initially, Autio (2014) found in his review that the literature on the topic is “quite fragmented” because research on “big-science innovation is not very well established within management disciplines, but rather, has been contributed by big-science domain researchers such as physicists and astronomers and often published outside the mainstream management and innovation journals” (p. 16-17). The sparse and fragmented nature of the literature on BigSci inter-sectoral collaboration and innovation appears mainly through case studies such as those about the European Organization for Nuclear Research, CERN, and its experiments (Åberg & Bengtson, 2015; Autio, Bianchi-Streit, & Hameri, 2003; Autio, Hameri, & Nordberg, 1996; Autio et al., 2004; Boisot, 2011; Byckling, Hameri, Pettersson, & Wenninger, 2000; Hameri, 1997; Hameri & Nordberg, 1999; Vuola &

Boisot, 2011; Vuola & Hameri, 2006). Other studies also investigate BigSci technological collaboration, exploring topics such as knowledge/technological creation, transfer and dissemination (Puliga et al., 2019; Simonin, 2004; Vuola & Boisot, 2011), and societal and economic impacts on companies' innovation capabilities and processes (Autio et al., 2004; Castelnovo et al., 2018; Dal Molin & Previtali, 2019; Florio, Giffoni, Giunta, & Sirtori, 2018; Vuola & Hameri, 2006).

According to the taxonomy of innovative companies (Pavitt, 1984), it is recognizable that industry, collaborating with BigSci organizations, is dominated by science-based companies whose primary sources of S&T come from government investments for funding public and private R&D activities. In other words, a significant part of their knowledge is based on public scientific programs such as research from BigSci projects but also their in-house R&D initiatives. Moreover, collaboration with BigSci organizations before, during and/or after the public procurement process provides learning, knowledge and technology transfer to the participant companies (Åberg & Bengtson, 2015; Autio et al., 2003, 2004; BigScience.dk, 2017; Dal Molin & Previtali, 2019; Pisano, 2006; Vuola & Boisot, 2011; Vuola & Hameri, 2006; Wiechers, Perin, & Cook-Deegan, 2013; Zuijdam, Boekholt, Deuten, Meijer, & Vermeulen, 2011).

Inter-sectoral collaborations are essential to BigSci, "by virtue of their engineering-intensive tasks and overarching mission" (Autio et al., 2004, p. 110). According to Autio (in all his papers, see, for instance, Autio, 2014; Autio et al., 1996, 2003, 2004) and to the Danish group of Industrial Liaison Officers, ILOs, (BigScience.dk, 2017), the participation of the private sector is generally limited to contracts for the industrial supply of complex and sophisticated technology specifically developed for the experiments to be performed. This type of contract represents a continuing demand from the BigSci organizations that can only be met by collaboration with the industry. Another essential aspect to consider in the private sector is commercial participation and it entails. The case of Celera Genomics and the 'threat' to the HGP is illustrative in this respect (Lambright, 2002; Collins et al., 2003).

A few studies on the construction of the LHC particle accelerator by Autio et al. (2004) and Vuola & Hameri (2006), on the ATLAS experiment at the LHC (Vuola & Boisot, 2011), and others on BigSci facilities (Autio, 2014) provide relevant results. These researchers used in-depth multiple case studies on inter-sectoral collaboration to model the joint innovation process between industry (suppliers) and BigSci organizations (public organizations). The resulting frameworks uniquely detail firm-level innovation processes that benefit from interactions with a high-tech learning center provided by the concentration of high-level expertise that only a BigSci project could provide. Their results showed that BigSci organization-industry relationships generated an industrial learning impact that increased the knowledge transfer's efficiency and volume. Thus, achieving more meaningful results than traditional university-industry collaborations (Autio et al., 2004; Vuola & Hameri, 2006). The reason for this observation is the particular characteristics combining fundamental research, extremely challenging engineering tasks, big high-tech facilities, strict schedules, and compatible absorptive capacities. However, the government needs to support these collaborative actions in order to power innovation and the economy in participating countries. Further information on the impacts of BigSci projects on innovation and the economy is addressed in Section 2.6.

In innovation studies, collaborations can be interactions among participants of complementary skills (Schrage, 1990) via formal and/or informal mechanisms (Das & Teng, 2000) where value creation (revenues) focuses on the cost and quality (engineering approach), and the utility and perception value from things (service approach) (D. Ho, 2007). While value capture (profits) is challenging and bridging the gap between it and value creation, it is still thought-provoking for economic studies (Germany & Muralidharan, 2001). In the BigSci context, the value creation/value capture dichotomy exists and is thoroughly debated since the end of the 1940s. BigSci projects can be considered as a virtuous cycle (Figure 2.2) where basic science often drives applied research (e.g., co-designed instruments in collaboration with industry) and innovation, which gives technology back to the basic research/BigSci endeavor, contributing to pushing out the knowledge frontier (Purton, 2015). Value capture is a consequence and part of this cycle.

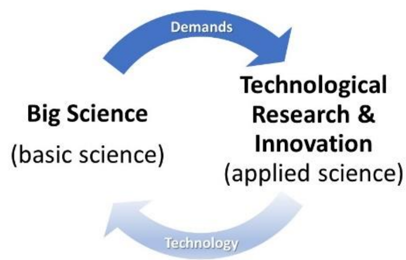

Figure 2.2 Illustration of the BigSci virtuous cycle inspired by Purton (2015).

Value creation and value capture are closely linked to knowledge absorptive capacity, referring to questions of collaboration (internal and external), cognition (created from prior knowledge of the individual and organizational level), requires investments in own R&D, is critical to innovation and in raising educational levels (W. M. Cohen & Levinthal, 1990). According to Autio et al. (2004), external and internal factors may improve the absorptive capacities of those involved in the process of knowledge transfer and even accelerate it in intra- and inter-firm/sector collaborations. It is a challenge to improve those capacities, especially in areas that require a high and varied level of basic scientific knowledge, such as those related to BigSci projects (Cooke, 2005). Ding & Huang (2010) pointed out that absorptive capacity also has a strong influence on the knowledge of outgoing spillover and the intensity of benefits it provides, particularly in technological collaborations.

Besides, Autio et al. (2004, p. 122) emphasized that “as demonstrated in our case studies, the learning and development benefits stemming from knowledge transfer may be considerable and may confer significant diversification advantages” for those involved, but always dependent on the specific absorptive capacity of each party. At the same time, Vuola & Hameri (2006) advocated that successful technological collaborations in BigSci projects demand matching people, needs, and time among the participants.

Many papers focus on the relationship between S&T collaboration, knowledge-based value creation processes, and value capture as Autio et al. (2004), Wu & Cavusgil (2006), Ding & Huang (2010), among others. While in the outcome perspective, the works are concerned with understanding how innovation is used by the participants of the collaboration that created it (Autio et al., 2004; F. S. Collins et al., 2003; Lambright, 2002; OECD, 2008; Pavitt, 1984; Pisano, 2006; Vuola & Hameri, 2006; Wiechers et al., 2013). Both aspects are complex and have nuances that vary in the scale and focus investigated.

The value capture by exploring the resulting innovation(s) from the collaboration can take several forms. Vuola & Boisot (2011) highlighted that improved social learning cycle, absorptive capacity, and network in different degrees (not necessarily formally agreed upon) at personal and institutional levels are outcomes shared by collaborators. In any case, primary outcomes are commercial. New products, technologies, and/or processes are patented, licensed, marketed, or sold by the parties, based on agreements and interests established in the formalization of collaboration, considering the new product's potential. The OECD (2008) gave a detailed description of how the resulting innovation from a technological collaboration will be explored by the participants commercially, highlighting that “companies need to decide if they want to commercialise the technology or product themselves or if they prefer to sell it” (p. 106). Also, the OECD (2008) pointed out that issues associated with intellectual property rights appear among the highest risk and concern for innovation collaborations, which in turn become more limited at the commercial stage.

More recently, value capture by intellectual property rights became more complicated in the BigSci context after the emergence of personal genomics firms created after the HGP and its extensions. According to the Genetics Home Reference (GHS, 2017), the gene patent regulation has several similarities but is specific for each country. For instance, in 2013, the Supreme Court of the United States decided it is not allowed to patent human genes in the U.S. because a gene is discovered not created and so there is no intellectual property to protect, invalidating more than 4,300 human genes previously patented (GHS, 2017).

2.5.3 Collaboration measurements

Given the full range of types of interactions, formalized or not, among scientists and the private sector, Katz & Martin (1997, p. 2) formulated and analyzed the following question: “How can one measure collaborative activity?”. To answer this question, they declared that collaborative research activities could be measured and indicated through several means, depending on the type, complexity, stage of development, and aspect of the collaboration investigated. Sonnenwald (2007,

p. 644) recalled that several research methods could be used to investigate scientific collaboration such as “bibliometrics, interviews, observations, controlled experiments, surveys, simulations, self-reflection, social network analysis, and document analysis”. Melin (2000, p. 33) was concerned with collaboration at an individual level and pointed out that “the amount of phone calls, international flights or the growing usage of e-mail are indicators that have been tried”.

The literature is usually interested in more easily implemented measures of collaborative research activities, particularly in its final stage or conclusion (its results and evaluation). Katz & Martin (1997) responded that measurement is conventionally done through bibliometric indicators, starting from the premise that all research collaboration results in publications (Price, 1986) – that is, in multi-authored papers. At an international level, Sonnenwald (2007, p. 652) indicated that those collaborative scientific activities could be “measured by co-authorship and joint projects”.

Katz & Martin (1997) highlighted that measurements of multiple-address papers are used at an institutional level, remembering that patents and licenses can also be used alone or in addition to articles. At the sectoral level, there is a distinct interest in collaborative activities. One path is to measure them through bibliometric means such as multi-address and/or multi-sector papers (Katz & Martin, 1997). However, recent studies showed that almost no publication involves private-sector co-authors (Youtie & Bozeman, 2014). Other measures of collaborative activities that are possible and complementary to bibliometrics, such as the distribution of research grants, focus only on the individual level of the collaboration (Bozeman & Corley, 2004; Lee & Bozeman, 2005). The authors also indicated that other significant benefits and/or impacts of collaboration might be perceived on larger scales like institutional, national, or international.

Bibliometric measurements are the most common approach to studying scientific collaboration, but they are severely limiting. As Larivière et al. (2006, p. 521) recalled, “in spite of its limitations, measuring collaboration on the basis of articles is probably the best approach currently available”. In publication and citation counts (most common in scientific collaborations), as well as in patent and license counts (most common in technological partnerships), their variations (fractional authorship – Lee & Bozeman, 2005), combinations (authorship, acknowledgment, and citation – “the Reward Triangle” – Cronin & Weaver, 1995), derived measures (multi-sector publication counts – Katz & Martin, 1997; impact factor analysis – Larivière, 2012) and their statistical analyses are used to study scientific collaboration in many ways. An integrated approach with bibliometric methods supplemented by qualitative methods can be used to construct empirically grounded theories of collaboration (Laudel, 2002); or be supplemented by interviews, questionnaires, financial indicators, or other social databases (Bozeman & Corley, 2004; Bozeman, Gaughan, Youtie, Slade, & Rimes, 2016; Lee & Bozeman, 2005; Melin, 2000). There is also a refined bibliometric approach proposed by Calero, Buter, Valdés, & Noyons (2006) to identify research groups in a particular scientific field using a combination of bibliometric mapping techniques and network analysis.

Leeming (2019, p. S37) showed that co-authorship is an increasing practice in international BigSci collaborations in "physics and astronomy, genetics, oncology and immunology", with a "record-breaking 5,154 authors" in one 2014 publication written by the Higgs boson collaboration. This BigSci practice promotes many examples of the phenomenon called hyperauthorship, which reinforces the Mertonian norm of communism (Cronin, 2001). It is worth noting that O.S. emerged from this institutional imperative that scientific findings are for society, not for property rights (Carillo & Papagni, 2014; David, 2014; Schroeder, 2007).

An alternative form of authorship is the contributorship and guarantor approaches to study each participant's actual contribution in a publication and, consequently, in a collaboration, remembering that contribution and job title are not synonyms (Cronin, 2001). Finally, from a webometric perspective, scientific collaboration studies could use an altmetrics approach to complement traditional measures of the impact of publications resulting from collaborations (Gunn, 2014).

Another approach to studying scientific collaboration from a bibliometric perspective is advocated by Cronin, Mckenzie, & Stiffler (1992) and Cronin & Weaver (1995): the acknowledgments-based approach. Laudel (2002) used co-authorship and acknowledgment to identify and categorize scientific collaborations concerning patterns of rewards: "collaboration involving a division of labor, service collaboration, provision of access to research equipment, the transmission of know-how, mutual stimulation and trusted assessorship" (p. 13). Larivière et al. (2006) reinforced the role and importance of acknowledgments as sub-authorship when they recalled that the types of contributions that merit co-authorship or inclusion in the acknowledgments section of a paper vary in their nature and by field, discipline, and particular teamwork culture. Recent studies such as

Paul-Hus, Mongeon, Sainte-Marie, & Larivière (2017) explore acknowledgments potential with promising results, especially for the assessment of collaboration in social sciences and humanities.

Larivière (2012), in his historical study on the use of bibliometrics, highlighted it as a tool for several disciplines, such as the library and information science or history and sociology of science, to develop research on scientific collaboration. However, the author pointed out that the most crucial benefit is the direct application of bibliometrics in research evaluation and monitoring, where the literature is very rich concerning collaboration; this is valid for the application of bibliometric in research on science and innovation policy, as well. The author also argued that this usage and increasing trend is more common in the medical and natural sciences. At the same time, the indirect benefits are economical and perceived in scientific policy decisions and actions. In particular, they are presented by the requirements, criteria, and decisions of the funding agencies and research councils. Almost all the articles cited in this text show a possible political and economic implication for their findings on collaborations.

The problem of activity monitoring and performance evaluation is present for O.S. and BigSci, which usually has a decisive impact on science and innovation policy, mainly on the distribution of grants. This subject is highly discussed, complex, and can be targeted at different communities. Metrics have been presented, from conventional bibliometrics to webometrics passing through new combined mixed proposals using economic and social indicators, qualitative and quantitative (Autio et al., 2004; Gunn, 2014; Hallonsten, 2013, 2016b; Vuola & Hameri, 2006). However, due to their complex and distinct natures, there are not any widely accepted means yet.

O.S. and BigSci collaborations measurements suffer from conceptual limitations such as authorship attribution practices of each discipline and individual detected by Paul-Hus et al. (2017) that can mask “team size and collaboration, as measured by co-authorship” (p. 82). Additionally, Laudel (2002) recalled that collaboratories’ activities “are measured poorly by formal communication” (p. 14) – that is, through bibliometric means. This situation affects many BigSci projects, which are based on collaborations in a variety of formats, including collaboratory and inter-sectoral collaboration. Thus, activity measurements of BigSci collaborations have been explored by some authors, such as Hallonsten (2016b), that emphasized that traditional bibliometric measures like publication and citation counts are simplistic and inadequate. The literature shows that measuring BigSci collaborative activities requires a systemic approach. For example, Autio et al. (2004)

suggested “patents and products, spin-offs, industrial product development, and mobility of people between science and industry” (p. 124). More recently, Hallonsten (2013) proposed a system for the assessment specific for synchrotron radiation facilities, called facilitymetrics, based mainly on three areas of performance measurement of the facilities (technical reliability, oversubscription rates, and publication output). Fenner (2014) and Gunn (2014) suggested altmetrics as a collaboration measurement approach for O.S. Facilitymetrics and altmetrics still miss improvements to be widely used

In BigSci projects, specific to physics and particle accelerators, patent and license agreements should be addressed. Autio et al. (2004) and Vuola & Hameri (2006) only mention these as possible indicators of performance evaluation of BigSci but do not address them in detail. Nevertheless, this subject is more complicated in the areas of biology, genomics, and proteomics that hold “large-scale genetic epidemiological studies and biobanks” (Knoppers et al., 2011, p. 1), produced by projects such as the HGP and its extensions (Gaskell et al., 2013; Khoury et al., 2009) or the BRAIN Initiative (Choudhury et al., 2014; Koch & Jones, 2016; Theil, 2015). Moreover, the delicate ethical aspects involving all participants in these experiments and projects are still widely discussed in the literature. For instance, Knoppers et al. (2011) propose a Code of Conduct for international data sharing that could also be applied to other disciplines in BigSci.

A recent study from *Collaboration and big science* to promote the 2019 Nature index (B. Wu & MacDonald, 2019) showed through infographics the richness of top 25 BigSci national and international, intra- and inter-sector, collaborations around the world, only in three disciplines: high-energy physics, life sciences, and genomics. The results come from bibliometric measures of collaborative articles in 82 high-quality journals and provide evidence that “big science is a global enterprise” (p. S28) with the most solid partnerships mainly at the national level.

2.6 Big Science and non-scientific impacts

Several aspects of the non-scientific impacts of BigSci could be highlighted, even though the sparse literature about the topic compared to other areas. For example, there are many studies (Autio, 2014; Autio et al., 1996, 2003, 2004; Vuola & Hameri, 2006)) showing that BigSci organizations are a fertile environment for technological innovation, an underutilized facet since their focus is almost always on the cutting-edge of the scientific research they lead. However, those authors recognized that these organizations could and should collaborate more systematically with the industry in order to improve the support to innovation and economy in participating countries, counting on government funding for these actions. Moreover, primarily those supplier firms represent an increasingly prosperous and motivated BigSci market. It is so attractive that there are private institutes dedicated to offering support services to BigSci contractors such as BigScience.dk, whose network consists of more than 200 companies and organizations only in Denmark (BigScience.dk, 2017). Even successful events like the Big Science Business Forum (BSBF) series bring thousands of small and big companies, BigSci organizations, scientific and government representatives worldwide to fruitful discussions and unique exchanges, improving the market (https://www.bsbf2020.org/).

Innovative technologies and processes, inspired and conducted by BigSci collaborations, driven to solve societal and scientific challenges, encompass not only high-energy physics but also all disciplines. The creation of the first biotechnology company (Genentech – today a member of the Roche Group) in 1976 marks the first case of science as a business, indicating that biotechnology could be used to develop drugs (Pisano, 2006). The literature also highlights that HGP’s lucrative expectations led to the emergence of commercial genomics, creating new companies in the genomics sector. Other existing biotechnology companies also began to operate in the area (Wiechers et al., 2013). The genomics industry, as well as other high-technology sectors like those in instruments and bioinformatics for DNA analysis and data mining, have kept collaboration with HGP`s extensions such as HapMap and EncoDE (Levina, 2010). All these R&D advancements were directly related to developing innovative new products and a niche market with a broad range of genetic services available.

The Science|Business report about BigSci (Purton, 2015) presents a long but not exhaustive list of BigSci achievements, which has been impacting many different areas of the economy. These have affected sectors as vast and varied as energy and environmental issues and medicine, consumer goods, and computing. The report also contains some recommendations to maximize the economic and social BigSci benefits such as “bridge the cultural gap between Big Science and industry… To gain the maximum benefit, the time from idea or discovery to the marketing of something useful needs to be shortened” (Purton, 2015, p. 8). Another recommendation states to “open the innovation process at the labs”, improving collaboration among “industry, entrepreneurs, investors, and other value-creators right from the outset of the innovation process is needed to turn more ideas faster to good use” (p. 8). Therefore, open innovation and BigSci could mutually benefit from each other as a more ‘open mind attitude’ relating to O.S. consolidates in all BigSci projects, regardless of the project’s primary discipline.

2.7 Big Science and governmental issues

BigSci has always demanded enormous investments and strict commitments from the government. So, this is not the first time “the rationale for public expenditure and political support for large-scale science infrastructure is commonly underpinned by a universalist logic of big science’s benefits” (Gastrow & Oppelt, 2018, p. 1). Nevertheless, this is not precisely what we observe at the local level with the Square Kilometre Array (SKA) telescope in South Africa (Gastrow & Oppelt, 2018, 2019). Recently, Davis (2019) exposed the social costs translated into native population protests in Hawaii against the construction of the U.S. - Canada Thirty Meters Telescope (TMT), agreeing with the African authors and also reminding the government of the need for improved economic and social benefits assessment of BigSci astronomical facilities, especially in developing regions or countries. On the other hand, in developed regions, local society deals differently with a BigSci facility and demands from the government a clear position about urban and environmental issues as well as an assessment of potential impacts in the local economy (Rekers & Sandell, 2016; Thomasson & Carlile, 2017). In any case, all BigSci stakeholders may share Lambright’s (2002) concern that “appearances can be as important as reality in government” (p. 30), in particular in a high global investment, scientific, technological and innovative context.

Furthermore, it would be innovative for BigSci projects to prioritize collaboration with local, thematic innovation systems, which also receive public research funding resources. It would be a way of optimizing resources, boosting the development of companies, and systematizing the interaction, as suggested by Vuola & Hameri (2006) or Gastrow & Oppelt (2018).

BigSci projects are often based on international S&T collaborations and also on managerial, financial and political partnerships (consortia). Some studies (Autio et al., 2004; Castelnovo et al., 2018; Eerme & Nummela, 2019; Vuola & Hameri, 2006) showed that private agents, including multinationals, and public agents have a lot to learn and explore, through systematic collaborations and partnerships, with BigSci projects and their facilities, particularly in high energy physics and space technology. BigSci projects associated with health research easily attract large biotechnology companies, whose interaction with public entities is historically intense and prolific (Berkley, 2020; J. Cohen, 2020; Koch & Jones, 2016; Pisano, 2006; Wiechers et al., 2013), but often troubled (F. S. Collins et al., 2003; Gaskell et al., 2013; Knoppers et al., 2011; Lambright, 2002; Levin & Leonelli, 2017; Maxson Jones et al., 2018), resulting in learning for both parties.

Recently, the growing perceived economic importance of S&T by governments has improved their support for BigSci initiatives (Katsnelson, 2016). For sciences in general, instead, intellectual property rights issues are one of the critical questions to be solved by STI policy in national and international scales (Choudhury et al., 2014; David, 2014; Knoppers et al., 2011; Koch & Jones, 2016; Linton, 2008; Papadopoulos, 2015; Schroeder, 2007).

The question about the valuation of science and its results, especially basic research and the onerous BigSci, is also a critical issue closely related to the funding guidance for scientific research. This ‘battle’ of values between basic and applied science began with Bush's landmark report (1945) and still lacks a strong and wide-accepted solution. Stokes (1997) proposed a two-dimensional quadrant solution, in which the ideal research fits into the ‘Pasteur’s Quadrant’, characterized to be the use-inspired research that has the potential to be useful and employed by scientists and society. Alternatively, Dudley (2013) proposed an updated version of the previous model considering three sectors (basic research, development and industry, and use-inspired research) that may interact and compete with each other for funding. The author also advocated that “history clearly shows how fundamental science drives revolutions in technology, and we should aggressively stress these benefits to policymakers” (p. 339). Other studies discussed the problem. For instance, Linton (2008) pointed out three main reasons for the difficulty of funding science, particularly BigSci (basic research):

- “Science is a worthwhile pursuit in itself is only the belief of a minority of the public [scientists]” (p. 799);
- “Science is economically worthwhile, but is difficult to value... The result is a valuation that captures the downside risk of scientific research while not acknowledging, recognizing, or valuing the upside potential that the research offers” (p. 799);

- "Social innovation must occur before the value of technical innovation can be obtained" (p. 800), the biggest challenge for getting support, particularly from the private sector.

In his discussion, Linton (2008) indicated that the third reason is the most difficult in the decision for funding and recalled the issue of intellectual property rights. More than this, those rights include the agreements for the dissemination of results through publications, conferences, and the media in general, and their respective conventions must be discussed and established by the STI policy.

Due mainly to their scale and impact, BigSci and O.S. are closely related to STI policy-making. This aspect plays an essential role in their survival strategy: they need allies (Schroeder, 2007), and to obtain these allies and the significant resources, BigSci scientists (and many of them advocate the O.S. claims as well) should "play a wide variety of different roles: administrators, lobbyists, 'coalition builders', economists, engineers, and so on" (Gingras & Trepanier, 1993, p. 7). In particular, lobbyists play a central role in the governmental policy-making process in which STI issues like BigSci and O.S. are embedded.

Beyond the unrestricted support of a large portion of the BigSci community, especially life science researchers, O.S. advocates rely on allies in research funding bodies, many young scientists, the unconventional group (not 'old school' fellows) in the academia, and some in non-governmental organizations (NGOs) such as scientific societies with a significant influence on the STI policy context. These allies are crucial for O.S. and its stakes (open data, open access, and open-source software) to create space and expand their domains in the context of science policy and ensure 'their place in the sun': a vigorous 'open science' policy such as the one achieved for international genomics data sharing (Knoppers et al., 2011).

O.S. and BigSci have many unexplored facets that could be used to measure and show their impact on society as shown by some authors like Autio et al. (2004), Nielsen (2011), Hallonsten (2013, 2016b), Bartling & Friesike (2014), Purton (2015), Crease & Westfall (2016) and Markram (2017). The appropriate measure of BigSci and O.S. impacts would bring benefits beyond political support because they would allow a better understanding of their contribution to society and hence the possibility of maximizing positive impacts and minimizing negative impacts.

According to Linton (2008), "a one-size-fits-all solution is inappropriate" (p. 800) in the pursuit of maximizing impacts to achieve the expected political and financial support for the implementation of BigSci and O.S. The author argued that one of the possibilities to increase the impact of BigSci and O.S. is to develop a more appropriate legal framework than the current one, used to guarantee the intellectual property rights of those involved in the initiatives. STI policy must institute well-defined rules for BigSci and O.S.

Therefore, the challenge maximizes the impact and achieves social innovation before the technique (Linton, 2008), which is more significant for physical sciences than for life sciences. However, all fields need to work better on their potentialities with more arguments. Dudley (2013) called on scientists to take a more proactive stance and defend basic research by showing policymakers and society its impacts.

Lastly, based mainly on bibliometric indicators, Heidler & Hallonsten (2015) and Hallonsten (2016b) argued that STI policy needs to extend performance evaluation beyond the frontiers of scientific productivity (counting articles), scientific impact (citations), and costs (investments), so that BigSci gets a 'fairer treatment', consistent with its relevance. Therefore, the government funding agencies and research councils would benefit from appropriate evidence, based on improved performance evaluation of BigSci projects, to decide about funding those initiatives.

2.8 Big Science and government decision-making

The decision process in the BigSci context is demanding and represents one of the essential management tasks to be performed by government decision-makers within a limited STI budget (Bana e Costa, Corrêa, De Corte, & Vansnick, 2002; Caruzzo, Blanco, & Joe, 2020). Nevertheless, many authors indicate the government decision-making as a source of relational problems among BigSci stakeholders (Gingras & Trepanier, 1993; Hellström & Jacob, 2012; Leach, 1973; Linton, 2008; Richardson, 2016; Theil, 2015; A. M. Weinberg, 1961, 1963, 1964, 1986; S. Weinberg, 2012). As BigSci projects grow and last longer, interests of scientific and industrial communities diverge from the government's, and national STI budget faces limitations, is the ideal scenario/motivation for the known 'Weinberg's scientific choice' and also claim to more active participation in public decision-making:

> It is hardly likely to appeal so strongly to the much larger part of society that elects the members of the legislature, and to whom, in all probability, good houses are more important than good science. Thus, as a practical matter, we cannot really evade the

> problem of scientific choice. If those actively engaged in science do not make choices, they will be made anyhow by the Congressional Appropriations Committees and by the Bureau of the Budget, or corresponding bodies in other governments. Moreover, and perhaps more immediately, even if we are not limited by money, we shall be limited by the availability of truly competent men. There is already evidence that our ratio of money to men in science is too high, and that in some parts of science we have gone further more quickly than the number of really competent men can justify. (A. M. Weinberg, 1963, p. 161)

Decision-making is a cognitive process of logical selection by a decision-maker (an individual or group of people) of the best choice among the various possible alternatives. It is an activity that involves a system of complex relations between the elements of objective nature, like characteristics of the alternatives and subjective elements such as values and preferences of the decision-maker (Bellut, 2002). Decisions can be classified in several ways: simple or complex, specific or strategic, immediate or long term, personal or industrial or governmental, mono- or multi-criteria, among others (Keeney & Raiffa, 1993). In any case, all types of decisions seek a good decision, one that "should be a logical consequence of what is wanted, what is known and what can be done" (Campello-De-Souza, 2007, p. 27).

The history of decision-making shows that its logic is rich, varies over time, and has been studied and improved since the early days of humanity because to act is to decide. Buchanan & O`Connell (2006) showed a brief and fascinating history of decision-making in their article and recalled that it, as a subject, permeates several disciplines such as "mathematics, sociology, psychology, economics, and political science" (p. 32). One of the best examples of combining research areas for decision-making is the award-winning prospect theory (Kahneman & Tversky, 1979; Tversky & Kahneman, 1992), where knowledge in economics and psychology resulted in one of the pillars of behavioral economics and a Nobel Prize (in Economics – in 2002). This theory provides a more realistic decision-making description than others associated with more quantitative approaches that seek optimal decisions. The general characteristics of decision-making are related to Keeney & Raiffa (1993):

- What is wanted: preferences and values of the actors involved;
- What is known: knowledge, information, perceptions, and the relationships between them in the circumstances of the case;

- What can be done: available action alternatives;
- Impacts.

It should be stressed that decision-making is not limited to a choice from different options but comprises the cycle with several successive interactions as exposed by Goodwin & Wright (2004), Franco & Montibeller (2010b).

The specificities of decision-making in BigSci refer to a complex subject. More than that, according to Goodwin & Wright (2004), decision-making related to similar issues is a complex problem involving multiple objectives, multiple criteria, and multiple stakeholders and requires a solution with a systemic approach. Nevertheless, recent studies indicate that the complexity of BigSci and the significant number of actors involved in the decision require improvements and rationalization of the process (Barré & Salo, 2002; Joss, 1999; Parthasarathy, 2010; Richardson, 2016).

In the BigSci context, decisions have different scales and impacts as in any other project. However, among its specific characteristics, like finance features and the diversity of the partners involved, the questions never refer to simple or trivial decision problems, but those of unique complexity that requires careful analysis by the decision and management teams that oversee the collaboration process (Lambright, 1998; Magazinik, Bedolla, Lasheras, & Makinen, 2019; Thomasson & Carlile, 2017). Therefore, the specificities of decision-making in BigSci reflect its peculiar characteristics such as pioneering, long-term, high investment, intellectual property, and inter-sectoral relationships that significantly affect a decision on this scale (Hallonsten, 2016a; Koch & Jones, 2016). The dependency extends to other points such as the primary research area, goals, structure, schedule, research, and the management team, but also government features like STI strategy and policies, international relations, the economic situation, trends, among others (H. Collins & Sanders, 2007; D. H. da Silva, 2005; R. da F. e Silva, 2013; Velho & Pessoa, 1998).

The decision-making process can be a complicated procedure that involves many stakeholders and different interpretations of the decision (Belton & Stewart, 2002; Goodwin & Wright, 2004). Particularly in BigSci, the choice of projects has impacts and, in many situations, it is not a mono-criterion problem that one solves satisfactorily by grouping the alternatives into a single criterion for a quantitative evaluation of economic efficiency (Castelnovo et al., 2018; Catalano et al., 2016; Edwards, Miles-Jr, & Von-Winterfeldt, 2007; Magazinik et al., 2019). In this context, from the government perspective, the decision on BigSci can be considered a multi-criteria decision because several qualitative and quantitative points, often affected by conflicting aspects, must be evaluated (Caruzzo et al., 2020; Keeney & Raiffa, 1993). Besides that, for non-scientists, BigSci activities are bordering on science fiction; the often unpredictable and unimagined impacts tend to take large proportions, affect science and society, academia and industry, cross political and geographic boundaries, and could be immediate and/or long terms – such as the recent discovery of gravitational waves after more than a decade of investment in the project (B. P. Abbott et al., 2016) or fusion for energy initiative (Puliga et al., 2019).

For Leach (1973, p.68), “no fundamental research project requiring high capital expenditure is likely to be justifiable in cost-benefit terms. But some criteria for research priorities need to be used in assessing projects”. Furthermore, Gingras & Trepanier (1993, p.25) point out that “any decision involving a major piece of research equipment is not simply an optimal-rational choice among a full list of perfectly defined possibilities”.

Some significant specificities are present, usually from the onset, in decision-making for any BigSci initiatives, as shown in Table 2.4.

Table 2.4 Decision-making specificities in BigSci

Specificity	Comment	Reference
Planning for Data Management and Preservation – DMP	Essential specificity in decision-making and project planning that does not usually get the attention it deserves. The authors highlighted the issue of Big Data produced by BigSci projects, and the problem of managing and preserving a large amount of data for an indefinite time and high-level clients (sophisticated users of international and multidisciplinary scientific collaboration).	(Bicarregui et al., 2013; Borgman, 2015)
Private sector participation	Another essential specificity of decision-making in BigSci under continuous evolution and discussion, especially regarding innovation policies and procurement practices, once BigSci organizations are public ones.	(Autio, 2014; Castelnovo et al., 2018; Dal Molin & Previtali, 2019; Eerme & Nummela, 2019; Green et al., 2015; Koch & Jones, 2016; Vuola & Boisot, 2011)
Lobbying and political pressure from those involved	The political aspect of BigSci is an unavoidable and forceful component and has the potential to cause instability, which is undesirable for the scientific community and its production of knowledge. Lobby activity can have a report format or depend on the BigSci leaderships.	(Gingras & Trepanier, 1993; Hiltzik, 2015; Lambright, 2002; Larsson, 2020; Leach, 1973; Purton, 2015; Westfall, 2016, 2018, 2019)
Governmental aspects	There are internal aspects associated with the country's socio-economic situation, development strategy, infrastructure, STI policies and practices, and external aspects associated with international relations and reputation, diplomacy, and interests. All of these aspects are specificities to be considered in the decision-making process of BigSci, given their long-term international collaborations and scientific, technological and socio-economic impacts.	(Autio, 2014; Cantner & Rake, 2014; Georghiou, 1998; Quevedo, 2013; D. H. da Silva, 2005; Vuola & Hameri, 2006; A. M. Weinberg, 1963)
Human resources	This sensitive specificity of decision-making of BigSci, related to the quantity and quality of human resources available, is as essential as the size and quality of financial resources, mainly dependent on the leadership's scientific, managerial and political skills.	(Hiltzik, 2015; Lambright, 2002; Larsson, 2020; Melin, 2000)

Table 2.4 Decision-making specificities in BigSci (cont'd)

International scientific collaboration	This common specificity of decision-making of BigSci refers to the choice between the alternatives of self-generated knowledge through in-house R&D expenditure, or knowledge transfers (collaboration), or a combination of the two.	(Autio, 2014; Beise & Stahl, 1999; Frenz & Ietto-Gillies, 2009; Mendoza & Vara, 2007; Simonin, 2004)
Intellectual Property Rights – IPR	Another sensitive specificity and crucial point in BigSci inter-sectoral collaborations and decision-making that encompasses topics such as open data, data sharing, international and local standards (for funders from different countries), patents, products, licenses, codes of conduct, dissemination of results and other complex legal aspects due to the international forum involved. HGP case is one emblematic example of the absence of an early decision on the subject with a subsequent disastrous trend and reactive decision-making to a threatening external factor.	(Clò & Florio, 2020; David, 2014; Ding & Huang, 2010; Frenz & Ietto-Gillies, 2009; Gurwitz & Bregman-Eschet, 2009; Khoury et al., 2009; Lambright, 2002; Leonelli, 2013; Levin & Leonelli, 2017; Maxson Jones et al., 2018; OECD, 2008)

Decision-making in BigSci is a multi-dimensional process encompassing early decisions and big decisions that the government should take. The early decisions allow initial informal inter-sectoral collaborations in BigSci projects to lead into subsequent trends in the project's evolution, positive and/or harmful ones, as shown by reported case studies (Autio, 2014; Autio et al., 2004; Gingras & Trepanier, 1993; Vuola & Boisot, 2011; Vuola & Hameri, 2006). Moreover, BigSci leads to big government decisions because the latter sets priorities for the country that will affect all society (Gastrow & Oppelt, 2019; Leach, 1973; Ridenour, 1947b; A. M. Weinberg, 1961, 1963; S. Weinberg, 2012). Those big decisions are characterized by Ullmann-Margalit (2006, p. 158) as:

- "it is transformative": promotes a significant transformation in society;
- "it is taken in full awareness": decision-makers are fully aware of their responsibilities;
- "the choice not made casts a lingering shadow": rejected options keep their presence, especially during evaluation moments.

Besides, it should be noted that government decision-making, particularly regarding BigSci, is not a sudden event, but is a complex, long, and negotiated process with multiple actors, multiple objectives, and high impact, as verified by all BigSci case studies published so far, in particular the historical ones.

Big government decisions are also hard decisions characterized by the fact that (Clemen, 1997):

- they are complex;
- they refer to a situation of inherent uncertainty;
- they face multiple objectives which lead to "trade-off benefits in one area against costs in another";
- they face multiple perspectives which lead to "different conclusions...particularly pertinent when more than one person is involved in making the decision".

For example, some experts from the billionaire Facility for Antiproton and Ion Research (FAIR) are having problems to raise an extra €1 billion from the public partners to complete the project in pre-pandemic times, and are already worried that "the huge cash injection could mean that big science projects in Germany and elsewhere will suffer" (Cartlidge, 2019). From this case, a primary governmental issue arises and reflects the central role of the government in BigSci affairs: decide on generous funding, as is vastly pointed out by the literature since Ridenour (1947a, b) until the present day. In this competitive environment, long-term and expensive BigSci projects must adapt to face new contexts to ensure sustainability (Brennen, 2018; Crease, Graham, & Folsom, 2019; Heinze, Hallonsten, & Heinecke, 2017), and improve usefulness as well as societal and economic impact (FAIR, 2020; Hallonsten, 2018; Westfall, 2019).

Nevertheless, it is the big decisions that are of most interest and concern to the mobilized people who worry about high-value and long-term public investments at the expense of other possible investments. This significant decision regarding priorities is increasingly tense, more complex, controversial, very subjective, and requires a systemic view of the problem in which the preferences and values of the decision-makers are valuable commodities. S. Weinberg gave a vivid account on his talk for the World Science Festival in 2011, exemplifying this situation:

> Not everyone feels this kind of fundamental science [BigSci] is of importance… a congressman that had taken the opposite view said: "it is not against science; it is not even necessarily against speaking in science, it is just we have to set priorities."
> I said, "I widely agree. Now experiments at the SuperCollider [a BigSci facility], the SSC, are going to help us discover the laws of nature, the principles governing everything. Won't you think that in a high priority?"
> I remember precisely what he said: "NO."
> What can we do? How do you make a case for someone who does not already feel the importance of what you are doing? Well, I think the least important argument we use or wish to use it is the technological spin-off. (S. Weinberg, 2011)

2.9 Problem structure and decision analysis

The purpose of problem structuring is to understand the objectives and perceptions of each stakeholder involved in the decision-making situation from a systemic point of view (Rosenhead & Mingers, 2001). In STI decision-making, recent studies indicate that the complexity of current scientific projects and the significant number of actors involved in the process requires improvement and rationalization in developing national S&T policies, primarily related to BigSci projects (Barré & Salo, 2002; Joss, 1999; Parthasarathy, 2010; Richardson, 2016). An alternative to solve this decision problem combines Operational Research methodologies (Mingers & Brocklesby, 1997).

The Operational Research community classifies them as Problem Structuring Methods (PSMs), such as SODA – Strategic Options Development and Analysis (Eden & Ackermann, 2001;

Georgiou, 2010). This last method, in particular, has high applications in the analysis of decision-making and planning in the public sector (Caruzzo, Belderrain, Fisch, & Manso, 2015; Georgiou, 2009; Hjortsø, 2004; Whitley & Doukaki, 1993). On the other hand, the other approaches encompassing quantitative methods such as multi-criteria decision analysis (MCDA) have been used in case studies of a selection of scientific projects financed by the government as well (Huang, Chu, & Chiang, 2008; A. C. S. da Silva, Belderrain, & Pantoja, 2010).

It is interesting to highlight some examples of the SODA application in decision-making and planning problems in the public sector. Georgiou (2009) analyzed the problems faced by Brazilian railroads by identifying and analyzing strategic options for the future development of the railways. Hjortsø (2004) analyzed the decision and tactical planning for a Danish environmental agency and the process of communication with citizens. While for Whitley & Doukaki (1993), the SODA was the support tool for the Greek State Bank administrators to develop effective strategies for information technology.

It is also important to emphasize that Georgiou (2008, 2009) proposed applying the SODA map as a way to identify and select the transformations, establishing the prioritization and the perception of the different systems identified, and the construction of their transformations. This aspect of the method is of great interest to this research work.

However, to the best of our knowledge, there is no document in the white or grey literature using a multi-methodology or PSM approach applied to the government decision-making process of BigSci investments. In general, the literature is limited to show only one aspect of how these choices are made, like Biermann (2001) discussing India’s problem in the usefulness of global environmental assessments for S&T policy-making. D. H. da Silva (2005) stated that the Brazilian participation in the ISS was the result of U.S.-Brazil’s foreign and security policy consideration. Decision-making processes related to S&T issues are much more complex than that because they evolve different stakeholders, their preferences, concepts, and criteria.

2.10 Concluding remarks

Chapter 2 briefly reviews the literature on BigSci, stretching back over more than 70 years. During this period, individual BigSci projects were the target of studies in several disciplines, from history to sociology, scientometrics, economics, policy, management, innovation, and others. Such a wide range of views is necessary to develop a taxonomy of BigSci to inform decision-makers about how best to invest and support such megaprojects.

From the historical perspective (Section 2.1), BigSci appears in the 16^{th} century and consolidates itself definitively as a 20^{th}-century phenomenon that results from science's evolution in searching for answers to increasingly complex questions in the natural and life sciences. Recently, a controversial point emerged from the literature: whether BigSci is associated with research fields other than physics.

Definition and classification discussions (Sections 2.2 and 2.3) are the scope of diverse proposed concepts and models according to different purposes, but none reached a workable definition or classification to the government's interest. The primary BigSci funder needs a systemic but accurate definition and a practical classification based on research disciplines. At last, the 21^{st}-century literature on BigSci shows small group efforts claiming their projects are BigSci as well, revealing BigSci can have many faces, stakeholders, and questions, unimaginable so far. In addition to those concerns, one curiosity was found: the first document where the term BigSci appeared in a scientific journal, in a discussion about funding and defense purposes in early post-WWII.

Scientific and technological collaborations (Section 2.5) were the natural and unavoidable path from Little Science towards BigSci facing increasingly complex questions to solve. In general, BigSci encompasses all forms of collaboration: multi- or trans-disciplinary; national and/or international; from the individual to the inter-sectoral level, the latter being essential and strongly linked to innovation. It is in constant justification of its value (capacity of worth for investment) through the balance between value creation and value capture. BigSci can benefit from open innovation and also potentially benefit it. Furthermore, BigSci presents challenges in activity measurements and evaluation; since bibliometric measurements are simplistic and inadequate for it and must be complemented by other methods.

Similar problems are also a reality for Big Data and O.S. (Section 2.4), which are usually present in BigSci initiatives. Bigness in volume, variety, velocity, management, and ethical issues accompany Big Data in all BigSci projects. While O.S. and its 'sharing philosophy' challenge scientists, managers, government, and the private sector. After all, BigSci, Big Data, and O.S. are buzzwords still needing to be clarified to minimize conflicts.

From humanity's earliest BigSci initiatives in astronomy to the present day, BigSci keeps on leading to conflicts, enormous budgets, scientific and non-scientific impacts, and big hard decisions; they are all government issues (Sections 2.6, 2.7 and 2.8). It is essential to note that the decision-making context in BigSci is not limited to the specificities mentioned previously and can be explored through a comprehensive approach and from different perspectives. Moreover, these decision specificities (Table 2.4) are not mutually exclusive, and the relationships and impacts between them must also be considered in more detailed models.

So far, there is a knowledge gap on how to define BigSci in a meaningful and useful way for the government (Table 2.2) as well as on how to categorize different types of BigSci based on research fields (Table 2.3). From the decision perspective, BigSci studies are very sparse, and thus, there is another gap to be filled with a non-conventional structured approach for decision-making analysis related to BigSci projects. In other words, the literature presents BigSci and decision-making as topics in some descriptive studies or using traditional approaches such as economic, evidence-based, or classical multi-criteria, but not from a multi-methodology approach.

Thus, as already mentioned in Section 1.2, we aim to contribute to filling such gaps in the literature by firstly proposing a definition and a detailed taxonomy. Both will be part of assisting tools to inform the government about whether a proposed project should invoke a systematic differentiated process for funding BigSci projects. If so, it is activated the complete proposed framework for the government decision-making of BigSci investments.

CHAPTER 3 METHODOLOGY AND DATA SET

The literature overview clearly highlighted that with few exceptions, BigSci issues had been mainly explored through case studies based on long-term empirical evidence from document analysis, periodic interviews, observations, surveys, and questionnaires. The evidence produced was usually restrictive to the specific cases and could hardly be generalized, only exposing the individual separated pieces of an overall complex puzzle associated with the general subject of BigSci. The publications described the different ways in which the historical, geographical, societal, scientific, economic and political contexts influence BigSci issues.

The development of solutions for the problems identified in the previous chapter as scientific gaps (Section 2.10) turned into our research objectives, which the primary goal is to propose a framework for the decision-making process of BigSci investments to support national governments with the participation of the scientific community and industry, as presented in Section 1.2. These demanded search, selection and adoption of an appropriate research approach, as mentioned in Section 1.3. Therefore, this chapter presents the methodology adopted as well as the data and information used to reach these research goals.

The research strategy selected to reach the primary and secondary objectives (Section 1.2) was the progressively focusing analytical strategy, from the macro (taxonomy/definition) level to the micro (decision framework) level. The research design carefully chosen was the inductive approach. The choice is an attempt to counteract some of the limitations of the more common longitudinal, long-term, qualitative works based on specific cases. It also offers a systemic view of BigSci, covering as many aspects as possible, in a 'whole BigSci picture' of an almost single moment in time, producing knowledge and new insights.

According to Petit & Durieux (2007), the inductive mode avoids formulating premature hypotheses, leading us to select a hybrid exploration research path to conduct our study. In other words, we adopted a theoretical frame from the academic literature and added an empirical exploration to address observed problematic facts such as the lack of a consensus on the BigSci definition, of a workable taxonomy, and of a decision framework, as well as scientific and industry complaints about no transparency process for decision-making. With this motivation in mind, this research set out to explore a variety of BigSci perspectives, promoting a new understanding of the phenomenon, rather than testing any hypotheses about it, going from observations to conclusions, from observed effects to conclusive causes, from data to conceptual frame (Petit & Durieux, 2007).

To the best of our knowledge, the choice of adequate data for our research problem of the government's decision to fund or not BigSci projects led us to the need for more information beyond the literature derived from the scientific community of all disciplines. We needed to find out perspectives from other BigSci stakeholders, beyond academia, that we could not directly observe in the literature. The matter is not that the literature is not valid or meaningful. However, it does not offer everything, such as the complexities of feelings, thoughts, intentions, judgments, values, preferences, perceptions, experiences that are a crucial part of making and taking decisions (Hämäläinen, Luoma, & Saarinen, 2013; Montibeller & Von-Winterfeldt, 2015). This limitation applies in particular to the government decisions related to BigSci. Thus, we had to ask people questions about those aspects, and we chose to interview actors involved with BigSci like high-level government decision-makers, representatives from industry, and scientific leaders. In this sense, 50 interviews dedicated to capturing the richness and complexity of the decision-making process related to BigSci, virtually impossible by other means, passed through a well-recognized and appropriate analysis specific to government affairs. The interviews provided fundamental data for this type of analysis, since they focus on events experienced by respondents, and not registered in documents, allowing the understanding of the objectives, perceptions, criteria, and preferences of the government decision-makers related to the BigSci decision process. This set of complementary data allowed a broad view to emerge from BigSci natural setting without pre-theoretical framing, consistent with the exploratory, inductive approach.

Important to note that Baumard & Ibert (2007) said that an “exploratory study, carried out through a qualitative approach, is often an essential prerequisite for any quantitative study in order to delimit the research question, to become familiar with this question or with empirical opportunities and constraints” (p. 104). Thus, the choice of a complementary (sequential) research strategy, or qualitative methods followed by a quantitative method, became the best option, characterizing this study as a multimethodology investigation. As we describe in the following sections, the qualitative methods adopted are qualitative metasynthesis, systematic inductive approach analysis, and SODA (Strategic Options Development and Analysis), while the quantitative method is MCDA (Multi-Criteria Decision Analysis).

It is essential to clarify that, in our research, we adopt the term 'multimethodology' when referring to our investigation methodological approach since it is the most popular term used among engineering, in particular in the operational research community (Mingers & Brocklesby, 1997). The third methodological paradigm received several other names as mixed methods, the most popular term used among social sciences, all of them to refer to the combination of qualitative and quantitative research methods to examine the same overall phenomenon (Johnson, Onwuegbuzie, & Turner, 2007; Schoonenboom & Johnson, 2017).

Once this research employs a progressively focusing approach to address its primary and secondary objectives, it presents three phases of data analysis that will be described in detail in the following sections:

- In the first phase (Phase A – Section 3.2), the analysis focuses on the macro-level and works on the comprehensive and workable taxonomy and definition of BigSci.
- In the second phase (Phase B – Section 3.3), following the progressively focusing approach, is an in-depth problem structuring, the analysis goes down to the meso-level and searches for the primary cause(s) of our research problem and strategic option(s) to solve it via stakeholders' perspective.
- In the third phase (Phase C – Section 3.4), the analysis meets the micro-level and builds the multi-criteria model.

Finally, all findings are logically integrated into a decision support framework for funding BigSci investments.

3.1 Data

Our empirical exploration is based on documents and interviews, as previously mentioned. This Section will elaborate on the qualitative nature of the collected data and their primary and secondary sources.

3.1.1 Secondary data

Secondary data of this work comprise a comprehensive and exhaustive search of the literature conducted over the available indexed scholarly publications on electronic bibliometric databases (white literature) and non-indexed documents (grey literature), including, but not limited to, discussion and working papers, official and intergovernmental reports, non-classified publications from government, NGOs and consulting companies, books, dissertations, theses, and alternative channels of communication as institutional websites.

The white literature or traditional bibliometric databases have limitations in terms of coverage (Larivière, 2012), justifying the need to extend the possibilities of investigation of this study beyond traditional academic peer-reviewed publications. Moreover, Larsen & von Ins (2010) analyzed the coverage limitations of bibliometric databases and the fast growth of the use of new channels like home pages. They found that the declining coverage of the central bibliometric databases and the limited data available for social sciences and humanities turns new publication channels or grey literature into an increasingly attractive alternative that must be considered in scientific studies. Furthermore, Adams, Smart, & Huff (2017) recommended, in the cases where specific questions in a new contemporary field are missing a consensual language, "the inclusion of grey literature not as a competing form of evidence, but as supplementary and complementary" (p.443). This inclusion broadens evidence sources significantly when non-academic audiences such as policy-makers and professionals from the private and third sectors constitute active parties.

Therefore, database selection included a variety of sources:

- academic literature electronic databases – seven subscribed databases in Web of Science (WoS) and Scopus;
- institutional databases – consulting organizations, international research institutes and intergovernmental organizations such as OECD, the United Nations (UN), or the European Commission (EC);
- search engines – Google Web and Google Scholar;
- relevant documentation about the topic provided by four consultants, two practitioners, and two policy experts.

The collection covers all available years to 2019 in all databases.

The search strategy keywords used 'Big Science' and variations like 'big-science' combined with boolean operator 'OR' for searching in the title, abstract, author keywords (white literature), or in the whole document (grey literature) to collect works related to the topic. The corpus comprised 793 (WoS) and 778 (Scopus) indexed documents and 171 documents from other grey sources, except for Google. Alvin Weinberg (1961) is the oldest peer-reviewed document found. A Google Scholar search generated around 25,300 results, including books, journal and proceeding articles. While a simple Google Web search produced about 1,390,000 results, containing non-indexed dictionaries, encyclopedias, books, working papers, journal articles, official and technical reports, institutional websites, magazines, newspapers, and videos. Despite all the problems and differences between databases, studies like Archambault, Campbell, Gingras, & Larivière (2009) showed that each search tool has successes and limitations inherent from database quality and software features.

Another severe restriction of all databases is the high cost to access them, except Google's family, which has severe quality limitations. As a consequence, the researcher does not access the integral database but a limited sample. So, to minimize this limitation issue, we used remote Virtual Private Network (VPN) access to the Integrated Library System of the University of São Paulo, Brazil (SIBiUSP), which offers more than 80 databases besides electronic books, journals, and a significant digital collection (http://www.sibi.usp.br/sobre/quem-somos/).

In short, any bibliographic study aiming to have a large-scale view of a subject will always be limited, providing a particular point of view of the bibliographic universe.

3.1.2 Primary data

Our research design recognized that several essential aspects of the decision process are not available in documents or literature. In order to evaluate the range of these perspectives, one-by-one interviews turned necessary to study our problem of government decisions of BigSci investments. The purpose of interviewing BigSci representative stakeholders was to allow us to capture the rich variation of their viewpoints on the funding decision problem and to be able to extract meaningful information about the problematic situation. Thus, following the literature, BigSci community members, in general terms, are scientists, the government, and the industry (Peacock, 2009), and so, those would be our targets for interviewing. To select them, we also resorted to the white and gray literature to identify scientific leaders of BigSci projects, representatives of industry involved in BigSci initiatives, government top decision-makers, and/or senior STI analysts advising these decision-makers, that have somehow previous experience on the decision-making process.

The interview format selected was the semi-structured or the general interview guide approach (Patton, 2002). The author also indicated the strengths and weaknesses of this approach, highlighting the increased richness of the data and the decreased comparability of the responses, respectively. So, we outlined a set of issues, mainly complementary to the literature, to be explored with each respondent, aiming to:

- learn to the fullest extent how the government and the public top decision-makers take and make decisions on BigSci issues since it is an understudied topic in the literature;
- improve knowledge about BigSci stakeholders and their respective roles, complementing the literature focused only on the ecosystem of high-energy physics research infrastructures (in all previously cited articles by Westfall, Hallonsten or Simoulin, for instance);
- check and enhance, if possible, the diversity of concepts of BigSci (see Section 2.2.2), capturing points of view beyond the literature.

Hence, our interview guide, serving "as a basic checklist during the interview to make sure that all relevant topics are covered" (Patton, 2002, p. 342) with each person interviewed, provided us the flexibility to establish a conversational style to ensure our interviewees could clearly understand the questions and answer comfortably, accurately and honestly to our questions, elucidating the topics. Our interview guide was intended to support a 30-minute interview and provided a guideline structure to develop and sequence questions as well as choose information to explore in-depth. The interview guide adopted is quite general, allowing respondents to answer the questions generically and/or referring specifically to BigSci project(s) the person was eventually involved, depending on the interviewee's style or available time to the meeting. Table 3.1 shows our interview guide structure.

Table 3.1 Interview guide adopted

Issue	Question
BigSci definition	What is BigSci?
BigSci stakeholders and roles	Who are the BigSci stakeholders? What are their roles and importance?
Government decision process of BigSci support	How is the decision-making process of BigSci funding? How is the stakeholders' participation? What is your evaluation of this process? Why? What are your suggestions for improving it?
In case of public top decision-makers	Elaborate on the decision-making process of BigSci investment. Elaborate on your role and participation in this process. Elaborate on the perceived need for improvement.
Closing questions	Any additional comments about BigSci and funding decisions? Do you believe there is any other person you know who would be interested in my research that you could indicate to me to have a similar conversation?

The additional 'closing questions' in Table 3.1 had the intention to capture extra meaningful information and promote the snowball or chain sampling strategy.

It is important to note that this interview exercise was submitted to the Comité d'éthique de la recherche avec des êtres humains of Polytechnique Montréal that approved our certificate of ethical conformity, CER-1617-12. The most sensitive ethical consideration involved in this research is related to the interviewee identification as well as the identification of the institutions to which respondents are affiliated. This confidentiality issue is solved when results, discussion, and findings are derived from an aggregate analysis of all interviews, not single conversations, and so, not reflecting individual positions on the matter. According to the consent protocol, the respondent had the freedom to allow her/his voluntary identification, conversation transcription, and publicization. If the interviewee disagreed with any condition of the consent statement, the interview did not take place.

The respondents were mainly contacted via institutional email, whose message consisted of a doctoral project summary, an invitation to the interview, and the first attempt of appointment. Individual interview scheduling took from one week to three months, with an average of 36 days exchanging around 12 emails to reach a final appointment. Our scheduling success rate, that is, the ratio between the number of people contacted and the interview's actual scheduling was 83%. In other words, 17% of the sent emails never received a reply. Thus, our total number of interviewees represents the maximum number of available people with the targeted profile we had access to, considering time and cost constraints. It is essential to highlight that most of the interviews had to be in-person due to the interviewee's high-ranking sensitive position.

Consequently, our set of interviewees comprised of 50 people selected to interview based on the documentation about BigSci and also on two sampling strategies, opportunistic or emergent and snowball or chain (Patton, 2002). The opportunistic or emergent sampling strategy is mainly responsible for choosing the three geographical locations from where the interviewees were, and the interviews took place as well as for the sample size and diversity. The opportunistic event was the Big Science Business Forum 2018, held in February 2018 in Copenhagen, Denmark, where the opportunity to interview the most relevant BigSci stakeholders in Europe happened. On the other hand, the other two location choices were naturally expected and mainly took advantage of the snowball or chain sampling strategy.

The interviewees' selection strategy took into account that the key respondents related to BigSci issues are a specific and small group, and there is a minimal risk of study focus dispersion. Interview length varied from twenty to 90 minutes, with an average length of about 30 minutes. All of them were audio-recorded, and the electronic files were kept on a server at Polytechnique Montréal, following the rules of ethical conformity.

As a short description of the interview sample:

- 50 semi-structured interviews;
- interviewees from Europe, Canada, and Brazil;
- number of respondents per country: Europe (20), Canada (15), and Brazil (15);
- interviewees set, formed by stakeholders intricately linked to BigSci, is constituted of 17 leaders from the scientific sector (scientists who work at universities, public laboratories and/or public research institutions), 19 high-level government representatives, and 14 seniors-managers from the private sector (industry);
- interviewees' professional profiles: full professors, principal investigators, directors and former directors of BigSci research institutions, former STI ministers, presidents, vice-presidents and former presidents of national funding agencies, senior advisors, CEOs;

- interviewee's background profiles: Table 3.2 shows the interviewees' background, where natural sciences I refer to physics, mathematics, astrophysics, and chemistry; natural sciences II refer to geology, biology, and biochemistry; social sciences refer to political sciences and psychology; and others refer to history and medicine.

Table 3.2 Interviewees' background

Background	**Interviewee**			
	Total	**Government**	**Private sector**	**Scientific sector**
Engineering	19	4	11	4
Natural sciences I	19	7	2	10
Natural sciences II	5	2	1	2
Social sciences	4	4	0	0
Others	3	2	0	1
Total	50	19	14	17

3.1.3 Summary

Our data set is differentially used and analyzed among the adopted methods. Thus, to clarify the data use, we expose in Table 3.3 how data was employed among the research phases and, consequently, among the methods.

Table 3.3 Distribution of data use

Phase	**Method**	**Primary data (interviews)**	**Secondary data (literature)**
A – taxonomy and definition	qualitative metasynthesis		X
	systemic inductive approach analysis	X only the question 'what is BigSci?'	
B – in-depth problem structuring	SODA	X full interview	
C – decision support framework	MAVT	X	X

3.2 Phase A – taxonomy and definition

This Section elaborates on the qualitative methods employed in Phase A of this research, focusing on the macro-level analysis and working on the comprehensive and workable taxonomy and definition of BigSci.

3.2.1 Qualitative metasynthesis

Originated in medicine and healthcare (Campbell et al., 2003; Tong, Lowe, Sainsbury, & Craig, 2008), systematic literature reviews have also become an increasingly used tool to systematically collect and analyze research in other disciplines, such as innovation studies (Autio, 2014). In the literature, most systematic literature reviews take one of the two forms: quantitative analysis or qualitative synthesis. Quantitative analysis, such as quantitative meta-analysis, or simply meta-analysis, is a statistical method that attempts to integrate a set of quantitative research, often focused on reducing findings to a standardized metric to have adequate statistical power to identify a cause and effect relationship (Campbell et al., 2003; Erwin et al., 2011). On the other hand, the authors indicated that a qualitative synthesis, such as metasynthesis, critical review, or a thematic synthesis, is a form of systematic literature review often used when there is interest in synthesizing qualitative research.

In this doctoral research, we adopted the qualitative metasynthesis method and organized our review along with fields of R&D, as it currently exists in the BigSci literature, to build an innovative taxonomy of BigSci. Qualitative metasynthesis, or simply metasynthesis and sometimes referred to as meta-ethnography, is a method that attempts to integrate and compare a set of qualitative research, often focused on producing interpretive results of the findings of the selected studies. In other words, it is “not only synthesizing the findings from a carefully selected pool of studies but also…actively engaged in a complex and in-depth analysis and interpretation of these data” (Erwin et al., 2011, p. 188).

Erwin et al. (2011) and Cooper (2015) provided a step-by-step approach to conduct a qualitative metasynthesis and a research synthesis, respectively, as well as Adams et al. (2017) for systematic reviews including the grey literature. The process “is comprehensive and rigorous at each step” (Erwin et al., 2011, p.191) to allow a higher likelihood of transparency, traceability, and replicability. Figure 3.1 summarizes the metasynthesis process. Further information about it follows below.

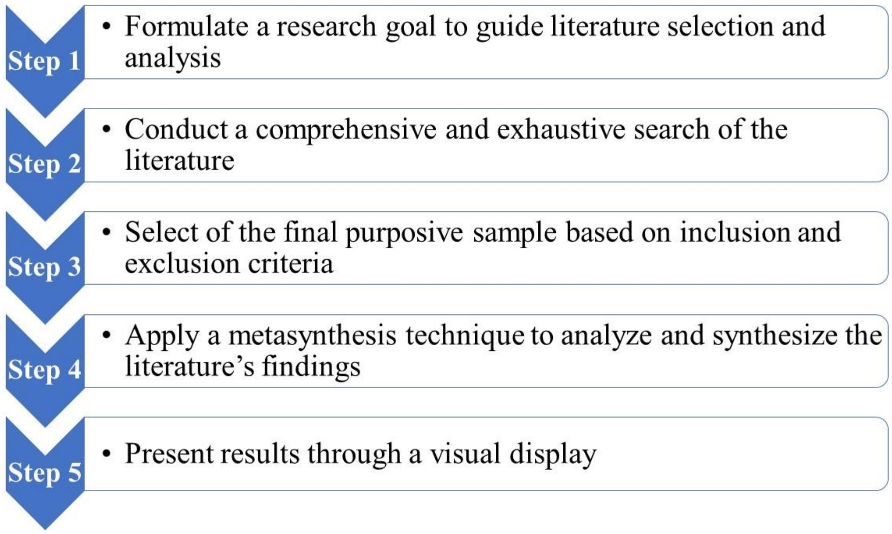

Figure 3.1 Process of qualitative metasynthesis inspired by Erwin et al. (2011), Cooper (2015), and Adams et al. (2017).

The first step of the metasynthesis is the attentive and crucial task of formulating the goal "to guide the selection and analysis of the literature to be synthesized" (Erwin et al., 2011, p. 192), ensuring this goal is clear and focused enough to allow the proper development of the following steps. While Step 2 requires considerable effort, time, and resources to develop a search of the literature as comprehensive and exhaustive as possible, focusing on the established goal. Step 3 is another fundamental task of the metasynthesis when is determined the selection of the final purposive sample. It consists of a screening process based on criteria for document inclusion and exclusion applied to all sources. This process should be inherently flexible; otherwise, essential documents may be excluded. It is also necessary to note that the criteria for document inclusion and exclusion assure the quality, validity, and reliability of the final purposive sample (Cooper, 2015; Erwin et al., 2011). Appraising of the final sample quality is grounded in: (a) high-level quality guided by peer-review, institution/author reputation or expert recommendation; (b) relevance and potential contribution to the research question; (c) grey literature with significant retrievability and credibility, allowing findings to be reported together (Adams et al., 2017).

In Step 4, among the several techniques for conducting metasynthesis analysis, we chose to apply a synthesis by interpretation (Rousseau, Manning, & Denyer, 2008), which showed to be the most suitable for this research because it "compiles descriptive data and exemplars from individual studies, building them into a mosaic or map…while attempting to preserve the original study's integrity" (p. 497). It organizes and synthesizes the literature to create new comprehensive interpretations by thematic or content analysis (Finfgeld-Connett, 2018). We adopted a technique to apply the synthesis by interpretation similar to the one adopted by Campbell et al. (2003), Tong et al. (2008), and Autio (2014):

- Recognition of the 'first-order constructs' by identifying the key themes: Key themes should be consistent with the goal of guiding the literature search and represent the most evident concept identified in all documents. Those constructs should be grouped in clusters.
- Identification of the 'second-order constructs': This step consists of thoroughly identifying even and distinct contents, developed by the original authors, within each document of each 'first-order constructs' cluster.
- Development of the 'third-order constructs': Analyzing and synthesizing the 'second-order constructs' reveal a new interpretation, derived from the synthesis of the purposive sample, and reach the research goal that guided the literature search from the onset. Moreover, this last step of the synthesis by interpretation adds dimensions that other means may not have identified.

Step 5 marks the effective presentation of results that have arisen through metasynthesis, and, according to the literature, depends on the target audiences who could "benefit the bridge from research to practice" (Erwin et al., 2011, p.195). The authors also indicated that presentations could have several graphical forms such as charts, figures, infographics, or even tables, promoting a useful synthesis of the findings, identifying patterns, and creating new comprehensive interpretations for the topic analyzed.

According to Rousseau et al. (2008), the strong central points of the employed qualitative metasynthesis are contextualization and generalizability, when synthesizing multiple qualitative documents taking context into account. The authors also analyzed the metasynthesis limitations, indicating three significant issues: replicability difficulties, potentially loss of information from quantitative data, and coding highly dependent on reviewer skills.

3.2.2 Systematic inductive approach analysis

According to Patton (2002, p. 432), "qualitative analysis transforms data into findings". The author also stated that the literature is abundant in guidelines for analyzing qualitative data and, regardless of the method, "the human factor is the great strength and fundamental weakness of qualitative inquiry and analysis" (p. 433). Over the past decades, discussions around scientific rigor to conduct qualitative analysis have been the concern of researchers employing qualitative methods and motivation for improvements (Gioia & Pitre, 1990). In this sense, we adopted a systematic inductive approach (Gioia et al., 2012) to analyze the question 'What is Big Science?' from all interviews (Table 3.3), based on a successful recent study on BigSci by D'Ippolito & Rüling (2019) that used such method. The systematic inductive approach analysis allows the conduction and presentation of inductive research, such as ours, ensuring scientific rigor (Gioia et al., 2012).

It is noteworthy that the primary data is the source, particularly the verbatim transcription of the answers to the question 'What is Big Science?' (Table 3.3). Those responses were quality-assured by comparing random samples of audio to transcriptions before analysis.

Our data analysis follows the Gioia et al. (2012) approach and consists of four steps of the progression from raw data to concepts, themes, and dimensions, in conducting the interview analysis:

1. Identification of the 'first-order concepts' that emerge directly from the interviews (open coding). In other words, this step promotes "an analysis using informant-centric terms and codes" (Gioia et al., 2012, p. 18) by carefully coding the answers using interviewee's terms to generate a no-distilled code list. According to the authors, in this first-order analysis, the expected number of categories tends to be extremely high, quickly reaching up to 100 first-order categories from up to 10 interviews, for instance.

2. Development of the 'second-order themes' by analyzing the 'first-order concepts' (previous code list), seeking commonalities and differences among the many categories. In other words, this step allows "one using researcher-centric concepts, themes, and dimensions; for the inspiration for the 1st- and 2nd-order labeling" (Gioia et al., 2012, p. 18), reducing the categories. Subsequently, the coding process produces a meaningful and more manageable coding structure that describes and explains a phenomenon of interest.

3. Refinement of the emergent 'second-order themes' into 'second-order aggregate dimensions'. This step extracts the essential meaning or most important aspects of the coding structure developed in the previous step, providing the final basis for building the data structure that describes and explains a phenomenon.

4. Effective presentation, preferably in graphic format, of results that have arisen through the systematic inductive approach analysis, allows configuring data into findings. In other words, it allows to begin thinking about "the data theoretically, not just methodologically" (Gioia et al., 2012, p. 21).

According to Gioia et al. (2012), the systematic inductive approach analysis's strong point is to engage a systematic rigor in conducting qualitative research, demonstrating connections between raw data and constructs development. The authors also analyzed the method limitations, highlighting the high dependence on researchers' skills.

The results of Phase A are presented in Chapter 4.

3.3 Phase B – in-depth problem structuring

This Section elaborates on the qualitative method employed in Phase B of this research, aiming to develop a rational analysis for an in-depth problem structuring for complex, uncertain, and conflict decision situations, using interviews with directly related stakeholders (Table 3.3).

3.3.1 Strategic Options Development and Analysis (SODA)

A problem structuring approach is critically useful when the studied problem is complex and involves multiple stakeholders, multi-objectives, and several alternatives. This approach compels the analyst to employ methods to understand the real problem effectively (Montibeller & Von-Winterfeldt, 2015; Rosenhead, 1996; Roy, 1993). These authors also highlighted that identifying the real problem or demand is mandatory in these cases; otherwise, the proposed solution or chosen alternatives will not meet the demand or solve the problem.

For Phase B and the problem structuring process, we chose SODA, one of the Problem Structuring Methods (PSMs) widely used in the Operational Research literature (Mingers & Gill, 1997; Mingers & Rosenhead, 2004). Such a method proved to be a successful alternative to real applications in public management issues, as also seen in the literature (Caruzzo et al., 2015; Georgiou, 2009; Hjortsø, 2004; Manso, Suterio, & Belderrain, 2015; Whitley & Doukaki, 1993).

The SODA method was developed based on cognitive mapping and combined with George Kelly's psychological construct theory (Eden, 1988, 2004) for decision-making in complex situations that cannot be resolved by formal quantitative models. This theory focuses on understanding, through mental constructs, the subjective meaning of what people express, how they understand the world, and build their knowledge, minimizing ambiguities in the analysis.

The SODA is a problem identification method using a visual map as modeling to obtain and record individual views of a problematic situation (Eden & Ackermann, 2001). The cognitive map can be defined as a hierarchy of concepts related by influencing connections between concepts' ends and means (Eden, 1988). Later, Eden (2004) also stated that this map could be used to structure, analyze, and make sense of the problem, and even that individual maps could be merged into one map, which would show a synthesis of the group's perception.

A fundamental principle of this method is that a construct has its complementary opposite, called the opposite pole. This 'negative pole' "gives meaning to the first pole" or original construct (Eden, 1988, p. 5), and allows to build the interviewee's reality, since the reality is composed of contrasts rather than similarities. Thus, the author declared that, based on this point, SODA could compare and contrast concepts because the model structured from constructs can identify trends as opposite poles. Moreover, Georgiou (2010) pointed out that this bipolar structure is advantageous for analysis because it offers more accurate meanings in each concept.

Table 3.4 shows an example of how one identical concept from two different interviewees can have different opposite poles or valid meanings for the same problem (Caruzzo et al., 2015). Say, for instance, that the weather forecast is described as useless. This description is unclear, not only because the term 'useless' has several synonyms that allow variations in understanding, but also because no options have been offered against which the meaning of useless can be deduced. To offer a strictly negative option, such as 'useful', does not help in trying to understand what is being meant. Is the weather forecast useless in the sense that the information is not accurate, or precise, or truthful, or perhaps correct? Or is the weather forecast useless as opposed to having a suitable format or perhaps appropriate? A more precise alternative is required to obtain at least an idea of what is meant, and this is what constructs do.

Table 3.4 Different perceptions of the same reality. Adapted from Caruzzo et al. (2015).

Interviewee	**Concepts**	**Opposite pole**
individual 1	weather forecast is not useful...	information is accurate
individual 2	weather forecast is not useful...	format is suitable

“Constructs are designed with two poles, whereby the second pole serves to clarify what is meant by the first pole.” (Georgiou, 2010, p. 2). From the example of Table 3.4, to say that the weather forecast is useless instead of accurate, or useless as opposed to suitable, already helps to understand more precisely the meanings in each case. Thus, in SODA format, those constructs would be written as follows:

the weather forecast is useless … information is accurate
the weather forecast is useless … format is suitable

To ensure the SODA analysis's validity before building and/or aggregating the map, the literature, therefore, recommends selecting some interviews for a second-round gathering. The analyst can thus present and discuss the single analysis with the interviewee, allowing checks and adjustments of the constructs, opposite poles, their real meanings, and respondent’s preferences (Ackermann & Eden, 2001).

The final result of the SODA analysis is a map representing an overview of the investigated context (Eden, 2004; Rosenhead & Mingers, 2001). Figure 3.2 exemplifies a SODA map with bipolar constructs causally connected, where AM means Aerospace Meteorology and WF, weather forecast (Caruzzo et al., 2015).

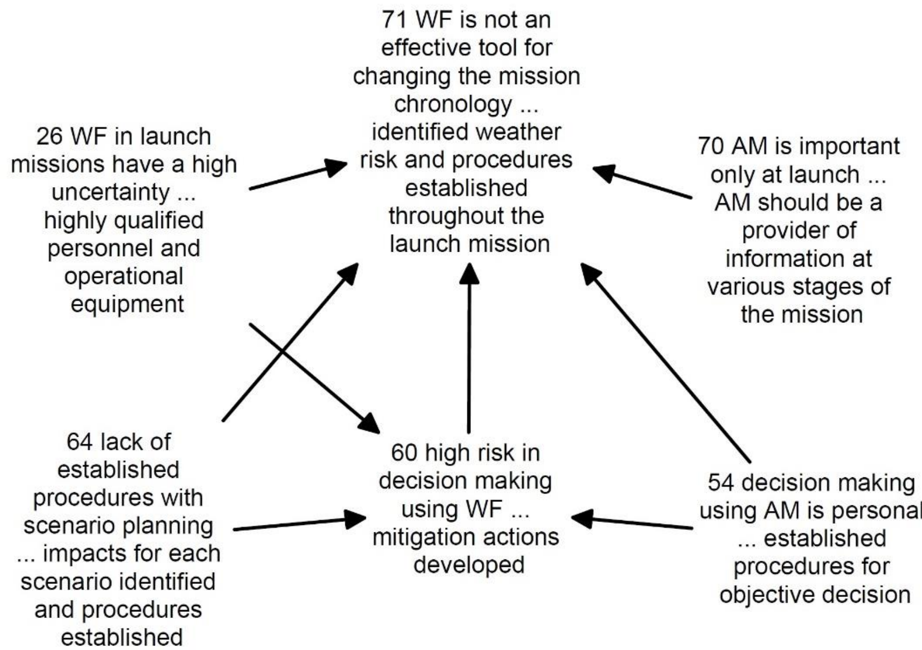

Figure 3.2 Example of SODA map. © Caruzzo et al., 2015. Reproduced with permission.

The SODA maps represent subjective data through a cause and effect process, which leads to decision-making, problem-solving, negotiations, the discovery of hidden aspects, and especially alternative strategies to the examined situation (Eden & Ackermann, 2001). According to Georgiou (2010), a SODA map can fit graph theory's analytical tools, providing the structural significance of constructs on the map. In this sense, the author indicated that:

- ‘constructs tail’ are constructs whose connections (arcs) only leave them (transmitters in graph language) and designate primary causes or existing basic facts;
- ‘constructs head’ are constructs whose connections (arcs) only arrive (receivers in graph language) and may mean results, objectives, consequences, goals, suggesting a preliminary notion of what the map is about;
- ‘strategic options’ are constructs directly connected to a construct head (no term in graph theory) and represent the end of reasoning sequence;
- ‘constructs implosion’ are constructs that directly receive a high number of connections (high in-degree in graph language) and indicate significant effects that affect many other constructs;

- ‘constructs explosion’ are constructs that transmit a high number of connections (high out-degree in graph language) and designate significant causes that affect many other constructs;
- ‘constructs dominant’ are constructs with a high total number of received and transmitted connections (high-degree in graph language) and may mean cognitive centrality and/or central relevance of issues (situations) in interviewee’s perceptions that affect many other constructs, indicating the significant issues that must be undertaken to reach the heads (results);
- ‘feedback loops’ represent areas of the critical collapse of the studied situation (cycles in graph language), and their identification and analysis are crucial.

The SODA analysis in this thesis follows the steps proposed by Eden & Achkermann (2001) and consists of five steps to building a SODA map, briefly listed below and shown in Figure 3.3:

1. <u>Extraction of the bipolar constructs from each interview and identification of thematic clusters (1st stage of SODA maps in Figure 3.3).</u> In other words, this step analyzes each interviewee’s answers and converts them into a set of bipolar constructs by carefully identifying the concepts (first pole constructs) and their corresponding, more precise meaning (opposite pole constructs). As constructs are identified, it is possible to recognize thematic clusters that emerge and organize the constructs by themes, facilitating the next steps in SODA analysis.
2. <u>Building each map (1st stage of SODA maps in Figure 3.3).</u> In this step, the bipolar constructs are causally connected to reflect the interviewee’s narrative reasoning.
3. <u>Validation of individual maps (1st stage of SODA maps in Figure 3.3).</u> Since people do not talk in bipolar constructs and, at times, opposite poles are deduced by the analyst. The respondents need to validate individual maps in the second round of interviews, characterized by the largest sample of interviewees as possible.
4. <u>Identification and categorization of groups (2nd stage of SODA maps in Figure 3.3</u>). In this step, all individual maps provide an overview of the sample and allow the analyst to identify

similarities. Then it is useful to categorize the individual maps into meaningful groups to proceed with the analysis.

5. Aggregation and synthesis of all individual maps into one final group map (2^{nd} stage of SODA maps in Figure 3.3). This step develops the group map by analyzing the individual maps, seeking shared concepts and differences among the thematic clusters previously identified (Figure 3.4).

6. Aggregation and synthesis of all group maps into one final aggregated map (3^{rd} stage of SODA map in Figure 3.3). This step extracts the essential and most important aspects of the analysis by refining the emergent group maps into one final aggregated map, analyzing, aggregating and synthesizing common concepts and differences among thematic clusters (Figure 3.4).

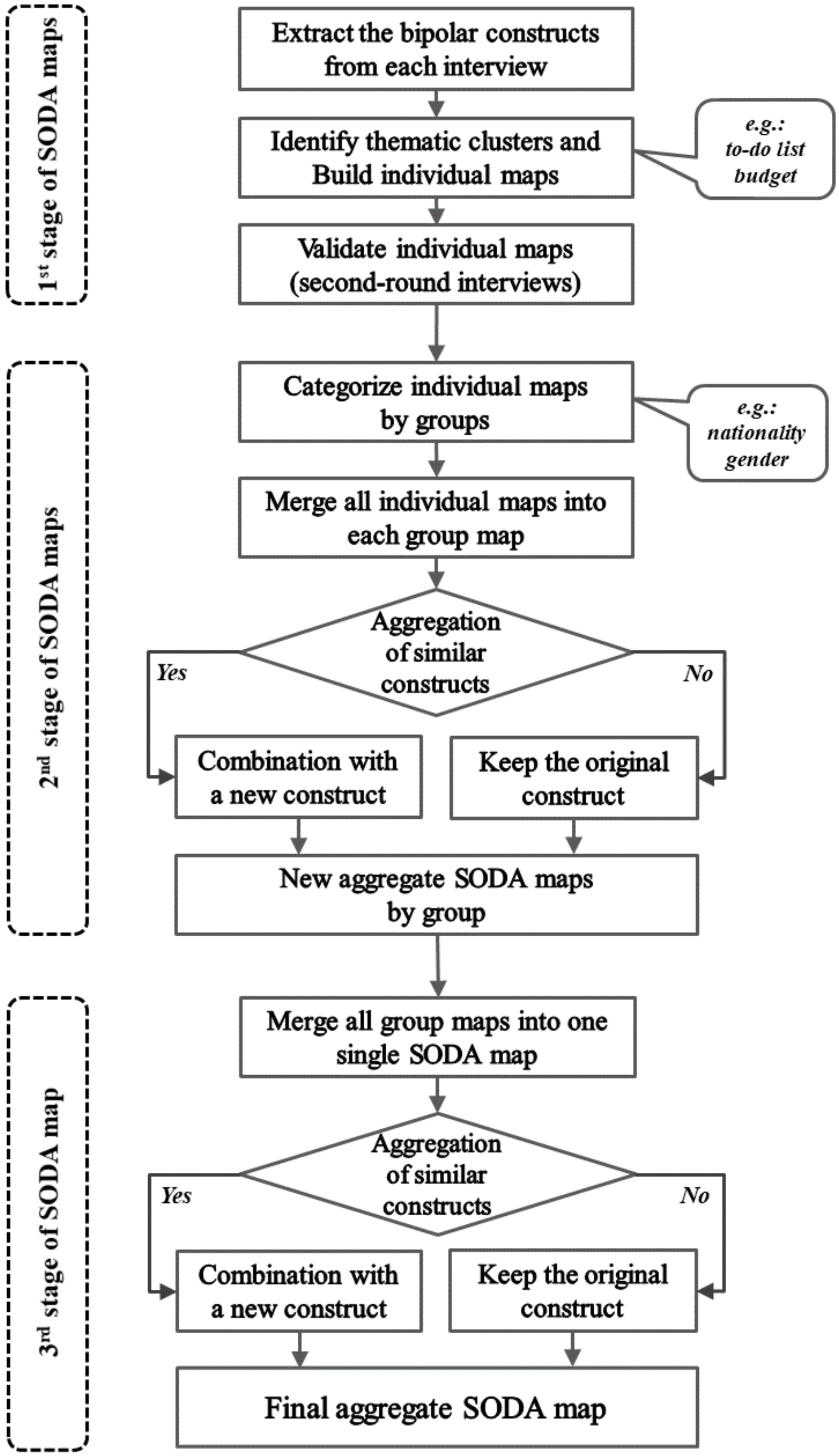

Figure 3.3 Building a SODA map inspired by Eden & Achkermann (2001).

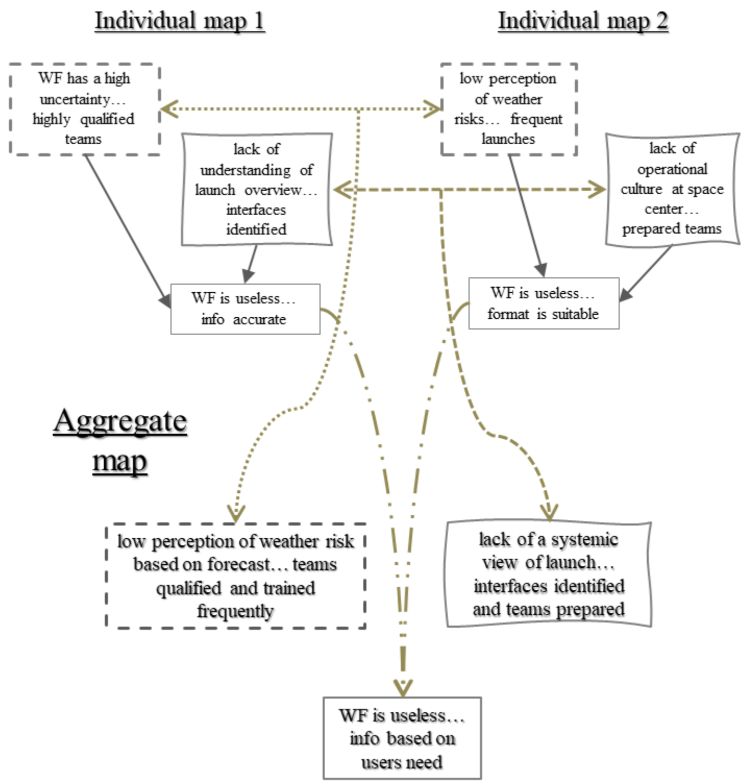

Figure 3.4 Example of SODA aggregate map building

According to Georgiou (2010) and Caruzzo et al. (2015), a strong point of SODA is to engage an analytical technique that removes the researcher bias as much as possible, leading her/him to describe the problem and seek a solution from the interviewee's point of view. In other words, SODA ensures an impartial and comprehensive analysis preventing the analyst’s perception, description and prescription of the problem to interfere in the analysis. Morita (2013) ensured that strictly following SODA analysis procedures brings reliability, and at least, the certainty that it describes the respondent's attitudes and behaviors regarding the interview topic.

Ackermann (2012) analyzed PSMs limitations, which includes SODA, and suggested the existence of three major problems:

- PSMs definitions are weak: despite the proven contribution, the methods do not lead to a single solution and do not show a consistent and coherent accuracy;

- challenge with scientific community acceptance: traditional Operational Research community considers PSMs as tools that still need rigor and variability of application;
- lack of empirical efficacy evidence: PSMs subjectivity allows obtaining insights, but it does not produce testable results.

In any case, according to Georgiou (2010, p. 8), the SODA method offers “a descriptive and exploratory approach” for decision-making processes, and this is one fundamental part of our research whose results are presented in Chapter 5.

3.4 Phase C – multi-criteria model

This Section elaborates on the quantitative method employed in Phase C of this research, aiming to develop a multi-criteria model using all data set (Table 3.3). It is essential to clarify that the adopted progressively focusing approach strategy needs to address the decision theory (Clemen, 1997) to transition from Phase B to C, where an intense complementary phase happens in our study, evolving from qualitative to quantitative methods. Decision theory has different applications and reliable mathematical dealing but also certain behavioral aspects. Once the literature indicates that the study subject is about real-life problem solving, it is, in general, subject to behavioral issues and effects (Hämäläinen et al., 2013). Moreover, as stated by Keeney & Raiffa (1993), Franco & Montibeller (2010a) and Hicks, Wouters, Waltman, Rijcke, & Rafols (2015), public decision-making uses quantitative and qualitative parameters. Hence, the best approach to our study combines a quantitative approach, based on mathematical models (Clemen, 1997; Keeney & Raiffa, 1993), with a qualitative technique, associated with studies of practical, real-world problems through new principles and modern instruments (Goodwin & Wright, 2004; Rosenhead & Mingers, 2001), and complement it by the innovative Behavioral Operational Research, supporting human problem solving by modeling (Hämäläinen et al., 2013; Katsikopoulos, Durbach, & Stewart, 2018).

3.4.1 Multi-Attribute Value Theory (MAVT)

The last phase of our sequential, progressively focusing research strategy used a quantitative method to develop a framework for the decision-making of BigSci investments empirically grounded and considering a systemic view. As highlighted in previous sections, the BigSci investment choice can be considered a multi-attribute decision because several qualitative and quantitative points must be evaluated. To do so, we chose the Multi-Criteria Decision Analysis (MCDA) approach for two main reasons: (1) it is a valuable, logical, consistent, and well-known method to deal with complex decision problems characterized as a choice of multiple criteria among multiple attributes and alternatives, and (2) multi-criteria analysis was developed to find global solutions choice problem which involves many stakeholders and different interpretations of the decision. Furthermore, the MCDA uses problem structuring results as a fundamental tool (Franco & Montibeller, 2010b).

MCDA is a method for comparing a set of alternatives concerning multiple objectives, using a set of decision criteria in order to bring out the 'best solution' (Figueira, Greco, & Ehrgott, 2005; Franco & Montibeller, 2010b; Keeney & Raiffa, 1993). Decision criteria are indicators to identify the extent to which the alternatives envisaged meet the objectives. These can sometimes be conflicting. Thus, after defining clearly the problem through problem structuring (causal map), the next step consists of identifying a set of criteria $C=\{c_1,...,c_m\}$ from a finite set of viable alternatives $A=\{a_1,...,a_k\}$.

In our study, criteria will be extracted from and in part based on the constructs of the SODA map (Phase B), regardless of its structure (Caruzzo et al., 2015; Georgiou, 2010), and on information from Phase A (Sections 3.2).

After identifying the criteria, the challenge of developing a practical aid model is to indicate the stakeholders' preferences and values regarding the several criteria and incorporate those into the model. As pointed out from numerous studies (Caruzzo et al., 2020; W. Ho, Xu, & Dey, 2010; Montibeller, Patel, & del Rio Vilas, 2020), the multi-criteria methods were the most appropriate for several selection situations when criteria are already determined.

Thus, for Phase C and the multi-criteria model, we chose MAVT, one of the MCDAs widely used in the literature (Belton & Stewart, 2002; Goodwin & Wright, 2004; W. Ho et al., 2010). MAVT is the most suitable multi-criteria approach when each alternative leads to a deterministic result, i.e., the problematic situation under consideration is characterized to be a decision under certainty and involves compensatory trade-offs (Caruzzo et al., 2020; Comes, Hiete, Wijngaards, &

Schultmann, 2011). Such an approach proved to be a successful alternative to real applications in public issues, as also seen in the literature (Bana e Costa et al., 2002; Caruzzo et al., 2020; Caruzzo, Cardoso, Vieira-Jr, & Belderrain, 2016; Ferretti, 2016).

Furthermore, to promote the compensatory exercise among criteria, it is necessary to determine their relative weights, once all criteria do not carry the same weight because they have relative importance. Thus, an interactive process between the interviewee and the analyst is established in a way that "the weight assigned to a criterion is essentially a scaling factor which relates scores on that criterion to scores on all other criteria" (Belton & Stewart, 2002, p. 135). According to the authors, these weights, known as swing weights, summarize the interviewees' preferences, translating their concept of 'importance' of the criteria into values as well as allowing discrimination between them. These weights also represent value trade-offs, where the most important have the highest values (Goodwin & Wright, 2004). Among the approaches to this elicitation procedure, the Swing Weights approach (Von-Winterfeldt & Edwards, 1986) is widely used and provides a set of values associated with criteria based on interviewees' preferences. Figure 3.5 provides a schematic representation of determining criteria's relative weight via Swing Weights.

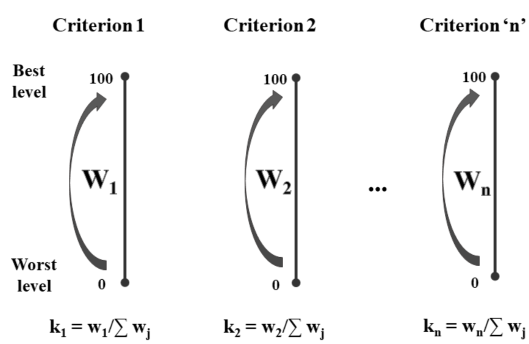

Figure 3.5 Elicitation procedure outline using the Swing Weights approach. © Caruzzo et al., 2016. Reproduced with permission.

It is noteworthy that in any evaluation, usually, not all attributes (thematic criteria set) carry the same weight. As mentioned earlier, it is necessary to apply the same elicitation procedure (Swing Weights approach) to incorporate the relative weight of attributes, allowing the compensatory exercise among them.

After determining the criteria's weights, the MAVT approach allows associating a real number or value V(a) with each alternative a, in order to produce a ranking of the alternatives consistent with decision-maker value judgments v_i(a) for each criterion i. In other words, it is possible to establish a simple mathematical expression for V(a) and also the most widely used since decision-makers from any background easily understand it (Belton & Stewart, 2002). Thus, Equation 1 below describes the value function V(a):

$$V(a) = \sum_{i=1}^{m} w_i \, v_i(a) \tag{1}$$

where,

V(a) is the global value of alternative a;

w_i is the weight of criterion i $(w_i > 0 \; and \; \sum_{i=1}^{m} w_i = 1)$

$v_i(a)$ is the value score of alternative a's performance on criterion i $(v_i\{worst_i\} = 0, v_i\{best_i\} = 100)$

Note that the stakeholder's aspiration is established by maximizing the partial value functions (v_i =100), i.e., maximizing all attributes considered. Nevertheless, in a real-world choice situation, this is not possible. Thus, within a MAVT, it is feasible to determine the ranking of alternatives that satisfy stakeholders' preferences with a compensatory approach and mutually independent solution. It means that the stakeholders can consider trade-offs to identify the best-ranking portfolio or approve a specific alternative.

Structuring the multi-criteria model in this thesis follows the tasks proposed by Franco & Montibeller (2010a) and consists of six tasks to building a multi-criteria model, briefly listed below:

1. <u>Structure the problem situation and define the problem/fundamental objective</u> by using a PSM such as SODA analysis, for instance.
2. <u>Define the value tree</u> by decomposing the fundamental objective/stakeholders' values into operational objectives and organizing them hierarchically. According to Franco &

Montibeller (2010b), causal maps may be the primary source of extraction and 'construction' of information from our sources such as the SODA maps (Figure 3.6).

3. Define attributes by specifying an associated attribute for each bottom level objective in the value tree.
4. Identify criteria by defining/creating criteria to assess a given attribute/characteristic of the decision options.
5. Elicit value functions and weights by modeling preferences and evaluating the decision alternatives through MAVT, for instance.

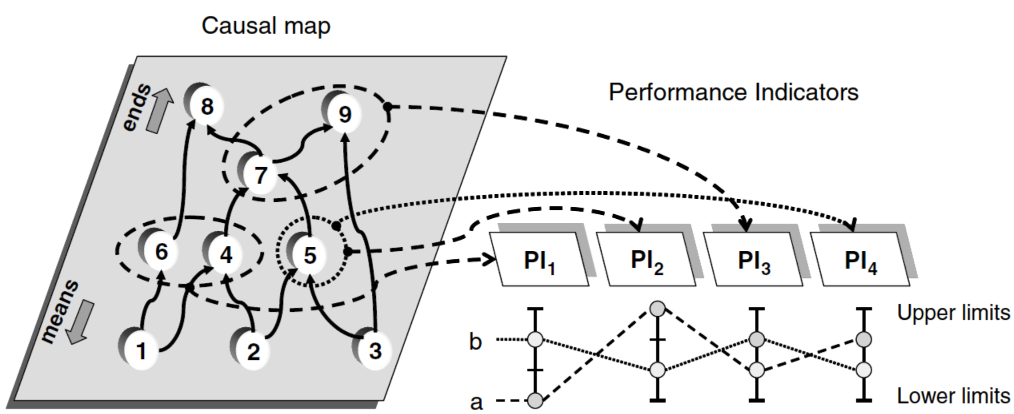

Figure 3.6 From causal map to operational objectives. © Montibeller & Belton, 2006. Reproduced with permission.

One great advantage of MAVT consists of, as discussed by Keeney & Raiffa (1993) and Figueira et al. (2005), the ability to aggregate multiple value attributes into a single value. In other words, the basic idea of considering all criteria entering into account, assign them a weight linked to their relative importance, compare each solution to all criteria, and finally aggregate the results to decide. Summarizing a decision support framework appeals to all decision-makers who want a structured decision process but do not have time to fully assimilate the whole set of objectives, criteria, and alternatives. So, aggregation into a single value facilitates the understanding of theory/model for non-expert stakeholders and allowing the decision support through a transparent and consistent assessment of options (Belton & Stewart, 2002; Caruzzo et al., 2018; Comes et al., 2011). Furthermore, the decision framework can be transformed into a numerical or categorical index, as a MAVT's byproduct, helping in customizing a decision support framework in many contexts (Caruzzo et al., 2018; MacKenzie, 2014; Wilson & Giles, 2013). MacKenzie (2014) highlighted that the development of a new index should be appropriate to the target audience to determine its final format and its implementation. From a behavioral perspective on decision processes (Hämäläinen et al., 2013; Montibeller & Von-Winterfeldt, 2015), it is essential to mention that indices from heuristics perspectives is another valuable recent tendency for these cases and help to understand the existence of motivational decision-making biases related to a multiple-choice selection.

Another great additional advantage of MAVT is to be highly customizable mainly through weight adjustments, adequate to each decision situation (Figueira et al., 2005; Franco & Montibeller, 2010b; Keeney & Raiffa, 1993).

The building of a multi-criteria model and the systemic decision support framework to ensure the scientific community and industry engagement and participation in the decision process of BigSci investments, including a BigSci Index, are presented in Chapters 6 and 7, respectively.

3.5 Concluding remarks

Chapter 3 presents the methodology adopted and the data set used to conduct an exploratory study with a complementary (sequential) research strategy to address its primary and secondary objectives.

The data were carefully collected in the white and gray literature as well as interviewees were meticulously selected (Section 3.1) to both ensure the most comprehensive set of information as possible about BigSci and the government decision process regarding it.

This research employs a progressively focusing approach in three phases of data analysis that was described in detail:

- Phase A (Section 3.2) macro-level analysis through the qualitative metasynthesis of the literature and the systematic inductive approach analysis of the answers to 'What is BigSci?' question from the interviews, intending to work on the comprehensive and workable taxonomy and definition of BigSci.

- Phase B (Section 3.3) meso-level analysis via application of the SODA to the interviews, promoting an in-depth problem structuring, identifying the primary cause(s) as well as the strategic option(s) to solve the BigSci decision problem through stakeholders' perspective.
- Phase C (Section 3.4) micro-level analysis employing the MAVT to build the multi-criteria model.

Finally, the integration of all Phases results in a decision support framework for funding BigSci investments, as presented in Figure 3.7, with the sequential steps taken to fulfill this research's goals.

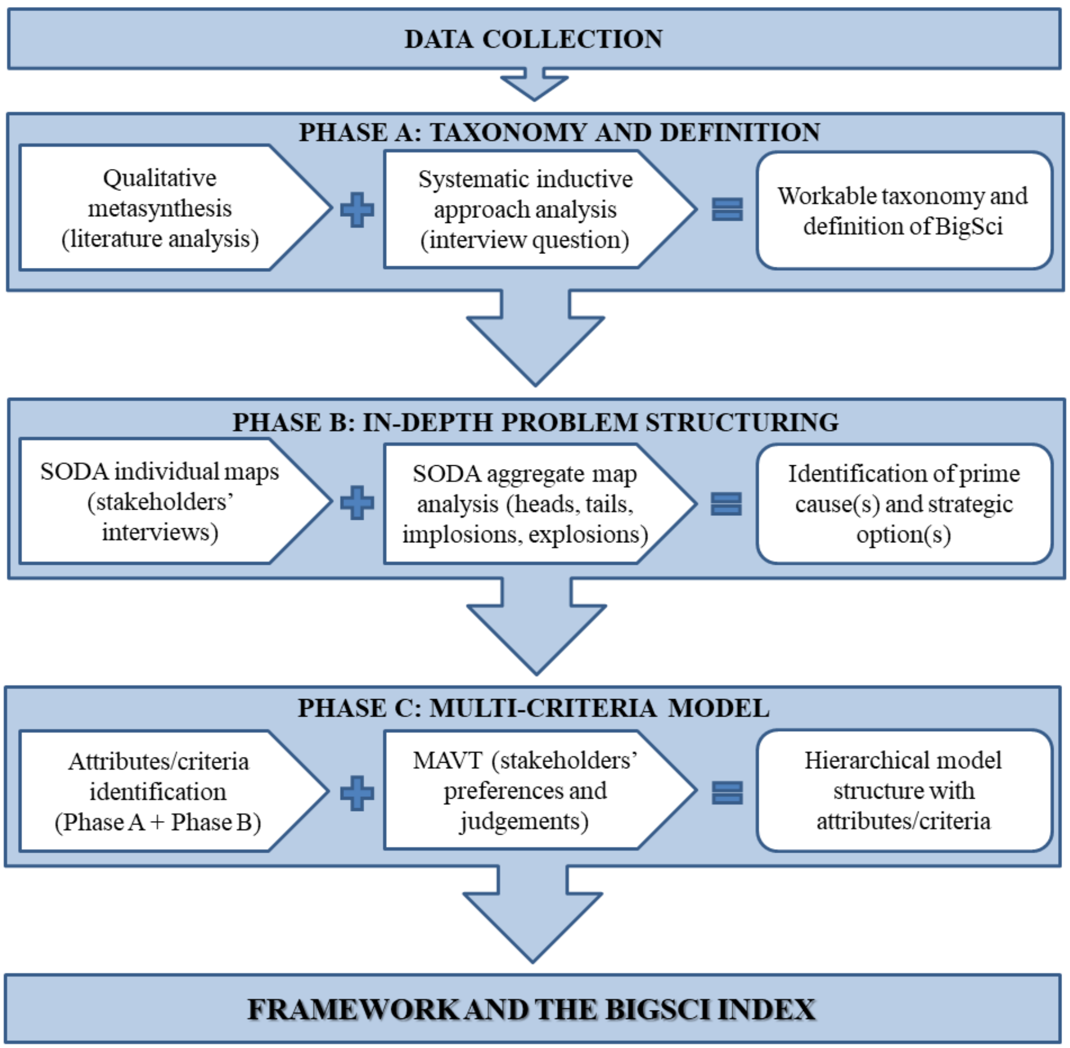

Figure 3.7 Description of the research design employed in this work

CHAPTER 4 TAXONOMY AND DEFINITION

Previously in the methodology chapter, we presented that each phase of this research produces significant findings that will be integrated into the final proposed framework to support the decision-making of BigSci investments. In general, governments distribute their STI investments according to the knowledge domains among their funding agencies (OECD, 2015); however, current BigSci taxonomies are not exactly practical for government purposes. So, in light of the literature, the very first step of this research consists of defining the types of projects that would be considered under the BigSci framework. That is, under the government perspective, what kind of proposal can be considered as a BigSci.

In the shadow of the atomic era, BigSci strong scientific research establishment and consequently, production and communication were almost all regarding military research and mainly physics, their importance and rationale. In a post-Cold War scenario, almost three decades later, the literature on BigSci has increasingly broadened its scope and showed more options relating to research fields claiming to be BigSci or to use the BigSci model or methods.

Although military and space exploration projects are closely linked to BigSci throughout its history, this study excludes these types of scientific initiatives in its findings. Due to their security and sensitive/dual-use technology natures, essential documents and information are generally confidential and have restricted access. This limitation does not affect the conclusions since our study is restricted to civilian research and strictly within the scientific realm.

In this chapter, we propose a taxonomy of BigSci by research fields followed by a workable definition. Although it seems illogical, two strong perceptions take place when exploring the literature on BigSci: (1) a varied set of research fields advocate to have BigSci projects, and (2) several and diverse definitions and concepts of BigSci appear over time. In common, both have no consensus in the scientific community. We chose first to learn the ‘whole BigSci picture’ (taxonomy) and then extract its essence (definition), counting with the additional contribution of interviews of BigSci high representatives stakeholders.

4.1 Building a taxonomy of BigSci based on research fields

Our survey of the literature highlighted the diverse nature of BigSci projects in all knowledge domains. Adopting a comprehensive perspective is essential for the government, the primary funder of such initiatives. To know whether or not a project is considered BigSci is a fundamental criterion to determine which projects would be considered under an adequate decision process of massive government investments. The systematic review of the literature undertaken in Chapter 2 review allowed us to recognize patterns among research fields and capture how the scientific community describes BigSci concepts and types, even indirectly, when reporting projects, programs, policies, evaluations, and concerns.

In the aftermath of the Manhattan Project, governments became aware of the importance of BigSci valuable investments and the need to master atomic, molecular and chemical physics. Henceforth, those topics dominated the white and gray literature until the early 1990s, providing evidence of a consensus among scientists, industry, and government around the characteristics of BigSci. Then, multidisciplinary approaches and more complex research questions eclipsed that consensus, and the literature offered a much broader landscape of BigSci, complicating action in the policy and public decision-making sphere. Because of this increased complexity, and of the fact that all extended and coordinated collaboration is now ‘claimed’ to be BigSci, a decision-making tool needs to be developed.

Classifications help us organize and synthesize studied objects, allowing new perspectives, findings, and understandings. Each categorization has a defined character. This chapter will propose a taxonomy of all the different characteristics pertaining to BigSci. This taxonomy will be based on a detailed classification of BigSci attributes described in Chapter 2. Our taxonomy’s goal is to preserve the BigSci ‘personality’ but unveil its contemporary faces with a specific character and purpose, which is to be useful and workable for the government in its evaluation and support of BigSci projects/initiatives.

Following the qualitative metasynthesis, we formulated as our research goal to guide the literature selection and analysis to obtain a spectrum of BigSci regarding research fields as broad as possible, aiming to build a taxonomy of BigSci based on research fields. With this goal in mind, we used the secondary data (Subsection 3.1.1), which provided a comprehensive and exhaustive search of the white and gray literature on BigSci. Thus, our original sample consisted of 1,571 indexed documents (793 from WoS and 778 from Scopus) and 171 documents from other grey sources.

Then, we selected the final purposive sample through a screening process based on criteria for documents inclusion and exclusion applied to all sources. This process was inherently flexible; otherwise, essential documents would be excluded. The used inclusion and exclusion criteria were:

- Inclusion: (a) documents in which it was possible to identify the title, abstract, keywords, first-page presenting concepts or characteristics related to BigSci in any discipline; (b) documents linked to the research purpose (for instance, megascience, global science, research infrastructure, large-scale scientific project); (c) documents recommended by experts.
- Exclusion: (a) language (exclude documents in any other language, except English, French, German, Portuguese, Spanish or Italian); (b) document type (exclude patent, book review, conference abstract, letter or biography); (c) author (exclude anonymous or undefined); (d) research area (exclude information/library science documents); (e) documents with no access to the full text (mandatory institutional subscription, internal private documents, or classified documents); (f) duplicated and spurious data.

It is important to note that the criteria for data inclusion and exclusion indicated above assure the quality, validity, and reliability of the final purposive sample.

The application of the abovementioned criteria to the original sample promoted a dramatic refinement. So, the first round of selection resulted in 371 peer-reviewed publications and 80 sources from grey literature. Following the suggestions of some authors who also used the same method (see Autio, 2014, for instance), we conducted a second round of selection gathering exercise among the documents surveyed. For this second round of reviewing the publications, we applied only one inclusion criterion: relevance for the research goal guiding the literature selection (spectrum of BigSci regarding research fields as broad as possible). Thus, we selected only those documents with a genuine BigSci emphasis highlighting characteristics of different disciplines, excluding irrelevant documents. This new refinement also produced a dramatic result, since there was quite a large number of documents using the ‘Big Science’ term, which were not relevant for our review. At last, the final purposive sample totalized 106 indexed publications and 12 grey literature documents.

The first-order analysis of the final purposive sample required that to be consistent with the research goal of our review (a spectrum of BigSci regarding research fields as broad as possible to build a taxonomy of BigSci based on research fields), we should consider ‘research fields’ as our first dimension. Therefore, the first-order analysis of the qualitative metasynthesis of the purposive literature sample recognizes BigSci ranging over a relatively broad spectrum of disciplines in all research domains, from physics and computer sciences to oceanography and evolutionary biology. Moreover, the literature shows BigSci as a multidisciplinary phenomenon in the majority of the documents; nevertheless, it is still possible to nominate a primary discipline related to each case, remembering that those disciplines do not have well-defined borders. In this sense, each document received one or more labels according to its content.

Those results were then clustered into research fields based on a close approximation of a well-known static high-level framework called Fields of Research and Development (FORD) from the Frascati Manual (OECD, 2015). The OECD FORD classification aims to be useful to governments because, in general, the governments distribute STI investments according to knowledge domains. Although the government is also our primary target audience for the taxonomy, we had to adapt the OECD (2015) categorization to our purposes, modifying one category and adding two others. Table 4.1 portrays our first dimension, ‘research field’, of our categorization resulted from the first-order synthesis.

Table 4.1 Research field as a BigSci dimension

Research field (1st-order construct)	**Examples of disciplines**
natural sciences I	physics, computer sciences, chemistry, astronomy and astrophysics, mathematics
natural sciences II	environmental sciences and ecology, biochemistry and molecular biology, oceanography, meteorology, and atmospheric sciences
engineering and technology	engineering in general, instruments and instrumentation, robotics, remote sensing, biotechnology and nanotechnology, telecommunications
medical and health sciences	genetics and heredity, life sciences and biomedicine, nutrition and dietetics, immunology, and virology
agricultural and veterinary sciences	agriculture, forestry, veterinary sciences
social sciences	social sciences in general, educational research, demography, physical geography, psychology
humanities and the arts	history, cultural studies, archaeology
RI (Research Infrastructure)	multidisciplinary user facilities or facilities open to small, short-term, multidisciplinary, independent projects
unidentified field (generic case)	no particular discipline

Our first results highlight that contemporary BigSci covers all categories of R&D fields and, as such, disagrees with the mainstream of New or Transformed BigSci (Crease & Westfall, 2016; Hallonsten, 2016a), which delimits the concept to multidisciplinary user facility initiatives. Moreover, our analysis also suggests that the traditional OECD (2015) classification, useful for governments, is not enough or adequate for BigSci issues. Regarding the 'natural sciences' category, we find the OECD's classification to be too broad for BigSci categorization purposes because, within this category, we can identify two distinct types of BigSci. For instance, BigSci projects in physics are too different from BigSci projects in biology, making it unfeasible to have both disciplines under the same category. Consequently, we divided natural sciences into two groups: natural sciences I with physics, astronomy and computer sciences, and natural sciences II, consisting of earth and biological sciences. Other categories follow the OECD (2015) classification, except Research Infrastructure (RI) and unidentified field. Few documents of the sample have a more theoretical/generic perspective, and it is not possible to relate it to any particular discipline or field, then resulting in the 'unidentified field' category.

The 'RI' category is a choice that needs to be better justified. RI or Research Infrastructure is not a new knowledge domain but reflects an increasingly used term in the literature. As previously shown in Chapter 2, RI is also a buzzword with some common BigSci characteristics; however, they are not synonyms (Hallonsten, 2020). For the purpose of this research, we define RIs as multidisciplinary user facilities or facilities open to small, short-term, multidisciplinary, independent projects (Table 4.1) such as a light synchrotron source. On the one hand, RI's planning, construction, commissioning, managing, oversight, and evaluation have initially been (from a historical perspective) and still are analogous to a BigSci project. On the other hand, RI's recent format differs from a BigSci project for its operations and the diverse nature of the objectives and impacts (multidisciplinary user facility). Thus, due to its original characteristics and increasing relevance regarding applications and potential benefits, we understand RI as a particular type of BigSci. A broader view of BigSci is not uncommon, for instance, a number of stakeholders share this understanding as exemplified by ESS (European Spallation Source) webpage (https://europeanspallationsource.se/ess-mandate) where they declare their mandate as "The next great Big Science facility, based on the world's most powerful neutron source, will make possible 'the new science'" (accessed on May 29, 2020).

Apart from the definition inaccuracy and indiscriminate use of the term, we can find BigSci projects nominated in all fields in the literature (Table 4.1). A visual display of the distribution of research fields along our purposive sample gives a relatively good overview of the publicized scientific initiatives self-nominated as BigSci. BigSci projects usually do lots of self-promotion in various communication channels, be as a form of accountability or search for support to keep the necessary investments for their existence or continuity. A. M. Weinberg (1961) predicted this trend declaring that "Big Science needs great public support, it thrives on publicity" (p. 161). In 2020, for instance, national newspapers announced amidst the coronavirus pandemic, the completion of Sirius, the brand-new 4th generation synchrotron light source in Brazil, as the Brazilian Synchrotron Light Laboratory (LNLS) ushered a new period: Brazil in a leading position in the production of the brightest of all the equipment in its energy class in South Hemisphere (Ribeiro, 2020). Thus, if the project does not appear in the white or gray literature, there are two options: either it is a classified/military project, or it does not exist.

Figure 4.1 illustrates how research fields are distributed over our sample, showing that there are fields well-represented in the literature and others scarcely present. It also shows that the most substantial part of our sample covers BigSci in the natural sciences I as well as medical and health sciences, while the ‘unidentified field’, from the few generic documents, and the agricultural and veterinary sciences represent the rarest category of our sample. In other words, when, only considering the quantity of research field representation, as expected, natural sciences I is the most prolific (35.6%) because this category encompasses the pioneer disciplines in BigSci (physical sciences); followed by medical sciences (21.9%), mainly with genomics associated documents, and natural sciences II (17%), with environmental sciences documents. RI (9.1%), with documents offering in-depth studies about multi-users’ facilities, and engineering and technology (6.9%) are topics more recently explored in the last decades. Engineering and technology follow such an increasing trend as a BigSci publication topic that an expert journal was even created in 2017. The Computing and Software for Big Science (https://www.springer.com/journal/41781) is dedicated to collaborative computing, hardware, architecture, software and data processing. The low frequencies for social sciences and humanities (SSH) topics (6.5%) were also expected because those fields are more resistant to work in extensive collaboration structures, and consequently in BigSci projects. Besides, SSH usually focuses their research on local-scale issues mainly published in books rather than in articles (Larivière, 2012; Larivière et al., 2006). This last factor is relevant, considering that our purposive sample for the literature review has only 6% of gray literature, which can be pointed to as a weakness of our study. Agricultural & veterinary sciences appear in only 1.7% of the documents, and it is not clear whether they have fewer projects or fewer articles[6]. The remaining 1.2% of documents with an unidentified research field was not used to elaborate our taxonomy.

[6] The causal factors are not the scope of this study.

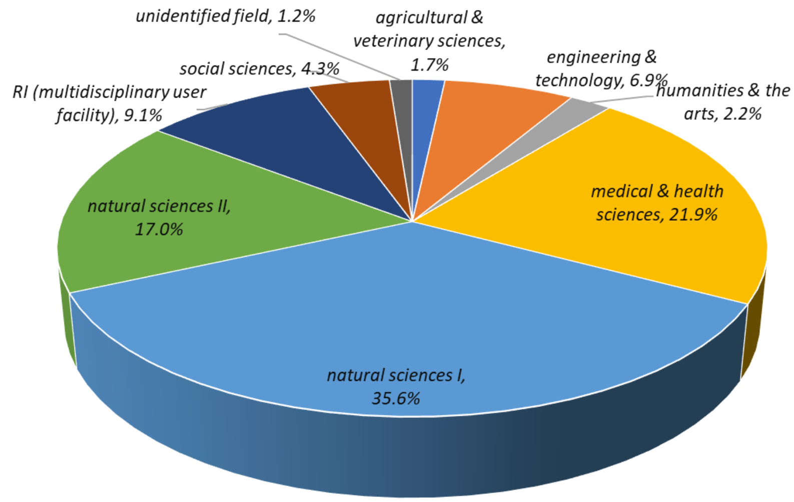

Figure 4.1 Research fields distribution in the purposive literature sample

We can preliminarily state that the strong and weak points of the taxonomy are analogous to the research field distribution in Figure 4.1. In other words, the better represented the field, the stronger (reliable) the information (characteristics) about it since the research field is the first/fundamental dimension of our taxonomy. Thus, to complement the literature review, it was essential to obtain complementary data for the agricultural and veterinary sciences via interview, as detailed in the following section.

The second-order analysis of the qualitative metasynthesis (Subsection 3.2.1) of the literature identified characteristics of BigSci projects in each research field, revealing the specificities of BigSci projects that are mentioned or discussed in each document. This intermediate step resulted in a long list of raw information demanding an enhanced analysis and synthesis that allow building a typology of BigSci. To exemplify the obtained second-order constructs in each research field, Table 4.2 summarises the information collected in each field by some of the authors whose work we reviewed.

Table 4.2 Examples of 2nd-order constructs

1st-order construct	**2nd-order construct**	**Reference**
natural sciences I	truly national laboratory; over twelve years of debate which involved every physicist; a large-scale accelerator; a progressive group of physicists were gradually taken out by the government; an amount in the range of 10 billion yen; combine the best of the technology at CERN and Brookhaven; developmental research which included electronics and data processing and computing; 'big' group-oriented science centered around a large-scale accelerator	Hayakawa & Low (1991)
natural sciences II	oceans and atmosphere as subjects of large, multinational global-scale scientific programs; multinational framework for studying large lakes on a global scale; interdisciplinary global scale programs; funding for each program ranges in the tens to hundreds of millions of dollars per year; based on global-scale human need, and with a stable platform of basic research; limnology community needs a long-term program similar to oceanic and atmospheric communities; the societal need for useable freshwater; economically valuable, with significant societal benefits	Reid & Beeton (1992)
engineering & technology	big science projects interested in achieving a comprehensive understanding of the functions of the brain, using Spiking Neuronal Network (SNN) simulations to aid discovery and experimentation; improve overall computational efficiency in distributed simulations: implicit synchronization, process handshake, and data exchange; minimizes the impact of communication on the overall simulation time; high-performance computing, where compute nodes are at increasing physical distances (sharing a board, within the same network group, or at remote groups)	Fernandez-Musoles, Coca, & Richmond (2019)
medical & health sciences	large-scale, high-throughput data generation and original computational approaches to analyze datasets; developments on wearables and electronic health records clinical trial design; real impact requires integrative and multi-disciplinary approaches blending experimental, clinical and computational expertise across multiple institutions; Big Data analyses; generation and computational mining of Big Data; the joint effort of large consortia to generate Big Data to help reach a common goal; current Big Data problems including infrastructure and ethical issues	Saez-Rodriguez et al. (2019)

Table 4.2 Examples of 2nd-order constructs (cont'd)

agricultural & veterinary sciences	field trials in the agricultural and ecological sciences involved a tremendous amount of time, space, cost, political investment, and sheer ambition; 'big science' form of field research	Cassidy (2015)
social sciences	large-scale, long-term research that probably can only be achieved through partnerships between research, practitioner and government communities; large-sample quantitative approach	Wall &Wood (2005)
humanities & the arts	large data projects; lack of large infrastructures does not mean lack of significant research questions; 'big history' projects need hundreds of millions of dollars; teams of distributed scholars sharing data, communicating and doing research online; collaboratories employ Web-based interface to users interacting with geographically distant colleagues within a virtual expert team, sharing the necessary instruments, resources, data, and knowledge; gathering global resources; distributed research centers facing significant technical and organizational challenges in collaboration	Dormans & Kok (2010)
RI	a facility designed and built specifically for producing and exploiting synchrotron radiation; $24-million project conceived about 1970, proposed in 1976, and operated in 1978; large scientific projects; big facility; large-scale construction and political promotion; radiation to determine protein structures; a considerable amount of money ($1 million per year) and personnel to operate the machine	Crease (2008)

The third-order analysis of the qualitative metasynthesis (Subsection 3.2.1) of the literature developed a high-level frame that enables to encompass the BigSci phenomenon comprehensively from the sparse and fragmented literature on BigSci (Autio, 2014), reflecting shared characteristics/dimensions among documents. In our study, the synthesis revealed 14 'third-order constructs' or disclosed dimensions that characterize BigSci in different knowledge domains. Table 4.3 describes each critical dimension synthesized from the third-order synthesis and is also considered to answer one of the secondary research questions.

Table 4.3 Description of the unveiled dimensions from the literature

Dimension (3rd-order construct)	**Description**
Facility type	Large research facilities in BigSci projects vary from infrastructure-based (large laboratories, big instruments, space devices) to network-based (distributed laboratories, equipment, or observation sites with central coordination). Sub-dimensions: infrastructure-based, network-based
Complex scientific questions	BigSci project objective is usually a complicated scientific question towards a solution to a global-level problem. Sub-dimensions: defined, user-based
Money required	BigSci projects are mainly funded by a single government or an international consortium depending on the country`s strategy, financial capabilities, and discipline. Project's full lifecycle of high capital investment and operation costs varies (in U.S. dollar) from extremely high (multi-billions), very high (hundreds of millions), high (tens of millions) to low (up to 10 million) Sub-dimensions: extremely high, very high, high, low
Project duration	BigSci projects' full lifecycle is dependent on discipline, the complexity of the studied object, methodology, technology readiness, financial and human resources availability. Duration varies from long-term (more than ten years), mid-term (up to 10 years), short-term (up to 1year). Sub-dimensions: long-term, mid-term, short-term
S&T stakeholders	S&T stakeholders of BigSci encompass big teams of scientists, technicians, engineers, experimenters, and administrators, although scientists often play the role of project managers. The number of people depends on the project`s nature and discipline and typically varies from thousands to tens. Sub-dimensions: big team, big network of small teams, multidisciplinary users & local scientists
Collaboration	BigSci projects are formal collaborative enterprises. Big teams of scientists, technicians, engineers, and administrators can work in multiple collaboration levels: national and/or international. Sub-dimensions: national, international, national & international
Multidisciplinarity	Due to their complexity, BigSci projects are multidisciplinary at some level, depending on the project`s objectives and approach. It can be a combination of disciplines in one research area (STEM/Health/SSH), a combination of two research areas (STEM+Health, STEM+SSH, Health+SSH), or a combination of all research areas also called transdisciplinary (STEM+Health+SSH). Sub-dimensions: STEM, Health, SSH, STEM+Health, STEM+SSH, Health+SSH, STEM+Health+SSH

Table 4.3 Description of the unveiled dimensions from the literature (cont'd)

Industry presence	The industry is always present in some way in BigSci projects, depending on the project objective, technological demand, and industry interest in the topic. It plays varied roles, combined or not: funder, partner (public-private collaboration), supplier, user, owner, operator, contractor, beneficiary (client), competitor, lobbyist, and/or study site. Sub-dimensions: funder, partner, supplier, user, owner, operator, contractor, beneficiary, competitor, lobbyist, study site
Technology dependency	The connection between BigSci and high technology is usually strong and dependent on the project's nature. So, the project can demand more hardware, more software, or both. Sub-dimensions: more hardware, more software, mixed
Technology transfer	Technology transfer is one of the most desirable benefits from BigSci projects, almost absent in military-nature projects. It can be more open, less open, formal, informal, and/or accelerated. Sub-dimensions: more open, less open, formal, informal, accelerated
Big Data	All BigSci projects generate, collect, and use Big Data, usually concentrated in vast databanks. So, they can be massive, structured, and demand high-speed access. Sub-dimensions: massive, high-speed, structured
Data sharing	Data sharing (open data) and e-science practices are increasingly common in BigSci projects. Data sharing is a hot topic of discussion in all research areas involving complex management and legal issues (ethical considerations, for instance). It depends on the project's arrangements and can be more open or less open (restrictive). Sub-dimensions: completely open, (partially) more open, (partially) more restricted
Innovation probability	The innovation of any type (product, process, or social) is a common consequence of any BigSci project, but not its objective. The probability can be high, medium, or low (qualitative scale). Sub-dimensions: high, medium, low
Potential impact (non-scientific)	All BigSci projects drive to high scientific impacts and have the potential to bring high non-scientific impacts in global, national, and local levels of society. Impacts can be on social, political, economic, environmental, and technological natures. Sub-dimensions: social, political, economic, environmental, technological

Those results (Table 4.3), derived from our exploration of the literature driven by the metasynthesis, revealed the crucial dimensions and respective sub-dimensions that remarkably characterize and differentiate the multifaceted contemporary BigSci in each research field. Within the rich and varied information gathered, we found mostly the perspective of a single group (scientists) of the BigSci community, mainly because they are the dominant BigSci stakeholder in the literature, our information source to build the taxonomy (Table 3.3).

Aware of this limitation of our study, but also of the fact that the scientific community is the most engaged stakeholder as a source of knowledge when the research field is the central issue, we adopted those dimensions (Table 4.3) to propose a taxonomy of BigSci. A visual display of the distribution of the dimensions along our purposive sample provides an overview of scientists' concerns about those dimensions when reporting or discussing BigSci in the literature. It is important to note that the scientists we refer here mainly encompass the authors who wrote the documents about BigSci, those that are part of the BigSci community and consist of information source for the documents through questionnaires, surveys, interviews or observations, as well as BigSci scientists who authored documents.

Figure 4.2 presents the distribution of dimensions in the purposive sample highlighting the dimensions that are more commented on, reported and discussed, and those that are less frequent in the authors' concerns. For instance, 'facility type' is the most frequent dimension present in the sample because the majority of the documents originated from research fields (natural sciences I and II, and RI) that usually justify their 'BigSci label' via large research facilities, be it infrastructure-based or network-based, still reflecting facility's size as the main feature of BigSci.

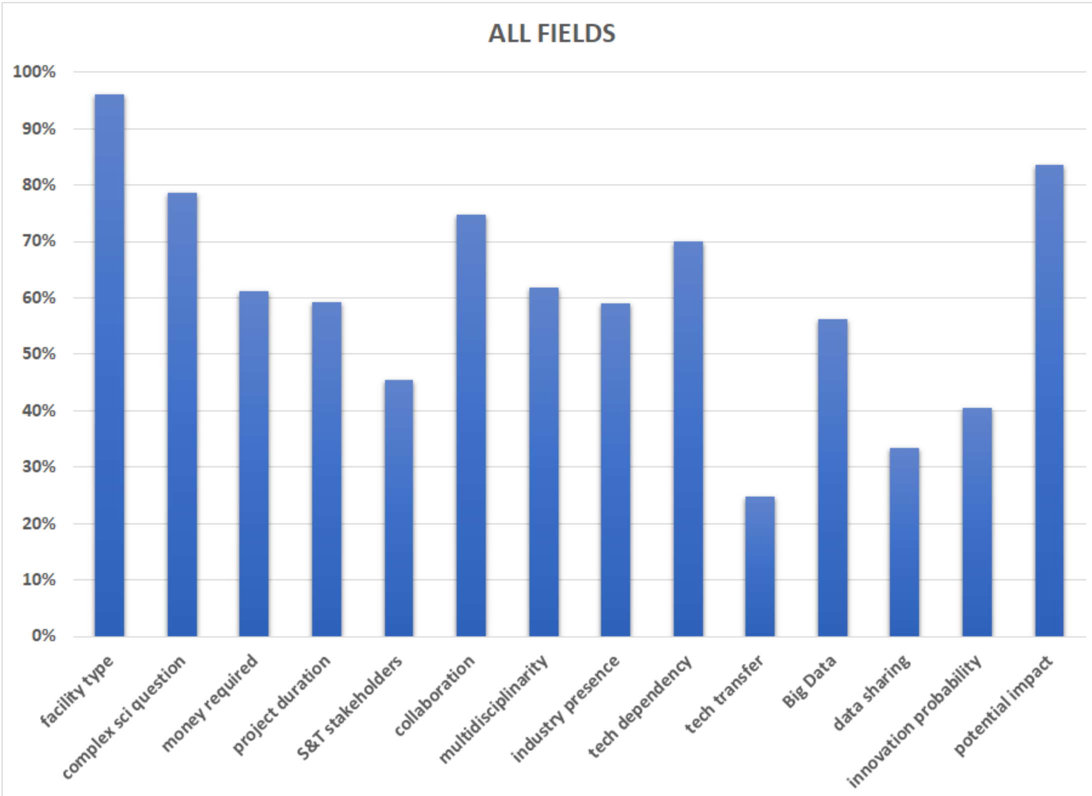

Figure 4.2 Dimensions distribution in the purposive literature sample

Then, the 'potential impact' is also much commented on and discussed in documents (Figure 4.2) associated with project assessment and measurement of non-scientific impacts to justify investments. In our opinion, these are not as deeply studied as they should be, probably due to the time demanding to observe those impacts, as well as they should not be the only justification for such a complex topic as BigSci investments. This latter issue recalls the purpose of our taxonomy as a part of a decision-making tool to support government decisions of BigSci investments.

At the other end of the spectrum (Figure 4.2), the less treated dimensions are 'technology transfer', 'data sharing' and 'innovation probability'. Those dimensions are more or less tied up. The low frequency in the sample of technology transfer and innovation coincides with the results obtained by Autio (2014). The author also demonstrated that those BigSci dimensions (technology transfer and innovation) are poor-explored and fragmented in the literature.

Regarding data sharing (Figure 4.2), the reason why such a complex dimension has a low frequency in the sample is not apparent, although it is a significant subject. In the literature, it is usually associated with O.S. discussions and particularly with ethical issues more than with hardware/software infrastructure-related issues. We understand that the main reason for this underrepresentation in the sample is our sample profile with many more documents in natural sciences I than in any other field. Data sharing and O.S. is a relatively recent but increasing practice within natural sciences I, as exemplified by the late creation of the CERN Open Data portal (2014) because they assumed such complex Big Data would not find usage outside CERN collaborations otherwise (Chen et al., 2019).

The other dimensions are relatively well represented, a vast majority showing representativeness values above 50%, except ‘S&T stakeholders’ (Figure 4.2). This dimension associated with information about the participants or teams in BigSci projects is not as ordinary as the facilities’ size in our purposive sample. The reason for that is probably that our purposive sample has a more technical profile, making this dimension below 50%. Otherwise, stakeholders and teams are a more regular topic in documents with a managerial or historical approach.

Information derived from Figures 4.1 and 4.2 reflects an overview of the empirical basis of our taxonomy. It is possible to identify that our purposive sample has strengths and weaknesses, i.e., which dimensions are high and low represented. An option to minimize the impact of low representativeness of dimensions could be alternative data sources such as interviews. Although our interview set has the primary purpose of complementing the literature (Section 3.1.2), our interviews were driven to capture points of view beyond the literature and about the government decision process. So, the interviews were barely used for complementing the information of the dimensions since the interviews did not focus on the taxonomy, which would demand another sample and interview guide.

A detailed display of the sample by research field allows us to identify specificities of each BigSci knowledge domain as well as highlight the strengths and weaknesses of our sample, i.e., the high-represented and low-represented dimensions per research field. Our proposed taxonomy is thus grounded in this empirical data. Figure 4.3 exposes each dimension’s profile by the research field.

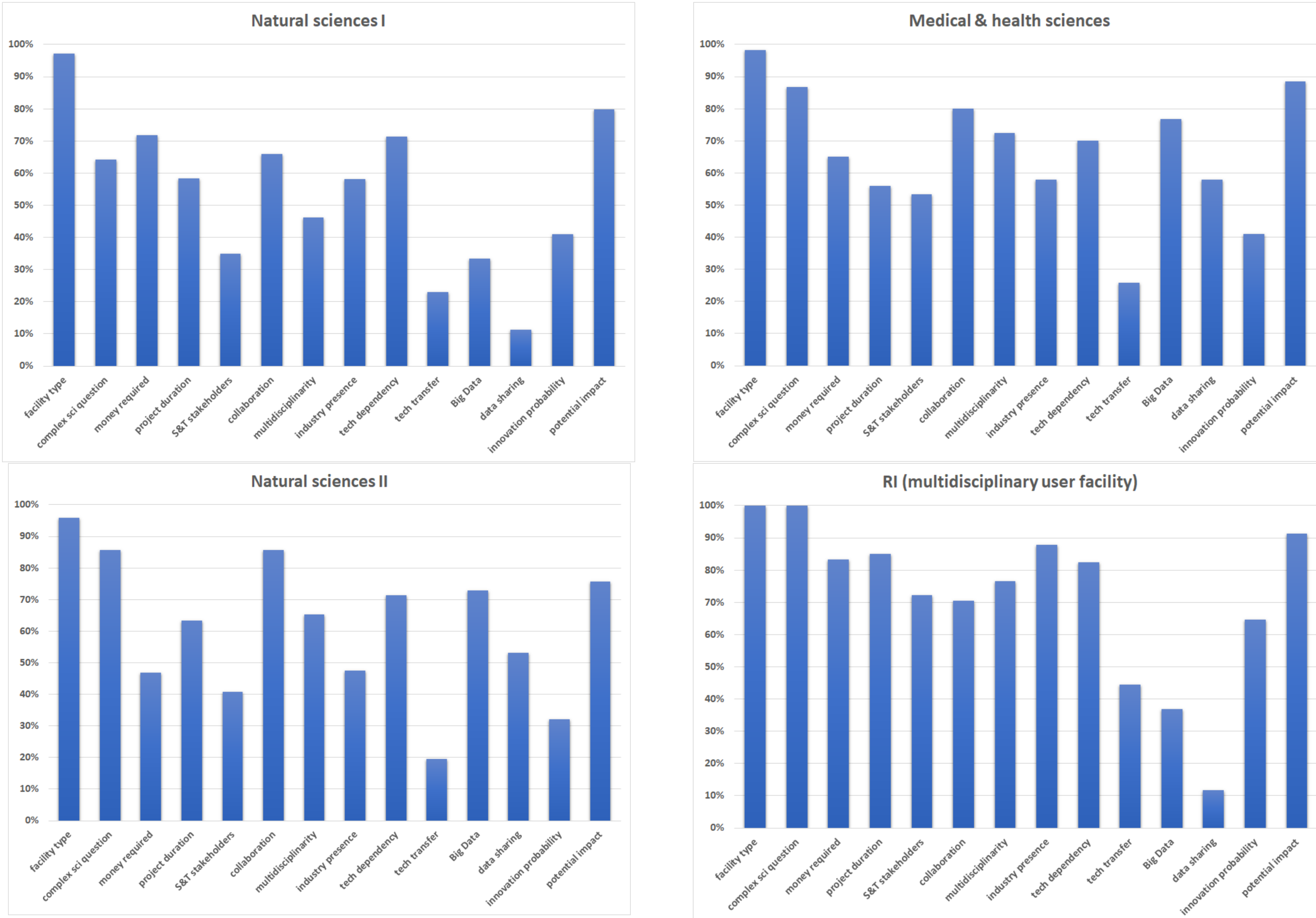

Figure 4.3 Dimensions' distribution by research field

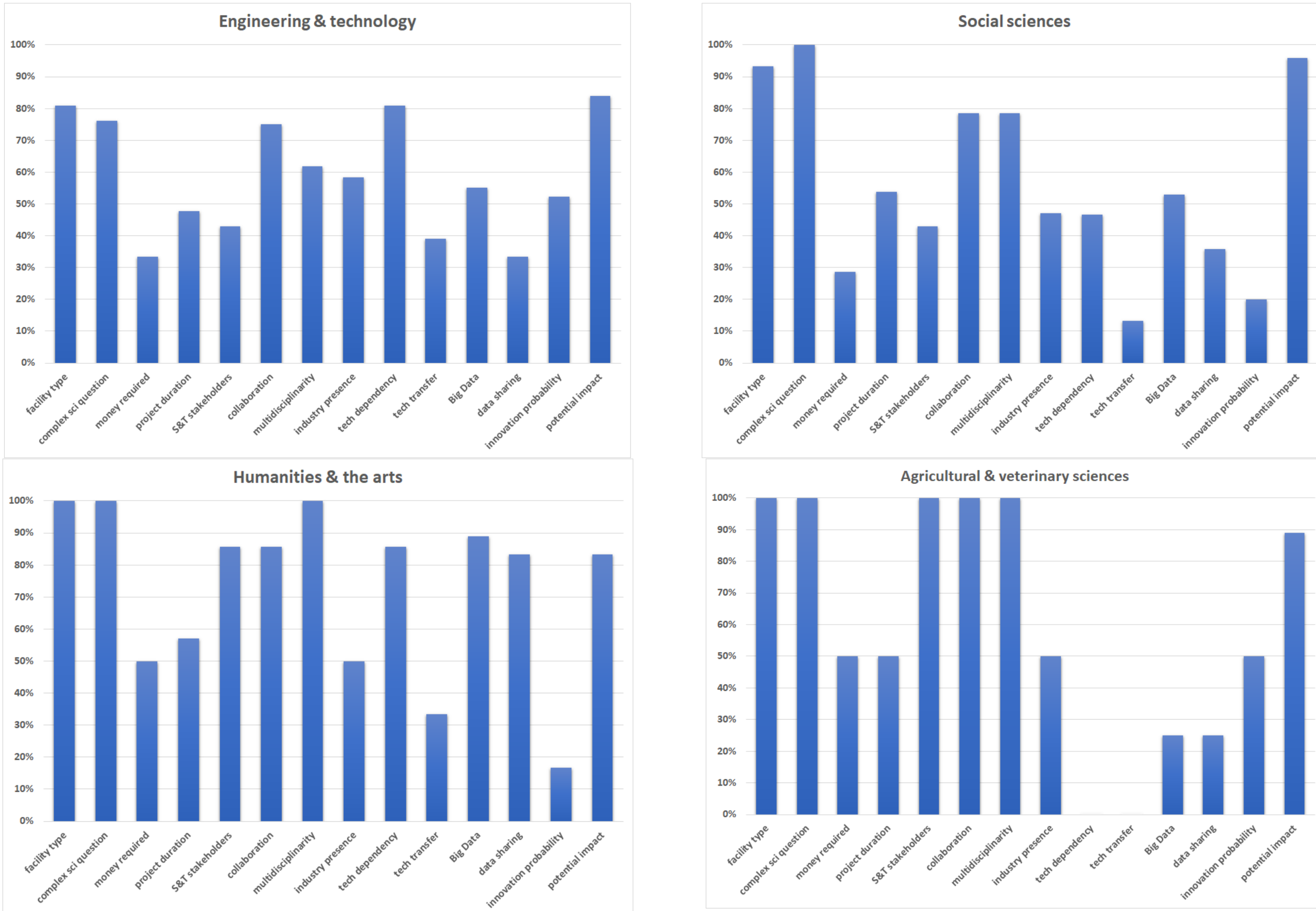

Figure 4.3 Dimensions' distribution by research field (cont'd)

Figure 4.3 displays the distribution of the fourteen dimensions for eight research fields over the purposive sample. It is possible to perceive that the different scientific groups in the BigSci community seem to have slightly different concerns, either due to the culture of the group or due to the maturity of the knowledge domain as BigSci. The previous discussion about dimensions representativeness regarding Figures 4.1 and 4.2 is also valid in Figure 4.3, where data is displayed in more detail.

From Figure 4.3, we may highlight the following aspects:

- Natural sciences I: different from all other research fields, it presents a low frequency of multidisciplinarity, probably due to this dimension evolution in the field; according to some historical studies (Kaiser, 2014, 2015), the participation of multidisciplinary teams varied over time in this domain, depending on externalities favoring it or not. Presently, this field exhibits an increasing trend of multidisciplinarity to address complex questions.
- Medical and health sciences: low frequency of innovation probability despite the well-known outcomes in this field, such as new products, treatments, and methods that could easily be called innovations. The reason for this low frequency is probably the selected documents of this field mainly focused on collaboration, Big Data, and ethical issues.
- Natural sciences II: although documents focus on collaboration (86%), they usually do not explore specificities about the participants, resulting in low frequency for S&T stakeholders.
- RI: the only dimensions below 60% of frequency (technology transfer, Big Data, and data sharing) are related to the users, not to the 'BigSci portion' of the RI (Crease & Westfall, 2016; Hallonsten, 2016a).
- Engineering and technology: this field has the most homogeneous dimensions distribution of the purposive sample, even with few documents (Figure 4.1).
- Social sciences and humanities: these fields have small partial samples with similar dimensions distribution, as expected.
- Agricultural and veterinary sciences: the smallest partial sample has its dimensions poorly represented, as expected, requiring critical complementation.

Table 4.4 provides a broad view of the main results from the metasynthesis analysis of a total of 212 documents from white and gray literature. The first row presents the eight research fields, including the category RI that is not a discipline, as explained earlier. The core column (left) is listed the fourteen identified dimensions that characterize BigSci in the documents. Each cell of Table 4.4 brings together the most frequent characteristic of each dimension (Table 4.3) for each research field, including the frequency value in percentages (number in parentheses). For instance, in the first column, Natural sciences I, and in the first row, Facility type, the cell ‘infrastructure-based (82.1)’ means that 82.1% of all documents giving information about the facility type of a BigSci project in natural sciences I indicate that the facility type is ‘infrastructure-based’.

The results in Table 4.4 reinforce the well-known characteristics of the traditional BigSci (in natural sciences I), such as infrastructure-based facility type, or the private funding of the renowned BigSci in medical and health sciences, or yet the very high investments of the celebrated RI. On the other hand, our results shed light on humanities, social and agricultural sciences where BigSci initiatives are not so frequent, are more recent, but still exist with their remarkable multidisciplinary characteristic.It is essential to declare that the review that follows (Tables 4.4, 4.5, and Figure 4.4) is indicative rather than conclusive, and the dimensions do not exhaust all analytical possibilities. Here we offer a preliminary map allowing further analysis using distinct assumptions to gain additional or alternative insights or to ask questions that we did not conceive yet.

Table 4.4 Broad view of our main results from the metasynthesis analysis

	Natural sciences I	**Natural sciences II**	**Engineering & tech**	**Medical & health**	**Agri & veterinary**	**Social sciences**	**Humanities & the arts**	**RI**
Facility type	infrastructure-based (82.1)	network-based (89.4)	network-based (70.6)	network-based (96.6)	network-based (100)	network-based (100)	network-based (85.7)	infrastructure-based (88.2)
Complex scientific question	defined (94.1)	defined (95.2)	defined (93.8)	defined (96.2)	defined (100)	defined (100)	defined (100)	user-based (64.7)
Money required	extremely high (40.5)	high (43.5)	extremely high (42.9)	high (43.6)	low (50) high (50)	high (100)	very high (33.3)	very high (46.7)
Project duration	long-term (83.3)	long-term (74.2)	long-term (80)	long-term (81.8)	mid-term (50) long-term (50)	long-term (85.7)	long-term (75)	long-term (64.7)
S&T stakeholders	big team (83.3)	big team (70)	big team (77.8)	big team (81.3)	big net of small teams (50)	big net of small teams (50)	big team (50)	multidisciplinary users & local scientists (76.9)
Collaboration	international (48.5)	international (57.1)	national & intl (33.3)	international (37.5)	national (75)	national (45.5)	international (50)	national & intl (33.3)
Multidisciplinarity	STEM (81.3)	STEM (50)	STEM (46.2)	health + STEM (69)	health + STEM (50)	STEM + SSH (45.5)	STEM + SSH (85.7)	health + STEM (46.2)
Industry presence	partner (37.3)	partner (24.1)	partner (50)	partner (31.9)	beneficiary (50) funder (50)	partner (50)	partner (66.7)	partner (27.8)
Technology dependency	more hardware (58.7)	mixed (62.9)	mixed (47.1)	mixed (61.9)	-	+ soft (42.9) mixed (42.9)	mixed (66.7)	mixed (50)
Technology transfer	formal (68)	more open (40)	formal (44.4)	formal (31.3)	-	formal (50) open (50)	open (100)	formal (87.5)
Big data	massive (60)	massive (51.9)	massive (43.8)	massive (49.3)	massive (100)	massive (55.6)	distributed (50) massive (50)	massive (71.4)
Data sharing	more open (50)	more open (80.8)	more open (42.9)	more open (64.9)	not specified (100)	more open (80)	open (40) + open (40)	less open (50) more open (50)
Innovation probability	high (95.3)	high (87.5)	high (90.9)	high (92)	high (100)	high (100)	high (100)	high (90.9)
Potential impact (non-scientific)	economic (29.3)	social (35.6)	political (26.9) technological (26.9)	social (40.2)	economic (37.5) social (37.5)	social (52.2)	social (40)	social (26.2) political (26.2) economic (26.2)

Finally, as a ‘zoom-in view’ of BigSci in the literature, Table 4.4 provides a synthesis of the observed dimensions in each research field, presenting the most frequent dimension characteristic allowing us to propose a taxonomy of BigSci. As such, we have reached the most crucial point in this Section: the proposed taxonomy of BigSci grounded in the empirical evidence from the literature, based on research fields, targeted to government purposes, and in two usable formats (textual in Table 4.5 and visual in Figure 4.4). Note that in Figure 4.4, the dimension ‘RI’ is not a research field, and as such, is not included in our graphical display.

This taxonomy is one of the foundations of the final bridge connecting stakeholders with our proposed framework for decision-making purposes for BigSci investments. In other words, the taxonomy will support the proposal pre-selection phase of the framework (Figure 3.2). Thus, in Table 4.5, we summarize our taxonomy proposition grounded by empirical evidence mainly from the literature in textual format.

Table 4.5 Taxonomy of BigSci by research fields

For…	Big Science is a project that…
…natural sciences I	…involves massive infrastructure (facilities and/or equipment); long-term, multidisciplinary, international collaborative teams. It may have a multi-tens of billions of global budget and industry participation often as partners. Example: James Webb Space Telescope – JWST (https://www.jwst.nasa.gov).
…natural sciences II	…involves long-term research, data sharing with a massive central data repository, using a network of instruments, observation sites, and/or small laboratories within big, collaborative, international teams. It may have a multi-tens of millions of global budgets. Example: Destination Earth – DestinE (https://ec.europa.eu/digital-single-market/en/destination-earth-destine).
…engineering and technology	…comprises a long-term development project to support other BigSci projects. It may have large teams, a multi-billion global budget, active industry participation, and high innovation probability. Example: Cyberinfrastructure for Data Management and Analysis – CyVERSE (https://cyverse.org).
…medical and health sciences	…encompasses a long-term, extensive network of small equipment/laboratories with central coordination, data-sharing practices, big multidisciplinary teams. Its multi-tens of millions global budget is partially funded by industry. Example: Human Brain Project (https://www.humanbrainproject.eu).
…agricultural and veterinary sciences	…comprises long-term, multidisciplinary, national collaborative teams working in a network of small laboratories with central coordination and Big Data sharing. It is partially funded by industry and has a high innovation probability. Example: C4 Rice Project (https://c4rice.com).
…social sciences	…involves long-term research with complex scientific questions, national collaborative teams, and industrial partners. It involves a multi-million global budget. Example: International Network of Health and Retirement Studies (https://hrs.isr.umich.edu/about/international-sister-studies).
…humanities and the arts	…involves an international network of field-research teams and small laboratories in a multidisciplinary collaboration with high technology dependency and industrial partnerships. Example: Time Machine Project (https://www.timemachine.eu).
…RI (multidisciplinary user facility)	…encompasses small-scale, multidisciplinary, short-term projects in large-scale facilities. It usually has a high innovation probability. Example: use of synchrotron and neutron radiation sources to chemistry, biology, material science, medicine, archaeology and art investigations, among others (https://www.diamond.ac.uk, for instance).

Moreover, because our purpose is to synthesize findings, look for patterns, create new comprehensive interpretations, and that our primary target audience is government decision-makers, we also chose a graphical representation of our taxonomy, as shown below in Figure 4.3.

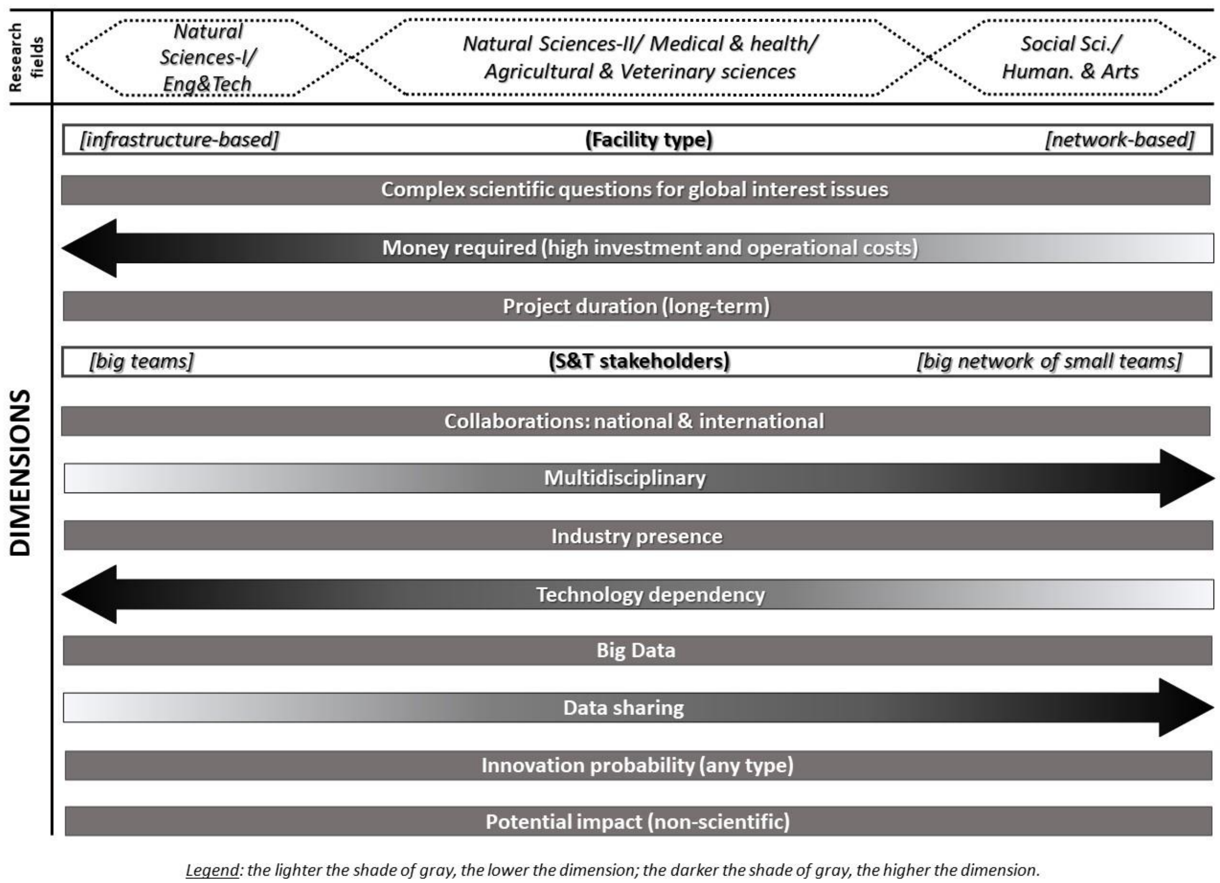

Figure 4.4 BigSci dimensions continuum through research fields: the BigSci family

The literature has discussed BigSci as a multifaceted topic: civilian and military; public, private and mixed funding; national government, intergovernmental organization and a consortium of countries funding and management; national and international collaboration; single field and multidisciplinary collaboration; basic, applied and mixed research purpose; bottom-up and top-down initiative; space and non-space research. When classifications exist (Table 2.3), they are often not the goal of their original work, nor do they have BigSci categorized by research fields.

Even though, Jackson (1976) mentioned that “what is a Big Science project in one discipline may not be so in another in terms of the size and cost involved” (p.213), the literature has dedicated decades in thinking BigSci only in natural sciences I. Considering that other forms of BigSci beyond physics are possible, for instance, Capshew and Rader (1992) qualified the HGP as BigSci. So, a BigSci taxonomy by research fields, built from the literature's synthesis, validated and complemented by interviews' analysis (see Section 4.2 for further details), should provide a comprehensive representation of BigSci dimensions (Table 4.4), a whole picture of present-day BigSci (Table 4.5 and Figure 4.4). Such information could prove valuable for the government and interested parties to ensure active participation in leading large-scale research initiatives.

Moreover, Figure 4.4 provides an effective and simple translation of the results (Table 4.5), particularly appropriate for the government as a target audience who could "benefit the bridge from research to practice" (Erwin et al., 2011, p.195) in this way.

Aside from the similarities, research fields have specificities (Tables 4.4 and 4.5):

- natural sciences I have prominent monuments dedicated to science;
- natural sciences II comprise big teams spread around global collection data sites;
- engineering and technology involve crucial projects and developments for big laboratories and other BigScis;
- medical and health sciences need big money from government and industry;
- agricultural and veterinary sciences develop innovative approaches to complex hunger global scientific questions;
- social sciences focus on long-term projects searching solutions to complex scientific questions around challenging societal matters;
- humanities and the arts concentrate on significant multidisciplinary work connecting big study sites and big laboratories;
- and finally, RI presents a high potential for innovative user's projects.

A taxonomy by research fields as the one proposed here (Table 4.5 and Figure 4.3) is a better fit because it can support a more transparent, informed, evidence-based decision-making in constrained science budget situations where the government needs to choose among different projects. “Weighing space against biology, atomic energy against oceanography, will be the very hardest [choice] of all to make” (Weinberg, A., 1961, p.163).

Table 4.5 and Figure 4.4 show in detail that BigSci now is a term that covers everything from extensive research facilities to international networks of researchers under ‘umbrella’ projects that do not require any structure at all other than basic laboratories. The proposed taxonomic system is a classification that does not rely on a single standard dimension but instead attends to the dynamic interaction among various dimensions. Thus, BigSci refers to a set of scientific projects all having differences among dimensions, such as research fields, but enough ‘family resemblance’ (Wittgenstein, 1965) or cluster concepts to be classified in the same ‘BigSci family’. It reflects a comprehensive taxonomy that demands a corresponding definition, even tackling the characteristic lack of boundaries and exactness. Therefore, all that remains is proposing a workable definition, considering our taxonomy by research fields, for distinguishing BigSci from other research initiatives allowing them to follow an appropriate funding process under government analysis.

Finally, BigSci has a very 'fuzzy' or ill-defined border (Figure 4.4). Exactly where that border is drawn is a matter of research field convention and is open to negotiation. Insights regarding the precise location of the 'boundary' of BigSci may vary considerably across disciplines, involved stakeholders and contexts, as well as overtime. We have thus arrived at our present-day BigSci taxonomy, revealing a ‘whole BigSci picture’.

4.2 Building a workable and comprehensive definition of BigSci

Definitions of BigSci (Table 2.2) cemented its association with scale, budget, complexity, scope, and impact. However, relevant authors advocated that many people, inside and outside of the academic environment, have used the term BigSci in a variety of ways (Olof Hallonsten, personal communication, February 24th 2017; Catherine Westfall, personal communication, April 28th 2017). On the one hand, inside of the academic environment, we found that

> Since it has become so well-known and has a rhetorical lure to it, it is almost impossible to avoid – try to write a book or article about something that could be called ‘Big Science’ without calling it ‘Big Science’ and you will not be taken seriously. (Olof Hallonsten, personal communication, February 24th 2017).

On the other hand, outside of the academic environment, BigSci can be, for instance, a current and high-tech business area for some specialized companies and organizations (https://www.bsbf2020.org). To the best of our knowledge, scholarly publications have never concerned about developing a definition of BigSci targeted to non-expert audiences, such as the government, allowing crucial improvements to public BigSci policies, procurements, or investment decisions. BigSci definition and taxonomy are critical enough to challenge governments and even reputable intergovernmental institutions like the OECD in its STI strategic guidance. Since 1992, with the creation of the Megascience Forum, seven years later updated to Global Science Forum (OECD, 2019b), the OECD gave up the term BigSci and has adopted megascience and then global science instead. Replacing BigSci by 'Research Infrastructure' also seems unpromising as we identified in the previous section (Table 4.1) as well as recently advocated by some authors (BSRI, 2019; Hallonsten, 2018, 2020). Nevertheless, due to its rhetorical attractiveness and simplicity, BigSci has still been used by politicians, industry, and scientific communities, as shown by our literature and interview samples. Even on sectorial congresses such as the Big Science Business Forum 2021 (2nd BSBF), BigSci is still used in a way "few can define or describe precisely but many feel able to recognize on sight" (Galison & Hevly, 1992, p.355).

Since it is impossible to get rid of this "addictive" term, the best solution is to work on the BigSci definition and the practical taxonomy as proposed here. Any definition requires method, analysis, and in-depth knowledge of the subject, and this is quite challenging for BigSci. Defining and categorizing BigSci is a prudent measure to support the strategic, tactical and operational levels of the national governments to ensure a coherent treatment to initiatives with long-term, substantial financial and workforce requirements in the context of scarce resources.

BigSci usually implies critical dimensions, which are a function of the discipline (Tables 4.3 and 4.4). However, when regarding all fields in the sample, the metasynthesis analysis points out:

- money required: 87.1% of all documents that discussed BigSci budgets present them in a scale varying between high to extremely high investments (tens of millions to multi-billion global costs) of capital and operation expenses, mainly funded by the government and eventually by the industry (15.7%);

- S&T stakeholders: 68.5% of all documents that discussed BigSci staffs declare BigSci projects require big teams of scientists, technicians, engineers, and managers, organized in national and international collaborations (67.6%) of multidisciplinary nature (89.5%);
- facility type: 42.5% of all documents that discussed BigSci infrastructure present them as centralized in large laboratories or big instruments, while 56.7%, as a network of distributed laboratories, equipment or observation sites with central coordination;
- other prominent features: 89.2% of all documents indicate BigSci aims to answer complex scientific questions in long-term projects (78.8%), using Big Data (52.9%) and more open data sharing practices (64.2%) as well as having formal technology transfer (51.4%) and a high probability of innovation of any type (92.1%).

Towards the end of the 20th century, not only projects in fundamental physics and astronomy but also in medical, earth and social sciences and humanities have increasingly been recognized as BigSci while emphasizing their non-scientific impacts, particularly socio-economic benefits to society (58.9%).

The first-order analysis of the systematic inductive approach (Subsection 3.2.2) examined the answers to the question 'What is Big Science?' from the interviews and identified an overwhelming list of concepts that arose directly from interviewees' terms. As expected, the number of categories that emerged from only one question in the 50 interviews was tremendous and equal to 718 'first-order concepts' related to the definition of BigSci, comprising a comprehensive list of terms. We also distributed them into three respondents' categories:

- <u>scientific sector</u> refers to the group of interviewees formed by academia representatives, principal investigators and researchers from public laboratories and/or research institutions who participate in BigSci projects, directors and former directors of BigSci research institutions;
- <u>government</u> refer to the group of interviewees formed by former STI ministers, presidents, vice-presidents and former presidents of national funding agencies, senior advisors, high-level public servants;

- private sector refers to the group of interviewees formed by senior managers, directors, presidents/CEOs, COOs, and ILOs.

Clustering the 'first-order concepts' was an attempt to organize and make sense in such an extensive open code list. When categorizing the respondents into these three categories, we reached 68 codes in the private sector group, 310 codes in the government group, and 340 codes in the scientific sector group. This initial step of the systematic inductive approach analysis of the interviews resulted in a long list of raw information, surely demanding further analysis, but already capable of providing evidence that the definition is problematic. Table 4.6 lists the obtained first-order concepts in each stakeholder group.

Table 4.6 Examples of first-order concepts

Group reference	**1st-order concept (open code)**
private sector	• BigSci is a business platform • today different people give different meanings to the definition of BigSci • BigSci is big business
government	• BigSci can involve things beyond the natural sciences, engineering, or health • Big Data sets are BigSci • BigSci is a buzzword
scientific sector	• BigSci is quite small in absolute terms • BigSci goes really to the core of questions • BigSci is what needs a big installation

Our second-order analysis of the systematic inductive approach developed thematic categories by analyzing and synthesizing commonalities among all 'first raw' concepts regardless of the group reference. Subsequently, the coding process produced a meaningful and more manageable coding structure that appeared to help to describe and explain the concept of BigSci empirically grounded. This exercise reduced the long open code list into 55 'second-order themes', and in a final round of the second-order analysis, we synthesized them into 14 themes, eventually suggesting complementarities to the 'second-order constructs' of the literature metasynthesis analysis. Except for two of them, we realized that the remaining themes reinforce Galison & Hevly's (1992) observation that many people can recognize and, in some way, describe or exemplify their understanding of the definition of BigSci. At this point, it is worth mentioning a personal impression during the interviews regarding the unexpected discomfort of almost all interviewees to answer the question ‘What is Big Science?’. The respondents reacted as if it were a tricky question or a mark of disapproval towards their free or careless use of the term. Table 4.7 summarizes the results.

Table 4.7 List of the unveiled themes from the interviews

2^{nd}-order themes	**Examples of 1^{st}-order concepts**
Always a large facility (laboratories, equipment, network) dependent on field	• large, comprehensive, sophisticated pieces of equipment after requiring their buildings, housings, facilities • tend to be large scale facilities • centralization of scientific research in large laboratories
Huge investment or multimillion budget in project lifecycle dependent on field	• substantial national investments in scientific capabilities • very often following significant investments • multimillion budgets
Big multidisciplinary teams dependent on field	• requiring the expertise of a broad range of experts • large-scale multidisciplinary team
Funding source can be national, international, public or public-private, dependent on project	• BigSci has funding from governments or international agencies is required • have to share the investments internationally • international venture fund
Inevitable political and/or industry support	• the government needs to develop the policy around large conceived projects and infrastructure • something where government, industry, and academia working together • the synergy between government and productive sector and academia
Always searching solution for complex questions or knowledge advancement	• the objective to make progress in the knowledge of nature, physics, chemistry, biology • BigSci is also big questions • deals with major complex research questions yet to answer • BigSci is big complex problems
Not always have strategic purposes, in general, top-down initiatives	• priority setting for BigSci needs a strategy • BigSci is a strategic choice • BigSci in a world of data, of interdisciplinarity, is a necessity
Non-scientific impacts desirable but not always present and hard to measure	• BigSci helps to develop economy, technology, employment • give a return to society for that kind of investment • BigSci extrapolates research results
Desirable international prestige or good reputation strongly dependent on field and project	• symbol to improve our reputation in the world • the key issue is BigSci ID image • it is about national prestige

Table 4.7 List of the unveiled themes from the interviews (cont'd)

Business opportunity happens according to the field, project goals, and management	• it leads to fantastic opportunities • it is good news for companies • source of new sales' contacts • hope for more orders in the area of research and development • for high technology companies, BigSci represents a large share of the market
Never without (big) collaboration	• effectively cannot be done without multiple players • the spirit of collaboration is congenital with the BigSci • it is about to solve problems nobody can alone
Space initiatives only scientific	• space for strategic reasons, secrecy, it is not BigSci • in space, the most strictly scientific research is BigSci • in non-scientific space initiatives, there are protected technologies under secrecy, not a BigSci spirit
Definition problem	• BigSci depends on which country you are talking about • BigSci is often the term used in the government • it has fuzzy boundaries • some people say it is a major science investment • some people say it is major facilities • some people say it is only university-based facilities • some people say it is international facilities • there are various definitions
Agricultural & veterinary sciences	• Big Science project articulating the research of making the agriproduct cycle more efficient • multidisciplinary approach (agronomy, civil and agricultural engineerings, atmospheric sciences) • the nation is a worldwide leader in the construction of those machines • world leader in research, genetic improvement of this plant • complete BigSci with all areas

The last two themes emerged naturally from the interviews. The 'definition problem' theme and respective concepts provided confirmatory evidence of the lack of a consensus in the BigSci definition, also perceived by other BigSci stakeholders beyond scientists. The scientific community perception about this definition problem is expressed in the literature (see Section 2.2.2). Such results from the interviews involved mentions of the BigSci definition problem expressed in a disinterested tone by some and criticized by others. In either way, the topic came from interviewees of the three stakeholders' groups, agree with the literature, and the interviews confirm the need for a solution towards a clear, workable definition, particularly in public matters.

While the 'agricultural & veterinary sciences' theme and respective concepts provided critical complementary information about BigSci in this research field, recalling its weak representativeness in our purposive sample (Figure 4.1) to build the taxonomy (Table 4.5 and Figure 4.4). This useful information came from a detailed declaration of one interviewee from the scientific sector group who participated in a BigSci project in agricultural sciences. From this statement, we could extract more information and reinforce some dimensions for the agricultural and veterinary sciences in the taxonomy, as shown below in Table 4.8.

Table 4.8 BigSci characteristics in agricultural & veterinary sciences derived from an interview

Dimension	**Subdimension**
Facility type	network-based
Complex scientific question	defined
Money required	not specified
Project duration	long-term
S&T stakeholders	big network of small teams
Collaboration	national
Multidisciplinarity	STEM
Industry presence	funder, beneficiary
Technology dependency	more hardware
Technology transfer	-
Big data	-
Data sharing	-
Innovation probability	high
Potential impact (non-scientific)	social, economic, political, environmental, technological

That information contributed to the final description of BigSci in this research field (Table 4.5).

Table 4.9 illustrates the second-order themes with a set of representative interviewees' quotes from each group (IND = private sector, GOV = government, SCI = scientific sector). In order to guarantee the anonymity of respondents, all the quotes will reference the group as opposed to the particular BigSci project, institution, or government organization.

Table 4.9 Second-order themes and representative quotes

2nd-order theme	**Representative quote**
Always large facility (laboratories, equipment, network) dependent on the field	It is large public funding, large equipment, large installations, large organizations, large engagements. This is the core of Big Science. (SCI) Why Big? Because to make this progress, big instruments are necessary. (IND)
Huge investment or multimillion budget in project lifecycle dependent on field	Big Science is the one that we achieve through very big collaborations across several nations, very often following big investments, with a lot of ramifications, which means that science is the ultimate goal…sort of environment that I would put Big Science (SCI) Most people like to think of Big Science as investments easily over one hundred million dollars with multiple countries engaged in a distributed research network. That's what usually big science refers to. (GOV)
Big multidisciplinary teams dependent on field	Big Science is the complicated multidisciplinary game-changing effort. (SCI) I guess I don't even think as much about size as I think about the breadth of what it is being covered, and so I usually think of it as multidisciplinary and requiring the expertise of a broad range of experts. I would say that is basically how I define it. (GOV) I think Big Science must be a really big and multidisciplinary science. (IND)
Funding source can be national, international, public or public-private, dependent on the project	Big Science has an essential element, which is the public intervention, public funding. You should lead a big funding that involves equipment which is also large, so it is large public funding. (SCI) Big Science projects that exceed the mandate of any funding agency to do themselves, and in the end, they are quite often of international nature, but they don't need to be. There is also Big Science of national scale. (GOV) Big Science is big…big in money required…It is Big Science when funding from the government is required or from international agencies. In any case, many different countries need to be involved in handling large budgets and manpower requirements. (IND)
Inevitable political and/or industry support	It was virtually impossible…for industry not to be engaged because for high technology companies, Big Science represented a very large share of the market. Before there was no discussion, political actors, governments were almost in that trade-off, cost-benefit, they were almost invariably deciding that it was advantageous to go for participating. (SCI) Big Science is big projects like CERN and ESS; government-backed; political; international. (IND)

Table 4.9 Second-order themes and representative quotes (cont'd)

Always searching solution for complex questions or Knowledge advancement	It is also an integrated problem, and then the broader question, the scientific question was the carbon balance...this is the big one. And this is not because the Amazon is giant. It is a big question, Big Science, in the sense of the complexity of the process. (SCI) Big science is those big projects, big infrastructures, big teams that work considerably in advancing the frontier of knowledge. A broad interest, an interest that goes beyond those specific interests of a particular country. (GOV) First Big Science is science; it means that the objective is to make progress in the knowledge of nature, physics, chemistry, biology. (IND)
Not always have strategic purposes, in general, top-down initiatives	And that means a country can invest in a small number of Big Science projects at the same time…you cannot fund many hundreds of these things in parallel. Most countries will support many hundreds of students, many hundreds of researchers, many universities, but only a small number of Big Science projects. And that is a measure. So, a priority setting for these projects is critical because you must have a strategy…You cannot fund 10 CERN projects and see which one is the best. So, you have to have decision making at the national level…So countries that are in the Arctic are interested in the impact on the Arctic ecosystem of climate change, countries in Africa would not. (SCI)
Non-scientific impacts desirable but not always present and hard to measure	They must evaluate and value other aspects. They must value the inspirational effect; they have to value the doctoral effect…the indirect impact which comes from people being trained, developing technology, and then spinning-off. (SCI) So, when you talk about big projects like climate change, like access to water, this kind of thing, then of course it grows. So as a government person, you must think about that as well. Yes, Big Science as science being exciting, but what is the impact on society. (GOV)
Desirable international prestige or good reputation strongly dependent on field and project	It was virtually impossible for political stakeholders not to participate because Big Science was a tool for foreign policies. (SCI) I think that Big Science in a world of data, of interdisciplinarity, is a necessity. It is not only about national prestige. (GOV) And every people in the world know France not only because we have…good food, beautiful landscapes, but also because we have ITER. And we need to create a symbol to improve the French reputation in the world; and from my point of view, this kind of symbol is really soft power. (IND)

Table 4.9 Second-order themes and representative quotes (cont'd)

Business opportunity happens according to the field, project goals, and management	For us, Big Science is a business platform, where new sales contacts are made, and old ones are maintained. We hope for more orders in the area of research and development. (IND) For some of them, Big Science is Big Business. For the bigger ones, Big Science is more business, and in theory and principle, there is a lot of money and should be an interesting market. (IND)
Never without (big) collaboration	So, see that in order to answer cutting-edge questions in science, we have to have equipment that a country alone can no longer afford. And that I call Big Science. (SCI) It is about getting together and solve these problems that nobody can alone. (GOV) And scientists cannot work alone. The result is that the spirit of collaboration is congenital with Big Science. (IND)
Space initiatives only scientific	When I just spoke about my concept of Big Science, I was referring to non-space projects, questions that need answers that cannot be paid by a country, and typically cost more than a billion dollars. In the space area,…cooperation is not so open...in 2012, I went to the IAU in Beijing. There I met an old friend from NASA, he was pissed off because...NASA does not allow him to participate in a scientific congress in China. No NASA funded or employee can participate in a scientific congress in China. So, what did he do? He took a vacation and went traveling...this thing in the space area, for scientific purposes…do not exist. (SCI)
Definition problem	I'm not sure whether there is only one definition. I know there is only one definition for Big Data, which is always misused; it is not a lot of data; it is the combination of data. And so Big Science might be not just one good definition. (SCI) It is really becoming very vague and very broad. So, from our point of view, that is not a workable definition. That is not something that we can use to make good decisions because it is becoming too vague. (GOV) It is an interesting approach since, indeed, today, different people will give a different meaning to the definition of Big Science. Even Wikipedia is uncertain about it. (IND)
Agricultural & veterinary sciences	It was one of the Big Sciences where there was more investment… it was a synergy between the university…and external demand, which is the government's concern about the country's performance in terms of climate and an opportunity detected by the productive sector. The productive sector immediately realized that there was an opportunity there…the private sector invested a lot ... the government put much pressure on encouraging research and development...And the university had an essential role in articulating this Big Science, from making the plant cycle more efficient...to genetic improvement. (SCI)

A step further in the second-order analysis of the systematic inductive approach of the interviews developed the understanding that BigSci is more complex and a straight definition in a paragraph would not be enough to disclose its multidimensional nature or be useful for our target audience, that is, the government. The aggregation of the second-order themes into high-level dimensions revealed a new structure and its strong interrelation with the proposed taxonomy developed in the previous section. Thus, we captured the relationships among the second-order themes and aggregated them in 3 'second-order aggregate dimensions' (Table 4.10). It is essential to stress that the themes 'definition problem' and 'agricultural and veterinary sciences' are out of the aggregation exercise because they do not have a direct link to the definition per se. The first will be discussed in the following chapter, and the second was treated previously (Table 4.8).

Table 4.10 Aggregation resulted from the analysis of relationships among principal codes

2nd-order themes	**2nd-order aggregate dimensions**
• always large facility (laboratories, equipment, network) dependent on the field • huge investment or multimillion budget in project lifecycle dependent on field • big multidisciplinary teams dependent on field • inevitable political and/or industry support • always searching solution for complex questions or knowledge advancement	themes that are almost always present
• funding source can be national, international, public or public-private, dependent on the project • not always have strategic purposes, in general, top-down initiatives • non-scientific impacts desirable but not always present and hard to measure • desirable international prestige or good reputation strongly dependent on field and project • business opportunity happens according to the field, project goals, and management	themes that are present sometimes
• never without (big) collaboration • space initiatives only scientific	themes that are never present

Finally, we reach the most crucial result in this section: the proposed definition of BigSci grounded in empirical evidence from interviews and also from the literature either from our proposed taxonomy or from the metasynthesis analysis regarding all fields in the sample. Therefore, from the analysis of the BigSci stakeholders' interviews and literature's findings, the essential and meaningful aspects of BigSci emerged towards a proposed BigSci definition for government purposes and in a workable format (box-ticking in Table 4.11). This definition is another foundation of the final bridge connecting stakeholders towards our proposed framework for the decision-making regarding BigSci investments. In other words, the definition, as well as the taxonomy, will support the proposal pre-selection phase of the framework (Figure 3.2).

Table 4.11 Definition of BigSci in box-ticking format proposed for government purposes

Big Science…	
…will normally include (mandatory)	☑ facility, distributed, mobile or virtual infrastructure on a specific theme; ☑ long-term initiative, usually more than ten years but depending on the discipline; ☑ full lifecycle capital investment and operational costs around ‘X’% of country’s STI budget, where ‘X’ varies with the scientific domain; ☑ multidisciplinary approach to solving big complex questions requiring high caliber scientists, technicians, and managers; high-tech approach and Big Data; ☑ private sector participation (funding, partnership, and/or business opportunity as a supplier, user, owner or operator); ☑ need for political and logistic support to ensure project sustainability.
…may also include (in some cases)	☑ opportunity to share costs and develop international relationships; ☑ potential long-term, scientific and non-scientific high impacts and benefits during all lifecycle and beyond; ☑ small-scale, short-term research on large-scale user research facilities.
…will generally exclude (mandatory)	☑ non-collaborative research; ☑ non-strictly scientific projects.

Among the government attributions, those related to BigSci include scientific planning and policymaking that demand more than a meaningful and useful taxonomy, but also a workable and updated definition of BigSci. Interviews’ analysis captured this definition problem amid BigSci dimensions, including crucial ones on agricultural and veterinary sciences (Table 4.7). It is a sensitive issue also recognized by the majority of the interviewees, particularly the government representatives: “The problem is deeper. We put our own interpretation on it. I think it is very important that the government articulate what it sees as Big Science.” (GOV)

Initially, from the government's perspective, it is the initiative's cost rather than size, human resources or high technology needs, or dominant research fields that categorize science. In other words, at the government's first sight, BigSci and little science are two types of science, based on cost. Also, according to Jackson (1976, p.213), "cost might be regarded as the bedrock" once "size and advanced technology both require considerable funding", and that is the way it has been until now. Once the cost is dependable on the discipline (Table 4.4), it is essential to qualify BigSci by research field to ensure any meaningful use of a taxonomy or definition by the government.

The substantial investment of government and industrial interests into academic science has profoundly impacted the evolution of BigSci over time. However, the dynamic nature of the subject imposes a limitation, and it warns that our proposal for a definition and taxonomy is a portrait in the timeline and demand frequent updates as remembered by one of the interviewees: "Big Science concept changes with time because science evolves and things that were not Big Science, became [Big Science]" (GOV). In any case, we noticed some degree of solidarity between the projects that are and become BigSci: "We don't buy the same things, but the challenges are similar: they need funding, they need to engage in the long-term, they need to engage the public" (SCI).

Not all BigSci is easily recognizable. Nevertheless, the concept has been mostly taken for granted, as though everybody knows what is meant by the term. This situation is not good for practical uses because "it is so inaccurate and ill-defined that anybody can put anything into it" (GOV), as observed by another interviewee. The concept of BigSci is not evident and free from problems, especially from a government perspective, where it should be as comprehensive as possible if appropriate policies are to be designed. According to the dictionary and encyclopedia definitions, BigSci could be defined as a large-scale scientific initiative based on public funding of one national government or a group of governments. However, this begs the question of exactly how big an initiative should be in order to constitute BigSci. For example, one could argue that the whole international research community working together to achieve a common scientific goal in a project funded by all nations is BigSci, encompassing researchers around the world exchanging ideas, hypotheses, methods, experiments, data, results and much more. In this way, BigSci could be confused with O. S. (Bartling & Friesike, 2014). Thus, this fragile definition of BigSci would bring in such large numbers of teams, organizations, and countries that it would be unfeasible to manage and to fund for all practical purposes.

On the other hand, one could formulate a sharp definition according to which only those scientific initiatives which demanded direct investments exceeding the capacity of a single nation throughout the project would be counted as BigSci. This definition immediately runs into a problem because each country has its long-term financial capacity and, as described in Table 4.4 and by Jackson (1976), no single financial criteria could fit all research fields. One of our interviewees also agreed with that:

> They recognize that each one of these facilities is different and simply making a dollar threshold often does not make any sense…they are facilities just too big and too expensive…academics being academics; they want something that is very straight forward; they want something that is what is the specific definition…for communication purposes…is a 100 million dollar threshold, so any facility that costs an initial capital more than 100 million dollars could be considered…the problem with that it is wholly arbitrary. It is a crude benchmark, and what if you are running 5 million dollars, won't they qualify? This is the problem to use a dollar benchmark: just below it? Just above it? Multiples above of it? And therefore, do I do categories? It doesn't work particularly well…but for communication purposes….because it is a lot of money, right? (GOV)

Thus, the application of the sharp definition to, say, Sirius, the new Brazilian synchrotron light source (CNPEM, 2018), or FAST, the Chinese Five-hundred-meter Aperture Spherical radio Telescope (Morelle, 2016), would suggest that they were not indeed BigSci because only their national governments have provided funding. The choice of those governments is quite bold, according to one interviewee:

> And so, we are talking about something where government, industry, and academia are working together on multi tens of millions, if not multi hundreds of millions, of dollars projects. This creates a lot of difficulties for many governments because governments often are not comfortable in funding these sizes of projects. (GOV).

Therefore, BigSci lies somewhere between these two extremes. The pursuit of a definition for BigSci could have a more diverse and inclusive approach but should provide meaningful and workable use of the term. Several authors have proposed different definitions of BigSci in the white and gray literature, as shown in Table 2.2. Clearly, different countries and stakeholders define BigSci in different ways:

- For me, Big Science has two components: one that has a big infrastructure, infrastructure, and services; a large and also diverse community that is in this part of the world. But the second part of Big Science is large conceived projects where we actually have a collaborative activity that is sufficiently large that needs specialized management. (GOV)

- Big Science is the complicated multidisciplinary game-changing effort that we have to undertake to tackle the really big complicated problems that affect, in our case, people in the north. So, it's very much about leading-edge science, complicated problems, things that matter to people. (SCI)
- I think it depends on which country you are talking about. For industry, it is very different. For some of them, Big Science is big business. For the bigger ones, Big Science is more business, and in theory and principle, there is a lot of money and should be an interesting market. (IND)

This variety arises from the various contexts in which the term is used and the need to gain support from a full range of research endeavors. We have undoubtedly been able to present, on each stakeholder of each geographic group (Brazil, Canada, and Europe), the most significant number of communications obtained.

It is also necessary to expose why ‘big technological projects’ (Faucher, 2000) are not part of our proposed definition of BigSci. According to Faucher (2000), a big technological project has five main linked characteristics: the large infrastructure size associated with it; the high-risk investment involved in the initiative; it is constituted by one single big project and not a set of small projects (indivisibility); there is no other project of the same nature/topic competing with resources (exclusivity); it promotes a national production sector and acquires or develops additional skills for it (structuring impact). On the one hand, a big technological project’s main objective is to provide society with equipment considered essential to economic growth. On the other hand, in our proposed taxonomy, BigSci for engineering and technology is a project that aims to develop technology to support other BigSci project(s) with a scientific objective. Thus, the big technological projects’ main goal was to develop technology for economic purposes and not for scientific purposes like in BigSci technological projects.

It is noteworthy that space projects have a similar situation. In other words, only space projects with scientific purposes are BigSci; other space projects with commercial or defense purposes are not BigSci and are usually surrounded by confidentiality issues:

> So, in the space area, what I mean, when we talk about Big Science, we have to separate the spatial area from the non-spatial one because the logic is not the same. When I just spoke about my concept of Big Science, I was referring to non-space projects, questions that need answers that cannot be paid for by a country and typically cost more than a billion dollars. In the space area, the figure is not a billion dollars, and scientific cooperation is not such an open thing. (SCI)

Finally, we recognize BigSci as a case of application of ‘family resemblances concept’ (Wittgenstein, 1965), since it is a term that could not be formally defined, but rather identified as a generic label or a function depending on the research field, as shown in Table 4.10. While the characteristics presented for distinguishing between BigSci and other scientific initiatives may apply in many public funding circumstances, they are nonetheless subjective regarding their significance, impact, or complexity. Our ticking-box proposal seemed to be suitable for a real-world situation in the case of the treatment of scientific initiatives for government funding, oversight, and evaluation.

4.3 Concluding remarks

Chapter 4 accurately reports the Phase A macro-level results, analysis, and findings as well as a necessarily rigorous scientific discussion. Phase A started the progressive approach to the primary goal of this research, achieving the two secondary objectives of building a taxonomy of BigSci based on research fields and a workable and comprehensive definition of BigSci.

The systematic literature review on BigSci (Section 4.1) shed light on its multifaceted nature and a new understanding of the phenomenon. Identified similarities and differences first organized by research fields allowed to develop an original taxonomy of BigSci (Table 4.5 and Figure 4.4). This categorization is very appropriate for our study purposes since it recognizes the peculiarities of BigSci according to knowledge domains, improving the ability to distinguish BigSci projects from regular R&D projects in any field, which is fundamental to our final framework.

In this sense, the taxonomy findings added to the interviews’ analysis (Section 4.2) resulted in an attempt to understand the multitude of concepts from BigSci stakeholders as well as to generalize the proposed taxonomy based on those stakeholders’ perspectives. Building a workable and comprehensive definition of BigSci fitted better in a ticking-box format (Table 4.11) since the phenomenon is far from simple or reducible in one sentence. This format is also very appropriate for our study purposes, playing a fundamental role along with the taxonomy.

Both the proposed definition and taxonomy of BigSci were mainly developed to support the proposal pre-selection step of the framework for government decision-making regarding BigSci investments. Therefore, justifying the ‘research field’ as the primary dimension of the taxonomy and the chosen format for the definition.

Finally, in this section, we also expose some elucidations about this part of our research to avoid misunderstandings and hasty conclusions regarding our findings.

We must recall that our research is not a longitudinal, long-term, qualitative work based on specific BigSci projects or a longitudinal bibliometric study on BigSci communication patterns. This section is a systematic literature review, covering as many aspects as possible, in a ‘whole BigSci picture’ of an almost single moment in time, producing knowledge and new insights. Thus, we cannot state or conclude, for instance, that the more traditional BigSci studies have explored a limited number of dimensions, and this skews over time the distribution of relevant dimensions. On the contrary, studies like Capshew & Rader (1992) or Galison & Hevly (1992) or all works by Alvin Weinberg explored many BigSci dimensions. The evolution of each BigSci dimension in each research field over time is complex and is not the subject (or goal) of our study. This kind of conclusion would require a different study, such as Kaiser (2014, 2015).

Likewise, we cannot state, for instance, that for the most recent BigSci studies on non-traditional BigSci projects, a wider array of dimensions were explored to justify their classification into the BigSci realm. Firstly, we observed that the exploration of dimensions depends on the research field and varies over time but surely reflects the author’s interests and concerns. Furthermore, the classification as BigSci provided by external authors or the auto nomination as BigSci by project’s members in non-traditional research fields is usually justified by the project scale or approach.

In short, we did not measure the evolution of dimensions in the literature on BigSci but analyzed and synthesized them to produce a more comprehensive understanding of the phenomenon.

We must also recall the primary goal of the interviews in this exploratory research. In this sense, the 50 interviews were dedicated to capturing the richness and complexity of the decision-making process related to BigSci, virtually impossible by other means. The interviews provided fundamental data for this type of analysis, since they focus on events experienced by respondents, and not registered in documents, allowing the understanding of the objectives, perceptions, criteria, and preferences of the government decision-makers related to the BigSci decision process. Nevertheless, information about BigSci taxonomy and definition, possible by the literature, were superficially explored via only one question, in an attempt to check and/or complement the literature. Moreover, it would be a brief opportunity to listen to other stakeholders, different from scientists, about their understanding of the term ‘Big Science’.

In the case of aiming to use interviews as an alternative data source to develop an in-depth comparison, pointing similarities and differences, confirming and complementing dimensions and sub-dimensions of the taxonomy by research field derived from the literature, it is required a completely different interview sample and interview guide. It would be another study where the interview sample would consist of BigSci scientists from all research fields and not formed by stakeholders associated with the BigSci decision process. As well as the interview guide would have much more than a vague general question regarding the topic. Furthermore, eventually, the best adequate tool for the task would rather be a questionnaire.

Therefore, the available data is not suitable for comparisons between BigSci dimensions derived from the literature and the interviews.

CHAPTER 5 IN-DEPTH PROBLEM STRUCTURING

The first results and discussion segment (Chapter 4) defined the initial criteria for the type of projects that would be considered under our final proposed framework for the decision-making of BigSci investments in a more transparent, informed and participative process as required by scientific and industrial communities. In the present chapter, the second step towards a BigSci decision framework presents a detailed analysis of the interviews of a number of individuals selected from an environment of densely interconnected stakeholders.

The literature recommends addressing this complex decision situation by first recognizing the usefulness of the problem structuring exercise in order to develop an in-depth understanding of the problem, identify its cause(s), and propose practical solutions. This approach is a way to "provide enough structure that those who must take responsibility for the consequences of the choices which are made, do so on a coherent basis and with sufficient confidence to make the necessary commitments" (Rosenhead & Mingers, 2001, p. 1). Moreover, structuring the problem allows to describe and solve it from the stakeholders' point of view with our minimum intervention (Montibeller & Von-Winterfeldt, 2015; Rosenhead, 1996; Roy, 1993). The authors also highlighted that identifying the real problem or demand is mandatory in these cases; otherwise, the proposed solution or chosen alternatives will not meet the demand or solve the problem.

It is essential to note that only the final aggregated results will be presented in this chapter in order to preserve the respondents' full anonymity (name, institution, country). All the quotes were carefully selected for the same reasons.

5.1 Mapping the BigSci decision problem

Criticism about the decision-making process of BigSci investments and its accountability brought general disapproval comments from our interviewees as well as definition issues, as shown in Subsection 4.2. This dissatisfaction affects even government representatives:

> There are great scientific interests for some people because you think they will lead to something else than fine Big Science projects…It's important to be able to communicate that to politicians, who invest in these things or who announced these things, should make sure that they understand fully what it is dealing with: taxpayers' money. And that means, therefore, that they need some sort of a framework or guidelines in it; good practice about

> they make a decision, on what basis they make a decision to invest in these things, and be able to demonstrate to their constituents that this is important and why. (GOV)

The era of BigSci has provoked grave concerns about the funding of science and how the government supports BigSci since Ridenour's (1947b) article. A. M. Weinberg's (1961) also discussed these topics, which were dramatically advocated recently by S. Weinberg (2011, 2012). Our interviewees agree with that:

> something where the government and industry and academia are working together on tens of millions, hundreds of millions of dollars projects, and creates difficulties for many governments because governments are not comfortable with these types of projects. The government has not well served our BigSci because they are, I would say, apprehensive about making the choices with taxpayers' money at this sort of level. They're very comfortable at making the levels of, let's say, ten million and less. That's fine. They can go through granting councils and various scholarship funds and whatever. But when you get to hundreds of millions, these are very tricky. (GOV)

As a tool to rationalize the nontrivial and complicated situation of BigSci investment decision-making, the SODA mapping exercise started by translating each of the 50 individual interviews into 50 individual sets of bipolar constructs. Bipolar construct, recalling Section 3.3.1 and Table 3.4, is that pair of concepts from one interviewee constituted by the original construct and its opposite pole, which helps to understand more precisely the meaning of the first (original) pole. Figure 5.1 shows a short extract from an interview and the corresponding bipolar construct, where blue represents the original pole and green, the opposite pole. On average, each interview resulted in 28 bipolar constructs.

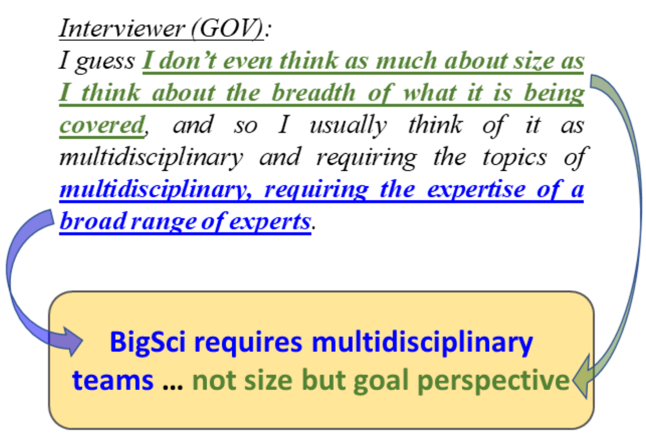

Figure 5.1 Example of a construct's extraction from an interview

As bipolar constructs were identified, it was possible to recognize thematic clusters since all interviewees share concerns, views, and understandings of the same problematic situation. In this sense, we organized the constructs by themes, categorizing the bipolar constructs according to 7 issues (clusters) that emerged from the individual map analysis. Although the names of the clusters are, in the main, self-explanatory, Table 5.1 describes each one derived from individual maps.

Table 5.1 Description of the revealed clusters from the individual SODA maps

Clusters on SODA map	**Description of the primary pole construct:**
Characteristic	has to do with BigSci characteristics.
Stakeholder	is related to BigSci stakeholders' issues, such as matters directly associated with the stakeholders' communities of scientific, industry and government representatives, politicians, decision-makers, managers, technicians, engineers, taxpayers, society in general.
International Collaboration	is related to BigSci international collaboration matters.
Management	is related to BigSci projects' management topic.
Impact	addresses significant BigSci non-scientific impacts (societal, political, economic, environmental, technological).
Decision	has to do with BigSci decision-making issues.
Future Need	addresses BigSci future needs of national significance associated with suggested improvements in BigSci decision problematic situation.

Next, each of the 50 constructs sets was designed into 50 individual SODA maps by causally connecting the bipolar constructs in a manner that reflects each interviewee's understanding of the problematic situation (see example in Figure 3.2).

All mapping and most analyses presented in this chapter were undertaken with the support of Decision Explorer® software[7] designed especially for SODA.

Proceeding with the SODA analysis (Section 3.3.1 and Figure 3.3), a second round of interviews with a possible sample occurred, where we presented and discussed the individual analysis with the interviewee, in particular, checking and adjusting the bipolar constructs. Once those validation meetings were strictly in-person, we had eight individuals to whom we had facilitated access.

[7] Analysis tool by Banxia® Software Ltd.

Since all individual maps provide an overview of the sample, we could identify similarities among them and, initially, categorize them by stakeholders, as previously done in the BigSci definition (Section 4.2). However, only the scientific sector group was internally homogeneous, considering the whole interview, and shared concerns, views, and understandings of the BigSci problematic situation. Industry and government groups presented significant inner differences, mostly reflecting the national context they belong to, making unfeasible those groups as a meaningful basis to proceed with the analysis.

Therefore, to start the second stage towards the final aggregate SODA map (see Figure 3.3), we recognized strong similarities among individual maps from interviewees of the same geographical region. Although this problem seems to be worldwide, as one interviewee highlighted: "Do you know that it is not only this country that suffers from this? Everyone, even richer as the U.S. suffers" (GOV). As a consequence, we created three subsets of maps: Brazil (15), Canada (15), and Europe (20), where the groups are almost equally represented.

We aggregated and synthesized each thematic cluster's commonalities in each of those three subsets, merging one individual map into another, resulting in a group map (see Figure 3.4). It is essential to note that the resulted group map is not the sum of all maps in the group but rather the aggregation and synthesis of constructs facilitated by identified clusters. For instance, the aggregation of two individual maps with 50 bipolar constructs each is not one aggregated map with 100 bipolar constructs. Hence, hundreds of bipolar constructs in each group were aggregated into 69 nodes in Brazil's map, 60 nodes in Canada's map, and 47 nodes in Europe's map.

In the third and last stage towards the final aggregate SODA map (see Figure 3.3 and Figure 3.4), we repeated the exercise of aggregation and synthesis. In other words, we identified similarities in each thematic cluster of each group map, aggregated and synthesized them, merging the three group maps into the final aggregate SODA map with 73 bipolar constructs. Appendix A provides this ultimate list of bipolar constructs. Table 5.2 shows the number of bipolar constructs in each cluster addressed by each group and the total number of bipolar constructs categorized in each cluster in the final aggregated SODA map.

Table 5.2 Clusters categories and breakdown of bipolar constructs

Cluster	Brazil	Canada	Europe	Total	Final Aggregated
Characteristic	4	11	8	23	6
Stakeholder	4	9	8	21	8
International Collaboration	7	1	6	14	5
Management	2	3	4	9	6
Impact	4	4	6	14	7
Decision	43	27	8	78	31
Future Need	5	5	7	17	10
Total	69	60	47	176	73

As mentioned in a prior example, Table 5.2 shows that the aggregation exercise is not a simple sum of single maps but a synthesis exercise. This table also indicates that any BigSci investment decision involves interrelated perceptions and interests from relevant stakeholders, as well as interconnected issues impacting upon such a decision.

Table 5.2 also allows us to identify the top issues which, according to this group of stakeholders, tackle the government BigSci decision investment using the bipolar constructs distribution in each group as evidence; we find that:

- constructs are relatively well distributed in almost all clusters in the European group, highlighting that three of them (Decision, Stakeholder, and Characteristic) have 8 constructs each.
- the Canadian group does not have a similar distribution pattern, but the top issues are the same as those in Europe (Decision, Stakeholder, and Characteristic), with 27, 9, and 11 constructs, respectively.
- Brazil is intensively focused on Decision issues with 43 constructs. In second place is International Collaboration concerns (7 constructs), both clusters reflecting recent complicated experiences in BigSci, followed by Future Need (5 constructs) indicating expectations.

Further noteworthy results about the distribution of the issues in the three geographical areas revealed by Table 5.2 concerns the differences between Brazil, Canada, and Europe, such as those regarding Decision, International Collaboration, and Characteristic. Though a statistical analysis of the results may seem relevant, it is neither part nor purpose of SODA's structuring problem method or pertinent for this research once our goal is not to compare these locations.

Nevertheless, we can briefly highlight that:

- Canada and Brazil have more concerns regarding Decision than Europe suggesting Europeans have a more mature BigSci investment decision process, often criticized by lack of transparency (Hallonsten, 2015; Theil, 2015). Other few assumptions may be considered: (1) their long-term adopted model of intergovernmental science and technology organization is responsible for this uniform distribution of issues; or (2) their dynamic organizational adjustments like the European Research Infrastructure Consortium (ERIC) introduced in 2008 (Moskovko, Ástvaldsson, & Hallonsten, 2019) assure such observed uniform distribution. In any case, European interviewees are not completely satisfied with the decision processes regarding BigSci investments and have similar complaints to those of the Canadians and Brazilians.
- Europe and Brazil have more concerns regarding International Collaboration than Canada, suggesting Canadians focus on building/improving a pan-Canadian own scientific infrastructure capacity in BigSci (Lejeune et al., 2020), on the critical need for more national inter-sectoral/disciplinary collaborations, and also tackling the diversity of national funding sources (provincial and federal) with, sometimes, conflicting procedures and requirements (Halliwell & Foxall, 2009). Alternatively, this result is a product of our sample and the Canadian context of increasing budget for STI (Canada, 2018).
- Europe and Canada have more concerns regarding Characteristic of BigSci than Brazil. This result, combined with that Brazilians are highly concerned about Decision, may suggest that BigSci and its complex matter are weakly known to them, in reality, except for the decision-making on the BigSci required high investment (Hook, 2018; MCTIC, 2016).

If the number of bipolar constructs in each cluster of the final aggregation is used as evidence, the top three issues, in order, are:

- the concerns of the Decision (31 constructs);

- the challenges and proposals to tackle the BigSci Future Need (10 constructs);
- and the role of each involved Stakeholder (8 constructs) in the BigSci context.

Therefore, the top issues indicate that BigSci investments depend strongly upon (1) an effective decision-making process; (2) updating the decision-making process according to the context in effect at the time it is used; (3) the ability to match actors involved with the necessary stakeholders in BigSci decision. These priority issues reflect the literature, where criticisms and recommendations indicated a mix of transparent, but effective, government decision-making process (Gingras & Trepanier, 1993; Leach, 1973; Linton, 2008; Theil, 2015; S. Weinberg, 2012), up to date knowledge of world BigSci landscape (OECD, 2019b), and active participation of interested parties in the decision process (Theil, 2015; A. M. Weinberg, 1963).

The 73 bipolar constructs (Table 5.2) resulted from merging the group maps into one final map upon which all subsequent analyses were based. The final SODA map yielded the distribution of types of dominant constructs shown below in Table 5.3. Dominants, recalling Section 3.3.1, are bipolar constructs with a high total number of links, having a relatively high degree or connections. In graph language, the high total number of received connections means a high total sum of indegrees and, regarding transmitted connections, refers to outdegrees. Degrees or connections in the final SODA map ranged from 1 to 19. The count listed in Table 5.3 was based upon a degree $\geq$ 10, that is, a number of constructs with at least 10 (causal) connections.

Table 5.3 Number of dominant constructs of a particular type per cluster

	Types of constructs			
Clusters	**Tails**	**Heads**	**Implosions**	**Explosions**
Characteristic	1	0	0	3
Stakeholder	0	0	1	2
International Collaboration	0	0	0	2
Management	0	0	0	0
Impact	0	0	0	1
Decision	0	1	2	1
Future Need	0	0	2	1
Total	1	1	5	10

Table 5.3 summarizes the final SODA map results according to the method (Section 3.3.1). It allows us to uncover the essential characteristics of the situation faced by BigSci stakeholders concerning government decision of BigSci investments. One peculiar aspect of Table 5.3 refers to

the results of cluster Management and its meaning. Firstly it should be highlighted that Management issues were quite frequent and relevant among all interviews and all ‘aggregation and synthesis’ exercises to reach the final SODA map with 6 bipolar constructs out of 73. However, considering an overall view of the interviewees (final SODA map), Management constructs matters are not prime causes (tails) or do not reflect objectives, outcomes, results, or consequences (heads) of the BigSci investment decision problem. Moreover, Management issues do not indicate significant effects (implosions) or major causes (explosions), affecting various other issues. In short, Management issues, in interviewees’ perceptions, do not have central relevance (dominants) to the decision situation in question, but still, it is a substantial aspect of the overall SODA map.

The subsequent four subsections will explore each of the four types of constructs, their meanings and implications. In the following analysis, the numbering of bipolar constructs is purely random and serves only to reference them (they will be referenced in italics throughout this chapter). Moreover, the arrows or links in the maps (see Figures 5.1 and 5.2) connect the bipolar constructs causally, and the three dots between constructs serve to distinguish the two poles, the primary pole followed by the alternative pole. Finally, the constructs refer to Big Science as BiS due to space constraints on the map.

5.1.1 Dominant constructs: tail or prime cause

In SODA maps, tails are known as prime causes. According to Table 5.3, there is one single prime cause or trigger to the BigSci investment decision problem. The Characteristic’s tail indicates that it is a crucial initiator:

- *5* BiS nature is to explore the frontier of knowledge … industrial applications aren’t the main activity

The map revealed that an intrinsic BigSci Characteristic could mainly promote its problematic regarding government investments decision. BigSci nature of exploring the frontier of knowledge makes those initiatives too complex and abstract to most people not directly involved in the technical part, and many times far from day-to-day reality and short-term economic and social benefits to society, usual in industrial applications research (applied science nature). This basic science nature of BigSci and its cutting-edge search is proudly, and sometimes sarcastically, emphasized by all interviewees. Still, none pointed out that it was the prime cause of all problems. In some way, this situation is recognized by the literature but not precisely highlighted as the prime cause of the investment problem. As already previously presented in Section 2.7, the Nobel laureate Steven Weinberg (2011) reported: “I said, ‘I widely agree…experiments…going to help us discover the laws of nature, the principles governing everything. Won’t you think that in a high priority?’…he [a senator] said: ‘NO’”. While scientists believe that “the least important argument we use or wish to use it is the technological spin-off” (S. Weinberg, 2011), all other BigSci stakeholders disagree and are interested in industrial applications research, economic development, and relatively short-term returns/benefits.

Figure 5.2 reveals part of our SODA map, highlighting the Tail’s connections (outdegree = 15) with bipolar constructs from all clusters. Thus, the magnitude of infrastructures, challenges, benefits, and duration (constructs *2*, *3*, *1*, *4*) of BigSci projects are only consequences of its audacious scientific goals and nature and not the main trigger of the investment decision problem. While the diverse and high defiant nature of BigSci projects makes it a global challenge to establish a general decision process for investments (Theil, 2015), those decisions are more complex than similar processes for regular scientific projects (constructs *72*, *50*, *63*). In recognition of the consequences of BigSci’s nature of aiming for high advanced knowledge, Future Needs emerged from the map.

- It requires an exclusive budget (construct *41*) as also recommended by Ridenour (1947b) more than 70 years ago.
- It needs a critical mass of the scientific community's quantity, quality, and excellence (construct *40*) justifying the involved high costs, as also pointed out by A. Weinberg (1963).
- It strives for improvements on BigSci procurements (construct *34*) as a way of enhancing industrial relationships, agreeing with many authors (Åberg & Bengtson, 2015; Autio, 2014; Autio et al., 2004; Biagioni, 2015; Castelnovo et al., 2018; Dal Molin & Previtali, 2019; Florio et al., 2018; Vuola & Hameri, 2006).

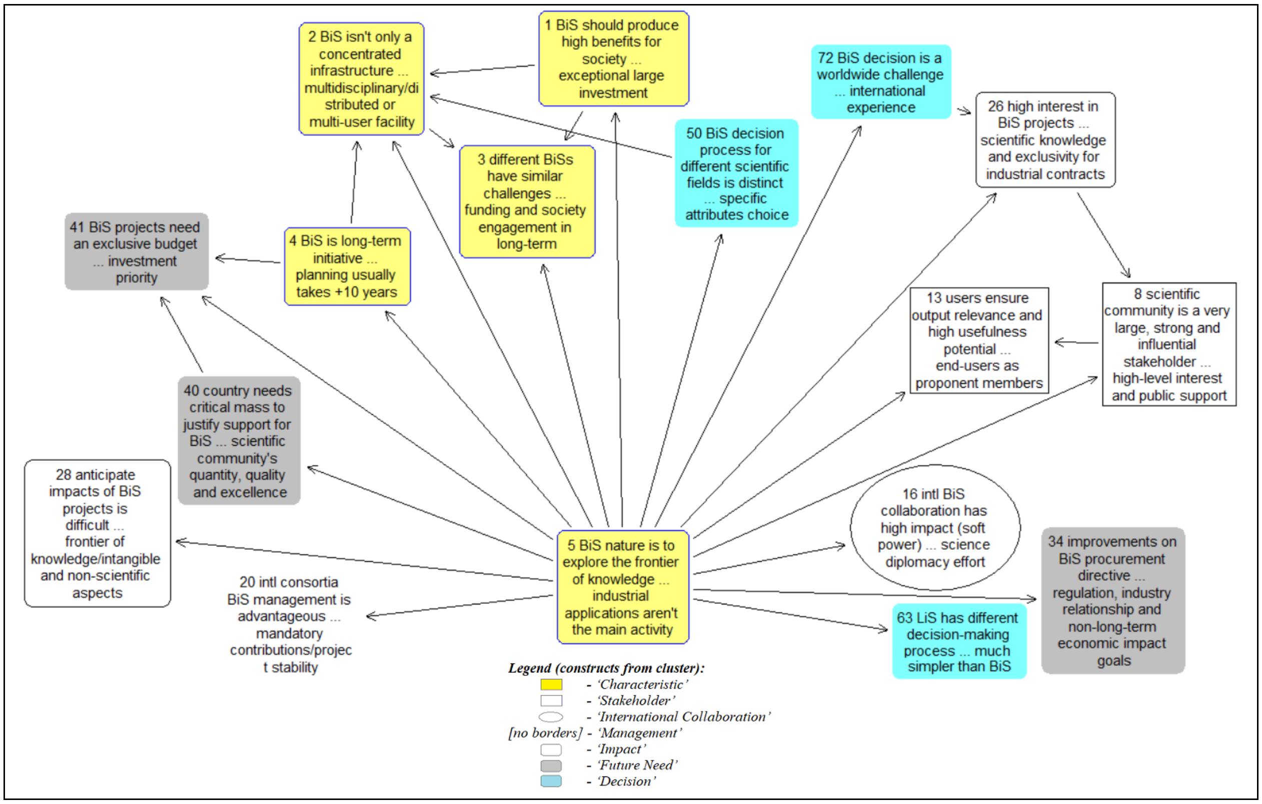

Figure 5.2 Constructs directly affected by the prime cause (tail = construct *5*)

The power of influence of scientists and users in the BigSci context is a consequence of all laypeople's respect for their search at the frontier of knowledge (constructs *8*, *13*) for solutions to global challenges. Although those scientists and users are not able to easily anticipate the non-scientific impacts of BigSci projects (construct *28*), there is a high interest (construct *26*) in non-scientific effects among government and industry communities, but not so much in the scientific community, as exemplified above (S. Weinberg, 2011). In contrast, the seemingly small contribution afforded by Management and International Collaboration hides a complex set of variables associated with science diplomacy efforts driven by consortia advantages and potential soft power (constructs *20*, *16*).

The multitude of consequences triggered by BigSci exploratory nature, including stakeholders' conflicts, impact assessment, and investment decisions, has detrimentally affected the practical understanding of the exact origin of BigSci support problems and, consequently, its effective solution.

5.1.2 Dominant constructs: explosions or major causes

In SODA maps, explosions indicate major causes and affect multiple areas of the map; they are also from where many issues stem or diverge. Table 5.4 presents the dominant explosions and their respective outdegree, excluding the tail mentioned above in the previous Subsection.

Table 5.4 Map dominant explosions

Bipolar construct	**Outdegree**
31 BiS has political impact ... scientific/economic/industrial development & policies	16
6 lack of BiS definition by government … stakeholders want specific one	13
1 BiS should produce high benefits for society … exceptional large investment	10
16 intl BiS collaboration has high impact (soft power) … science diplomacy effort	10
37 lack of systemic roadmap for BiS … framework for encompassing all disciplines	9
4 BiS is long-term initiative … planning usually takes +10 years	8
7 industry is a stakeholder … build facilities, push tech frontier, innovation source, and spin-offs	8
8 scientific community is a very large, strong and influential stakeholder … high-level interest and public support	7
18 share goals and principles are required by government for BiS collaboration … cost sharing	6
49 government decision making in BiS isn't transparent … political-driven	6

An especially interesting exploding construct was identified in the map and Table 5.4: bipolar construct *31*. Several factors combined draw attention to this exploding construct. It has an outdegree of 16, making it the largest explosion in the entire map (Figure 5.3), even more than our tail with an outdegree of 15. Undoubtedly, it is a significant cause influencing the whole situation but also the most polemical of the map: it concerns BigSci political impact and related policy-making. Any discussion about BigSci political impact will inevitably point to multiple and collateral effects such as international relations and soft power (construct *16*), mandatory requirements for international collaborations aiming cost-sharing (construct *18*), or the lack of transparency in government decisions of BigSci investments (construct *49*). The latter, in particular, has been the topic of discussions and concerns in the literature for decades (Gingras & Trepanier, 1993; Hallonsten, 2015; Lambright, 1998; Leach, 1973; Theil, 2015).

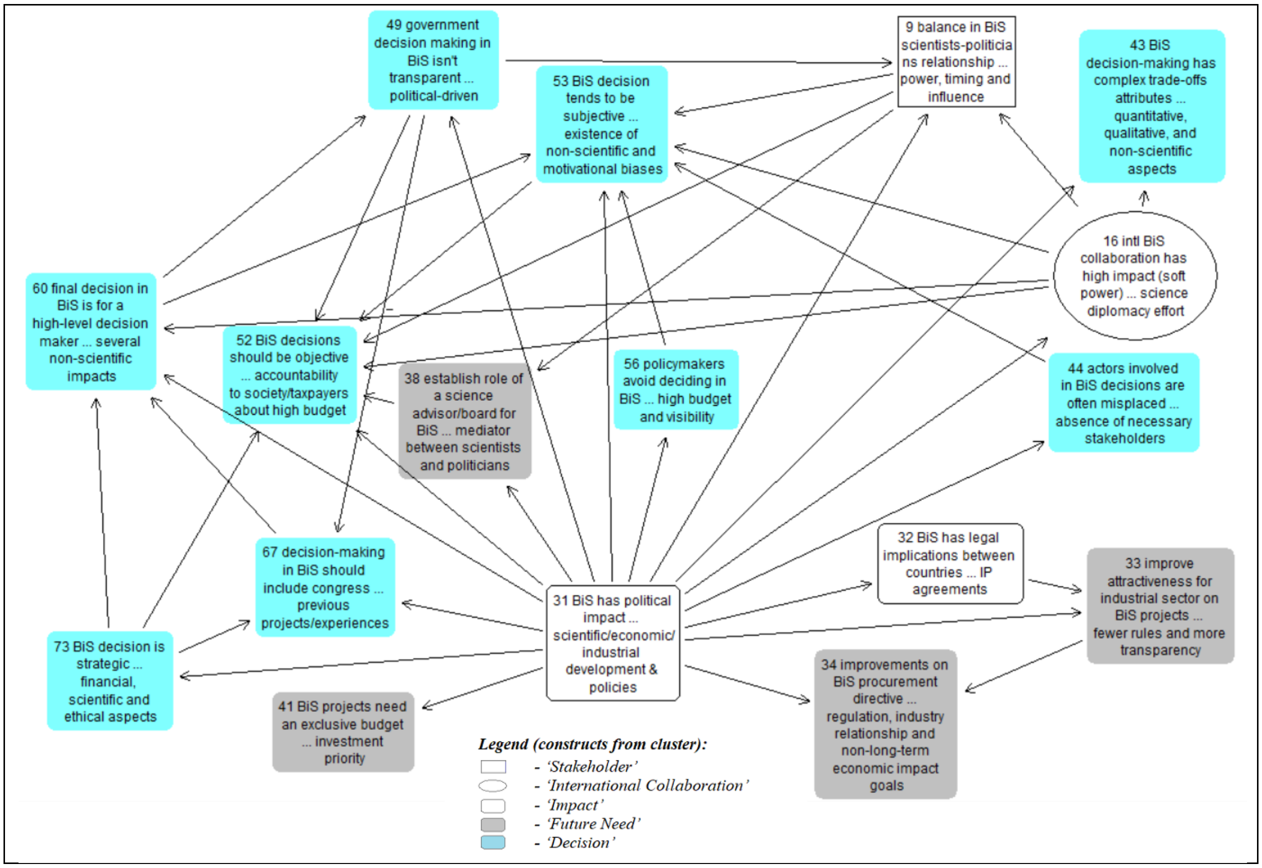

Figure 5.3 Example of an explosion in our SODA map

The primary cause recognized as the map's tail (construct *5*) reflects that BigSci issues are too vague and too broad, and the political impact (construct *31*) reinforces those features, resulting in a series of deficiencies:

- lack of transparency in the decision, rendering it political-driven (construct *49*);
- lack of workable parameters to ground the decision, such as a BigSci definition, meeting the demands of the involved stakeholders (construct *6*);
- lack of a systemic roadmap for BigSci, encompassing all disciplines and supporting the government's scientific, economic and industrial development planning (construct *37*).

Any kind of non-scientific benefits to society is highly desirable and demanded to justify such exceptionally huge and long-term investments with taxpayers' money (constructs *1*, *4*). In particular, the scientific impacts are usually too complex and abstract in their intrinsic nature (construct 5) to assure the public support alone. BigSci benefits assessment is another hot topic in the literature, highly investigated and more recently explored (Castelnovo et al., 2018; Florio, Forte, Pancotti, Sirtori, & Vignetti, 2016; Magazinik et al., 2019; Puliga et al., 2019). Nevertheless, they are still symptoms, not the prime cause of the problematic situation regarding BigSci government support.

Scientific and industrial communities share interests in BigSci initiatives (constructs *8*, *7*), leading them to claim to participate and favorably influence the government decision-making process in terms of BigSci investments.

In brief, Table 5.4 makes explicit a list of significant causes of the problematic practice of public financial support of BigSci. This situation points out that the political impact and listed correlated public issues as primary significant reasons, particularly the government's non-transparent decisions of huge long-term investments with taxpayer's money.

5.1.3 Dominant constructs: implosions or major effects

In SODA maps, implosions indicate significant effects affected by multiple areas of the map; they are where various issues culminate or converge. Table 5.5 presents the dominant implosions and their respective indegree, excluding the head that will be discussed in the next Subsection.

Table 5.5 Map dominant implosions

Bipolar construct	**Indegree**
41 BiS projects need an exclusive budget … investment priority	11
9 balance in BiS scientists-politicians relationship … power, timing and influence	9
53 BiS decision tends to be subjective … existence of non-scientific and motivational biases	9
33 improve attractiveness for industrial sector on BiS projects … fewer rules and more transparency	8
43 BiS decision-making has complex trade-offs attributes ... quantitative, qualitative, and non-scientific aspects	6

Similar to the analysis of explosions, an especially interesting imploding construct was identified in the map and Table 5.5: bipolar construct *41*. It has an indegree of 11, making it the second-largest implosion in the entire map, following closely the head (construct *52*), which has an indegree of 14 (Figure 5.4). Indeed, construct *41* indicates a major effect as well as a significant construct from the Future Need cluster. It also represents a challenge to overcome or an opportunity to take towards the strategic objective (the head of the SODA map – construct *52*) regarding the

BigSci decision problem under consideration. The construct *41* concerns an exclusive budget for BigSci projects, separated from the regular federal STI annual budget of the national governments. Any discussion about BigSci budget passes through public investment prioritization, be it among federal strategic plans for the country, among social benefits, wage plans, national labor agreements, international trade agreements, expected incomes and taxes, or yet among STI large and small investment strategic plans and projects. Investment prioritization is generally a hard challenge for any nation (construct *72*). Then, an exclusive budget for BigSci generates a new challenge: prioritize among projects of different scientific fields. The government's decision of BigSci investment is not a problem per se. However, it seems to be a situation, born together with BigSci, facing the challenging (still) future need of an exclusive budget, as Ridenour pointed out in 1947. Nevertheless, a challenge with complex trade-off attributes to make decisions encompassing quantitative, qualitative and non-scientific aspects (construct *43*), as provoked by A. Weinberger (1961), and later recommended by the author in 1963 and some others more recently (Catalano et al., 2016; Hicks et al., 2015; Lambright, 1998; Linton, 2008).

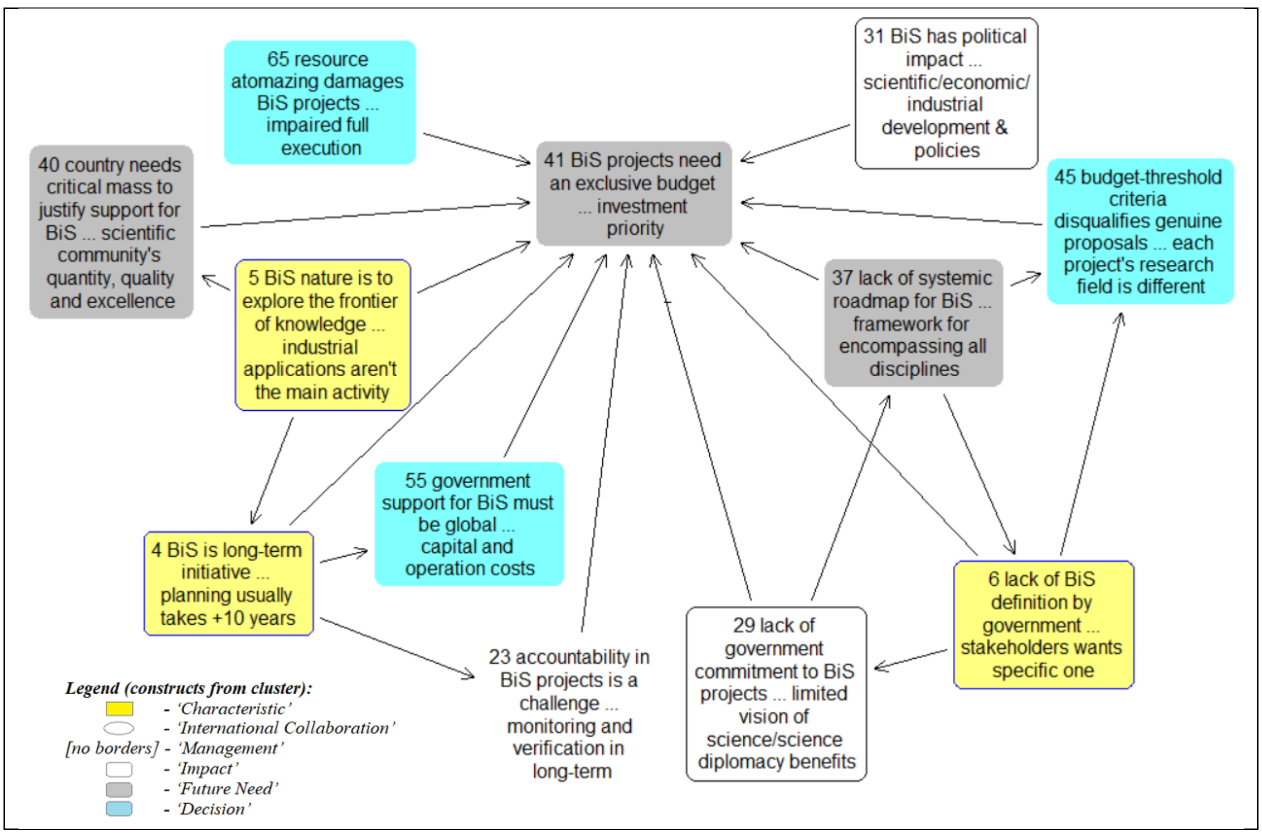

Figure 5.4 Example of an implosion in our SODA map

Long-term financial responsibility, fewer rules and bureaucracy, and more transparency in public BigSci issues are severe considerations for improving opportunities and enhancing attractiveness for industrial sectors in BigSci initiatives (construct *33*), mainly towards knowledge and technology transfers and innovation. The literature has many studies and recommendations to government on how to turn BigSci into a much sought after endeavor for industrial partners favorably bridging all stakeholders (Åberg & Bengtson, 2015; Autio, 2014; Autio et al., 2004; Biagioni, 2015; Castelnovo et al., 2018; Dal Molin & Previtali, 2019; Florio et al., 2018; Vuola & Hameri, 2006).

Although Stakeholder, Decision, and Future Need concentrate the five significantly imploding constructs, one particularly significant bipolar construct emerged from the analysis: construct *9*. It derives from the Stakeholder cluster and has nine bipolar constructs leading into it. It refers to the challenge of achieving a balanced relationship between BigSci scientists and, on the other end of the scale, the politicians, influencers, or high-ranking government decision-makers. Conflicting issues regarding timing (Aguilaniu, 2019), power and influence over the society's opinion (3M, 2019) have been under scrutiny, particularly recently with the global coronavirus pandemic, when governments have gotten lost in uncertainties between science outcomes and recommendations, as well as between economic decline and social crisis (Chang & Velasco, 2020; Nicola et al., 2020; Ozili & Arun, 2020).

BigSci projects are long-term commitments and the decision's subjectivity trend (construct *53*), due to motivational and non-scientific biases from government decision-makers, is a severe significant consequence of the lack of decision support structures like systemic roadmaps (construct *37*), BigSci definition (construct *6*), workable thresholds addressing proposals (construct *64*), and also necessary stakeholders in proper positions and roles in the decision process (construct *44*).

In brief, the imploding constructs indicate that part of the solution of BigSci investment decision depends on them and can be understood as challenges that compromise the long-term legacy and image of BigSci to society and even the country's international reputation.

5.1.4 Dominant constructs: head and strategic options

In SODA maps, heads mainly reflect objectives, goals, purposes. According to Table 5.3, there is only one Head, construct *52*, offering a good idea of what the problematic situation under analysis is about:

- *52* BiS decisions should be objective ... accountability to society/taxpayers about high budget

This Head revealed a deeper and more powerful central Decision problem regarding government choices of BigSci investments. It also pointed out that the one single goal to achieve a solution to this BigSci decision problematic situation is to promote a decision-making process that should be objective, i.e., grounded on qualitative and/or quantitative criteria. It is not a matter of solving stakeholders' conflicts or promoting a better BigSci related decision by only including other interested stakeholders in the process. The practical solution to the problematic situation aims to develop an objective decision-making process regarding BigSci investments. It is mandatory to remind that those complex decisions usually come with another additional hard choice regarding selecting proposals from different disciplines. This extra challenge makes objectivity and rationality in the government decision-making even more crucial to assure accountability to society and taxpayers of such incredibly high budgets involved. Alvin Weinberg, in a 1963 article in Minerva, wrote that the decision situations demanding priority setting among scientific fields in BigSci, due to limited money, must be based on objective and transparent criteria, mainly "technological merit, scientific merit and social merit" (Weinberg, 1963, p. 164).

Figure 5.5 reveals part of our SODA map highlighting the Head's connections with bipolar constructs from all clusters, except Management. Thus, the scope and scale of the potential non-scientific benefits and impacts of BigSci (constructs *1*, *16*, *31*) require particular attention and drive the need for an objective decision. When evaluating significant investments such as BigSci projects, taxpayer's expectation of a paradigm shift in decision-making (constructs *53*, *49*, *62*), as well as a strategic (construct *73*), careful (construct *71*), impartial (construct *58*), and technically supported process (constructs *66*, *38*, *9*, *51*, *54*) need to be fulfilled.

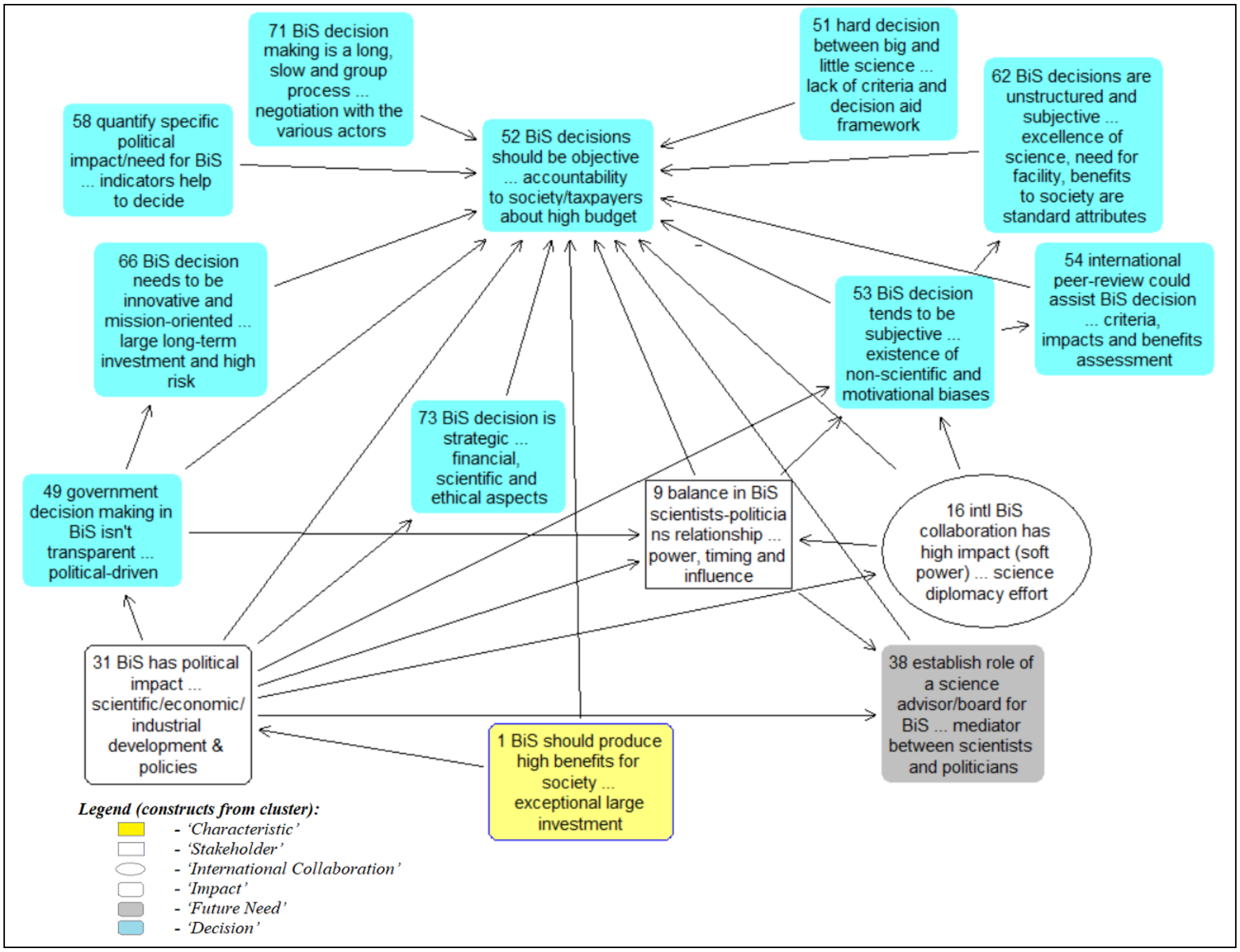

Figure 5.5 Constructs directly leading to the objective (head = construct *52*)

In SODA maps, alternative constructs with direct links to a head are called strategic options, from which the methodology takes its name, and reflect the opportunities available through which a particular result (head) may happen. In other words, the alternative constructs offer good ideas or paths for how the problematic situation under analysis may eventually find a solution (reach the goal/head) according to stakeholders' vision. Thus, Figure 5.5 also reveals numerous possible strategic options available to tackle the goal (construct *52*). Strategic options may be highlighted for emphasis, and in Table 5.6, they appear in bolds.

Table 5.6 Map strategic options

Bipolar constructs	**Cluster**
1 BiS should produce high benefits for society … **exceptional large investment**	Characteristic
9 balance in BiS scientists-politicians relationship … **power, timing and influence**	Stakeholder
16 intl BiS collaboration has high impact (soft power) … **science diplomacy effort**	International Collaboration
31 BiS has political impact … **scientific/economic/industrial development & policies**	Impact
38 establish role of a science advisor/board for BiS … **mediator between scientists and politicians**	Future Need
49 government decision making in BiS isn't transparent … **political-driven**	Decision
51 hard decision between big and little science ... **lack of criteria and decision aid framework**	Decision
53 BiS decision tends to be subjective … **existence of non-scientific and motivational biases**	Decision
54 international peer-review could assist BiS decision … **criteria, impacts and benefits assessment**	Decision
58 quantify specific political impact/need for BiS … **indicators help to decide**	Decision
62 BiS decisions are unstructured and subjective … **excellence of science, need for facility, benefits to society are standard attributes**	Decision
66 BiS decision needs to be innovative and mission-oriented … **large long-term investment and high risk**	Decision
71 BiS decision making is a long, slow and group process ... **negotiation with the various actors**	Decision
73 BiS decision is strategic ... **financial, scientific and ethical aspects**	Decision

We found, from Figure 5.5 and Table 5.6, that the attempts to address the objective through these options depend on several work fronts:

- Characteristic, Impact and Decision – long-term, huge, high-risk investment in mission-oriented BigSci associated with scientific/economic development requires social and political responsibilities (constructs *1*, *66*, *31*);

- Stakeholder, Future Need and Decision – non-scientific and motivational biases require long and careful negotiation between BigSci scientists and government decision-makers with the help of a well-designated mediator such as a science advisor (constructs *53*, *9*, *71*, *38*);

- International Collaboration – science diplomacy efforts contribute significantly to establish successful BigSci international collaborations and consequent high impact and soft power (construct *16*);
- Decision – strategic BigSci decisions need a decision support framework based on standard attributes, criteria, and indicators, considering scientific and non-scientific aspects and assessments and avoiding only political-driven biases (constructs *51*, *58*, *54*, *62*, *73*, *49*).

Each of those four critical work fronts, indicated by the interviewed stakeholders, has the potential to profoundly modify the analyzed problematic situation, reaching the objective, and consequently, a solution. Here, our research will propose a framework as recommended above and so a possible solution to the problem of government decision of BigSci investments.

5.2 Concluding remarks

Chapter 5 describes Phase B meso-level results, analysis, and findings as well as a general discussion, including the SODA analysis of the interviews and interpretation of results. Phase B gave a further step in the progressive approach to this research's primary goal, reaching another secondary objective of structuring the problem of government BigSci investments.

An in-depth rational analysis for a complex and/or conflict situation, like the one investigated in our research, required an exploratory approach before any prescriptive action towards a practical choice to improve, change or solve the BigSci problematic situation. This problem structuring approach through SODA mapping (Section 5.1) allowed to understand the decision problem in detail, identifying the origin and the resolution of the analyzed problem from the stakeholders' point of view. Moreover, SODA allowed uncovering the meaning of what the interviewees said, minimizing ambiguities.

In this sense, we found that the origin (tail) of the decision problem of BigSci investments is not the enormous amount of money required but the complexity of playing with the 'almost science fiction nature' of BigSci exploration beyond the frontiers of knowledge (Section 5.1.1). We also learned that our investigated problem's strategic goal (head) is to achieve an objective decision process and not merely to include scientific and industrial communities in this process (Section 5.1.4). Besides, stakeholders' perceptions generated the strategic options, paving ways for problem-solving and allowing us to choose one option to develop: a framework grounded on quantitative and qualitative criteria to support decisions of BigSci investments.

Enormous budgets to build supercolliders with circumferences of many kilometers and misunderstood value to almost all society exemplify our problematic real-world situation of BigSci investment decision. Examples comprise the US$21-billion Circular Electron Positron Collider (CEPC) in China to be completed by 2050 (Borak, 2019), or the €21-billion Future Circular Collider (FCC) in Switzerland to begin construction by 2038, and the extra funds to CERN's participation in a separate International Linear Collider (ILC) in Japan (Castelvecchi & Gibney, 2020).

Finally, in this section, we also expose a few elucidations about this part of our research to avoid misunderstandings or hasty conclusions regarding our findings.

We faced the challenge of obtaining the highest-quality information possible by interviewing people who have the information we need and learning with them. This exercise is "largely dependent on the interviewer" (Patton, 2002, p. 341). Among other factors, it was noticeable that the interviewer's nationality caused different reactions among the interviewees, affecting the quality of information derived from the interview.

We must also recall that the usefulness of our results from the SODA map is restricted to decision problems regarding new BigSci investments because this was our focus in collecting the stakeholder's interview, and that is what the map is about. So, the results cannot be extended to another critical type of BigSci investment decision related to Management: funding BigSci project continuation. In this sense, there are two types of situation:

- when there is no longer scientific relevance (construct *24*). This problematic situation emerged from our interviews and analysis as well as from the literature where the solution has been to turn BigSci projects into multiuser RIs (Crease & Westfall, 2016; Hallonsten, 2016a, 2020; Lillian Hoddeson et al., 2008; Westfall, 2019).
- and when there is a severe apparent management problem. This problematic situation emerged from the literature where different solutions were adopted, such as cancel the project (Kevles, 1997; Lambright, 1998) or implement organizational/governance profound changes (Theil, 2015).

CHAPTER 6 MULTI-CRITERIA MODELING

In the second results and discussion segment (Chapter 5), we structured the BigSci investments' problem, revealing its prime cause and strategic options towards a solution, based on stakeholders' perceptions. In this chapter, the third step towards this research's main goal (Section 1.2) presents the development of a multi-criteria model, identifying (eliciting) government decision-makers' values, preferences, judgements, and criteria related to BigSci investments.

While science and technology have always been essential to and driven by warfare, the increase in military funding of science following the WWII was unprecedently high (Forman, 1987; Heyck & Kaiser, 2010; Kaiser, 2002; Smith & Tatarewicz, 1994). This trend brought many concerns and discussions regarding government decision of BigSci investments, putting it under scrutiny by the scientific community and society in general (Gingras & Trepanier, 1993; Hellström & Jacob, 2012; Johnston, 2018; Leach, 1973; Linton, 2008; Ridenour, 1947b; A. M. Weinberg, 1961, 1963, 1964). It is noteworthy that A. M. Weinberg spent a significant part of his career as a competent and vigorous advocate of BigSci and technoscience solutions to societal problems reflected in his long series of publications (Johnston, 2018). In particular, his 1964 article in Minerva pointed out:

> I turn now to the broader question: what criteria can society use in deciding how much it can allocate to science as a whole rather than to competing activities such as education, social security, foreign aid and the like? That such a question can assume any urgency is in itself remarkable. To have suggested that the Federal Government of the United States would be spending about 3 percent of the gross national product for research and development would have been unbelievable 25 years ago. Most of the new attitude toward government support of science and technology was prompted by war and fear of war… As science has become big, it has acquired imperatives, just like any other activity of government, to expand and to demand an increasing share of public resources, and now, for the first time, it has become big enough to compete seriously for money with other major activities of government. (A. M. Weinberg, 1964, p. 3)

BigSci has always meant significant challenges, whether scientific or not, and BigSci nature makes all issues related to its support and investments a harder one, as previously discussed in Chapter 5. While it is possible to study BigSci by describing, analyzing and explaining its macro-level aspects, all of which undeniably essential, it is also possible and desirable to investigate the complex micro-level features of BigSci, such as government decisions criteria for investments. Thus, Chapter 6 will focus on the multi-criteria model, paving the way for adopting the Decision's strategic option unveiled by the BigSci problem structuring in the previous chapter.

6.1 Building the multi-criteria model of BigSci investment decision

Without a doubt, a great many highly useful and revealing information from our interviews and the SODA analysis genuinely contributed, in addition to the literature, to understand the phenomenon of contemporary BigSci as understood here, its role in society, and more specifically, the process of government decision-making of its investments. Moreover, those sources constitute crucial elements or “a prelude to the structuring of an MCDA [Multi-Criteria Decision Analysis] model” (Franco & Montibeller, 2010, p. 1). Thus, the first action towards a multi-criteria model was done in Chapter 5 by structuring the BigSci investment problem situation and defining the problem of achieving an objective decision process for civil BigSci investments.

Once again, all those sources contributed to the next tasks towards building a multi-criteria model for BigSci investments: structure a value tree and develop attributes for bottom-level objectives (Section 3.4.1). So, we decomposed the overall objective into operational objectives or stakeholders’ values based on extraction and ‘construction’ of information (Franco & Montibeller, 2010b; Montibeller & Belton, 2006) from our sources such as the SODA maps (e.g., Figure 5.5), the literature (e.g., Halliwell & Foxall, 2009; OECD, 2019a) or our interviews’ set. The exercise of structuring the value tree resulted in Figure 6.1 that presents a value tree for evaluating different BigSci projects for investments. From SODA analysis but not restricted to, we extracted that the stakeholders are concerned with an objective decision-making process to perform such evaluation, conformity to their rules/values, and also supported by verifiable facts, evidence and analyses, taking into consideration the potential benefits to society (e.g., new vaccine), availability of technology and experts, and project’s global costs.

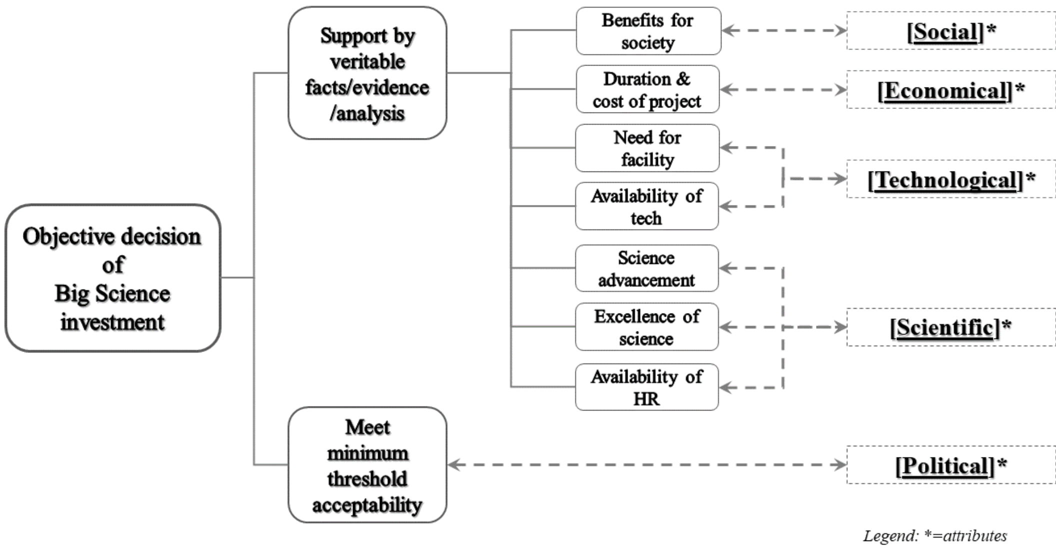

Figure 6.1 A value tree for achieving an objective decision of BigSci investment

Furthermore, it may well be argued that to achieve an objective decision process for civil BigSci investments, clearly defined and transparent quantitative and qualitative attributes are required (Hicks et al., 2015). Thus, defining the attributes consisted of translating each objective/value at the bottom level of the value tree (Figure 6.1) into attributes in order to, each one of them, evaluate a specific characteristic of the decision option. This exercise resulted in five attributes set to measure the achievement of the operational objectives: scientific, technological, social, economic, and political, as shown in Figure 6.1. Although the names of the attributes are, in essence, self-explanatory, Table 6.1 describes each one of them.

Table 6.1 Description of the attributes of the multi-criteria model

Attribute	**Description**
Scientific	Criteria set related to the BigSci project's scientific features under consideration, mainly analyzed and assessed by a scientific commission.
Technological	Criteria set related to the BigSci project's technological features under consideration, mainly analyzed and assessed by an industry commission.
Social	Criteria set related to social impacts and benefits of the BigSci project under consideration, mainly analyzed and assessed by government analysts.
Economic	Criteria set related to economic impacts and benefits of the BigSci project under consideration, mainly analyzed and assessed by government analysts and an industry commission.
Political	Criteria set related to political issues affecting and influenced by the BigSci project under consideration, mainly analyzed and assessed by government analysts.

Those five attributes do not encompass BigSci conceptualization/categorization issues. In other words, the multi-criteria model is restricted to evaluate BigSci investments and to categorize whether a scientific proposal is BigSci or not.

The other challenging task to conclude the transition from the SODA map to the multi-criteria model is to identify/create criteria associated with the attributes (Section 3.4.1). An essential aspect of identifying/creating criteria is to use several information sources, in our case, SODA maps, the literature, and the interviews.

For instance, in 2012, transposing A. M. Weinberg's criteria for scientific choices (A. M. Weinberg, 1963, 1964) for today's decisions, Hellström & Jacob (2012) updated and complemented the criteria for priority setting in science policy. Those prior proposals added to other studies about the socio-economic impact of BigSci (Horlings, Gurney, Somers, & Besselaar, 2012; OECD, 2019a) and our interview's analysis through SODA allowed us to build a list of 24 main criteria (first-level) and 17 sub-criteria (second-level) encompassing all five attributes described above. This exercise followed the relevant considerations recommended by Belton & Stewart (2002) to all multi-criteria approaches. In other words, our criteria set is characterized to be as simple, understandable and measurable as possible to be operational, complete, but concise and non-redundant, assuring independence in each criterion judgement as well as value relevance. Besides that, the choice of the sub-criteria/indicators taken to evaluate the criteria tries to be as comprehensive as possible to cover all research fields' specific main features as well as takes current practices, but does not discuss them since it is not our study's goal.

Among the bipolar constructs derived from the SODA analysis (Appendix A), some directly address BigSci decision-making issues, including criteria and attributes, such as constructs *48*, *50*, and *73*. Those constructs expose the stakeholders' position, highlighting that BigSci decision-making cannot be based only on economic and scientific criteria; it needs specific attributes for distinct scientific fields; and it is strategic encompassing financial, scientific, and ethical aspects.

One common aspect to all following subsections regards the customization of the multi-criteria model. To this research, we understand customization as the process of conforming the proposed multi-criteria model and framework to the decision-maker or group of decision-makers who apply it to BigSci investment choices. This process involves identifying the decision-makers' preferences, judgments, and weights regarding each attribute, varying accordingly to the BigSci investment case. It also encompasses the elicitation process (Section 3.4.1) of weights, impact levels, anchor values, and value functions for each criterion by a specific expert team, considering the decision-maker's preferences and the project's primary research field.

In addition, tables in the subsequent five subsections will expose the identification and source of each criterion of the five attributes as well as a 'first guess' for their respective impact levels/anchor values that may be determined by the expert team in charge of this task. It is noteworthy that the expert team has a crucial role in establishing the indicators for the qualitative criteria such as 'Basic science', 'Dual-use tech', and others (see Tables 6.2 – 6.6). A detailed definition of all criteria is available in Appendix B.

6.1.1 Scientific attribute and corresponding criteria

This Scientific attribute measures, defines and articulates several operational objectives associated with the intrinsic complexity of providing verifiable facts/evidence/analysis concerning scientific issues. Nevertheless, in a less standardizing identification, the defined/created criteria to assess scientific characteristics of the BigSci investment proposals (decision options) are mainly derived from SODA analysis and the literature, as presented in the table below. Table 6.2 presents the set of first-level and second-level criteria that constitutes the Scientific attribute, including quantitative ones denoted by an '*' and main features. A detailed description can be found in Appendix B.

Table 6.2 Criteria and main features of Scientific attribute

1st-level criteria	**2nd-level criteria**	**Measurement unit**	**Anchor values / impact levels**	**Source**
Basic science	-	Experts judgement (scientists)	0 = no 50 = partial 100 = yes	(OECD, 2015; A. M. Weinberg, 1963)
Knowledge frontier	-	Experts judgement (scientists)	0 = minimal 50 = partial 100 = yes	Constructs *28*, *46* (Appendix A)
Human resources	-	Experts judgement (scientists)	0 = low 50 = medium 100 = high	Constructs *30*, *40* (Appendix A)
Topic nature	-	Experts judgement (scientists)	0 = full 50 = partial 100 = no	Interviews with scientific and government representatives
Team excellence	HI publication*	Number of publications in Q1 journals	0 = minimal 50 = good 100 = excellent	Construct *40*, *62* (Appendix A) (Florio, Forte, Pancotti, et al., 2016; Hallonsten & Christensson, 2017; OECD, 2019a)
	Book & chapter*	Number of books and book chapters	0 = minimal 50 = good 100 = excellent	(Florio, Forte, Pancotti, et al., 2016; Hallonsten & Christensson, 2017; OECD, 2019a)
	Citation*	Total number of citations	0 = minimal 50 = good 100 = excellent	(Giffoni et al., 2018; OECD, 2019a)
	Patent*	Number of patents granted	0 = minimal 50 = good 100 = excellent	(Autio et al., 2003; OECD, 2019a)
	Grants*	Number of national and international grants	0 = minimal 50 = good 100 = excellent	(Brottier, 2016; OECD, 2019a)

The Scientific attribute encompasses qualitative and quantitative variables, which explains the different measurement units in Table 6.2. By measurement units for the qualitative scientific criteria, we understand the experts' judgement as the analysis and assessment of evidence related to a given criterion by an expert group based on clearly defined and transparent objectives, values and preferences of the decision-maker or group of top decision-makers involved. The idea of counting on expert teams to aid the strategic decision-making of complex problems in the public sector, such as BigSci investments, is consistent with the literature (Caruzzo et al., 2020; Cuoghi

& Leoneti, 2019). Moreover, as pointed out by one interviewee regarding stakeholder involvement in the decision process: "Who needs to be involved? Or who is involved? It is not necessarily the same thing" (interviewee from the government). Thus, we had the opportunity to suggest the participation and composition of expert teams who needed to be involved, according to our understanding. In this research, regarding the Scientific attribute, we suggest that the scientific expert team (commission) should be formed by an independent and small (up to 10 members) group of international multidisciplinary high-level scientists, consistent with the literature as well (Hellström & Jacob, 2012; A. M. Weinberg, 1963).

Moreover, it is evident that quantitative criteria are usually less ambiguous than qualitative ones, particularly when comparing BigSci projects of different disciplines. So, the critical point to turn this feasible is the normalization promoted via expert judgement and anchor values/impact levels. Comprehensively, the upper and lower limits of the criteria's anchor values should be "well-specified (maximum feasible and minimum acceptable, respectively) otherwise it would distort value trade-offs" (Franco & Montibeller, 2010, p. 8).

Therefore, the impact levels and their respective anchor values represent the potential worst and best ranks of each criterion according to the preferences of the top decision-maker or group of top decision-makers. Thus, we categorized all criteria between potential worst and best impact levels based on the literature, the interviews, or from the expert teams. Next, we normalized them into a numerical index between 0 and 100 (value function, $v_a: R \rightarrow [0{,}100]$) respectively, adopting a linear value function, for simplicity reasons (Table 6.2). Here, we may recall from Section 3.4.1 that the value function is defined by the best and the worst levels (anchor values) and is used to estimate intermediate impacts for each criterion. This relation can be expressed by a linear function or any other mathematical one (Caruzzo et al., 2018).

Regarding the quantitative criteria, referenced in Table 6.2 by an '*', the measurement unit follows their specific nature. Therefore, publications are measured in the number of publications (articles, papers), for instance.

However, to be meaningful and comparable across different criteria, those measures must pass through a 'unit conversion', from quantitative values to impact levels and using value functions. The process to do so encompasses two parts. The first step consists of translating the measures into a ‘best/worst level’ with respective reference values by an adequate expert group. For example, for a given discipline, the scientific commission determines that 7000 citations is the reference value for ‘best’ concerning a top scientist and 20 citations is the reference value for ‘worst’. Those reference values are then normalized, varying from 100 for ‘best’ to 0 for ‘worst’. This normalization is the same approach as the one already applied for the qualitative criteria and used to assess high and low values for a single criterion value function in traditional decision analysis (Belton and Stewart, 2002). Thus, following our previous example, 7000 citations turn into impact level ‘excellent’ (anchor value = 100) and 20 citations, impact level ‘minimal’ (anchor value = 0). All quantitative criteria must pass through this procedure since this normalization facilitates evaluating the performance of each criterion on a numerical scale [0, 100].

It is important to recall that all criteria follow Belton & Stewart (2002) recommendations, being as simple, understandable, measurable, relevant, and non-redundant as possible to be operational. Thus, for instance, even the use of sub-criteria such as ‘Book & chapter’ or ‘Citation’ in the ‘Team excellence’ criterion is not ambiguous or inadequate to the assessment of BigSci projects of different disciplines; however, it assures independence in each subcriterion judgement as well as value relevance.

6.1.2 Technological attribute and corresponding criteria

There are five main criteria in structuring the proposed multi-criteria evaluation model concerning the Technological attribute (Table 6.3). The definition of those criteria aims to measure the achievement of the objective, represented in the value tree (Figure 6.1), to support an objective decision of BigSci investments with verifiable facts, evidence and analyses related to technological issues. The transformation of BigSci necessary technologies topics, present in the literature and the SODA analysis, into broad range criteria, can be checked in Table 6.3 and Appendix B.

Table 6.3 Criteria and main features of Technological attribute

1st-level criteria	2nd-level criteria	Measurement unit	Anchor values / impact levels	Source
Facility/tech	-	Experts judgement (scientists)	0 = yes/unique 25 = yes/network 50 = no/intl 100 = no/exist	Construct 7 (Appendix A) Interviews with scientific, industry and government representatives Several documents (Barker & Halliwell, 2018; Halliwell & Foxall, 2009; OECD, 1993)
Tech readiness	-	Experts judgement (industry)	0 = low 50 = medium 100 = high	Construct 39 (Appendix A) Interviews with scientific, industry and government representatives (Héder, 2017)
Industry capacity	-	Experts judgement (industry)	0 = low 50 = medium 100 = high	Construct 36 (Appendix A) Interviews with industry representatives (Autio, 2014; BigScience.dk, 2017; OECD, 2019a)
Dual-use tech	-	Experts judgement (industry)	0 = yes 50 = partial 100 = no	Interviews with industry and government representatives
DMP	-	Experts judgement (industry)	0 = no 25 = satisfactory 50 = good 100 = excellent	(Bicarregui et al., 2013; Lucchese, 2018)

The previous discussion about the Scientific attribute concerning the methodology application is valid to the Technological attribute.

The Technological attribute encompasses only qualitative variables measured by expert judgement. This turn, we suggest that the industry expert team (commission) should be formed by an independent and small (up to 10 members) group of national multisectoral industry representatives encompassing areas such as civil engineering and building, mechanical engineering, power supply, hardware and software, and control systems, high-tech companies, among others, consistent with the interviews.

The impact levels were defined as well as their respective anchor values to all criteria based on the literature and the interviews and also adopting a linear value function (Table 6.3).

6.1.3 Social attribute and corresponding criteria

In the case of Social attribute, we tried to identify, to be best of our knowledge, which criteria met the recommendations by Belton & Stewart (2002) aforementioned and included in the multi-criteria model. However, Social criteria refer to potential effects and are sensitive to a ‘causality problem’ (Martin & Tang, 2007) in which it is unclear what benefits/impacts can be attributed to what cause, i.e., BigSci project. At the end of this exercise of identifying the Social criteria, we adopted a slight standardizing bent, and it can perhaps be argued that the social benefits/impacts of basic science projects such as BigSci are not trivial to measure (Magazinik et al., 2019), and the proposed Social attribute is not as comprehensive as it should be. Table 6.4 and Appendix B present our proposed criteria.

Table 6.4 Criteria and main features of Social attribute

1st-level criteria	**2nd-level criteria**	**Measurement unit**	**Anchor values / impact levels**	**Source**
Knowledge sharing	-	Experts judgement (analysts)	0 = no 50 = partial 100 = full	Construct *42* (Appendix A) Interviews with industry representatives (Autio et al., 2003, 2004; OECD, 2019a)
Training program	-	Experts judgement (analysts)	0 = no 50 = partial 100 = full	Construct *35* (Appendix A) Interviews with scientific and industry representatives
National / International impact	Society awareness	Experts judgement (analysts)	0 = no 50 = partial 100 = full	Constructs *3*, *11*, *35* (Appendix A) (Gastrow & Oppelt, 2018, 2019; OECD, 2014, 2019a; TheTauriGroup, 2013)
	International reputation	Experts judgement (scientists)	0 = low 50 = medium 100 = high	Interview with government representative (Lambright, 1998, 2002; Larsson, 2020) Jury’s recommendation
Local impact	HDI*	Estimated index value	0 = low 50 = medium 100 = high	Constructs *3*, *35* (Appendix A) (Gastrow & Oppelt, 2018; UNDP, 2020)
	Tourism*	Estimated number of visitors	0 = low 50 = medium 100 = high	Construct *42* (Appendix A) (Florio, Forte, & Sirtori, 2016; Hallonsten & Christensson, 2017)
	Education level*	Estimated number of MScs and PhDs	0 = low 50 = medium 100 = high	Interviews with government representatives (Gastrow & Oppelt, 2018, 2019; OECD, 2019a; PwC, 2016)
Local needs	-	Experts judgement (analysts)	0 = high 50 = partial 100 = low	Constructs *1, 35* (Appendix A) (Godin & Doré, 2007; OECD, 2019a; Rochow et al., 2012)

The previous discussion about the Scientific attribute concerning the methodology application is also valid to the Social attribute.

The Social attribute encompasses qualitative and quantitative (referenced in Table 6.4 by an '*') variables measured by expert judgement and specific measurement units, respectively. This turn, we suggest that the government expert team (commission) should be formed by an independent and small (up to 10 members) group of senior specialized government analysts/officers encompassing areas such as STI, economy, international relations, among others, consistent with the interviews.

The impact levels were defined as well as their respective anchor values to all (quantitative and qualitative) criteria based on the literature and the interviews and also adopting a linear value function (Table 6.4).

6.1.4 Economic attribute and corresponding criteria

Another problem in measuring impacts/benefits is attribution (Martin & Tang, 2007) to what portion of benefits/impacts should be attributed only to BigSci projects compared to other inputs. Social and Economic, even Political, criteria are too close and interrelated, even compromising fundamental properties like non-redundancy, independence and value relevance in each criterion judgement (Belton & Stewart, 2002), that they could then be grouped into one single Socio-Economic attribute. Although this choice could be coherent with some authors (Brottier, 2016; Florio, Forte, & Sirtori, 2016; PwC, 2016; TheTauriGroup, 2013), we chose to follow OECD (2019a) due to its extensive expertise and experience in the topic, keeping the attributes separated. Another key complementary issue to take into account is that the economic benefits/impacts of publicly funded basic research such as BigSci is real, substantial, take different forms (Florio, Forte, Pancotti, et al., 2016; Purton, 2015), varying with "scientific field, technology and industrial sector" (Salter & Martin, 2001, p. 527). It might be argued that in this research, those specific issues do not take a prominent place in the development and analysis of the proposed multi-criteria model of evaluation BigSci investments. However, a detailed study and analysis of criteria, indicators, and their natures are not pertinent or the goal of this research. Table 6.5 and Appendix B present our proposed criteria of the Economic attribute.

Table 6.5 Criteria and main features of Economic attribute

1st-level criteria	**2nd-level criteria**	**Measurement unit**	**Anchor values / impact levels**	**Source**
Local impact	GDP*	Thousands of USD	0 = low 50 = medium 100 = high	Construct *35* (Appendix A) Interviews with government representatives
	Jobs*	Number of jobs/employees	0 = low 50 = medium 100 = high	Construct *35* (Appendix A) Interviews with scientific, industry and government representatives (Gastrow & Oppelt, 2018, 2019; Godin & Doré, 2007; OECD, 2019a; TheTauriGroup, 2013)
	Start-ups*	Experts judgement (analysts)	0 = low 50 = medium 100 = high	Constructs *35*, *47* (Appendix A) Interviews with industry and government representatives (Autio, 2014; OECD, 2019a; TheTauriGroup, 2013)
Industry funding	-	Experts judgement (industry)	0 = no 50 = medium 100 = high	Constructs *15*, *42* (Appendix A) Interviews with government representatives (Biagioni, 2015; OECD, 2019a; Salter & Martin, 2001)

Table 6.5 Criteria and main features of Economic attribute (cont'd)

Industry participation	-	Experts judgement (industry)	0 = no 50 = medium 100 = high	Constructs *15*, *34*, *42* (Appendix A) Interviews with industry representatives (Autio et al., 2004; Biagioni, 2015; Dal Molin & Previtali, 2019; ESS, 2018; OECD, 2019a; Rochow et al., 2012)
Tech transfer	-	Experts judgement (analysts)	0 = no 50 = conditional 100 = unconditional	Constructs *34*, *42* (Appendix A) (Autio et al., 2003; STFC, 2014; Vuola & Hameri, 2006)
Global cost	Capital/year *	Hundreds of millions of USD	0 = extreme 50 = high 100 = standard	Interviews with government representatives (Barker & Halliwell, 2018; Biagioni, 2015; Catalano et al., 2016; Halliwell & Foxall, 2009; Linton, 2008)
	Operation/year*	Hundreds of millions of USD	0 = extreme 50 = high 100 = standard	Interviews with scientific and government representatives (Barker & Halliwell, 2018; Florio, Forte, Pancotti, et al., 2016; Florio, Forte, & Sirtori, 2016; Halliwell & Foxall, 2009)

The previous discussion about the Scientific attribute concerning the methodology application is also valid to the Economic attribute.

The Economic attribute also encompasses qualitative and quantitative (referenced in Table 6.5 by an '*') variables measured by expert judgement and specific measurement units, respectively. In this turn, we suggest that the expert teams evaluating the Economic attribute be formed by the industry and the government commissions, consistent with the interviews and the literature.

The impact levels were defined as well as their respective anchor values to all (quantitative and qualitative) criteria based on the literature and the interviews and also adopting a linear value function (Table 6.5).

6.1.5 Political attribute and corresponding criteria

In the evaluation of the BigSci investment problem, all the criteria related to the potential political benefits/impacts from a given project proposal were mainly derived from the interviews. As pointed out by some interviewees, building a proxy or operationalizing the political benefits/impacts of a scientific project are challenging and when regarding BigSci is even more. The intrinsically/increasingly international nature of BigSci and innovation makes criteria/indicators virtually impossible to measure the Political attribute (Martin & Tang, 2007). Then, the Political attribute, or rather, the so necessary attempt to evaluate it, can be seen as an effort to quantify through indicators the BigSci political impacts and needs to support decision-making as mentioned in construct 58 (Appendix A). Table 6.6 and Appendix B present our proposed criteria of the Political attribute.

Table 6.6 Criteria and main features of Political attribute

1st-level criteria	**2nd-level criteria**	**Measurement unit**	**Anchor values / impact levels**	**Source**
STI strategy	-	Experts judgement (analysts)	0 = low 50 = partial 100 = full	Construct *31*, *69*, *70* (Appendix A); Interviews with government representatives; (STFC, 2014)
Top-down demand	-	Experts judgement (analysts)	0 = low 50 = partial 100 = full	Constructs 9, 46 (Appendix A); (Melin, 2000)
Data sharing	-	Experts judgement (analysts)	0 = no 50 = conditional 100 = open	(Barratt, Wang, & Binney, 2016; Knoppers et al., 2011; OECD, 2008, 2019a)
Diplomatic interest	Collaboration	Experts judgement (analysts)	0 = low 50 = partial 100 = high	(OECD, 1993); (Swap, personal communication, August 3rd, 2020)
	Geopolitical	Experts judgement (analysts)	0 = low 50 = partial 100 = high	Construct *49* (Appendix A); Interviews with scientific and government representatives; (Thomasson & Carlile, 2017)

The previous discussion about the Scientific attribute concerning the methodology application is valid to the Political attribute.

The Political attribute, as the Technological one, encompasses only qualitative variables measured by expert judgement. In this turn, we suggest that the expert team evaluating the Political attribute be formed by the government commission, consistent with the interviews and the literature.

The impact levels were defined as well as their respective anchor values to all criteria based on the literature and the interviews and also adopting a linear value function (Table 6.6).

In general, the frequent BigSci project timescale of decades can bring problems in measuring/evaluating the potential political impacts/benefits like early measurements can give a false idea that BigSci brings short-term benefits (Martin & Tang, 2007). This situation would be evidence of the conflicting timescale between science and politics. Nevertheless, above all, there is no perfect measure, criteria and/or indicator to provide verifiable facts, evidence and/or analyses to ensure an objective decision of BigSci investment, but only imperfect or partial ones.

6.2 Concluding remarks

Chapter 6 exposes Phase C micro-level results, analysis, and findings as well as a general discussion regarding the developed model. Phase C reached the last secondary objective of identifying the government decision-makers' values, preferences, judgements, and criteria related to BigSci investments, paving the way for problem-solving and developing a framework grounded on quantitative and qualitative criteria to support decisions of BigSci investments, this research's primary goal.

The development of the Decision's strategic option of an objective decision process grounded on quantitative and qualitative attributes and criteria (Subsection 5.1.4) required the translation of the SODA map concepts into multi-criteria modeling (Section 6.1), founded in the MAVT. Our model combined and synthesized the most relevant features indicated by our interviewees, the SODA map analysis and the literature concerning the government decision problem of BigSci investments identifying the government decision-makers' values, preferences, judgements, and criteria regarding BigSci investments.

Our proposed model with 24 main criteria and 15 sub-criteria (Figure 6.1 and Appendix B) follows the literature recommendations. Thus, it is as simple, understandable and measurable as possible to be operational, complete but concise and non-redundant, assuring independence in each criterion judgement as well as value relevance. It is necessary to note that our criteria list is not definitive, or the matter is restricted to it, but our list is the result of a first approach; it is relatively short and straightforward and subject to improvement.

Implementing our multi-criteria model into a useful decision aid tool still requires the establishment of weights for criteria and attributes determined by the top decision-maker or group of top decision-makers, using procedures such as the Swing Weights (Section 3.4.1). The elicitation procedure is part of our framework's customization and will be discussed in the next chapter.

Finally, we can highlight some promising aspects of our proposed multi-criteria model:

- it can offer evidence to an informed and structured government decision of one BigSci project investment;
- it can promote the ranking of BigSci projects when competing for government financial support simultaneously and under a limited budget scenario;
- it demands the participation of representatives of the scientific and industrial communities and also the government technical body of analysts/officers, meeting the participation expectation of all stakeholders, even though this specific aspect had lost central importance after the problem structuring results in Chapter 5;
- it can guide improvements on initial BigSci project proposals or even in science policies.

Our multi-criteria model (Tables 6.2, 6.3, 6.4, 6.5, and 6.6) is the core of the decision support framework for funding BigSci that will be discussed in the following chapter.

Lastly, Figure 6.2 shows the multi-criteria tree, a graphical presentation of our multi-criteria model. This visual format helps a comprehensive understanding of the model as well as represents the basis of the objective decision process of civil BigSci investments with clearly defined and transparent attributes and criteria, as pointed out in one of the strategic options, previously revealed in Chapter 5.

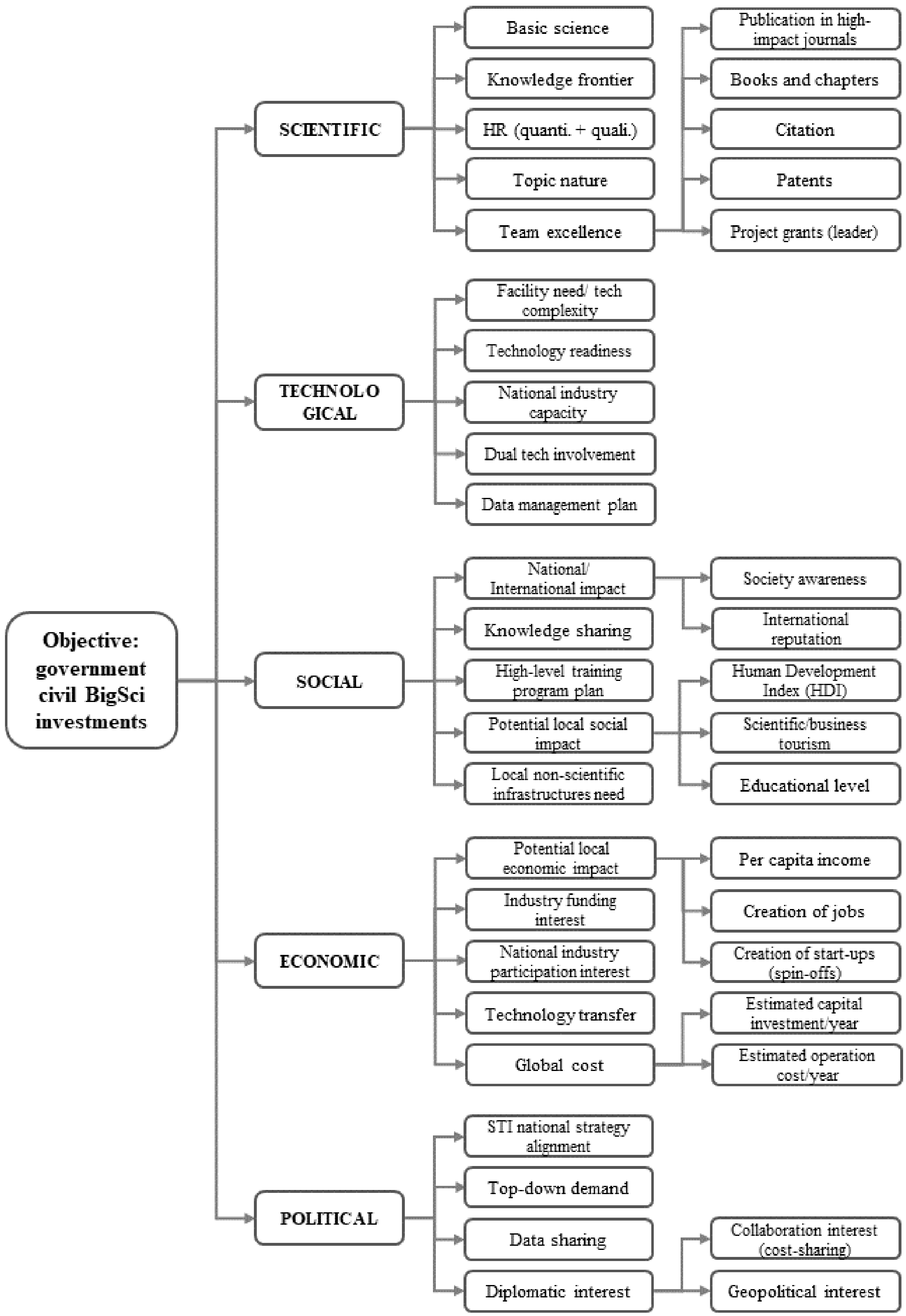

Figure 6.2 Final multi-criteria hierarchical structure

CHAPTER 7 DECISION SUPPORT FRAMEWORK

After achieving all secondary objectives (Section 1.2) in the previous chapters (Chapters 4, 5 and 6), this chapter focus on the primary goal of this research, presenting the complete proposed solution for the government decision of civil BigSci investments. This solution offers a government decision support framework based on standard attributes, criteria, and indicators, considering scientific and non-scientific aspects and assessments, and avoiding political-driven biases. Moreover, this solution provides an alternative to support national governments to improve their capacity in making informed and structured decisions of BigSci investments with the participation of the scientific, industry and government experts communities.

Putting the analysis into a broader perspective and relating it to our broader understanding of the theme of BigSci, it cannot be neglected that the fundamental motivation for the emergence of a decision support framework addresses the single, complex, conflicting problem of the government's decision to fund or not BigSci projects. Moreover, the growth of contemporary BigSci in quantity, diversity, and costs deepens the utility and need for such a tool.

It should also be stated that regarding government decision-making, much research in political science (Araral, Fritzen, Howlett, Ramesh, & Wu, 2012) about public policy-making processes adapted and adopted the garbage can model (M. D. Cohen, March, & Olsen, 1972). Such a model of organizational decision is based on "problems, solutions, and participants move from one choice opportunity to another in such a way that the nature of choice, the time it takes, and the problems it solves all depend on a relatively complicated intermeshing of elements" (Cohen, March, & Olsen, 1972, p. 16). However, this decision algorithm model focused on the alternatives is not appropriate to our approach because it 'collects' solutions even before understanding the real problems to be solved (structure the problem) as well as the decision-makers' preferences, values, and judgements (Keeney & Raiffa, 1993; Rosenhead & Mingers, 2001). In our case, we search for a decision support framework to recommend BigSci investment options, not to point 'ready' alternatives to the government decision.

In this chapter, the following actors are involved in the decision-making process:

- high-ranked government decision-makers: decision-makers from the highest/top levels of the national government such as president, prime minister, minister, or equivalent (construct *60*);
- three expert commissions (Subsections 6.1.1, 6.1.2, 6.1.3): international multidisciplinary scientists or the scientific commission (construct *54*), national multisectoral industry representatives or the industry commission (construct *34*), and senior specialized government analysts/officers or the government commission (construct *67*);
- special advisory group: mediators between expert commissions and top decision-makers (construct *38*).

7.1 The proposed framework and the BigSci Index

The proposed framework can now be built once all required elements are available. In this Section, they will be put together and combined to offer a solution to help the high-ranked government stakeholders make and take decisions on BigSci investment as well as meet the scientific and industry communities' demand for participation in this process. Our robust framework addresses a decision support process following five phases (Figure 7.1) and can work for both bottom-up and top-down (solicitation of proposals) initiatives. It is noteworthy that our research, and consequently, our framework, is only for civil BigSci project proposals and does not address decisions related to the hard problem of funding BigSci project continuation when it is no longer scientifically relevant (construct *24*).

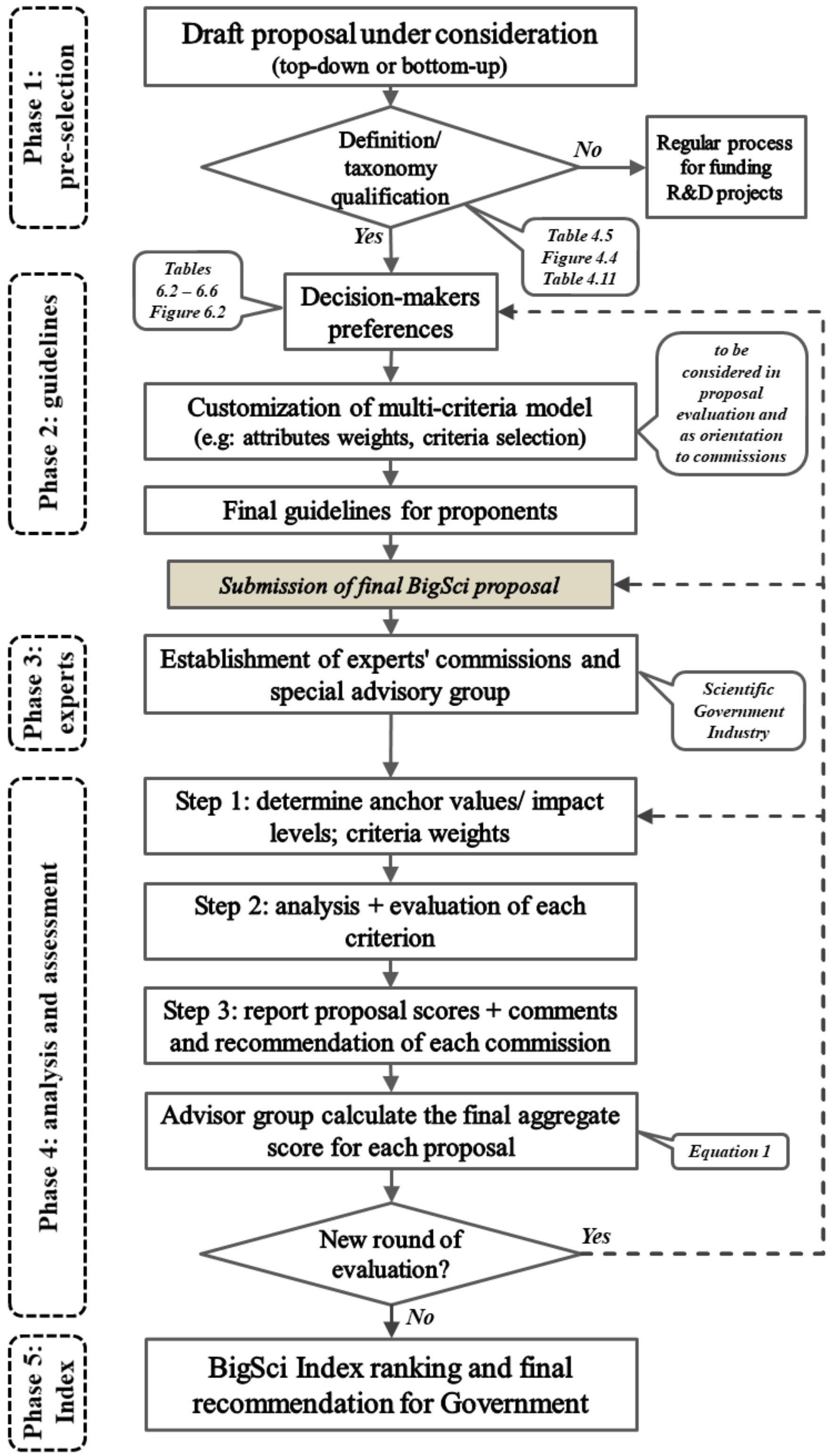

Figure 7.1 Flowchart of phases for application of the proposed decision support framework

Remarkably, the decision-making of BigSci investments is a long, slow and group process encompassing negotiation with the various actors involved (construct *71*) and this framework does not reflect the final choice but a recommendation. It is a tool to support the final decision of a high-level government decision-maker (construct *60*) after several scientific, technological and non-scientific aspects of the BigSci proposal be carefully analyzed and assessed by experts groups.

7.1.1 Phase 1 – proposal pre-selection

BigSci proposals are often brought forward in a bottom-up fashion from a group of scientists who wishes to explore new ideas and concepts at the frontier of knowledge requiring significant financial support to do so. Proponents can be from any research field, but also the government itself in a top-down fashion, not so frequent at present days, counting on the interest and support of the scientific and industry communities (construct *68*). Any kind of BigSci proposal demands an appropriate approach in analysis and assessment, which should be customized according to discipline, the national and international contexts, and the preferences of the top government decision-makers (constructs *48*, *50*, *63*). Moreover, analyzing and assessing BigSci proposals from a single discipline or several must follow the same process, assuring a fair, independent and objective expert judgment in supporting government decision of BigSci investments.

The general characteristics and nature of BigSci projects initially proposed can differ and have to be understood and discussed in a pre-selection phase grounded in our BigSci definition ticking-box (Table 4.11) as well as our taxonomy (Table 4.5 and Figure 4.4). This phase is crucial to select BigSci proposals, which must proceed towards the following steps of the framework, from other smaller-scale projects, which must go under a more straightforward regular process for supporting scientific initiatives (construct *63*). Nevertheless, there may be occasions when an initial proposal is not adequately formulated, leading to a misinterpretation of its characteristics and nature. Therefore, it should be returned to the proponents for appropriate elucidations and adjustments. And then to a new pre-selection round to avoid disqualifying genuine BigSci proposals (construct *45*).

7.1.2 Phase 2 – systematic guidelines

Proceeding to elaborate a final BigSci project is challenging as the proposals tend to arise in diverse formats well suited with the primary discipline's original proposals, demanding clearly defined and transparent guidelines to allow adequate comparisons among projects. The determination of those guidelines is the first part of our multi-criteria model's customization based on the preferences of the high-ranking government decision-maker or group of decision-makers. In other words, the stakeholders are responsible for choosing and weighing attributes from the model according to their preferences; this selected set would work as guidelines for the elaboration of the final and complete proposal since it is the basis for the analysis and assessment of the BigSci project. This step is crucial to assure decision-makers will use the recommendations derived from the framework as indicated by the literature (Caruzzo et al., 2020; Montibeller et al., 2020; Montibeller & Von-Winterfeldt, 2015; Nikou, Moschuris, & Filiopoulos, 2017; Roy, 1993).

Therefore, each BigSci proposal should be assessed in the broader context of the high-ranking decision-makers' preferences. In this context, all BigSci proposals should include systemic and reasonably detailed descriptions of crucial information that will provide evidence concerning each attribute and criterion under consideration with a view on the expected outcomes and return on the investment. These guidelines to the final BigSci proposal will also help assess the success, impacts and benefits of the proposed project in the future. The customization of the multi-criteria model allows transparent comparisons between intradisciplinary as well as interdisciplinary competing proposals, or even the detailed evaluation of a single one, avoiding scientific, non-scientific and motivational biases (construct *53*). Moreover, the structured and customized final BigSci proposal is a fundamental ground for the complex process of analysis and evaluation run by the expert groups.

It is essential to highlight that from this Phase ahead, the used multi-criteria model is not the original one, but customized by the decision-makers, where the essence of their preferences and concerns is exposed and guides the whole recommendation or decision-aid process.

7.1.3 Phase 3 – expert engagement

With the final BigSci proposals available, the framework must require the engagement and buy-in of senior government technical analysts/officers and other key experts (representatives from scientific and industry communities) early in the final proposal development process. Those experts constitute the three ad-hoc commissions mentioned in the prior Section. They must be identified in the preliminary stages of the final proposal development, along with the actions that have to be taken to engage them. Also, early discussions and agreement of the roles and government financial contributions (payments) of the various experts must be established, both in analyzing and assessing the BigSci project proposals when moving forward in the following phases. The engagement of expert commissions of international multidisciplinary scientists, national multisectoral industry representatives, and senior specialized government analysts/officers as well as a select advisory group is crucial to driving the BigSci proposal forward.

7.1.4 Phase 4 – analysis and assessment

Before starting their works, each commission receives detailed orientations from the high-level decision-makers or from a special advisory group, created to be the mediator between decision-makers and experts. Those orientations expose the preferences and concerns of the interested decision-maker and provide further information to each expert commission to develop the task.

The role of the expert commissions is crucial in Phase 4. Each commission should proceed as follows:

- 1st step – further customization of the 'Phase 2 multi-criteria model', determining, according to the expert's judgment, the anchor values/impact levels and the weights for its specific set of first- and second-levels criteria;
- 2nd step – the analysis and assessment of each level criterion under its responsibility, based on the 1st step values and weights, resulting in a partial set of criteria marks for each proposal;
- 3rd step – a report to the special advisory group with information about each BigSci project under consideration encompassing the scores of the specific set of sub-criteria/criteria analyzed and assessed as well as respective comments and recommendations.

The special advisory group receives each commission's report and calculate the final scores considering the criteria/attributes hierarchical scheme (Fig. 6.2) and the weights of the attributes from the (group of) decision-makers, reaching the first version of the final recommended ranking of BigSci proposals. We recall that setting the attributes' weights is an interactive process widely presented by the literature (Belton & Stewart, 2002; Caruzzo et al., 2016; among others) and described in Section 3.4.1. This ranking is submitted to the high-level decision-makers who evaluate the result.

The perfect alternative with the best rank for all criteria and attributes is impossible in a real-world decision-problem, leading to a compensatory process with trade-offs between attributes and/or criteria. In other words, the extent to which excellent performance on one attribute/criterion can compensate for weaker performance on other attributes/criteria. This 'weight elicitation exercise' (further details in Section 3.4.1) is staged by the decision-makers involved in the process with the special advisory group's aid. The recommended ranking should pass through a sensitivity analysis that reveals which criteria are the most relevant in the proposals' evaluation process. This information is critical for the trade-off led by the decision-makers and to understand their impacts from a global perspective. In this case, the government top decision-maker or group of top decision-makers must clearly express meaningful preferences and trade-offs between attributes/criteria to keep the decision process objective and transparent. For example, according to the national and international context, government top decision-makers can prefer a BigSci project with a lower performance on scientific attribute compensating a higher performance on political and social attributes or any other combination.

The decision-makers' evaluation of the first version of the final ranking of options can result in immediate acceptance as well as the decision support framework fulfills its mission. However, this situation seems unlikely, particularly regarding complex and conflicting decision-processes of high investments in the public sector, such as BigSci. In these cases, decision-making is a long and slow group process because it involves negotiation with the various actors (construct *71*). In particular, the literature related to the history of science (see, for instance, Westfall, 2012, 2016, 2018, 2019), and the interviews with scientists and government representatives asseverate the decision-making process of BigSci investment can easily take years, often decades. It is natural to expect significant changes in national and/or international contexts in such a timescale, turning the first ranking results essentially meaningless. Above all, the decision-makers learn with the decision process as well as their preferences also change over time (Comes et al. 2011; Caruzzo et al. 2018), demanding refinements of the weights of attributes and/or criteria. Thus, the process of assessing weights is repeated as many times as needed until the resulting attributes and/or criteria weights reflect clearly the decision-makers' preferences (Hand, Wibbenmeyer, Calkin, & Thompson, 2015). Resuming the assessment and analysis of our framework, in a simple situation, the special advisory group recalculates the final scores and redo the ranking; otherwise, the BigSci proposals under consideration are returned to the proponents for new adjustments (Phase 2), and then, once again, they should be resubmitted to expert groups evaluation (Phase 4).

The framework should involve an interactive approval/ranking process to ensure BigSci projects are given ample feedback to best frame their proposals. In the case of project proposals from different research fields under consideration, each project would be processed individually, respecting its domain specificities reflected on criteria's weights and reference values. All proposals would also be analyzed based on the same decision-maker's preferences reflected on attributes' weights. After all necessary interactions, as mentioned earlier, each individual proposal would reach a final score that would drive to a grounded recommendation, ensuring information and evidence to be used by the decision-maker in the final decision.

Furthermore, the framework should have a mechanism to ensure that a final recommendation is made promptly. This action will help to avoid situations where proponents are endlessly told to consider other options, make improvements, reduce the scope and costs, attract foreign partners, among other possibilities. A disapproving recommendation is better than no recommendation, as it releases proponents to pursue other endeavors or alternative funding sources.

7.1.5 Phase 5 – BigSci Index

Trouble in turning the results of our multi-criteria model into an easy workable tool for government decision-makers towards an evidence-based decision of BigSci investments requires transforming this complex result associated with multiple attributes into an index. This new index must be suitable for the target audience (MacKenzie, 2014) and facilitates the understanding of decision-makers who do not have specific knowledge regarding the technical aspects involved (Magazinik et al., 2019; Montibeller & Franco, 2010).

In this sense, we propose the BigSci Index as the ultimate tool of our framework that helps the decision-maker to identify when the BigSci project under consideration is a good alternative of investment or not. Thus, we can aggregate final and partial (individual attribute) scores to support better evidence-based choices, as presented below in Table 7.1.

Table 7.1 Definition of BigSci Index proposed for government purposes

Concept	**Score**
Excellent = recommended	Final score and all attributes scores are above 90
Good = recommended with restrictions	Final score is between 75 and 90 and: • if the majority of the attributes scores is above 80, then it is suggested that the project needs minor adjustments • else project needs major adjustments
Poor = not recommended	Final score and the majority of attributes scores are below 75

Finally, the special advisory group can deliver to the high-level government decision-maker or group of decision-makers the final ranking of BigSci proposals and the respective BigSci Indices, ensuring a consistent, structured, transparent, objective, informed and evidence-based support for the making and taking a decision of BigSci investments.

7.1.6 Validation

Although it may appear natural that an application of the proposed framework is missing, the complexity and depth of such an assignment do justice to the complex situations of projects' investments it aims to evaluate. Unlike a statistical study in which it is possible to predict variables, in our study, every single case of BigSci proposal and its respective associated government decision-maker(s) or group of decision-makers should mandatorily be considered individually. In other words, the application of the proposed framework is an interactive process between the involved actors (decision support analysts, commissions/advisory groups, decision-makers, and proponents). Those interactions produce the commissions' composition, impact levels, weights for each attribute, criterion, and sub-criterion, and any attempt to extract such information from the white and/or grey literature or even from our interview set is meaningless and useless for any category of BigSci project. Even in a generalization mode, suggesting weights for attributes or criteria that would be more important for specific types of projects to promote illustrative example(s) makes no sense.

It is essential to shedding light on the framework application issue since only presenting/describing it does not seem enough or too 'theoretical'. Therefore, it is not possible to extract the appropriate weights for traditional and well-documented BigSci projects such as LHC or HGP in order to redo the decision process, except the Phase 1 (proposal pre-selection), testing whether they would pass through the definition/taxonomy criteria with success. At this moment, we understand this assignment is useless to validate our proposal, and as well because literature about projects like those is the basis of the development of the taxonomy/definition.

In any case, revisiting the literature, few authors studied BigSci projects and the related decision-making processes. To the best of our knowledge, almost all documents regard projects in physics, particularly particle accelerators, reflecting the traditional concept of BigSci. The only exception constitutes articles about HGP (Collins, Morgan, & Patrinos, 2003; Lambright, 2002). Thus, those studies and respective analyses would not have changed their results and conclusions if they considered our taxonomy because none of them exposed any concern or question about being a BigSci project, even they have this certainty based on different concepts. In other words, they did not report any proposal pre-selection step (Phase 1) to demonstrate the projects qualified as BigSci and for an appropriate decision process for funding. On the other hand, articles about BigSci in other scientific fields discuss different aspects rather than decision processes, mainly because most of them still work on convincing the general scientific community about their BigSci status.

Moreover, in those case studies about BigSci and decision-making, our framework's application is sometimes impossible due to the used dataset and approach. For instance, research using cost-benefit analysis, based on measured project's outcome such as publications and technology spillover, did not investigate the government decision on BigSci investment, but in fact justify it, simply because

> It counts about 50 years prior to the commissioning. Amount of people and investment is a significant part of the assessment, as a "past investment cost" in case of CNAO. To gather this data is quite difficult and sometimes impossible, mainly considering the IT state at that time. Sophisticated data storage and databases were not available at the time. (Magazinik et al., 2019, p. 12)

Also, to apply our framework, it is mandatory information from the decision-maker involved in the investment decision process that is not usual in articles. In CERN/CNAO mentioned above, it seems quite impossible to obtain them considering the timescale.

Other case studies, with a more historical perspective, used a narrative analysis based on documents and interviews to describe and analyze the investment decision process of specific BigSci projects (Gingras & Trepanier, 1993; Jacob & Hallonsten, 2012; Leach, 1973; Rekers & Sandell, 2016; Theil, 2015; Thomasson & Carlile, 2017; Westfall, 2016). Data content and timescale also make (almost) impossible applying our framework in those case studies. Otherwise, if the authors had available and sufficient data regarding the decision-makers involved in the investment decision process, they could try to identify the weights of attributes and criteria and apply the framework, at least partially. They could then compare the ‘application’ results to what really happened and eventually assess the impact/benefit/relevance of a structured decision process for BigSci issues. The comparison could never be used to evaluate whether the decision made was right or wrong, but eventually, good or bad (Belton & Stewart, 2002; Keeney, 1996). Furthermore, to submit old and already carried out BigSci projects, or even imagined ones, to committees by asking them to apply the proposed framework is not another way to test its usefulness or even the applicability of the multi-criteria model.

Other documents, with a mainly planning perspective, used to prioritize BigSci initiatives (Hershberger, 2020; OECD, 2019b; Turner, 2019) could not serve as an attempt to test the proposed analytical framework or be analyzed to see whether these prioritization mechanisms are comparable or compatible with the proposed framework. The reason is that all cases mentioned above are mainly planning documents, not decision processes on BigSci investments per se. The application of our proposed framework would be a subsequent process where the BigSci project proposals would be assessed in five main aspects to support the government funding decision.

Due to temporal constraints, evaluation of the framework is not possible. This point represents a significant limitation of this work. Future research could continue from this point. The ideal evaluation of the proposed framework would be an action research approach. However, considering the BigSci time scale from design to operations (whole decision process) be around 30 years for physics (Benedikt, 2016), 15 years from planning to completion in medical sciences (Lambright, 2002) or even undetermined for some exceptionally avant-garde projects (Regev et al., 2017); action research should not be feasible as well.

Albeit there are some case studies like Autio et al. (2004) that took ten years of observation and research to produce an article about LHC, partial application in case studies is an option for evaluation and testing. According to Yin (2009), one in-depth case study would be sufficient for the purpose because it deals with a situation with extreme characteristics, and therefore a unique studied phenomenon. A possible target is Sirius, the new Brazilian synchrotron light source, whose lifecycle so far lasts 17 years: initial ideas started in 2003; its first conceptual pre-proposal was delivered to the Ministry of Science, Technology and Innovation (MCTI) in 2008; the favorable decision for the investment was in 2011; and the first research station, still in the commissioning stage, has started operating on July 2020, observing crystals of a coronavirus protein (https://www.lnls.cnpem.br/sirius-en/). Another target could be the Large Latin American Millimeter Array (LLAMA), an international collaboration to create a radio observatory in the Argentine Andes, whose conception started in 2016, and its site is under construction in 2020 (https://www.llamaobservatory.org/en/about.html). Alternatively, another target could be the European Spallation Source (ESS) in Sweden, still under construction since 2015 (https://europeanspallationsource.se/). The most essential characteristic of all those projects to be eligible as a case study to apply our framework is the possibility of conducting in-depth interviews with the decision-makers involved in the investment decision process.

A final alternative to validate the framework would be to run a new round of interviews with selected stakeholders, presenting the proposed framework and questioning their opinion about it and its impact as a mechanism to improve the relationship between the parties involved.

7.2 Concluding remarks

Chapter 7 attained the primary goal of this research, presenting our proposed framework and BigSci Index.

We developed a framework for the government decision-making process of BigSci investments to support national governments to improve their capacity in making informed and structured decisions with the participation of the scientific community and industry, including the BigSci Index (Section 7.1) to facilitate the understanding. Moreover, our proposed framework is customizable, flexible and adaptable to any high-level government decision-makers demanding an informed, structured and more transparent decision process of BigSci investments and ensuring active participation of the scientific community and industry.

Our research indicates that any BigSci proposals should be evaluated on scientific, technological, social, economic and political elements selected by high-ranking government decision-makers through their preferences. Such a procedure would ensure the customization of our multi-criteria model as well as our framework. We do not have results showing our framework's use because BigSci investments are long-term decision processes with several interactions and negotiations among the involved actors, as discussed. Even one example of the application of the framework for a specific BigSci case, which would be useful for illustrating its use and relevance, not for validation purposes, is revealed to be unfeasible. However, we described our framework as detailed as possible since it is not feasible to apply it, and so, testing and adjusting it to reach a better proposal.

Our proposed framework's key feature is its ability to analyze, assess as well as compare civil BigSci project proposals from any discipline and any origin (bottom-up or top-down initiative), supporting national government decision-making of BigSci investments. The resulting ranking of BigSci projects and respective BigSci Indices are not intended to prioritize projects directly but only provide the evidence and basis for funding recommendations. It could even inspire creating an overview document that would work as the pipeline of proposed and potential BigSci projects supported by the government.

Implementation of a more clearly defined BigSci framework to help the decision-making of BigSci investments would demonstrate that the government is taking steps to resolve accountability issues related to STI expenditures as well as ensure that decisions are made with the appropriate objectiveness.

CHAPTER 8 CONCLUSION AND RECOMMENDATIONS

What happens when a complicated government decision situation with multiple and conflicting objectives, stakeholders, and priorities, eventually involving problems of a global scale and extremely high cost, demands top decision-makers to take responsibility for the consequences of the choices which will be made? The prevailing situation does not concern warfare or national security issues, at least not directly related as some decades ago, but it is associated with BigSci investments. BigSci, a target of complaints that simultaneously marvels and intimidates decision-makers, politicians, and society. BigSci and its science-fiction feature that inspired and has reached miracle status when the American avant-garde artist, Laurie Anderson, started her successful career describing in a song a futuristic world thanks to “Big Science. Hallelujah.” (Anderson, 1983).

Motivated by the challenge to contribute to a comprehensive solution to meet scientific and industrial communities' claims about a more transparent, informed, structured, evidence-based decision-making process on BigSci projects as well as to help the government to do so, we accepted the challenge. Furthermore, we set as our primary goal to propose a framework for the decision-making process on BigSci investments to support national governments to improve their capacity in making informed and structured decisions with the scientific community and industry participation.

Therefore, a complex challenge evades a simple solution, and to achieve that, we needed to tackle other problems translated into secondary goals. One of them, the proposed taxonomy, unveiled the evolution of the phenomenon that went ‘beyond traditional BigSci’, naturally expanded over other knowledge domains further than physics.

8.1 Conclusions

We started our investigations with the phenomenon of BigSci, which revealed a big challenge when the literature has deemed impossible an updated and systemic definition and taxonomy of BigSci but instead has offered new terms with similar buzzword problems. Nevertheless, the goals and methods of research scientists and politicians can be difficult to sync up, and early attempts to produce a workable definition and taxonomy of BigSci turned to be a marginal success. Chapter 4, starting a fundamental step toward our primary goal, looked at the white and gray literature available on BigSci, a large and varied set of documents analyzed through qualitative metasynthesis and complemented with a systematic inductive approach analysis of one question of our interviews. Our results established 1947 as the year of the first appearance of the term ‘Big Science’ in the literature, advanced the knowledge with a current comprehensive taxonomy by research fields for government purposes, and boosted a proposed definition in a workable format for the government. We showed that contemporary BigSci could encompass all research fields and tried to orchestrate the multifaceted BigSci in one comprehensive definition, both essential to achieving our primary goal. Our present-day BigSci taxonomy reinforces its dynamic nature, and our ticking-box definition proposal seemed to be suitable for several cases, such as the treatment of scientific initiatives for government funding, oversight, and evaluation.

Science is increasingly called on to develop methods that evaluate complex and conflicting problematic situations like the one we studied with scientific rigor. A few decades ago, SODA was designed to allow a rational analysis and structuring of nontrivial uncertain and complex situations, with minimum analyst’s interference, undertaking problem description and resolution from the stakeholder’s perspective. This ability suited our intentions to explore 50 exclusive interviews with BigSci high-level stakeholders from Europe, Canada, and Brazil. Since SODA analysis endeavored to bring satisfying answers to understand in-depth the real problem to be solved, we found out that the prime cause of the problem is the BigSci nature of exploring cutting-edge topics as well as some strategic options to materialize the solution. In Chapter 5, we described this trajectory search for an in-depth understanding of the government decision of BigSci investments, and we discussed the usefulness and limitations of our results, including the non-applicability to situations of funding BigSci project continuation. A step further and beyond toward our goal achievement, we built our multi-criteria model in Chapter 6, the core of our decision support system. Our model has two strong points: consider attributes and criteria, beyond economic issues, mainly derived from the involved stakeholders’ values, and the top decision-makers directly determine the weights of attributes and criteria via a dynamic elicitation process. Both features look for the most favorable proposal opportunities regardless of the scientific field and undoubtedly reflect the decision-makers’ preferences, objectives, and values.

Turn to Chapter 7, we finally reached our primary goal and presented our proposed framework for the government decision of BigSci investments. We conducted our final research from a particular point because we did not have the opportunity to apply it in a real-world situation. Our framework with five Phases encompassing our previous results of taxonomy and definition added to a customizable multi-criteria model is in a position to bring a measure of a scientific solution to the government. In particular, our framework sought to tackle the emergent interests of the different stakeholders, frequently in conflict, using scientific methods like MCDA to build a transparent and evidence-based solution to BigSci investments, with trade-off capabilities. Drawing on a flowchart format (Figure 7.1), we crafted a procedure that entailed the scientific and industrial communities and government analysts posing commissions on the decision process, implementing a routine to address BigSci proposals to their analysis, assessment, and recommendation. The results were so encouraging that we also created a BigSci Index to become a tool for decision support of government BigSci investments.

The adoption of a framework for the decision-making of BigSci investments would help to ensure that decisions are well-informed, follow best practices, and involve a rational, structured and objective process. Benefits include more effective use of public funds and greater clarity and transparency in decision-making. These, in turn, would translate into increased social, economic and political benefits from BigSci investments. Furthermore, the adoption of the proposed framework, and consequently, the proposed taxonomy and definition, has the potential to change how the government plans, funds, oversights and evaluates BigSci investments, making it more transparent and rational, besides records/tracks the whole process as continued best-practice learning for future decision-making.

8.2 Limitations

While this research adopted two main empirical data sources and four different methods, including qualitative and quantitative approaches, their intrinsic limitations (see details in Chapter 3) delimits our results and findings.

The sample of 50 interviews contains precious resources for this research's goals but is not suitable for comparative studies or elicitation of weights for attributes and criteria of the proposed framework. The necessary interviewee's profile restricted the number and amount of interview rounds to refine and enhance the available data and results.

Moreover, the proposed attributes/criteria set of the multi-criteria model is not definitive, or the matter is limited to it, but the set is the result of a first approach; it is relatively short and straightforward and subject to improvement.

The problem of data availability and timescale of BigSci projects represents a severe limitation and is neither workable nor within reach of this research for the purposes of applying the proposed framework.

8.3 Recommendations

Our recommendations are strategic and based on our in-depth problem structuring of BigSci investments:

- long-term, huge, high-risk investment in mission-oriented BigSci associated with scientific/economic development requires social and political responsibilities;
- non-scientific and motivational biases require long and careful negotiation between BigSci scientists and government decision-makers with the help of a well-designated mediator such as a science advisor;
- science diplomacy efforts contribute significantly to establish successful BigSci international collaborations and consequent high impact and soft power;
- strategic BigSci decisions need a decision support framework based on standard attributes, criteria, and indicators, considering scientific and non-scientific aspects and assessments and avoiding only political-driven biases. Our proposed framework followed those objectives.

8.4 Future works

This scientific work is intended for a continuous update due to the dynamic nature of the topic and public purposes. It is strongly recommended that an application (case study or action research) of our proposed framework be the target for further research and discussion for how our framework might work as well as the broad criteria prescribed. The ideal assignment is to develop an action research, following a BigSci project from conception to the final investment decision, via observation, interviews, and application of our proposed framework. Candidates closer to the ideal conditions are, for instance, DestinE, ITER, Sirius, LLAMA, or ESS. The framework application results should be incorporated into an improved version of the proposed framework before being used in a real-world situation.

Since the proposed attributes/criteria set of the multi-criteria model is not definitive, it could be subject to future work. This improvement could include an expanded/diversified literature review and/or interview sample from which an updated SODA and multi-criteria analyses may provide new insights regarding attributes and criteria. For example, in the five identified attributes, there is no cultural attribute distinct from the social one, taking into account the cultural aspect of BigSci projects.

It is essential to consider that all the research development occurred before the global coronavirus pandemic. The impact of this public health emergency on the state of the world science, particularly BigSci, is unpredictable and must be a topic for consideration and on the related government STI policies and strategies in a scenario of deep economic recession. In this sense, scenario planning is an excellent methodology to realize the impact on BigSci and its investments in a post-pandemic new world.

New perspectives from the growth and diversification of concept itself and the question of what useful categories it corresponds to specific scientific projects/proposals to the disclosure of cause and solutions and a process built and expected to be used, bring about exciting research questions to advance the knowledge from where we left. What are the impacts on STI policies considering the proposed definition/taxonomy of BigSci? Given a recent historical overview of decisions of BigSci investments, what are the lessons learned? How do the north-south, north-north and south-south BigSci collaborations work, including main characteristics and impacts? What are the similarities and differences in the government investment decision-making processes between Western and Eastern BigSci? Considering the application of the proposed framework, what are the impacts for the planning, evaluation, funding and oversight of BigSci investments? How are the BigSci environment and the main stakeholders' interactions? Why does a scientist choose to participate in a BigSci project? Is BigSci crucial for science, technology, innovation? Is BigSci the only way to solve global challenges, or is there another better option (model)? How to measure and predict the political and social values and impacts of BigSci? Those are some of the topics that can and should, be explored in future studies. Besides, the always current Alvin Weinberg's (1961) questions regarding the growth of BigSci: "Is Big Science ruining science?"; "Is Big Science ruining us financially?"; and "Should we divert a larger part of our effort toward scientific issues which bear more directly on human well-being than do such Big Science spectaculars as manned space travel and high-energy physics?"

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APPENDIX A FINAL SODA MAP DETAILED FEATURES

List of 73 bipolar constructs in our final SODA map, ordered by construct reference number and showing the cluster under which, each was categorized. For each bipolar construct, the ‘Links to’ column indicates those constructs (by their reference number) to which it connects (symbolized by ‘>’) and is equal to that construct’s outdegree. For example, construct *2* leads to constructs *12*, *3* and *51* and has an outdegree of 3; construct *12* leads to constructs *45* and *50* and has an outdegree of 2. The ‘+’ or ‘−’ signs prefixing the constructs’ reference number indicates an unsigned (positive) arrow or a signed (negative) arrow. From the information on the ‘Links to’ column, the entire map can be reconstructed.

Bipolar construct	**Cluster**	**Links to**
1 BiS should produce high benefits for society ... exceptional large investment	Characteristic	1 > +31 +52 +48 +47 +42 +35 +2 +3 +7 +11 +36
2 BiS isn't only a concentrated infrastructure ... multidisciplinary/distributed or multi-user facility	Characteristic	2 > +51 +3 +12
3 different BiSs have similar challenges ... funding and society engagement in long-term	Characteristic	3 > +6
4 BiS is long-term initiative ... planning usually takes +10 years	Characteristic	4 > +70 +69 +30 +23 +2 +14 +41 +55
5 BiS nature is to explore the frontier of knowledge ... industrial applications aren't the main activity	Characteristic	5 > +16 +72 +50 +34 +28 +26 +20 +4 +3 +2 +8 +1 +13 +40 +41 +63
6 lack of BiS definition by government ... stakeholders wants specific one	Characteristic	6 > +53 +50 +49 +48 +45 +44 +29 +27 +2 -15 +17 -38 +41
7 industry is a stakeholder ... build facilities, push tech frontier, innovation source, and spin-offs	Stakeholder	7 > +42 +33 +32 +31 +25 +21 +36 +39
8 scientific community is a very large, strong and influential stakeholder ... high-level interest and public support	Stakeholder	8 > +46 +31 +9 +10 +13 +18 +19
9 balance in BiS scientists-politicians relationship ... power, timing and influence	Stakeholder	9 > +68 +38 +65 +53 +52 +29 +59
10 weak scientists-industry connection on BiS ... budget competition	Stakeholder	10 > +65 +25 +17
11 society supports investment in BiS ... project survival to changes in government	Stakeholder	11 > -47 -27 +4 +9

12 civilian and military BiS are different ecosystems ... distinct goals but slightly interrelated	Stakeholder	12 > +50 +45
13 users ensure output relevance and high usefulness potential ... end-users as proponent members	Stakeholder	13 > +11
14 project managers are mandatory in BiS projects ... used to manage high budgets	Stakeholder	14 > +15
15 relevant criteria to start BiS collaboration ... country reputation in economy, scientific community, infrastructure and industry	International Collaboration	15 > +43
16 intl BiS collaboration has high impact (soft power) ... science diplomacy effort	International Collaboration	16 > +53 +52 +43 -29 +22 +11 +15 +9 +17 +60
17 industry intl collaborations in BiS are limited ... dependent on project's rules	International Collaboration	17 > -33 +39
18 share goals and principles are required by government for BiS collaboration ... cost sharing	International Collaboration	18 > +43 +15 -17 +12 +19 +36
19 intl BiS collaboration is quite easy ... scientific community used to work in collaboration	International Collaboration	19 > +12
20 intl consortia BiS management is advantageous ... mandatory contributions/project stability	Management	20 > +19 +15
21 intl consortia BiS management disadvantage is inability to react quickly ... under formal regulations	Management	21 > +17 +61
22 BiS model is critical for management ... multi- or single-country	Management	22 > +18 +17
23 accountability in BiS projects is a challenge ... monitoring and verification in long-term	Management	23 > +15 +14 +39 +41 +56
24 funding BiS project continuation is hard question ... no longer scientific relevant	Management	24 > +23 +9 +10 +55
25 running BiS projects needs adaptations to all participants ... inter-sectoral partnerships	Management	25 > +24
26 high interest in BiS projects ... scientific knowledge and exclusivity for industrial contracts	Impact	26 > +30 +7 +8 +38
27 BiS perception issue with sensitive harzard topics ... general public opinion	Impact	27 > +42 +40
28 anticipate impacts of BiS projects is difficult ... frontier of knowledge/intangible and non-scientific aspects	Impact	28 > +66 +51 +9 +24 +23

29 lack of government commitment to BiS projects ... limited vision of science/science diplomacy benefits	Impact	29 > -18 +15 +37 -41
30 BiS investment has HR impact ... scientists' attraction	Impact	30 > +8
31 BiS has political impact ... scientific/economic/industrial development & policies	Impact	31 > +73 +67 +53 +52 +49 +44 +43 +34 +33 +32 +9 +16 +38 +41 +56 +60
32 BiS has legal implications between countries ... IP agreements	Impact	32 > +33 +21
33 improve attractiveness for industrial sector on BiS projects ... fewer rules and more transparency	Future Need	33 > +34 +36
34 improvements on BiS procurement directive ... regulation, industry relationship and non-long-term economic impact goals	Future Need	34 > +25
35 BiS projects as an inspirational effect for new generation ... economy and society well-being based on scientific knowledge	Future Need	35 > +30
36 BiS organizations partnerships (tech, software, know-how) should be encouraged ... complementarities and spin-offs	Future Need	36 > +34
37 lack of systemic roadmap for BiS ... framework for encompassing all disciplines	Future Need	37 > +53 +50 +47 +45 +44 +6 +2 +41 -62
38 establish role of a science advisor/board for BiS ... mediator between scientists and politicians	Future Need	38 > +52 +18
39 BiS policymaking must strike a balance between scientific and technological development ... incentive to industrial participation	Future Need	39 > +33
40 country needs critical mass to justify support for BiS ... scientific community's quantity, quality and excellence	Future Need	40 > +30 +36 +33 +41
41 BiS projects need an exclusive budget ... investment priority	Future Need	41 > +14
42 BiS needs to be in Pasteur's quadrant ... highlight socio-economic return on investments	Future Need	42 > +11 +33
43 BiS decision-making has complex trade-offs attributes ... quantitative, qualitative, and non-scientific aspects	Decision	43 > +48 +54 +55 +58
44 actors involved in BiS decisions are often misplaced ... absence of necessary stakeholders	Decision	44 > +53

45 budget-threshold criteria disqualifies genuine proposals ... each project's research field is different	Decision	45 > +48 +41
46 scientific goals are not defined by political stakeholders ... bottom-up initiatives	Decision	46 > +68 +49 +9
47 decision-making for BiS space project is complicated ... low perception of scientific and economic impacts comparatively	Decision	47 > +46
48 BiS decision-making cannot be based on economic/scientific criteria only ... other gains analysis	Decision	48 > +51
49 government decision making in BiS isn't transparent ... political-driven	Decision	49 > +67 +66 +52 -11 +9 +61
50 BiS decision process for different scientific fields is distinct ... specific attributes choice	Decision	50 > +2
51 hard decision between big and little science ... lack of criteria and decision aid framework	Decision	51 > +52 +43
52 BiS decisions should be objective ... accountability to society/taxpayers about high budget	Decision	Head
53 BiS decision tends to be subjective ... existence of non-scientific and motivational biases	Decision	53 > +62 -52 +54
54 international peer-review could assist BiS decision ... criteria, impacts and benefits assessment	Decision	54 > +52
55 government support for BiS must be global ... capital and operation costs	Decision	55 > +67 +41
56 policymakers avoid deciding BiS ... high budget and visibility	Decision	56 > +53 -58
57 decision-making process in public sector is more complex ... private sector has less bureaucracy	Decision	57 > +33 +34
58 quantify specific political impact/need for BiS ... indicators help to decide	Decision	58 > +52
59 interface scientist-government is important ... high impact on BiS decision	Decision	59 > +43 -29
60 final decision in BiS is for a high-level decision maker ... several non-scientific impacts	Decision	60 > +53 +49
61 consortium decision-making process is less open and transparent ... many countries consensus	Decision	61 > +60

62 BiS decisions are unstructured and subjective ... excellence of science, need for facility, benefits to society are standard attributes	Decision	62 > +52
63 LiS has different decision-making process ... much simpler than BiS	Decision	63 > +65 +51
64 lack of workable thresholds on BiS proposals ... quantitative framework to aid decision-making	Decision	64 > +53 +45 +49
65 resource atomizing damages BiS projects ... impaired full execution	Decision	65 > +41
66 BiS decision needs to be innovative and mission-oriented ... large long-term investment and high risk	Decision	66 > +52
67 decision-making in BiS should include congress ... previous projects/experiences	Decision	67 > +60
68 top-down decision in BiS difficult to execute ... lack of support from the scientific community	Decision	68 > +62
69 BiS convincing is an ongoing effort ... long-term goals (political timing)	Decision	69 > +71 +9 +66
70 BiS must be aligned with long-term planning ... avoid political variability	Decision	70 > +69
71 BiS decision making is a long, slow and group process ... negotiation with the various actors	Decision	71 > +67 +52
72 BiS decision is a worldwide challenge ... international experience	Decision	72 > +73 +26
73 BiS decision is strategic ... financial, scientific and ethical aspects	Decision	73 > +52 +67 +60

APPENDIX B DETAILED DESCRIPTION OF THE MULTI-CRITERIA MODEL

List of 24 first-level criteria and 10 second-level criteria (sub-criteria) of our proposed multi-criteria model, the presentation order is purely random and shows the attribute under which each criterion was categorized. For each criterion, the 'Measurement unit' column indicates those indicators or who assesses the criterion; and the 'Anchor value/Impact level' column is equal to the primary evaluation reference. For example, the criterion 'Topic nature' is assessed by Scientists judgment ('Measurement unit'), and the reference values for each impact level are 0 for fully sensitive topics, 50 for partially sensitive topics, and 100 for no sensitive topics. The '*' sign prefixing the criteria indicates there are sub-criteria to which they are connected and work as indicators to assess the criteria. From the information on the 'anchor value/Impact level' column, added to the respective weighs for all criteria and attributes selected by the decision-maker, it can be calculated the final value V (Eq. 1) of the BigSci proposal under consideration.

- **ATTRIBUTE: SCIENTIFIC**

Criterion	**Description**	**Measurement unit**	**Anchor value/ Impact level**
Basic science	This criterion assesses the BigSci project's objective from the perspective of its nature. BigSci is expected to be an empirical basic scientific inquiry that aims to improve theories or predictions or simply curiosity-driven in complex topics. Industrial applications are not the primary activity or objective and, eventually, is not even considered. We follow the Frascati Manual definition: "Basic research is experimental or theoretical work undertaken primarily to acquire new knowledge of the underlying foundation of phenomena and observable facts, without any particular application or use in view." (OECD, 2015, p. 29)	Scientists judgement	**0 = no** = project's objective is mainly applications **50 = partial** = project's objective is partially basic science and partially industrial applications **100 = yes** = project's objective is only basic science (not applied science)
Knowledge frontier	This criterion assesses the potential scientific impact of the BigSci project.	Scientists judgement	**0 = minimal** = minimal advancement

	BigSci is expected to explore the frontier of scientific knowledge, projects which engage with international challenges and highlight the importance of collaboration between disciplines. The broader the impact, the better, that is, the advancement of the project's primary field is not isolated from other fields, there are complementarities.		in the frontier of knowledge **50 = partial** = advancement in the frontier of only one discipline **100 = yes** = advancement in the frontier of more than one discipline
Human resources	This criterion assesses the team size, expertise, and experience, or the number or the amount large enough to execute the BigSci project and produce the expected results. In other words, the quantity, quality, availability, distribution and excellence of human resources (human capital/talent) involved in the BigSci project for achieving the expected outcomes. Human resources encompass big teams of scientists, technicians, engineers, experimenters, and administrators (including project managers).	Scientists judgement	**0 = low** = no critical mass available **50 = medium** = critical mass available **100 = high** = critical mass available exceeded
Topic nature	This criterion assesses how sensitive and/or under restriction the main scientific topic of the BigSci project is. The general public opinion/perception about BigSci projects working with potential sensitive hazard topics is fundamental regarding taxpayer's support of such investments.	Scientists judgement	**0 = full** = fully sensitive topic **50 = partial** = partially sensitive topic **100 = no** = no sensitive topic
*Team excellence	This criterion is a comprehensive assessment of the academic excellence of the principal investigator or group of principal investigators of the BigSci project. It is assessed through five sub-criteria reflecting conventional indicators of evaluation: publication in high-impact journals, books and chapters, citations, patents and project grants. Those indicators of scientific activity vary with the research field, and thus,	Scientists judgement	

	the scientific commission should be responsible for reference values of the assessment (anchor values/ impact levels).		
HI publication	This sub-criterion of the 'Team excellence' criterion assesses whether the number of publications in international journals with high impact (Q1 journals) is that one expected for an extensive experienced world-class PI team. Q1 (first quartile from highest to lowest based on impact factor or impact index) journals are the most prestigious journals (top 25%) within a subject area (more information, see http://help.incites.clarivate.com/).	Number of publications in Q1 journals	**0 = minimal** **50 = good** **100 = excellent**
Book & chapter	This sub-criterion of the 'Team excellence' criterion assesses whether the number of books and book chapters authored by the PI team is that one expected for an extensive experienced world-class PI team.	Number of books and book chapters	**0 = minimal** **50 = good** **100 = excellent**
Citation	This sub-criterion of the 'Team excellence' criterion assesses whether the number and quality of publications are the ones expected for an extensive experienced world-class PI team. In other words, if the total number of citations received by publications which are including authors from the PI team, reflects the necessary excellence of a BigSci scientific leader group.	Total number of citations	**0 = minimal** **50 = good** **100 = excellent**
Patent	This sub-criterion of the 'Team excellence' criterion assesses whether the number of patents developed or co-developed by the PI team, preferable patents with commercial use, is the ones expected for an extensive experienced world-class PI team. This subcriterion measures its impact on innovation, development of cooperation networks with industry, and even the usefulness of the patents developed.	Number of patents granted	**0 = minimal** **50 = good** **100 = excellent**

Grants	This sub-criterion of the ‘Team excellence’ criterion assesses whether the PI team’s capacity to attract funding and excellence of its projects is that one expected for an extensive experienced world-class project leader group. In other words, if the total number of projects funded by national and international sources, including industry funds, granted for the leader group reflects the expected for an extensive experienced world-class PI team.	Number of national and international grants	**0 = minimal** **50 = good** **100 = excellent**

- **ATTRIBUTE: TECHNOLOGICAL**

Criterion	**Description**	**Measurement unit**	**Anchor value/Impact level**
Facility/ tech	This criterion assesses the need for building a major or unique facility, with an extremely high technological complexity, contributing to the global scientific community. Other possibilities in BigSci initiatives are: (i) building a national facility as part of a global network and with a high technological complexity; (ii) being a partner in an international facility abroad; (ii) no need for building: (a) the facility is already available and no need of improvements; (b) the facility is already available and needs a few minor improvements; (c) the facility is already available and needs major improvements.	Scientists judgement	**0 = yes/unique** = need for building/unique facility in the world **25 = yes/network** = need for building/part of a global network **50 = no/intl** = need for participation/international facility **100 = no/exist** = no need/facility already available
Tech readiness	This complex and crucial criterion is broadly used for decision-making concerning technology status, transition, risk management, and funding. It is categorized by nine levels, from TRL 1 (only basic	Industry judgement	**0 = low** = all tech involved is a novelty (TRL 1 to 3) **50 = medium** = tech involved demanding main improvements

	principles are available and future research and development are mandatory) to TRL 9 (technology proven in operational environment). Technology readiness levels are a widely known type of measurement system, in particular in the space area, used to evaluate the maturity level of a specific technology. For more information, see Héder (2017).		and few novelties (TRL 4 to 7) **100 = high** = tech involved demanding few improvements and no novelties (TRL 8 an 9)
Industry capacity	This criterion measures the capacity of the national industry to develop the needs of the BigSci project, from civil engineering and building to high-tech instruments and devices. It measures the amount and quality of resources (workforce, physical and digital infrastructures) present in a country that will enable the industry to produce and meet the project's demands. It also has to do with making in-house or buying or subcontracting from abroad, specific components, or even the entire production from abroad, when the national industry does not have the in-house capacity.	Industry judgement	**0 = low** = up to 50% of the project's tech demand can be fulfilled by national industry **50 = medium** = 50-75% of the project's tech demand can be fulfilled by national industry **100 = high** = all project's tech demand can be fulfilled by national industry
Dual-use tech	This criterion is sensitive concerning political, diplomatic and economic issues and assesses the potential dual use of the technology involved in the BigSci project. In other words, technologies that are generally used for civilian purposes, but which may have military applications. Generally speaking, they encompass missiles/rockets, nuclear/high-energy physics, artificial intelligence, or biochemical products.	Industry judgement	**0 = yes** = potential dual-use tech involvement **50 = partial** = partially potential dual-use tech involvement **100 = no** = no potential dual-use tech involvement
DMP	This criterion is sensitive and complex concerning technology, costs and agreements, and it assesses the quality of the Data Management and Preservation planning, including hardware, software, security, and management, of the BigSci project. It	Industry judgement	**0 = no** = no specific plan **25 = satisfactory** = satisfactory plan (not complete) **50 = good** = good plan (not complete)

	is almost always related to Big Data aspects and policy and restrictions requirements of funders, typically subject to international agreement and legislation in different countries.		**100 = excellent** = excellent plan (complete)

- **ATTRIBUTE: SOCIAL**

Criterion	**Description**	**Measurement unit**	**Anchor value/Impact level**
Knowledge sharing	This criterion assesses scientific training plans for undergraduates and technological training plans for industry people. It measures human resources' potential impact (development of new skills and knowledge) due to the BigSci project.	Analysts judgement	**0 = no** = no scientific/technological training plans **50 = partial** = only scientific or only technological training plan **100 = full** = scientific and technological training plans for both audiences
Training program	This criterion assesses high-level training program plans for graduates and post-docs. It measures the BigSci project's role in the training of future scientists. This inspirational effect also brings the indirect impact of future scientists being trained, developing technology, and even spinning-off.	Analysts judgement	**0 = no** = no high-level training program plans **50 = partial** = high-level training program plan only for masters or only for PhDs or only for graduate students or only for post-docs **100 = full** = high-level training program plans for all future scientists
*National / International impact	This criterion is a multifaceted assessment of the potential national and international societal impact of the BigSci project. It is assessed through two sub-criteria, reflecting general indicators of social impacts/benefits: society awareness and international reputation. Since those indicators have different natures, each of them should be assessed by different expert teams responsible for reference values of the assessment (anchor values/ impact	Analysts / scientists judgement	

	levels). In other words, government analysts and scientists should perform the evaluation.		
Society awareness	This sub-criterion of the 'National / International impact' criterion assesses planning for visits and events dedicated to a non-expert audience, mainly local or regional, but not restricted to them. The educational and outreach activities have a potential indirect impact on participants' knowledge and skills. It may also encompass the public visibility of the BigSci project, in online media, for example, and the project's popularity and interest. This measure also reflects society's support for the BigSci project.	Analysts judgement	**0 = no** = no plans for outreach activities **50 = partial** = plan only for guided visits or only for outreach events, social media, and consultations, mainly for local/regional community **100 = full** = plans for a comprehensive set of outreach activities
Internationa l reputation	This sub-criterion of the 'National / International impact' criterion assesses the international reputation of scientific leaders involved in and supporting BigSci projects, in particular responsible for activities such as counseling, lobbying, public relations, and outreaching knowledge related to the project dedicated to expert and non-expert audiences, mainly national or international, but not restricted to them. It may also encompass the public visibility of the BigSci project in all media as well as the project's popularity and interest. It is highly dependent on the research field. This indicator counts the number of international scientific awards and invitations to international lectures. This measure also reflects the excellence of the scientists involved in and supported the BigSci project.	Scientists judgement	**0 = low** = no international relevant awards or invitation for relevant lectures **50 = medium** = few international relevant awards or invitation for relevant lectures **100 = high** = significant number of international relevant awards or invitation for relevant lectures
Local needs	This criterion assesses local non-scientific infrastructures' needs and requirements due to the BigSci project. It also represents potential societal benefits such as the building of energy/water supply infrastructure,	Analysts judgement	**0 = high** = high need or few pre-existent non-scientific infrastructures **50 = partial** = partial need or satisfactory

	waste management, schools, hospitals, cultural/entertainment places, among others, to meet demands from an increase and/or new distribution in the local population.		pre-existent non-scientific infrastructures **100 = low** = no/low need or few necessary improvements to the pre-existent non-scientific infrastructures
*Local impact	This criterion is a complex, comprehensive assessment of the potential local societal impact of the BigSci project. It is assessed through three sub-criteria reflecting conventional indicators of social impacts/benefits: HDI, tourism and education level. Those indicators widely vary depending on the BigSci project and local context, and thus, the government analysts should be responsible for reference values of the assessment (anchor values/ impact levels).	Analysts judgement	
HDI	This sub-criterion of the 'Local impact' criterion assesses the potential increase of the local Human Development Index (HDI), a widely known composite index. It encompasses three dimensions: health (life expectancy at birth), education (mean of years of schooling for adults aged 25 years and more and expected years of schooling for children of school entering age), the standard of living (gross national income per capita). For more information, see http://hdr.undp.org/en/content/human-development-index-hdi.	Estimated index value	**0 = low** = low potential increase **50 = medium** = medium potential increase **100 = high** = high potential increase
Tourism	This sub-criterion of the 'Local impact' criterion assesses the potential creation and/or increase in scientific and business local tourism. It encompasses visitors, temporary scientific and business people directly related to the BigSci project visiting or living in the local area where the	Estimated number of visitors	**0 = low** = low potential increase **50 = medium** = medium potential increase **100 = high** = high potential increase

	facility/headquarters of the project would be located, as well as on-site scientific, technological and/or business conferences, seminars, workshops and/or meetings.		
Education level	This sub-criterion of the 'Local impact' criterion assesses the potential increase number of high-skilled local residents, providing potential indirect benefits for local society. This measure may include, but not be restricted to, scientists, engineers, industry people and administrative staff related to the BigSci project.	Estimated number of MScs and PhDs	**0 = low** = low potential increase **50 = medium** = medium potential increase **100 = high** = high potential increase

- **ATTRIBUTE: ECONOMIC**

Criterion	**Description**	**Measurement unit**	**Anchor value/Impact level**
Industry funding	This criterion assesses the level of interest of the industry to fund the BigSci project. It also works as a proxy to understand the level of industry attractiveness to the BigSci project and its innovation potential.	Industry judgment	**0 = no** = no/low industry interest to be a funder **50 = medium** = partial industry interest to be a funder **100 = high** = high industry interest to be a funder
Industry participation	This criterion assesses the level of the general interest of the national industry to participate in the BigSci project. The industry is a fundamental stakeholder in a BigSci initiative and plays varied roles, combined or not: partner (public-private collaboration), supplier, user, owner, operator, contractor, beneficiary (client), and/or study site.	Industry judgment	**0 = no** = no/low national industry participation interest **50 = medium** = partial national industry participation interest **100 = high** = high national industry participation interest
Tech transfer	This criterion assesses the proposed processes for sharing or transfer technology, technical knowledge, designs, prototypes, materials, inventions, and software from the BigSci project to any	Analysts judgment	**0 = no** = no technology transfer plan **50 = conditional** = technology transfer plan with major restrictions

	national organization. The technology transfer process encompasses IP agreements, patenting, licensing, etc.		**100 = unconditional** = technology transfer plan with minor restrictions
*Global cost	This criterion is a comprehensive assessment of all lifecycle costs, from conception to eventual conclusion or decommissioning of the BigSci project. It encompasses capital investments and operation costs, which reflect the two sub-criteria used to measure this criterion. Those indicators of demanded funding vary widely and depend on the primary research field and estimated duration of the BigSci project, and thus, the government analysts should be responsible for reference values of the assessment (anchor values/ impact levels).	Analysts judgment	
Capital/year	This sub-criterion of the 'Global cost' criterion evaluates the proposed sum of money to provide the permanent fixed assets of the BigSci project, including facility building costs, specific instrumentation development and production costs, computational hardware costs, among others. The investment is analyzed by fiscal year to allow government budget planning and management.	Hundreds of millions of USD	**0 = extreme** = extremely high cost **50 = high** = very high cost **100 = standard** = standard cost
Operation/year	This sub-criterion of the 'Global cost' criterion evaluates the proposed sum of money to ensure the normal day-to-day of running the BigSci project, including implementation, repair, maintenance and administration of all research activities, eventual rent and insurance, marketing costs, travel and events expenses, supplies and suppliers contracts, grants, salary and wage expenses, among others.	Hundreds of millions of USD	**0 = extreme** = extremely high cost **50 = high** = very high cost **100 = standard** = standard cost

	The expenditure is analyzed by fiscal year to allow government budget planning and management.		
*Local impact	This criterion is a complex, comprehensive assessment of the potential local economic impact of the BigSci project. It is assessed through three sub-criteria reflecting conventional indicators of economic impacts/benefits: HDI, tourism and education level. Those indicators widely vary depending on diverse factors such as the BigSci project and local/regional context, and thus, the government analysts should be responsible for reference values of the assessment (anchor values/ impact levels).	Analysts judgment	
GDP	This sub-criterion of the ‘Local impact’ criterion assesses the Gross Domestic Product (GDP) per capita of the local area or region where the facility/headquarters of the BigSci project would be located during and after its existence. It includes public administration, health and education and social security values.	Thousands of USD	**0 = low** = low potential increase **50 = medium** = medium potential increase **100 = high** = high potential increase
Jobs	This sub-criterion of the ‘Local impact’ criterion assesses the potential creation of new direct and indirect jobs in the local economy as well as the creation/increase of highly-skilled employees in the local facility/headquarters of the BigSci project, such as scientists, engineers, technicians and administrative staff. So, this sub-criterion measures indirect benefits for the local economy as new taxpayers, for instance.	Number of jobs/employees	**0 = low** = low potential increase **50 = medium** = medium potential increase **100 = high** = high potential increase
Start-ups	This sub-criterion of the ‘Local impact’ criterion assesses the potential creation and/or increase	Analysts judgment	**0 = low** = low potential increase

	of start-ups, in particular technological, created with the support of the BigSci project (spin-off companies).		**50 = medium** = medium potential increase **100 = high** = high potential increase

- **ATTRIBUTE: POLITICAL**

Criterion	**Description**	**Measurement unit**	**Anchor value/Impact level**
STI strategy	This criterion assesses the level of alignment of the BigSci project with the national STI strategy. It also works as a proxy of the commitment level of the long-term goals of the project with the nation's interest.	Analysts judgment	**0 = low** = low alignment with the STI national strategy **50 = partial** = partial alignment with the STI national strategy **100 = full** = it is part of the STI national strategy
Top-down demand	This criterion considers whether the BigSci project is a top-down national demand. In other words, it analyzes if high-ranking national government decision-makers ordered scientific research on a specific topic to the scientific community based on national emergent needs or interests or priority policies.	Analysts judgment	**0 = low** = scientific community demand **50 = partial** = partially meet government demand **100 = full** = government demand
Data sharing	This criterion assesses the level of alignment of the plan of access and use of the data produced by the BigSci project to the government data sharing policy. Those data would be primarily accessed by national public entities, the national private sector, or the international community.	Analysts judgment	**0 = no** = does not meet government data sharing policy **50 = conditional** = partially meet government data sharing policy **100 = open** = completely meet government data sharing policy
*Diplomatic interest	This criterion is a complex, comprehensive assessment of the diplomatic interest of promoting international relationships through scientific collaborations associated with the BigSci project. It is assessed through two	Analysts judgment	

	sub-criteria reflecting its main motivations: collaboration and geopolitical. Those indicators widely vary depending on depends on various factors such as research topic and country international relations issues, and thus, the government analysts should be responsible for reference values of the assessment (anchor values/ impact levels).		
Collaboration	This sub-criterion of the 'Diplomatic interest' criterion assesses the level of the government interest to promote international scientific collaboration in the BigSci project. It also works as a proxy to understand the level of international community attractiveness to the BigSci project or its potential for cost-sharing.	Analysts judgment	**0 = low** = no/low interest in diplomatic/international relations for the project **50 = partial** = indifferent/partial interest in diplomatic/international relations for the project **100 = high** = high interest in diplomatic/international relations for the project
Geopolitical	This sub-criterion of the 'Diplomatic interest' criterion assesses the level of the government interest to promote international relations grounded on non-scientific goals such as desirable international prestige, strong political, economic and/or cultural influence or good reputation in the international arena.	Analysts judgment	**0 = low** = no/low interest in diplomatic/international relations for the project **50 = partial** = indifferent/partial interest in diplomatic/international relations for the project **100 = high** = high interest in diplomatic/international relations for the project