Building Excellence

The Expert Panel on Leading Practices for Transforming Canadian Science Through Infrastructure

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BUILDING EXCELLENCE

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THE COUNCIL OF CANADIAN ACADEMIES
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This report was prepared for the Government of Canada in response to a request from Public Services and Procurement Canada. Any opinions, findings, or conclusions expressed in this publication are those of the authors, the Expert Panel on Leading Practices for Transforming Canadian Science Through Infrastructure, and do not necessarily represent the views of their organizations of affiliation or employment, or the sponsoring organization, Public Services and Procurement Canada.

Library and Archives Canada

ISBN: 978-1-926522-71-5 (electronic book)   978-1-926522-70-8 (paperback)

This report should be cited as:
Council of Canadian Academies, 2019. *Building Excellence*, Ottawa (ON): The Expert Panel on Leading Practices for Transforming Canadian Science Through Infrastructure, Council of Canadian Academies.

Printed in Ottawa, Canada

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Canada This assessment was made possible with the support of the Government of Canada.

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Expert Panel on Leading Practices for Transforming Canadian Science Through Infrastructure and Workshop Participants

Under the guidance of its Scientific Advisory Committee, Board of Directors, and the Academies, the CCA assembled the Expert Panel to lead the design of the workshop, complete the necessary background research, and develop the report. The Panel directed the CCA in identifying the experts who participated in the workshop. Each expert was selected for their expertise, experience, and demonstrated leadership in fields relevant to this project.

Expert Panel

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Message from the Chair

Science and technology (S&T) are not top of mind for the majority of Canadians when they think of the federal government. This is understandable but also unfortunate, as most of us tend to overlook the incredibly important role that federal S&T activities play in such areas as safeguarding national security, improving public health, innovating new solutions in support of our economy, managing natural resources, protecting the environment, providing the science to support climate change policies, and regulating in the public interest.

Federal S&T activities are performed in close to 200 laboratories and other major facilities located throughout Canada. This infrastructure supports research, technology development and related scientific activities such as monitoring and surveillance across a broad spectrum of work, from ocean science and nuclear physics to archaeology and automotive safety. Most federal S&T facilities, however, are showing their age. On average, these facilities are over 40 years old, and nearly half were built before 1975. In a recent assessment of federal S&T facilities in the national capital area, one third were identified as requiring attention, and of these, a large majority were rated as being in either poor or critical condition. Meanwhile, capital spending on S&T facilities in the federal government has been essentially flat for more than a decade.

Recognizing an increasingly urgent need for reinvestment, the federal government in its 2018 budget committed $2.8 billion to renew its science and technology facilities. Importantly, this funding will not only provide for infrastructure renewal but will also promote a rethink of how government supports S&T — in part through the construction of multi-purpose, collaborative spaces that bring together scientists and engineers from across federal departments and from the academic and private sectors to promote and pursue shared research agendas. Collaboration, especially with academic science, is critical to the success of federal S&T and is a central feature of *Canada's Science Vision*.

Investments in S&T infrastructure have long time horizons. Getting these investments right is critical to ensuring the success of Canadian science for decades to come. To that end, I was honoured to have the opportunity to chair this Expert Panel to examine leading practices that can support this vitally important initiative. We as a panel undertook a wide-ranging review of leading practices world-wide and benefitted from insights shared at a workshop of experts with diverse perspectives and experiences. This report represents the culmination of our work.

I would like to thank Public Services and Procurement Canada for sponsoring this project and the Institute on Governance for supporting the secondment of Jeff Kinder as our very capable Project Director. I am also grateful to the Council of Canadian Academies and its staff for the outstanding support given to the panel, as well as to the workshop participants for generously sharing their time and expertise. And of course, I would like to sincerely thank my fellow panel members who were unfailingly enthusiastic, insightful and good humoured throughout the process.

I believe this assessment is timely and necessary if Canada is to be, and be seen to be, a leader in transforming science for society through the next generation of S&T infrastructure, and I am optimistic this report will be valuable to policymakers as they move this initiative forward.

Wendy Watson-Wright, Chair
Expert Panel on Leading Practices for Transforming
Canadian Science Through Infrastructure

Message from the CCA President and CEO

The CCA has been assessing the state of science and technology in Canada periodically since 2006 and to Canada's credit, these assessments have repeatedly affirmed our capacity to contribute to global research and technological development at the highest levels. As a country, we continue to produce a non-trivial share of the world's highly cited research, and have maintained our ability to participate in cutting-edge science in many domains.

However, any sense of complacency arising from such successes would be misplaced. Our ability to participate in world-leading science today is largely the result of farsighted investments made years, even decades, ago. Today's generation of researchers are often working in research facilities and laboratories that were designed and built in the latter half of the 20th century. These facilities have served Canadian scientists well, but many are straining to keep up with the pace of scientific and technological advancement, or are simply in need of major repairs or replacement. In some instances, they impede rather than promote excellent research, which made the federal government's recent commitment to renewing federal S&T infrastructure all the more timely.

For this reason, CCA was pleased to receive a request from Public Services and Procurement Canada to convene an expert panel to explore leading practices for evaluating science and technology (S&T) infrastructure proposals. Given the scale and importance of the government's planned investments, it is prudent to ensure that Canada benefits from the accrued wisdom, and resulting best practices, that can be garnered from similar initiatives and experiences in other jurisdictions.

Chaired by Dr. Wendy Watson-Wright, the Expert Panel has now completed its important work. I am grateful for the time and energy they put in to produce an assessment that cannot help but inform decisions for years (and possibly decades) to come. The challenges involved in renewing the federal government's S&T facilities are considerable, but the insights provided here will do much to ensure that federal decision-makers are well-informed and well-supported as they move forward with this important initiative.

Eric M. Meslin, PhD, FCAHS
President and CEO

Acknowledgements

The Panel wishes to thank the following people and organizations for sharing their expertise on S&T infrastructure investments: Mona Nemer, Chief Science Advisor, Government of Canada; Bryony Butland, Programme Director UK Infrastructure Roadmap, United Kingdom Research and Innovation (UKRI), Science and Technology Facilities Council (STFC); David Moorman, Senior Advisor, Policy and Planning, Canada Foundation for Innovation (CFI); Dominik Sobczak, Executive Secretary, European Strategy Forum on Research Infrastructures (ESFRI); and Ryan Winn, Acting Branch Manager, Research Policy and Programs Branch, National Collaborative Research Infrastructure Strategy (NCRIS).

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Peer Review

This report was reviewed in draft form by reviewers selected by the CCA for their diverse perspectives and areas of expertise. The reviewers assessed the objectivity and quality of the report. Their confidential submissions were considered in full by the Panel, and many of their suggestions were incorporated into the report. They were not asked to endorse the conclusions, nor did they see the final draft of the report before its release. Responsibility for the final content of this report rests entirely with the authoring Panel and the CCA.

The CCA wishes to thank the following individuals for their review of this report:

David Castle, Vice-President Research and Professor, School of Public Administration; Adjunct appointment Gustavson School of Business, University of Victoria (Victoria, BC)

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Janet E. Halliwell, President, J.E. Halliwell Associates Inc. (Salt Spring Island, BC)

Alan Winter, BC Innovation Commissioner, Government of British Columbia (Victoria, BC)

The peer review process was monitored on behalf of the CCA's Board of Directors and Scientific Advisory Committee by **Stuart MacLeod, FCAHS,** Professor of Pediatrics (Emeritus), University of British Columbia. The role of the peer review monitor is to ensure that the Panel gives full and fair consideration to the submissions of the peer reviewers. The Board of the CCA authorizes public release of an expert panel report only after the peer review monitor confirms that the CCA's peer review requirements have been satisfied. The CCA thanks Dr. MacLeod for his diligent contribution as peer review monitor.

Key Findings

Science conducted by the federal government is essential to support the health, security, and well-being of people in Canada. This undertaking requires world-class science and technology (S&T) infrastructure that supports the needs of government scientists in delivering on their mandates. It also increasingly relies on collaborations that cut across departmental, sectoral, and disciplinary boundaries. Infrastructure, however, is only one component of a science ecosystem — people are the heart of a successful, collaborative S&T ecosystem.

Leading practices in decision-making for S&T infrastructure investments take into consideration four principles: scientific excellence, collaboration, feasibility, and broader impacts.

These principles help ensure that S&T infrastructure investments build for a future in which agile, cross-disciplinary, collaborative facilities allow government scientists to engage meaningfully with each other, as well as with collaborators from academia, industry, Indigenous communities, non-governmental organizations, and local organizations, to meet challenges as they arise. Robust evaluations of infrastructure investment proposals also consider the needs of government science, including the urgent need to address existing deficits in infrastructure.

Evaluations of scientific excellence for government S&T infrastructure investments differ from those in academia or industry because they must include consideration of government mandates.

Federal S&T infrastructure investments must deliver on government mandates and objectives. These investments must support discoveries, insights, and innovation as well as enabling high-quality, rigorous monitoring, surveillance, and regulatory science. Mandates and objectives can change over time; considerations for future needs can be addressed explicitly in the flexibility, connectivity, and modularity of the proposed facility design.

S&T infrastructure that supports collaboration can amplify science outcomes and lead to solutions for complex challenges.

Collaborative S&T infrastructure proposals highlight the ways that new users can find opportunities for engagement within a facility, and support building relationships by addressing potential barriers to access. Dedicated, professional support staff hold the institutional knowledge that facilitates relationship building and enables new collaborations to face future challenges. S&T infrastructure proposals that provide different types of spaces — such as private, formal meeting, semi-open, open, virtual, and overbuilt spaces — support different but equally vital aspects of collaborative work.

Assessing the long-term feasibility of proposed S&T infrastructure requires consideration of ownership, governance, and management, particularly for shared facilities.

Evaluating feasibility requires the expertise of scientific and non-scientific professionals (e.g., in technical, financial, managerial, social, regulatory, environmental, and other areas) and is distinct from assessing scientific excellence. A stage-gated process allows for the evaluation of technical and financial readiness, risk, ownership and governance structures, contractual obligations, and other aspects of feasibility, using criteria explicitly tied to expectations for success at different stages of the infrastructure life cycle.

The broad economic and social impacts of proposed large-scale S&T infrastructure projects are typically included in the evaluation process.

Though future impacts are difficult to assess, proposals can be evaluated on the credibility and logic of the pathways to expected impacts. Including perspectives from a wide variety of stakeholders from across different disciplines and sectors helps to provide a comprehensive assessment of such pathways.

A "middle-out" approach to developing proposals facilitates relationship building from the outset of the proposal process and can ensure the success of collaborative S&T infrastructure.

In a middle-out approach, funders request proposals that address specific objectives and manage a process in which the community refines proposals collaboratively. This approach allows the S&T community to co-create promising proposals that meet government needs. In contrast, bottom-up approaches (developed solely by the community) might overlook government-mandated activities and top-down approaches (developed solely by funders) might limit collaborative opportunities.

A clear vision and strategy for prioritizing S&T infrastructure investments (e.g., roadmapping) is critical to the decision-making process.

Strategic planning exercises, such as roadmaps, are a leading practice for informing decisions regarding the development of national S&T infrastructure. A rapid, high-level overview may be better suited than an in-depth, complex assessment to deliver timely, well-placed S&T infrastructure investments to meet the current and future needs of government science.

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1

Introduction

In *Budget 2018*, the Government of Canada committed $2.8 billion to renew its science laboratories through the Federal Science and Technology Infrastructure Initiative (GC, 2018a, 2019a). This investment in government science is intended to “advance interdisciplinary research on, among other things, climate change, ocean protection, and human health” (GC, 2018a).

One component of the initiative is the construction of multi-purpose, collaborative facilities that bring together federal scientists from different departments and agencies to pursue science that supports evidence-based decision-making (GC, 2018a, 2019a). In particular, the initiative allows the government to consider how to use its science and technology (S&T) real property investments to help federal government science overcome barriers to collaboration, become more efficient, and build synergies among programs. The new facilities “will be built to achieve a net zero carbon footprint,” and “a new science infrastructure program management office [will] support the renewal of federal laboratories” (GC, 2018a).

Beginning in 2019, the federal government will consider approaches to assess S&T infrastructure investment opportunities that reflect their new vision for the federal S&T enterprise as collaborative, adaptive, and efficient (GC, 2019a). As well as supporting greater collaboration within federal government science, this vision sees the federal science ecosystem engaging more directly with federal research funding agencies (the Canadian Institutes of Health Research, the Natural Sciences and Engineering Research Council, and the Social Sciences and Humanities Research Council), the Canada Foundation for Innovation (CFI), post-secondary institutions, research hospitals, provinces and territories, municipalities, the private sector, and Indigenous groups (GC, 2019a).

1.1 PANEL CHARGE AND SCOPE

Public Services and Procurement Canada (the Sponsor) asked the Council of Canadian Academies (CCA) to assess the evidence on leading practices for federal S&T infrastructure investment decisions. Specifically, the Sponsor posed the following questions:

> *What is known about leading practices for evaluating proposals for science and technology infrastructure investments that is relevant to Canadian federal science for the future?*
>
> *What processes and advisory structures have been used for reviewing proposals for significant science infrastructure investments, and what is known about their strengths and weaknesses?*
>
> *What guiding principles and criteria can help assess proposals that support the federal vision for science in Canada, including, for example, interdisciplinarity?*

The CCA appointed a four-member expert panel (the Panel) to identify and assess relevant evidence on the topic and develop a report. In consultation with the Sponsor, the Panel confirmed the scope of the assessment, which included investments in S&T infrastructure that is multi-sectoral, multidisciplinary, and multi-departmental. These investments will be focused on government mission-oriented (or priority-driven) research and development (R&D) and related scientific activities (RSA), such as regulatory science and long-term data collection and monitoring. Out of scope were facilities housing a single department, non-federal science infrastructure, mobile assets (e.g., vessels), global research infrastructure (e.g., CERN), and large infrastructure for basic research (e.g., telescopes).

Although the Panel defined infrastructure broadly, the focus of this assessment is primarily on buildings and facilities. However, S&T infrastructure can include a variety of resources, as depicted in Figure 1.1:

- equipment, instruments, and tools;
- knowledge-based resources such as libraries, archives, specimen collections, and databases;
- cyberinfrastructure, communications, and IT support including hardware, software, services, and personnel;
- animal colonies, cell lines, and plant or bacteria strains;
- technical support staff and services; and
- administrative, management, and governance structures.

(Neal *et al.*, 2008)

1.2 APPROACH TAKEN AND EVIDENCE CONSIDERED

There is limited publicly available evidence on infrastructure evaluation processes for intramural government S&T facilities. Therefore, the Panel looked to organizations that evaluate proposals for research infrastructure dedicated to basic discovery-oriented research, including large-scale big science facilities. The review of these organizations was complemented by interviews with individuals familiar with top research infrastructure programs around the world. Specifically, the Panel examined evidence for reviewing research infrastructure proposals in:

- Australia: National Collaborative Research Infrastructure Strategy (NCRIS);
- Canada: Canada Foundation for Innovation (CFI);
- Denmark: Nationalt Udvalg for Forskningsinfrastruktur [National Committee for Research Infrastructure] (NUFI);
- European Union: European Strategy Forum on Research Infrastructures (ESFRI);
- Germany: Bundesministerium für Bildung und Forschung [Federal Ministry of Education and Research] (BMBF);
- United Kingdom: Science and Technology Facilities Council (STFC); and
- United States: Major Research Equipment and Facilities Construction (MREFC).

See Appendix for an overview of these organizations.

To inform its consideration of leading practices, the Panel reviewed evidence from the literature for investing in and maintaining collaborative S&T infrastructure, including: evidence on outcomes from collaborative research; theories of cross-sectoral integration and complex decision-making; and methods of supporting greater collaboration system-wide.

The Panel also convened a one-day workshop of 13 experts (Workshop Participants) to review the evidence collected and provide insight. Workshop Participants represented a broad range of expertise, including research and research administration, scientific facility management, sociology of scientific collaboration, and innovation systems.

This report synthesizes key theoretical and practical considerations in developing principles, criteria, and decision-making structures and processes for assessing and investing in collaborative S&T infrastructure. Unless otherwise referenced, the findings of this report reflect observations made by the Panel, after due consideration and deliberation of the evidence and insights from the workshop.

1.3 CONTEXT FOR FEDERAL GOVERNMENT SCIENCE IN CANADA

> Canada's world-class federal science supports evidence-based decision-making, which improves our quality of life, our economy and our future prosperity.
>
> (GC, 2018a)

Intramural federal government S&T encompasses "all systematic activities which are closely concerned with the generation, advancement, dissemination and application of scientific and technology knowledge in all fields of science and technology, that is, the natural sciences and engineering, and the social sciences, humanities and the arts" (StatCan, 2017). This includes R&D as well as RSA such as "data collection, information services, special services, and studies and education support" (StatCan, 2017). RSA includes surveillance and monitoring activities as well as the product testing and standardization required to ensure the safety and well-being of people in Canada (StatCan, 2007) — important activities not generally performed in academic research or industrial R&D (EAGGST, 2014). RSA represents much of the federal intramural scientific activity and largely differentiates government science from the science performed in other sectors (EAGGST, 2014; StatCan, 2019a).

KEY ELEMENTS OF S&T INFRASTRUCTURE:

1. Libraries, archives, specimen collections, databases
2. Tools, equipment, instruments
3. Communications/IT support services
4. Support staff and workers
5. Animal colonies or cell lines or plant and bacteria strains

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Figure 1.1

What Is S&T Infrastructure?

S&T infrastructure is defined broadly as the facilities, equipment, resources, governance structures and services that are necessary to enable scientists and other researchers to perform their work.

Federal scientists work in a variety of departments and agencies with diverse mandates, from exploring the High Arctic (e.g., Polar Knowledge Canada) to protecting Canadians (e.g., Defence Research and Development Canada). Their work supports:

- regulatory, surveillance, and monitoring activities necessary for the safety and well-being of people and the environment (e.g., food inspection, vehicle testing);
- basic, cutting-edge science that responds to society's needs (e.g., predictive climate models, fighting emerging infectious diseases); and
- transformative, high-risk, high-reward research and technology development at the forefront of knowledge and innovation (e.g., artificial intelligence, nanotechnology).

Departments and organizations may have overlapping scientific interests and infrastructure needs. The federal government strives to recognize and leverage expertise and knowledge of cutting-edge developments in complementary fields to address complex public policy challenges (GC, 2018a).

Generally, individual departments and agencies are responsible for investment in federal S&T infrastructure. They spend, on average, between $300 to $400 million annually on capital expenditures relating to S&T, amounting to about 6% of total federal intramural spending on S&T (StatCan, 2019b). With the exception of a temporary spike in 2010–2011, capital spending on S&T in the federal government has shown limited growth since the early 2000s (StatCan, 2019b). In 2014, an expert advisory group found that "the current state of S&T real property and equipment negatively impacts the ability to fulfill mandates" and called for a coordinated approach to infrastructure renewal (EAGGST, 2014). *Canada's Science Vision* also recognizes the need to modernize federal S&T infrastructure (GC, 2019b).

1.4 PRINCIPLES FOR LEADING S&T INFRASTRUCTURE INVESTMENT PRACTICES

Canada's Science Vision is intended to make science more collaborative; support evidence-based decision-making; foster the next generation of scientists; and promote equity, diversity, and inclusion among researchers (GC, 2019b). In this context, the Panel deliberated on the collected evidence, as well as insights from the workshop, and identified four principles that guide evaluations of proposed S&T infrastructure investments:

- Cultivating scientific excellence
- Supporting collaboration
- Ensuring feasibility
- Delivering broader impacts

The Panel used these principles to focus discussion on leading practices for developing criteria, decision-making processes, and advisory structures. The principles emerged from conversations with the Sponsor and were refined based on examination of the evidence from Canada and other jurisdictions, and Panel deliberations. The principles were tested with Workshop Participants to ensure that they sufficiently captured the breadth of relevant considerations.

Chapters 2 to 5 consider in depth each of the four principles and the available evidence on their relevance to S&T infrastructure investments. Chapter 6 examines key elements for consideration in developing decision-making processes and advisory structures. The report concludes with the Panel's final reflections on its charge, highlighting their collective insights into leading practices for evaluating proposed S&T infrastructure investments.

2

Cultivating Scientific Excellence

Striving for excellence is foundational to scientific endeavours. All organizations the Panel examined conduct a review of the scientific excellence of research infrastructure proposals by engaging relevant, and often external, scientific experts. Criteria associated with scientific excellence are similar among organizations, although the exact terminology and specific criteria may differ (STFC, 2010; BMBF, 2015; Danish Agency for Science, 2015; ESFRI, 2016; CFI, 2017a; Gov. of Australia, 2018; NSF, 2018). Scientific excellence is a function not only of the physical infrastructure, equipment, and connectivity required to produce high-quality findings, but also of the scientists, support staff, and governance structures essential to the operations of a science facility. Ensuring the quality of the R&D and RSA produced by S&T infrastructure requires consideration of the needs of federal scientists to deliver on their mandates, as well as the potential to advance knowledge and pursue discoveries.

2.1 WHAT IS SCIENTIFIC EXCELLENCE?

Reviews of scientific excellence in the context of federal S&T infrastructure proposals consider delivering on government mandates and objectives; supporting discoveries, insights, and innovation (R&D); and maintaining high-quality monitoring, surveillance, regulatory science, and other RSA.

The evaluation of scientific excellence depends on context. As Ferretti *et al.* (2018) note, “the quality of an indicator of research excellence crucially depends on its use.” Government scientists perform science to fulfil mandates that range from ensuring the health and well-being of Canadians to supporting economic prosperity through technological development. These varied contexts give rise to diverse indicators of what constitutes excellence.

For government science oriented to creating new knowledge or discoveries, excellence criteria may be aligned with those of academic science (e.g., publications) or industrial R&D (e.g., patents, and new products or processes). In contrast, excellence for regulatory science is a function of the rigour, quality, and reliability of research methods and outcomes that deliver on government mandates. Because of these differences, evaluations of scientific excellence in government S&T infrastructure proposals include criteria relevant to the core responsibilities, mandates, and goals of the departments and stakeholders involved.

Additionally, Workshop Participants expressed concern about the potential to lose sight of the broader objectives of infrastructure investments when reviewing scientific excellence. Actors in a system who win an early advantage tend to be rewarded with more advantages, eventually eliminating competition, a phenomenon called “success to the successful” (Meadows, 2008). Groups with support or experience in writing funding proposals may thus have an advantage in a competitive review process (Neal *et al.*, 2008). At face value, this might not seem to be an issue — rewarding groups who perform well according to set criteria appears to satisfy the need to ensure scientific excellence. However, for government science in the service of an established mandate, the goals of scientific excellence must not be met at the expense of other departments’ abilities to fulfill their mandates.

Ferreira *et al.* (2015) found that, as part of a robust and broad review system, open peer review (i.e., in which authors and reviewers are visible to each other) can improve the quality of reviews, by increasing the independence of reviewers and decision-makers and allowing for greater standardization of the review’s elements. The Panel observed that making infrastructure proposals and reviews visible (for example, through an online system) in a multi-stepped decision-making process (i.e., stage-gated, discussed in Section 4.1), allows participants to identify opportunities to build collaborations through the proposal-development process.

2.2 ADAPTABILITY, FLEXIBILITY, AND CONNECTIVITY

Mandates and objectives change over time; forward-looking organizations address future needs by incorporating flexibility, connectivity, and modularity into the design of the proposed facility.

Understanding what scientific excellence means over the life cycle of proposed infrastructure (i.e., development, design, construction, operation, and divestment) is essential to cultivating and sustaining excellence. Workshop Participants explained that infrastructure should benefit from an adaptable and flexible design that can support changing government priorities, new research directions, and new technologies over the long term. Thus, infrastructure investments must be future facing and attempt to anticipate long-term technological, social, and economic changes. However, a tension can arise between planning infrastructure to meet the needs of current users and allowing for flexibility to address shifting goals (Ribes & Finholt, 2007). To address this tension, flexibility can be maximized through the design practice of modularity, where repeated elements in a building plan can be repurposed in different configurations and scales to meet expressed needs (Edwards, 2013).

The scientific excellence of infrastructure is, in large part, a function of the scientific activity it enables, which is often measured by the products created by its staff and users. These include data, models and analyses, advice and decision support, scientific publications, government reports, educational materials, standards, patents, and technologies. Therefore, attracting high-quality personnel is critical to maintaining excellence over the life cycle of the infrastructure. Attracting such staff and users can be achieved by establishing policies that ensure ease of access to the facility (including connectivity), cutting-edge equipment, desirable and inclusive workspaces, and the capacity to accommodate user needs.

2.3 PEER REVIEW IS A LEADING PRACTICE IN EVALUATING SCIENTIFIC EXCELLENCE

Practices for evaluating scientific excellence, such as peer review, can be structured to meet the needs of government science, including the urgent need to address existing deficits in infrastructure.

Peer review, in some form, is used to evaluate scientific excellence by all the organizations examined for this assessment. The peer review process is familiar to scientists: fellow scientists with some expertise in the field (peers) evaluate a manuscript or funding proposal and recommend action (approval, revision, or rejection) to a decision-maker such as a journal editor or funding review board. The nature of peer review can vary substantially — from a subjective assessment with little guidance or direction, to quantified scores of specific criteria (see review by Ferreira *et al.*, 2015). Workshop Participants remarked that, while peer review is the leading practice in evaluating scientific excellence, questions remain about how best to perform it, particularly in the context of assessing the scientific excellence of an infrastructure project rather than a research project. Questions include whether qualitative or quantitative review should be used (or some combination thereof) and which metrics should be chosen as indicators of scientific excellence. For particular consideration is whether an indicator is chosen because data to address it are easily obtained or because it accurately reflects the relevant aspect of excellence (Ferretti *et al.*, 2018).

Setting explicit criteria to score a proposal quantitatively appears to reduce bias (such as consideration of race or gender) in the peer review process but does not eliminate it (Eblen *et al.*, 2016). Moreover, scientific excellence has a subjective aspect; Workshop Participants expressed concern that framing peer review as scoring a set of discrete, quantifiable criteria could privilege a mediocre option over a better one. That is, proposals that score mid-level across all criteria could score higher overall than proposals that score very high on some criteria but low on others. Thus, desirable aspects of the latter may be lost in a process that lacks a holistic, qualitative aspect to the peer review; quantitative indicators should inform, but not replace, expert judgment (CCA, 2012).

Additionally, there is no broad consensus on the optimal number, expertise, and diversity of external reviewers in science funding policy (e.g., Mayo *et al.*, 2006; Marsh *et al.*, 2008; Snell, 2015). The U.K. National Institute for Health Research uses an internal review board that shortlists applications and discusses the comments and scores provided by external peer reviewers to make funding decisions (Sorrell *et al.*, 2018). In a study examining the review process for 280 full applications, agreement between internal and external reviews did not show any additional improvement with greater than four peer reviewers; it therefore concluded that there was little value in having larger numbers of peer reviewers (Sorrell *et al.*, 2018). For S&T infrastructure proposals, the number and diversity of reviewers for scientific excellence might reflect the number and diversity of S&T programs included in the proposed facility. For example, CFI Expert Committees typically include three to eight members with specific knowledge and experience; the final number depends on the breadth and quantity of proposals to be reviewed (CFI, 2017b).

Workshop Participants highlighted the importance of having the relevant expertise for reviewing the scientific excellence of proposed S&T infrastructure — expertise that may not always be available in Canada. Thus, engaging international experts may be valuable. Furthermore, a diverse set of expertise is necessary when evaluating the scientific excellence of infrastructure (versus a research project), including non-scientific expertise in fields such as architecture, design, research administration, and facilities management, among others. Such a diversity of expertise is also needed for evaluations of feasibility (see Chapter 4 for further discussion).

3

Supporting Collaboration

Collaboration, which is central to *Canada's Science Vision* (GC, 2019b), is increasingly important for accessing knowledge and skills from across government and different sectors to address urgent and complex challenges. Such challenges can often be "interlaced with interdependencies that have no respect for disciplinary silos," solutions to which become apparent only through "trans-disciplinary co-creation and engag[ement] of representatives from different sectors" (Banerjee, 2014). Furthermore, collaboration among organizations and scientists can amplify science outcomes and improve broader impacts. For example, in examining 108,803 projects funded between 2009 and 2017 by the U.S. National Institutes of Health, Zhang *et al.* (2018) found organizations that collaborated were more productive in producing patents, and principal investigators who collaborated had more publications and higher citation rates.

S&T infrastructure can be an important catalyst and facilitator of collaboration across disciplines and sectors. Two important and related effects of research infrastructure on collaboration were identified in analyses of CFI's outcome measurement studies, which evaluate the medium- and long-term outcomes of CFI investments in research infrastructure (Rank & Halliwell, 2008). The first is the *facility effect*, which refers to "the collective power of integrated suites of state-of-the-art equipment, usually housed in purpose-built facilities, and deliberately sited to maximize their accessibility, and multidisciplinary, multi-sectoral effects" (Rank & Halliwell, 2008). The facility effect was found to lead to "significantly increased multidisciplinary and cross-sectoral research cooperation" (Tremblay *et al.*, 2010). Furthermore, the impact of the facility effect on collaboration was found to be "greatly strengthened" by the *organization effect* — the impact of careful, strategic planning of activities, research plans, and facility design (Rank & Halliwell, 2008). When such planning was less cohesive, the effects on collaboration were less prominent (Tremblay *et al.*, 2010).

Workshop Participants noted, however, that collaboration may not always be conducive to achieving government objectives or priorities, and mandating collaboration in all cases is not ideal. They underscored the importance of having a clearly defined goal that needs to be addressed through collaboration. Moreover, there are multiple potential barriers affecting the likelihood of successful collaboration (Box 3.1).

Box 3.1
Potential Barriers to Collaboration

Collaboration may be limited by:

- Differences in professional cultures across sectors, departments, and disciplines/fields;
- Restrictive user-access policies for facilities and equipment;
- Security requirements, including physical access, security clearance, and chain of custody of evidence;
- Different incentive structures related to tenure, promotion, and hiring among sectors and disciplines;
- Different policies and interests for intellectual property, connectivity, and data sharing;
- Inadequate or ineffective communication among participants; and
- Misalignment of management structures, policies, goals, salaries, and motivations among collaborators.

3.1 TYPES OF COLLABORATION ACROSS DISCIPLINES

There are important distinctions among multidisciplinary, interdisciplinary, and transdisciplinary collaboration to consider when evaluating proposals for collaborative S&T infrastructure.

Cross-disciplinary research is the integration of knowledge, methods, concepts, or theories from at least two disciplines that results in new insights into, or understanding of, a complex problem or issue (Wagner *et al.*, 2011). Within cross-disciplinary research, a distinction is often made among multi-, inter-, and trans-disciplinary research (e.g., Sonnenwald, 2007; Campbell *et al.*, 2015; Adams *et al.*, 2016), typically defined in terms of increasing levels of integration.

Multidisciplinary research brings together expertise from different disciplines to address a particular research question but does not involve a genuine integration of knowledge (Bruce *et al.*, 2004; Campbell *et al.*, 2015). Different disciplinary elements retain their individual identities, and research results are often interpreted from the perspective of each contributing discipline. Multidisciplinary research is sometimes described as “no more and no less than the simple sum of its parts” (Wagner *et al.*, 2011).

Interdisciplinary research seeks genuine “cross-disciplinary outcomes” (Adams *et al.*, 2016). Knowledge, data, methods, concepts, and theories from different disciplines are integrated “to create a holistic view or common understanding of a complex problem” (Elsevier, 2015) that is “generally beyond the scope of any one discipline” (Campbell *et al.*, 2015). This research often explores new knowledge in the space between traditional disciplines and can lead to the emergence of new disciplines (e.g., biochemistry emerged from research at the interface of biology and chemistry). As Wagner *et al.* (2011) summarizes, the “critical indicators of interdisciplinarity in research include evidence that the integrative synthesis is different from, and greater than, the sum of its parts.”

Transdisciplinary research transcends the traditional academic discipline-based approach to knowledge generation by drawing upon academic disciplines as well as non-academic partnerships to create knowledge relevant to a problem (Campbell *et al.*, 2015). It is a “mode of knowledge production that draws on expertise from a wider range of organizations, and collaborative partnerships for sustainability that integrate research from different disciplines with the knowledge of stakeholders in society” (Wagner *et al.*, 2011).

It is important to clearly distinguish among different types of cross-disciplinary research in evaluating proposals for S&T infrastructure in order to ensure that (i) the type of collaboration suggested is aligned with the objectives or capabilities that the infrastructure is intended to address, and (ii) the infrastructure (including its management and governance structures) is appropriately designed to facilitate particular types of collaboration.

3.2 WAYS TO SUPPORT COLLABORATION ACROSS SECTORS

Cross-sectoral collaboration amplifies science outcomes and is a central focus of research in science policy. However, in practice, there are different ways for organizations to encourage such collaborations.

In recent decades, efforts to facilitate innovation and improve scientific outcomes have shifted away from actors in single sectors and toward interactions among sectors, cross-sectoral collaboration, and the emergence of hybrid organizations. As a result, the interactions and relationships among actors across a science and innovation ecosystem have become a central focus of science and innovation policy and research (Ranga & Etzkowitz, 2013).

One way of conceptualizing cross-sectoral collaboration is through the *triple helix model*, in which innovation, economic growth, and social development are fostered by increased collaboration, greater overlap, and reduced boundaries among government, academia, and industry — the three strands of the helix (Etzkowitz, 1993, 2008). However, this can be challenging because each sector has a traditionally well-defined role and a distinct identity that includes “specific ways of working, values, and differing uses of scientific knowledge” (Rosenlund *et al.*, 2017). Cross-sectoral collaboration also involves each sector taking on characteristics traditionally in the sphere of another sector. As a result, institutional spheres begin to overlap, sectoral boundaries become less well defined, and hybrid organizations are formed at the intersections between sectors (Etzkowitz & Leydesdorff, 2000; Etzkowitz, 2008). This is facilitated, in part, by exchanges among personnel, who bring ideas and values from one sector to another and who foster cross-sectoral collaboration and mutual understanding (Etzkowitz, 2008).

The objective of triple helix policy-making is “an innovative environment consisting of university spin-off firms, tri-lateral initiatives for knowledge-based economic development, and strategic alliances among firms (large and small, operating in different areas, and with different levels of technology), government laboratories, and academic research groups" (Etzkowitz & Leydesdorff, 2000). Governments often support such arrangements through regulation, policy-making, financial incentives (direct or indirect), legislation, or the creation of new organizations to promote innovation and collaboration (Etzkowitz & Leydesdorff, 2000).

In recent years, some have argued that the triple helix model should be expanded to a quadruple helix that includes civil society or a quintuple helix model that includes the environment (Carayannis & Campbell, 2009; Carayannis & Campbell, 2010). The quadruple helix model emphasizes the importance of culture and values, as well as the role of the media, in national innovation systems and stresses the need to consider these factors in innovation policy. The quintuple helix model is described as "a framework for interdisciplinary analysis and transdisciplinary problem-solving in relation to sustainable development" and emphasizes that knowledge production and innovation must be contextualized within a society's natural environment (Carayannis & Campbell, 2010).

All helix models highlight important considerations in evaluating proposals for investments in S&T infrastructure. The triple helix underscores the importance of cross-sectoral collaboration; the quadruple helix emphasizes the need to consider the public interest, which is particularly relevant in government mandate-driven science; and the quintuple helix offers a framework to address the goal of sustainable S&T infrastructure, with a net zero carbon footprint — a commitment in the Federal Science and Technology Infrastructure Initiative.

3.2.1 Supporting Collaboration in International Jurisdictions

The organizations reviewed for this assessment are all committed to developing shared research infrastructure to encourage collaboration. However, they differ in the particular models, frameworks, and strategies they employ, which is reflected in the decision-making processes used in each jurisdiction (see Chapter 6).

STFC (United Kingdom) provides researchers with access to research infrastructure in its national laboratories (STFC, 2018). Institutions that host research infrastructure supported by BMBF (Germany), ESFRI (European Union), MREFC (United States), NCRIS (Australia), and NUFI (Denmark) are required to enact policy that provides researchers with access to shared research infrastructure (BMBF, 2015; Danish Agency for Science, 2015; ESFRI, 2016; Gov. of Australia, 2018; NSF, 2018). CFI (Canada) strongly encourages institutions to develop collaborations with partners from other sectors, including government and industry, although such collaboration is not a requirement for funding (CFI, 2017a).

In addition, STFC operates research and innovation campuses around its national laboratories that facilitate academic and industrial collaboration (STFC, 2018). ESFRI's role as a strategy forum allows stakeholders at the institutional, regional, national, European, and global levels to position their research infrastructure initiatives within a broader European context (ESFRI, 2018a). MREFC requires proposals for new infrastructure projects to be coordinated with other organizations in order to identify opportunities for collaboration and cost-sharing (NSF, 2018). The NCRIS decision-making process is specifically designed to identify and prioritize shared research infrastructure needs through bottom-up consultation and collaboration with the research community and other stakeholders (Gov. of Australia, 2010). The Danish Ministry of Higher Education and Science funds several "dedicated national collaborations on research infrastructure" that provide Danish researchers with access to national facilities and data (UFM, 2019). Germany's federal departmental research institutions are required to make their research infrastructure available to external researchers, groups, and organizations to facilitate networking and collaboration in the German research and innovation system (BMBF, 2018).

3.3 COLLABORATIVE INFRASTRUCTURE OFFERS DIFFERENT TYPES OF WORKSPACES

To foster collaboration, S&T infrastructure can benefit from several particular types of workspaces and from workspace design that is aligned with the objectives of the scientific activities.

Successful collaboration requires an investment of time and energy, predicated on mutual trust among collaborators (Hara & Solomon, 2003; Manzini, 2014). For such engagement and relationship building, potential collaborators must encounter each other, either in shared physical spaces or through shared social or professional networks.

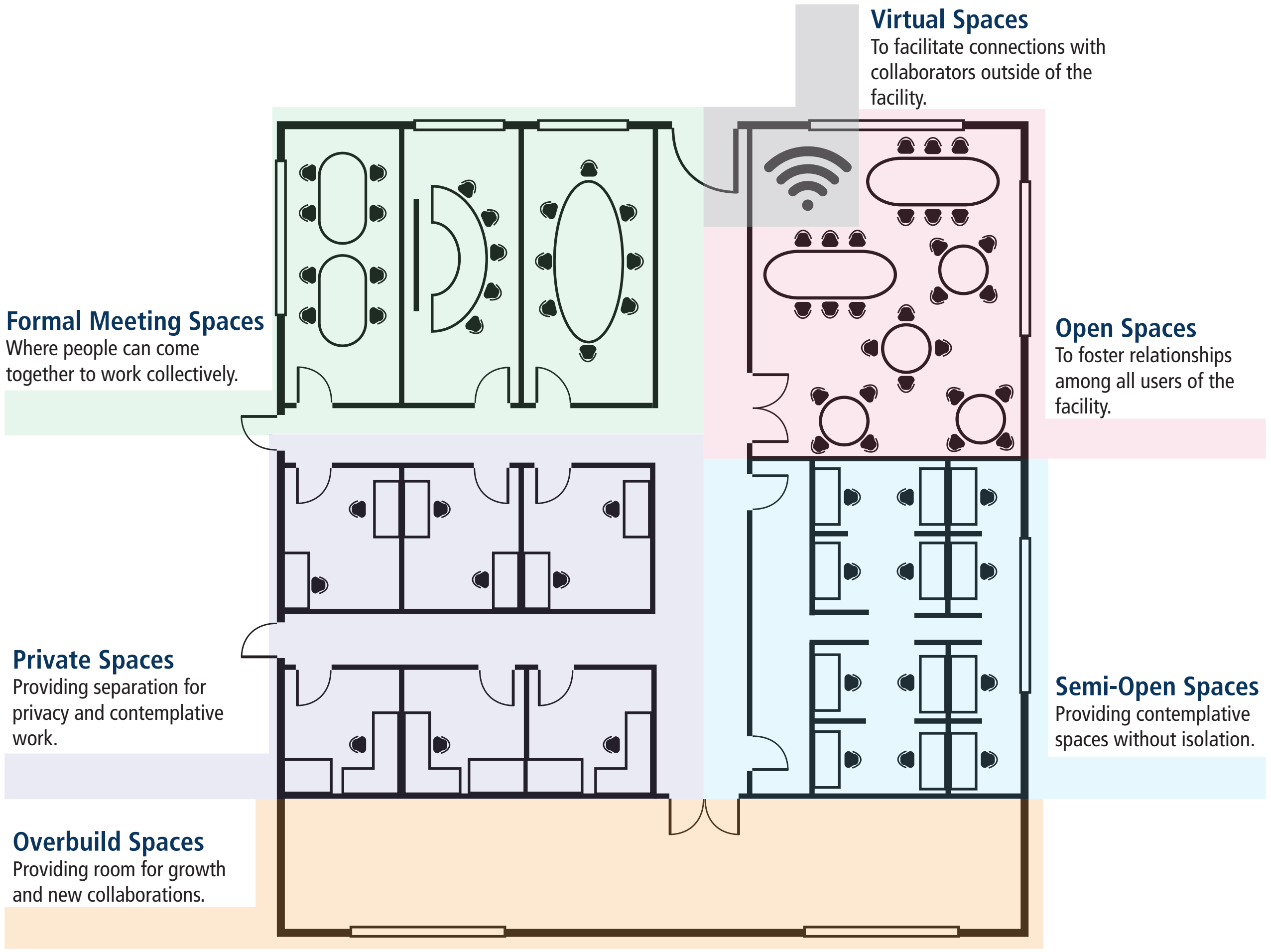


Figure 3.1

Six Types of Spaces to Support Collaboration

Users of collaborative S&T infrastructure require different types of physical space in which to conduct their work, including private spaces (e.g., offices), formal meeting spaces (e.g., conference rooms), virtual spaces (e.g., connectivity), open spaces (e.g., cafeteria, break rooms), and semi-open spaces (e.g., cubicles). In addition, flexibility and adaptability to new collaborations are enhanced by overbuilding (building more space than currently needed in order to provide room for growth).

In a pilot study of scientists at two University of Michigan buildings, Owen-Smith *et al.* (2012) found that the co-location of scientists (in the same building, on the same floor) and the overlap of shared space (common areas, large laboratories) had positive effects on forming new collaborations and securing external funding. However, a one-size-fits-all approach to designing physical spaces for collaboration is inappropriate, as the style of interactions among researchers varies considerably across groups. Owen-Smith *et al.* (2012) noted variation in the types of research networks (e.g., tightly knit and scheduled versus diffuse and opportunistic), as well as in the specifications and needs of the research itself, that likely influence how co-location affects the development of new and productive collaborations. According to Wagner and Watch (2017), "[f]or the physical design of space, this translates into creating flexible and highly responsive spaces that allow people, in a range of group configurations, to decide what works."

In S&T infrastructure design, the physical requirements for laboratory spaces (e.g., because of equipment size, safety protocols, and security requirements) constrain flexibility and responsiveness. Additionally, research scientists need different spaces depending on their tasks for the day (e.g., lab work, discussion with colleagues, or reading and writing). Placing quiet, contemplative areas next to busier, communal places can create noise and distraction. For example, people working at the Francis Crick Institute's central London laboratory found the areas set aside for quiet work were too close to the loud noise of the central atrium (Booth, 2017). Moreover, the physical proximity of individuals in a building matters less to the development of new collaborations than the likelihood that their paths will cross as they move through a building (from labs and offices to washrooms, entrances, common areas, etc.) (Kabo *et al.*, 2014).

Over the last three decades, much consideration has been given to designing and developing workspaces that foster creative collaboration and innovation (e.g., the movement toward open offices, which was also driven by cost savings), while balancing individuals' need for privacy, quiet, and solitude (e.g., Congdon *et al.*, 2014; Coester, 2017). Careful consideration of the need for different types of workspaces should not be an afterthought but, rather, can be reflected in the evaluation criteria for S&T infrastructure proposals and factored into decision-making processes. Workshop Participants identified six types of physical space needed in collaborative infrastructure (Figure 3.1).

4

Ensuring Feasibility

Investments in S&T infrastructure involve a large amount of money, time, and personnel, and the consequences of such decisions will be felt for 50 or more years (i.e., the entire life cycle of an infrastructure project). The Organisation for Economic Co-operation and Development (OECD) Global Science Forum has identified failure to fully account for all costs of research infrastructure as a systemic difficulty (OECD Global Science Forum, 2008). Cost estimates made in early phases of infrastructure designs need to be re-evaluated throughout the life cycle of the infrastructure; particular consideration must be given to contingency planning and operating costs to ensure long-term sustainability (OECD Global Science Forum, 2008). For example, in Taiwan, a lack of consideration of the full life cycle caused challenges in managing their research infrastructure, including problems with securing stable funding, allocating resources for operating costs and skilled labour, and upgrading and decommissioning older infrastructure (Lin *et al.*, 2017).

4.1 STAGE-GATED REVIEWS AS A LIFE CYCLE APPROACH

Feasibility assessments can be directly linked to specific objectives and goals through stage-gated reviews. In such reviews, technical and financial readiness, risk, governance structures, contractual obligations, and other aspects of feasibility are evaluated using criteria explicitly tied to expectations for success at different stages of the infrastructure life cycle.

A stage-gated review process is used to evaluate large research infrastructure proposals funded through the MREFC by the National Science Foundation (NSF) in the United States (NSF, 2017). Proposals for large facilities are overseen by an integrated project team, with subgroups responsible for scientific and technical oversight, financial oversight, and risk assessment. The MREFC life cycle identifies decision points and authorities responsible for those decisions throughout development (from idea to proposal), design (conceptual, preliminary, and final phases), construction, operations, and divestment (see Figure 6.1). The NSF's *Large Facilities Manual* provides in-depth direction on the processes used to create and sustain research infrastructure funded through the MREFC (NSF, 2017).

The Panel defines *ensuring feasibility* as ensuring that infrastructure proposals are achievable and practicable, and that infrastructure is successfully deployed and becomes a sought-after resource for government scientists and other users throughout its life cycle — from development and design through construction, operations, and divestment. Ensuring feasibility requires consideration not only of financial and technical readiness, but also of:

- management and human resources;
- legislative and policy aspects, including relationships among federal, provincial, and territorial governments;
- community integration, licensing and zoning, and public acceptability;
- scalability;
- long-term sustainability;
- stakeholder engagement and collaborative relationships; and
- physical location, including access to housing and transportation, as well as political and regional economic considerations.

Lin, (2017), NSF(2017),
and Workshop Participants

Workshop Participants also noted that infrastructure can never be "all things to all people;" instead, evaluation of infrastructure proposals should focus on specific, achievable outcomes (e.g., developing specific capacities to deliver on government mandates, community engagements, and research collaborations) and ongoing assessment to ensure those outcomes are met. They further found that an iterative, stage-gated process for proposal review is a leading practice in developing, evaluating, and demonstrating feasibility as a project matures.

4.2 LONG-TERM FEASIBILITY DEPENDS ON REGIONAL INTEGRATION

Choosing a site for an S&T infrastructure project can be a strategic opportunity to build mutually beneficial relationships with local organizations, communities, educational institutions, and industries, while also supporting growth and prosperity; conversely, a poorly sited facility, built without adequate consideration of such factors as transportation and accommodation for users, may have difficulty sustaining itself over the long term.

The development of new knowledge and technology depends on the complex relationships and interactions among the elements of the system, which include the local organizations, communities, and institutions where infrastructure is built. In regional innovation systems theory, a central tenet is that "geography is fundamental, not incidental, to the innovation process itself" (Asheim & Gertler, 2005). This view "emphasizes the importance of clusters and geographical proximity as catalysts of knowledge development and exchange" and the ways in which such factors are "critical to the production of innovation and regional growth" (Doloreux, 2004).

One reason that geography matters to innovation is that infrastructure benefits from regionally based capabilities in the form of personnel, infrastructure, networks and communities, procedures, and various types of local organizations (Holbrook & Wolfe, 2005). For example, the Bedford Institute of Oceanography in Dartmouth, Nova Scotia, has been owned and operated by the federal government since 1962 (GC, 2018b). It houses scientists, engineers, technicians, managers, and support staff from four federal departments: Fisheries and Oceans Canada, Natural Resources Canada, Environment and Climate Change Canada, and the Department of National Defence. The location of the Bedford Institute of Oceanography on the shore of the Bedford Basin provides opportunities for collaboration with local industry (e.g., the Centre for Ocean Ventures and Entrepreneurship), academic institutions (e.g., Dalhousie University), as well as international partnerships (e.g., the Ocean Tracking Network and the Ocean Frontier Institute) (GC, 2015a, 2015b; COVE, 2018; OFI, 2019). Other institutions with strategic regional integration in Canada include the Institute of Ocean Sciences in Sidney, British Columbia (GC, 2016), as well as the Innovation Superclusters Initiative, which consists of regional superclusters such as the Protein Industries Supercluster, a centre for agri-food enabling technologies located in the Prairies (GC, 2019c). The institutions in a particular region affect the relationships and interactions among the actors in the innovation system, which include universities, public agencies, research organizations, businesses, venture capital firms, and other knowledge-dependent organizations (Edquist, 2006). Regional institutions — including norms, conventions, attitudes, values, routines, expectations, established practices, policies, and laws (Asheim & Gertler, 2005; Edquist, 2006) — help generate the trust needed for the flow of knowledge and technology among organizations (Gertler & Wolfe, 2004) and help foster a shared common culture, which can facilitate interactions and relationships (Doloreux, 2004). Some researchers argue that "the regional innovation systems approach is particularly appropriate for understanding how the innovation process operates in diverse regional economies such as those found in the Canadian federation" (Holbrook & Wolfe, 2005).

4.3 GOVERNANCE, OWNERSHIP, AND MANAGEMENT

Evaluations of the feasibility of shared S&T infrastructure require explicit consideration of ownership, governance, and management structures to ensure effective, efficient, and sustainable operations.

Workshop Participants stressed that an essential element of ensuring feasibility is professional, permanent support staff to help build and sustain collaborative relationships among users and institutions sharing the infrastructure by providing a common point of contact. Clear governance structures, ownership and accountability for infrastructure, and capable management all help to facilitate smooth operations and ensure sustainability over the long term.

A concern for any shared resource, such as S&T infrastructure, is the tragedy of the commons, in which individual users (or groups of users) exploit resources at the expense of other users, eventually leading to the loss of those resources for everyone (Hardin, 1968; Ostrom, 1990). Regulating access and providing education on the use (and potential abuse) of the resource can help avoid overexploitation (Meadows, 2008). Additionally, creating a direct feedback loop (e.g., through professional technical or management staff responsible for the maintenance of facilities and equipment) can ensure that individuals who abuse a resource feel a direct impact, rather than the effect being distributed among all users (Meadows, 2008). While Workshop Participants did not identify a particular ownership or management model as a leading practice, in their experience, a key feature of successful shared infrastructure is operations and governance local to the facility, to ensure timely and accessible feedback and assistance for staff and users.

There are various governance and management models, both within and among jurisdictions. For example, STFC owns and operates a number of national laboratories across the United Kingdom, giving researchers access to shared scientific infrastructure that supports research in physics and astronomy (STFC, 2018). These labs are intended to promote collaborative research and facilitate national research capability (STFC, n.d.). In Germany, the federal government maintains approximately 40 departmental research institutions, mainly to conduct research to deliver on government mandates (BMBF, 2018). However, as a rule, these institutions are also required to make their research infrastructure available to external researchers, groups, and organizations (BMBF, 2018). In this way, they facilitate networking and collaboration in the German research and innovation system.

The U.S. Department of Energy oversees National Laboratories and Technology Centers — specialized government-sponsored research facilities that support basic research in the physical sciences (Brown, 2018). Half of the users of these facilities are U.S. academics, both faculty and students or postdoctoral fellows; other major user groups are federal employees of the national laboratories and other federal organizations, as well as international academics, with smaller proportions of users coming from industry, not-for-profit, and other sectors (Brown, 2018). For example, the Lawrence Berkeley National Laboratory in Berkeley, California, has been managed by the University of California since its founding in 1931 (Berkeley Lab, n.d.-b). Teams of scientists from multiple sectors (e.g., academia, government, and private industry) compete for access to analyze materials and run experiments at these facilities; information on how to apply for access is freely available online (Berkeley Lab, n.d.-a). Other national laboratories are managed as government-owned, contractor-operated facilities (GOCO), operated by non-profit companies or limited liability companies comprising multiple partners (Battelle Memorial Institute, 2018).

As the size of a research group increases, scientific work becomes more highly organized and begins to display features of bureaucratic structuring such as division of labour, standardization of work processes, hierarchical organization, and decentralization of decision-making (Walsh & Lee, 2015). As a result, there is a corresponding need for more specialist positions in the scientific workforce to perform technical work (Walsh & Lee, 2015). Professional staff responsible for operations, with the authority and capacity to respond to challenges such as procuring equipment or requisitioning a repair, are integral to world-class infrastructure. Moreover, professional staff are a reservoir of institutional knowledge that may otherwise be lost as users and collaborators move on to other projects and facilities.

4.4 SUSTAINABILITY, ACCESSIBILITY, AND COLLABORATION

The long-term sustainability of collaborative S&T infrastructure relies on attracting new users, building collaborative relationships, and making facilities accessible to a wide variety of users.

Workshop Participants noted that the feasibility of new S&T infrastructure to support collaboration relies on preparatory work that puts in place meaningful links to enable effective collaboration, such as maximizing opportunities for new users and partners to find and engage in opportunities for collaboration. In an analysis of the TeraGrid computing infrastructure, Zimmerman and Finholt (2007) note that such research infrastructure often lacks the capacity to directly interact with its many potential users. Gateway organizations can mediate the interactions between an infrastructure and potential users. Such organizations help make the use of infrastructure compatible with potential users' needs, values, expectations, practices, and experiences; they may be contracted to provide communication and facilitation services or may be an embedded part of the S&T infrastructure (Zimmerman & Finholt, 2007). Similarly, CFI's Research Facilities Navigator offers a searchable online directory to enable any user to identify and locate resources supported by CFI funds (CFI, n.d.-a), providing potential users a clear point of entry for a facility. ESFRI, BMBF, and NCRIS consider the Findable, Accessible, Interoperable, and Reusable (FAIR) principles as important for the operation of research infrastructure, particularly with respect to data preservation and management (Wilkinson *et al.*, 2016; German Council of Science and Humanities, 2017; Gov. of Australia, 2017; ESFRI, 2018b).

After users identify a collaborative opportunity, relationship building among the users, centred on shared infrastructure, is needed for collaborations to develop. Many factors contribute to the success of geographically distributed collaborative scientific research projects (known as *collaboratories*) (Olson *et al.*, 2002). The most important factor is simply a readiness to collaborate, which depends on participants' motivation to collaborate, shared principles of collaboration, and experience with collaboration. Such readiness is often driven by a particular need that requires collaboration to achieve a scientific goal. Clearly established procedures for collaboration and agreements about access to data, resources, and expertise are also helpful for facilitating collaboration (Olson *et al.*, 2002). Other factors include the technological readiness of the infrastructure itself and a minimal threshold of technological readiness in the relevant scientific communities, as familiarity with technologies, datasets, and analyses varies among disciplines (Ribes & Finholt, 2007). As Edwards *et al.* (2007) point out, excluding fields that are not technologically ready can lead more prepared fields to "capture" infrastructure. User-centred design is vital to addressing these issues (Olson *et al.*, 2002; Ribes & Finholt, 2007).

Concerns related to the sustainability of shared infrastructure include how to motivate participants to contribute to its sustainability and how to align their goals and interests (Ribes & Finholt, 2007). When participants in a system (e.g., federal science-oriented departments, industry sectors, academics) have varied goals, policy changes may result in participants taking actions to protect their own goals at the expense of the goals of others (Meadows, 2008). Setting mutually acceptable shared goals before developing policy helps participants who agreed to those goals feel accountable in implementing the policy (Meadows, 2008). Engagement alone, however, is not sufficient to avoid policy resistance; the participants' input needs to be reflected in decision-making process (Mease *et al.*, 2017). Policy resistance can be considered a failure of collective action: a change in method can benefit participants collectively, but only if all individuals make the change together (Ostrom, 1990). This means finding a way to align the interests of the individual with that of the collective before implementation (Ostrom, 1990; Nielsen, 2012). Aligning money, mandate, measurement, and motivation is key to collaborative S&T infrastructure (Figure 4.1).

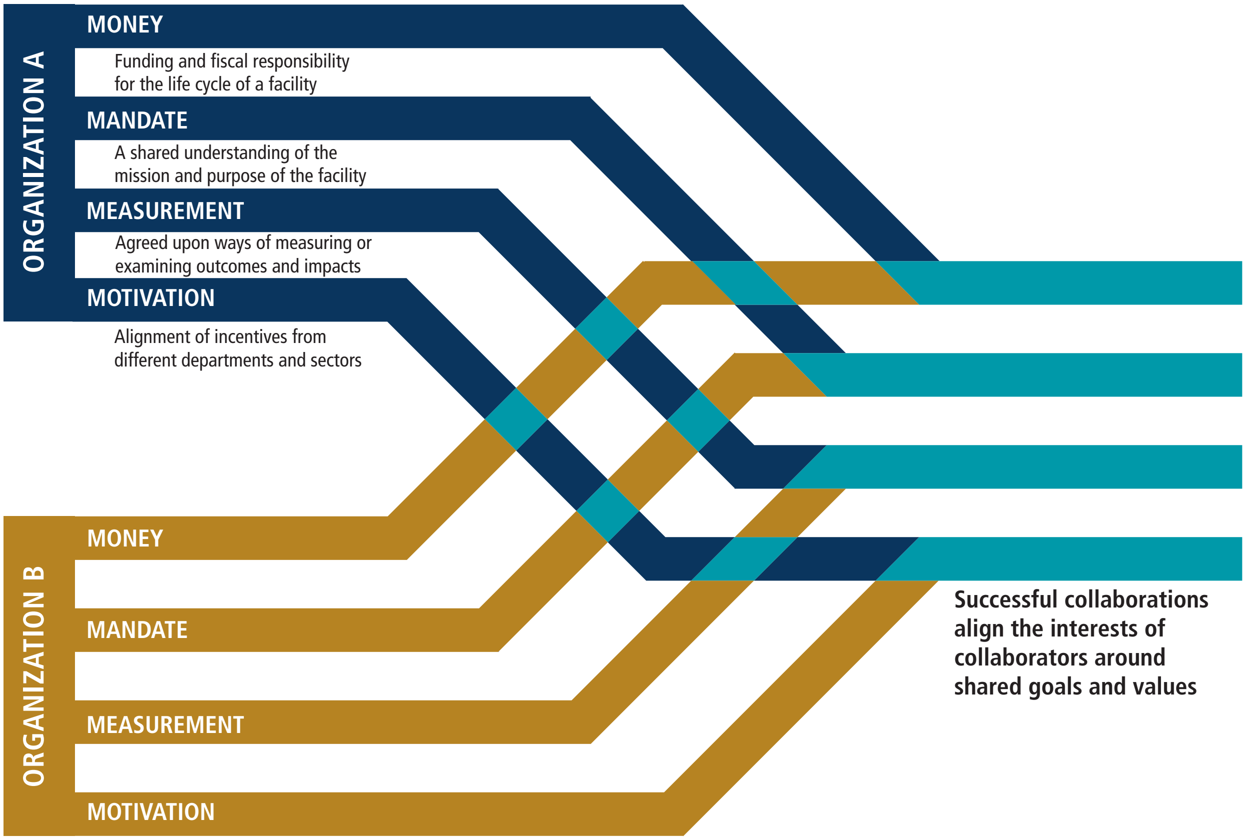


Figure 4.1

Shared Goals and Values of Collaborators in S&T Infrastructure

The success of collaboration in shared S&T infrastructure depends on aligning participant's interests around shared goals and values, including money (e.g., funding, fiscal responsibility), mandate (e.g., mission, purpose), measurement (e.g., evaluating outcomes), and motivation (e.g., shared understanding of incentives).

4.5 ASSESSING FEASIBILITY REQUIRES A DIVERSITY OF EXPERTISE

A diversity of expertise is needed to assess the wide range of factors — technical, financial, logistical, managerial, and other — that affect the feasibility of S&T infrastructure. Also needed is a decision-making process that can synthesize information from a diversity of professional fields.

Bringing diverse expertise to the assessment of S&T infrastructure is the best way to support assessment of feasibility, regardless of the criteria used in such assessment. Relevant experts at different stages of proposal development may include professional research managers, technicians, civil engineers, architects and designers, business managers, accountants, economists, and human resources professionals. Having scientists involved in the assessment ensures that the needs of the users are met. Scientists can also help the assessment team develop a mutual understanding of the goals of the infrastructure and build productive relationships across departments and sectors.

Because the development of shared S&T infrastructure involves the collective efforts of various sectors, organizations, departments, users, and disciplines, differences across professional cultures can increase the risk of misunderstanding and mistrust. To mitigate this risk, Finholt and Brinholtz (2006) argue that regular and frequent opportunities for communication across multiple levels of the organization are needed during the development process. Face-to-face communication is particularly important, especially in the early phases. In addition, it may be useful to have participants with diverse professional backgrounds who can act as “translators” across professional cultures, and attention should always be focused on user requirements (Finholt & Brinholtz, 2006).

5

Delivering Broader Impacts

When prioritizing research infrastructure investments, organizations frequently assess broader economic and societal impacts (Box 5.1). Science conducted by government is rarely entirely basic or applied; rather, it is often use-inspired, balancing scientific exploration with societal goals (Stokes, 1997). The scientific and societal value of use-inspired research are inextricably linked, and judging projects on these two values separately does a disservice to potentially valuable research (Stokes, 1997). As Gregory *et al.* (2012) state, "[m]aking good choices requires the thoughtful integration of science and values — the technical assessment of the consequences of proposed actions and the importance we place on the consequences and our preferences for different kinds of consequences — as part of a transparent approach to examining a range of policy options." For government science, broader impacts are implied in the public mandates that the science supports; however, all jurisdictions examined in this report explicitly consider the potential broader impacts of proposed research infrastructure in their assessments. As noted in Chapter 1, the organizations in these jurisdictions are typically assessing proposals for research infrastructure dedicated to basic discovery-oriented research, rather than mandate-driven government science.

Box 5.1
Potential Broader Impacts of S&T Infrastructure

Broader economic and societal impacts may include the following:

- local, regional, or national economic benefits, including company formation, job creation, and development and commercialization of new technologies;
- impacts related to training and talent development, attraction, and retention across the entire spectrum of skills involved in staffing and using the infrastructure;
- benefits for nearby communities such as employment and spending in the local economy as well as adverse effects, including poor infrastructure siting and increased traffic;
- support for multiple ways of knowing, including Indigenous knowledge, as well as advancing Canada's commitments to equity, diversity, and inclusion;
- public science education, engagement, and outreach opportunities, and citizen science related to the research undertaken at the facility; and
- influence on government policy, practices, and regulation at the federal, provincial/territorial, and municipal levels.

5.1 ROBUST EVALUATION OF BROADER IMPACTS RELIES ON MULTIPLE PERSPECTIVES

Objective evaluation of the broader impacts of proposed S&T infrastructure requires perspectives from multiple disciplines and sectors.

Evaluating potential broader impacts of a proposed S&T infrastructure project for government science benefits from considering commitments to equity, diversity, and inclusion, as well as broader department or agency mandates. Consequently, such evaluations require expertise from within government. Socio-economic impacts of infrastructure involve not only the specific infrastructure proposed, but also government policies on procurement and construction practices. A diversity of perspectives is needed to ensure a robust and defensible evaluation of the broad range of potential impacts. According to Workshop Participants, directly extending invitations to specific reviewers is often key to acquiring such diverse perspectives.

CFI uses a special multidisciplinary advisory committee to review proposals when the number of qualified and deserving projects submitted exceeds the available budget (CFI, 2017a, 2017c). Instead of further reviewing scientific merit (which has already been done), this advisory committee considers the strategic value of proposed infrastructure projects to maximize use, enable multidisciplinary and multi-sectoral research, and capitalize on areas of regional and national strengths (CFI, n.d.-c).

5.2 INDICATORS OF BROADER IMPACTS

Though future impacts are difficult to assess, proposals can be evaluated on the credibility and logic of the pathways to expected impacts, and on proposed metrics and plan for evaluating broader impacts over the long term.

Future impacts cannot be directly measured and are difficult to assess. However, proposals can be evaluated on the credibility and logic of the pathways to expected impacts and their relevance to the specific priorities and objectives of an infrastructure investment. For example, making a facility open, in some capacity, to businesses and the public is one means of promoting broader impacts. A pathway to this impact would be incorporating public-facing elements into the design of the infrastructure (e.g., visitor centres, exhibits, libraries, auditoria, guided tours). Plans for facilitating public engagement through partnerships with museums and science centres; citizen science initiatives; educators in science, technology, engineering, and mathematics; science communicators; or other non-profit organizations, can also demonstrate a credible pathway to broader public engagement.

Additionally, Workshop Participants noted that, regardless of the metric, a great deal of uncertainty is often associated with measuring broader impacts. Therefore, it is necessary to evaluate the proposed metrics and plan for evaluating broader impacts over the long term, as well as the pathways to impacts, rather than the impacts themselves.

Finally, evaluation of broader impacts should consider both positive and negative outcomes and take into account counterfactuals and opportunity costs of reasonable alternatives. However, Workshop Participants did not suggest that the proposal itself include negative outcomes and counterfactuals; rather, they found that explicit consideration of these aspects in the evaluation process is a leading practice.

6

Decision-Making Processes and Structures

The decision-making processes and structures used to evaluate research infrastructure proposals vary among jurisdictions (Figure 6.1). Despite sharing some common features, these processes differ in how priorities are set and in how and by whom proposals are evaluated. No single practice is best suited to all contexts, and different models and strategies are available for assessing multiple, competing criteria in the decision-making process. However, certain types of practices may be better aligned with the objectives of *Canada's Science Vision* and the Federal Science and Technology Infrastructure Initiative (Section 6.5). The processes examined by the Panel reflect examples of publicly available decision-making processes for academic research and other research of a fundamental nature, and may need to be adapted or adjusted to meet the expectations and requirements for government science.

6.1 STRATEGIC ROADMAPS CAN HELP IDENTIFY PRIORITIES

Strategic planning exercises, such as roadmaps, are a leading practice to inform decisions on the development of national S&T infrastructure.

Strategic roadmaps — often referred to simply as *roadmaps* — are a type of planning exercise for policy-makers, the scientific community, and other stakeholders to inform decisions about investments in national research infrastructure (OECD Global Science Forum, 2008). Roadmaps typically assess current research infrastructure needs and capabilities, guide the evaluation of proposals for new projects, and prioritize investments. Roadmapping allows scientists and policy-makers to make informed decisions about investment priorities across disciplinary boundaries, in the context of a national strategic plan (Science-Metrix, 2014). Roadmaps generally focus on investments in new research infrastructure and do not address issues for existing infrastructure, such as their continued operation, need for upgrades, or decommissioning. Although such considerations can be vital to assessing future needs, it may be unrealistic to fully deal with them in a standard roadmapping exercise (OECD Global Science Forum, 2008).

Typically, a government department or funding agency initiates the process, laying out the rationale and scope for upcoming investments in new research infrastructure (OECD Global Science Forum, 2008). Often, an independent entity that is well-regarded, trusted, and credible in the scientific community is appointed to create the roadmap (OECD Global Science Forum, 2008); such entities can include a Chief Science Advisor, a national scientific academy, a scientific advisory body, or an ad hoc group of scientific experts.

The OECD (2008) identifies clarity, completeness, and transparency as key factors in the success of roadmapping. The context, rationale, goals, procedures, and desired outcomes must be explicitly stated and well defined. However, Workshop Participants cautioned against endless "action displacement" activities (i.e., continued planning that delays action). A rapid, high-level overview may be better suited than an in-depth, complex assessment of needs in delivering timely, well-placed infrastructure investments to meet the current and future needs of federal government science. Thoughtful consideration of a decision-making process before it is launched is important to maintaining the process over time; continuity allows potential users to develop familiarity with and confidence in a decision-making process.

6.2 THE STRUCTURE OF DECISION-MAKING PROCESSES VARIES ACROSS JURISDICTIONS

Decision-making processes for identifying and prioritizing investments in S&T infrastructure can be structured in a variety of ways and are generally aligned with the objectives of the funding body. Three variations in decision-making approaches are (i) top-down versus bottom-up, (ii) competitive versus collaborative, and (iii) open versus directed calls for proposals.

6.2.1 Top-Down Versus Bottom-Up

Two basic decision-making structures can be identified in the jurisdictions examined in this report: top-down and bottom-up. In a top-down model, a government or responsible authority identifies a specific need or priority, often within an explicit funding envelope. The objective may be to strategize future research capabilities (e.g., BMBF, ESFRI) or distribute available funding to address a particular priority (e.g., most CFI funds, NUFI). Evaluators assess proposals based on criteria set by the responsible authority; such criteria may extend beyond scientific excellence to include collaborative opportunities or broader impacts. In contrast, a bottom-up model (such as NCRIS) maps capacity, determines needs, and identifies gaps and opportunities through conversations in the research community and among relevant stakeholders (Gov. of Australia, 2017). Such a structure privileges the perspective of the users of S&T infrastructure in identifying the problems that investments are intended to address and the appropriate solutions.

6.2.2 Competitive Versus Collaborative

Most jurisdictions examined in this report use a competitive selection process in which proposals for research infrastructure are individually assessed and compared, with successful projects selected for funding and/or inclusion in strategic roadmaps (e.g., BMBF, CFI, ESFRI, STFC). In contrast, NCRIS uses a non-competitive process, developing a roadmap collaboratively with Australia's national science system and appointing facilitators to develop an investment plan in consultation with stakeholders (Gov. of Australia, 2010, 2017).

Workshop Participants noted that planning and designing S&T infrastructure collaboratively encourages future working relationships. Making proposals visible and accessible to all potential stakeholders (e.g., by providing a platform where stakeholders can read and comment on proposals) can create a forum for discussion and development of ideas among groups who may not otherwise have the opportunity to interact. Maintaining a transparent, collaborative proposal development process can also help identify opportunities for research collaboration and facilitate relationship building among applicants.

6.2.3 Open Versus Directed Calls for Proposals

Open calls do not require proposed S&T infrastructure to enable particular capabilities or types of research. By contrast, in directed calls for proposals, a central authority (typically, a government) pre-determines specific capabilities or types of research that the infrastructure must support. Many jurisdictions use a combination of both. ESFRI's pan-European roadmap is based on an open call, although the proposals are typically directed at enabling capabilities reflecting the priorities of ESFRI's member states (ESFRI, 2016). CFI also generally uses an open call (CFI, 2017a); however, some of its funding programs may be more directed (e.g., Cyberinfrastructure Initiative) (CFI, n.d.-b). For government science, S&T infrastructure must enable government scientists to meet core departmental responsibilities and mandates.

6.3 REVIEW BODIES AND EVALUATION PROCESSES

Structuring the evaluation of S&T infrastructure investment proposals requires consideration of: the type and composition of review bodies, thresholds for eligibility, and the sequencing of different types of reviews.

6.3.1 Internal and External Review Bodies

All organizations examined in this report have an identified authority, usually an appointed or elected board or council, that ultimately decides which infrastructure proposals are included in strategic plans and/or have access to funds. Both internal and external review bodies inform such decisions. Typically, internal review bodies ensure that proposals meet minimum eligibility standards and strategic goals, while external review bodies assess and rank the proposed project according to specified principles and criteria (e.g., STFC, 2010; BMBF, 2015; Danish Agency for Science, 2015; ESFRI, 2016; CFI, 2017a; Gov. of Australia, 2018; NSF, 2018).

6.3.2 Eligibility Reviews

Nearly all organizations reviewed in this assessment begin the proposal evaluation process with an assessment of eligibility. CFI requires all institutions applying for funding to confirm their eligibility (CFI, 2017a). STFC reviews a preliminary proposal (a business case) before returning it to the lead organization and requesting a full proposal (STFC, 2017b). ESFRI's Executive Board reviews all proposal submissions for eligibility before assigning other review bodies (ESFRI, 2016). The U.S. NSF Program Officer and staff, as well as the MREFC Panel, review all applications to the MREFC fund internally, and the NSF Director must approve them before projects can move into the conceptual design phase (NSF, 2017).

6.3.3 Sequencing and Stage-Gating

Separate evaluation committees typically review different aspects of research infrastructure proposals, such as scientific excellence, economic and technical feasibility, and broader impacts, either in parallel or sequentially. The sequence of different types of evaluations can privilege the requirement of scientific excellence or align it with parallel assessments of feasibility and impacts.

The Strategy Working Group at ESFRI conducts its scientific evaluation in parallel with the Implementation Group's reviews of maturity (i.e., feasibility); the two groups work together to check minimal requirements and harmonize results from different fields to present a combined report and recommendation for each proposal to the Executive Board (ESFRI, 2018a). BMBF's assessment of research infrastructure proposals features two separate, parallel processes: a scientific and an economic evaluation. Each process includes both external (mainly international) experts and internal members of the German government (BMBF, 2013).

At CFI, expert review committees first vet all eligible proposals and evaluate their scientific excellence on a five-point scale from "exceeds criterion" to "does not satisfy criterion" before multidisciplinary assessment committees review successful proposals more broadly (CFI, 2017b). Similarly, in Germany, the Helmholtz Association uses two sets of criteria to evaluate proposals for new infrastructure: (i) scientific excellence and strategic importance, and (ii) feasibility and impacts (Helmholtz Association, 2011). Only proposals that are assessed as "excellent" or "very good" on the first set are subsequently assessed on the second.

To access MREFC funds, proposals move through an iterative, stage-gated process that includes an integrated project team for coordinating project oversight from design through to construction (NSF, 2017). Advancing to the subsequent design phase requires multiple reviews and recommendations, including detailed budgets, costs, and, in the later phases, risk analyses. In addition to scientific merit, technological readiness and the project management capabilities of the proposal team are considered when prioritizing MREFC proposals (NSF, 2017).

6.4 MODELS AVAILABLE FOR EVALUATING MULTIPLE, COMPETING CRITERIA

Quantitative decision analysis methods and qualitative structured decision-making techniques can help assess proposals with multiple competing criteria.

The evaluation of an S&T infrastructure proposal that satisfies the Panel's four principles will include multiple criteria that may be complementary, unrelated, or antagonistic. Furthermore, the exact relationships among criteria may be a point of uncertainty and disagreement. Decision-analysis methods, such as multiple criteria decision analysis (also referred to as multiple criteria decision-making) and multi-attribute utility theory, can be used to simulate and rank probabilistic models of potential relationships among criteria (e.g., Wallenius *et al.*, 2008). Such modelling exercises can include quantification of criteria related to feasibility, such as building costs, construction time, and overhead.

Modelling approaches, however, have drawbacks. No model perfectly describes reality (Gregory *et al.*, 2012) and decision-makers may place too much faith in model outcomes. Decision analysis addresses only elements of the problem that are included in the model (Keeney, 1982), and the quality of the analysis depends on the quality of the inputs to the model (the "garbage in, garbage out" problem). If important criteria are excluded, or if the value or weighting of criteria are poorly understood or mischaracterized, the output of a formal modelling analysis can be skewed, unrealistic, or inapplicable to the actual decision. However, despite these limitations, such approaches can still add value to the decision-making process. Decision-analysis tools have expanded to applications in research funding allocation (e.g., Hall *et al.*, 1992), clinical medicine (e.g., Dolan & Veazie, 2017; Sałabun & Piegat, 2017), government agencies (e.g., Kurth *et al.*, 2017), and environmental management (e.g., Majumder, 2015). It has also been

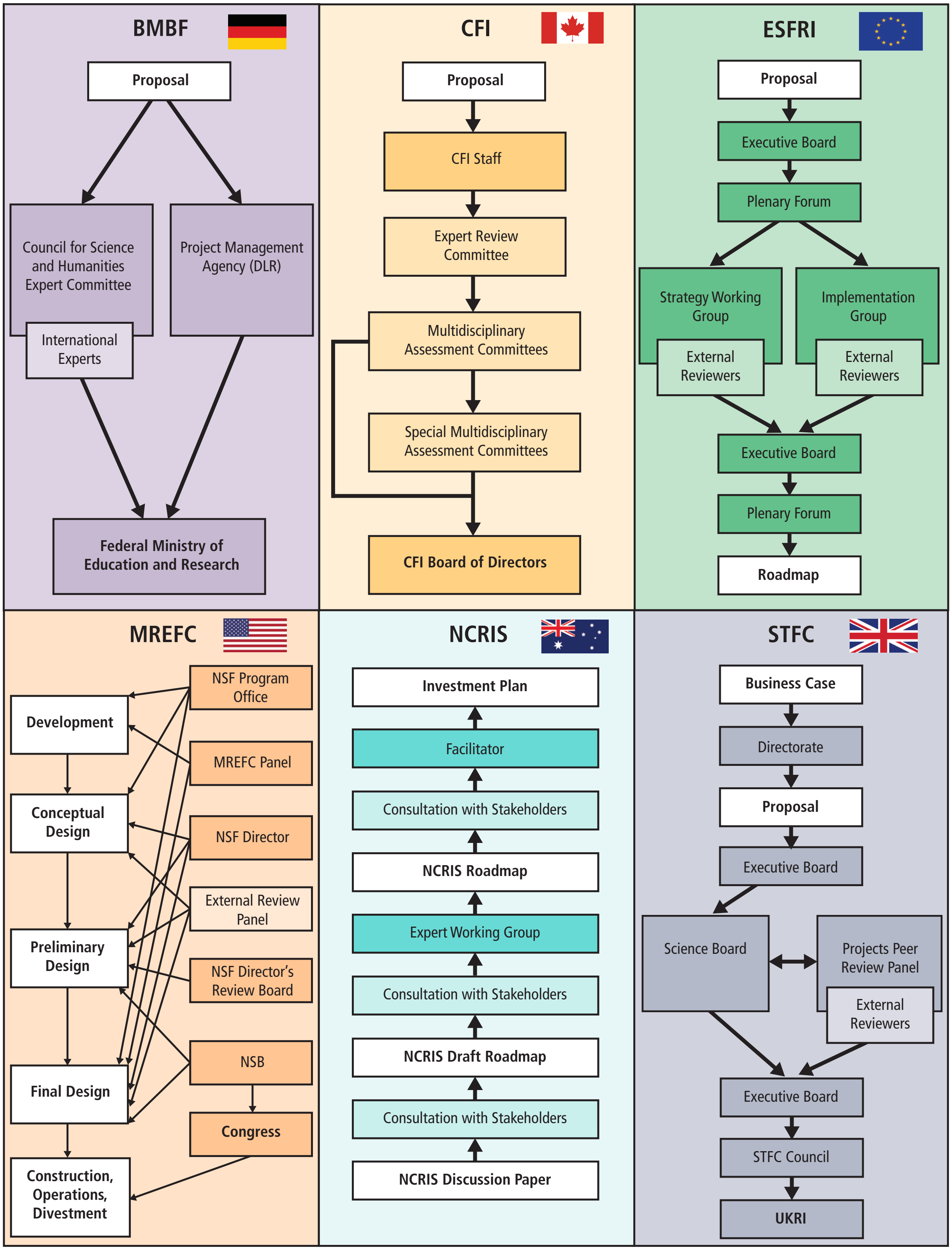


Figure 6.1

Comparison of Project Approval Processes for Research Infrastructure

The figure presents conceptual maps of project approval processes for six research infrastructure strategy and/or funding review bodies around the world: BMBF (Germany), CFI (Canada), ESFRI (European Union), MREFC (United States; NSB: National Science Board), NCRIS (Australia), and STFC (United Kingdom; UKRI: United Kingdom Research and Innovation). White boxes indicate deliverables; light-shaded boxes indicate the engagement of external experts.

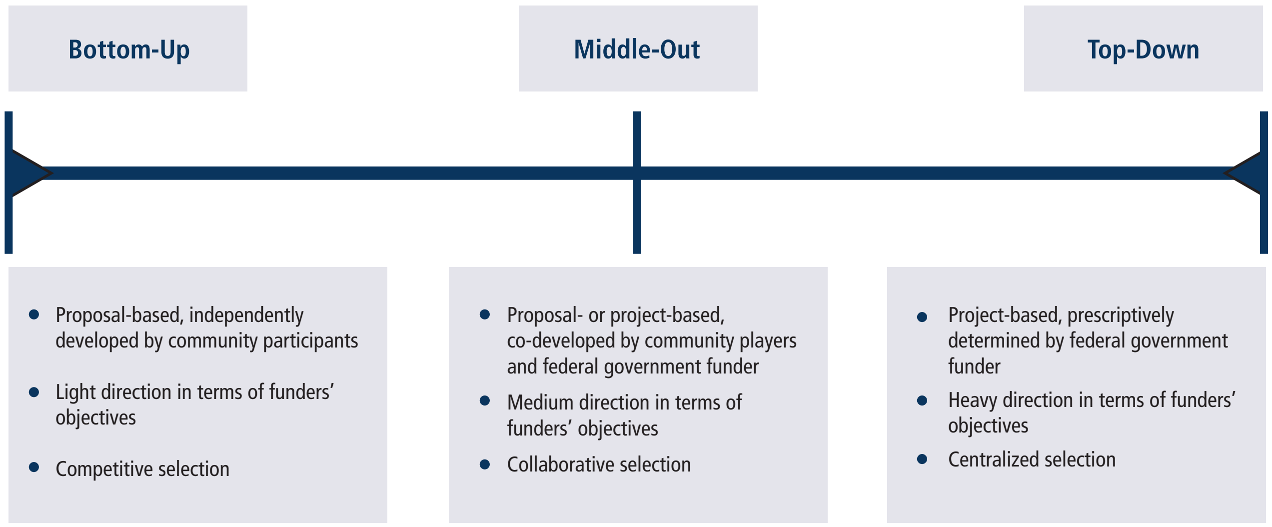
argued that these tools can provide a transparent and flexible process to more effectively prioritize investments in research infrastructure (Keisler *et al.*, 2017).

Structured decision-making is a qualitative approach that draws on the formal methodology of decision analysis, as well as other theoretical frameworks such as the integration of systematic analysis and deliberation, constructed preferences, and value-focused thinking (Gregory *et al.*, 2012). Structured decision-making has emerged as a practical guide to making rigorous and defensible environmental management choices. While assigning quantitative weights and values to specific criteria is not necessarily part of structured decision-making, the method does require participants to discuss these elements explicitly. Participants arrive at a consensus on objectives, performance measures, areas of uncertainty, alternative options, and the characteristics of relevant trade-offs, although consensus may not be achieved in the actual decision. An open and transparent discussion on how and why choices were made, and the flexibility to revisit the choice in the future following data collection and analysis (i.e., adaptive management), can help generate support (if not complete agreement) among stakeholders (Gregory *et al.*, 2012).

6.5 CONSIDERATIONS IN A GOVERNMENT SCIENCE AND TECHNOLOGY CONTEXT

In a government S&T context, a co-created approach between top-down and bottom-up decision-making processes, called a "middle-out" approach, is a promising model.

The design of the decision-making process can support the guiding principles. For example, having a clear understanding of a government's mandates and objectives for infrastructure investments, as well as identifying areas for capacity building or maintenance and future exploration, can help define scientific excellence for infrastructure proposals. Setting priorities or goals may take the form of a roadmapping exercise. If it is co-created with stakeholders, a roadmap can also provide an opportunity to develop collaborative relationships. No single model for soliciting and evaluating infrastructure proposals will suit all situations. Rather, a variety of options are available when considering aspects of the decision-making structure and process, and these can be chosen to implicitly or explicitly support different guiding principles.



- Proposal-based, independently developed by community participants
- Light direction in terms of funders' objectives
- Competitive selection

- Proposal- or project-based, co-developed by community players and federal government funder
- Medium direction in terms of funders' objectives
- Collaborative selection

- Project-based, prescriptively determined by federal government funder
- Heavy direction in terms of funders' objectives
- Centralized selection

Figure 6.2

Spectrum of Decision-Making Processes

A simplified spectrum of options for decision-making processes for S&T infrastructure investments, ranging from bottom-up to top-down.

While a decision-making process can vary in several dimensions, a simplified spectrum situates the process from bottom-up to top-down extremes (Figure 6.2). For example, at one end, community-based proposals may drive an open, bottom-up process — with little direction in terms of the specific government project objectives for infrastructure — decided through competition among proposals. At the other end, in a highly directed, top-down process, infrastructure may be developed to meet a specific project need, with little opportunity for input from the scientific community and largely centralized decision-making.

Between these two extremes, an approach described by the Panel as "middle-out" captures elements from both ends of the spectrum. This allows for more or less direction from funders, with proposals or projects developed through a collaborative decision-making process involving community members and funding bodies.

By making proposals visible to all potential proponents (e.g., through an online platform) and providing opportunities for feedback and discussion, a decision-making process can support collaborative opportunities. Stakeholder engagement in, and co-creation of, a proposal early in the decision-making process can also help build trust, relationships, and mutual understanding before a collaborative S&T infrastructure project begins operation. Moreover, allowing for multiple iterations (i.e., a stage-gated design process) can provide a platform for new relationships among otherwise isolated actors, can foster self-selection among proposals, and can encourage proponents to form collaborations in later stages of design. Including a variety of potential stakeholders at multiple stages can reduce the first-mover advantage and provide a platform for all participants to identify areas of interest and contribute to proposal development. Requiring proposals to reach a certain stage of development before opening them up to broader discussion and input may help to ensure that science-driven mandates are prioritized.

7

Final Reflections

Infrastructure is one critical component of the science ecosystem, along with people, equipment, information, and institutions. In the Panel's view, infrastructure is a means to an end; it is essential to the delivery of outcomes but not at the expense of the other components. Delivering effective S&T outcomes and broader impacts requires particular consideration of the *people* who support collaboration and integration of the ecosystem.

Considering all components of the ecosystem in assessing infrastructure proposals helps make investments supportive of the whole. Such considerations can be made explicit by including criteria that respond directly to the principles of scientific excellence, collaboration, feasibility, and broader impacts. Leading practices point to S&T infrastructure that is accessible, inclusive, flexible, and connected. Including scientists, especially social scientists, Indigenous knowledge-holders, and local communities in the design and use of infrastructure strengthens Canada's science ecosystem. Thoughtful consideration of decision-making criteria and processes helps all participants benefit from a robust, consistent approach to ensure rigorous, high-quality government science.

In the Panel's view, there is an exciting opportunity for Canada to lead the way in evaluating proposals for government S&T infrastructure investments. The Panel hopes that this report lays a foundation on which to build infrastructure that supports *Canada's Science Vision*, transforms Canadian science, and makes our nation a safer, healthier, and better place to live.

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Appendix

Table A.1

Comparison of International Research Infrastructure Strategy and/or Funding Review Bodies

	Operates Facilities/Labs	Provides Funding	Provides Researchers with Access to Infrastructure	Approach to Fostering Collaboration	Develops Roadmaps
BMBF (DE)	Host institutions and national or international consortia operate research infrastructure funded through the BMBF Roadmap.	Provides funding for the development and construction of research infrastructure (and some upgrades), but not operational funding.	A review of access policies is included in the scientific evaluation criteria.	Provides funding for international, multilateral research infrastructure.	Has developed 2 roadmaps: the first in a pilot phase (2011-2013) and the second scheduled to be released.
CFI (CA)	Universities and non-profit research institutions own and operate CFI-funded research infrastructure.	Provides up to 40% of the cost of development and construction of research infrastructure, but not operational funding.	Hosting institution is encouraged to make the infrastructure available to other users, including those from other sectors, particularly the private sector. However, this is not a requirement.	CFI "strongly encourages" institutions to develop collaborations with partners from other sectors, including government and industry. However, this is not a requirement.	CFI does not use strategic roadmaps, but does require recipient organizations to have strategic plans in place.
ESFRI (EU)	Research infrastructure that is included in ESFRI roadmaps is operated by host institutions in EU member states, associated countries, and/or EIROforum members (e.g., CERN).	Research infrastructure included in the ESFRI roadmap is funded by EU member states, associated countries, and/or EIROforum members.	ESFRI projects must have an access policy for researchers, typically based on the European Charter for Access to Research Infrastructures (to whose development it contributed).	ESFRI acts as an informal strategy forum that "enables stakeholders at the institutional, regional, national, European and global level to position their [research infrastructure] initiatives within a broader context."	Has developed 5 roadmaps (2006, 2008, 2010, 2016, and 2018).
MREFC (US)	NSF rarely maintains ownership of research infrastructure that it funds; operation and maintenance is the responsibility of the funding recipient, typically a university or universities, or other research organizations.	Provides funding for construction of research infrastructure, but not operational funding; operations and research funding can be provided by the NSF R&RA account.	To be eligible for MREFC funding, a project should be accessible to an appropriately broad community of users on the basis of merit (one of the selection criteria).	Proposals for projects should be coordinated with other organizations and countries to explore potential opportunities for collaboration and cost sharing.	NSF's annual Facility Plan serves as a strategic roadmap.
NCRIS (AU)	NCRIS-funded infrastructure is operated by partners including universities, publicly funded research agencies, state and federal government departments and agencies, international bodies, and industry.	Provides funding for operating and capital expenses for research infrastructure.	Requires host institutions to implement "open access" regimes. Access is based on principles of merit, national interest, and commercial benefit.	Bottom-up, non-competitive process. Requires host institutions to implement access arrangements.	Has developed 4 roadmaps (2006, 2008, 2011, 2016).

continued on next page

	Operates Facilities/Labs	Provides Funding	Provides Researchers with Access to Infrastructure	Approach to Fostering Collaboration	Develops Roadmaps
NUFI (DK)	Danish universities and national research institutions operate the research infrastructures funded through the Danish National Roadmap on behalf of national consortia.	Provides up to 50% of the cost of establishment and implemenation of research infrastructure, but not operational funding.	Inclusion in the National Roadmap requires host institutions to open the infrastructure to other users.	Danish Ministry of Higher Education and Science funds several "National Collaborations on Research Infrastructure."	Has developed two roadmaps (2011, 2015).
STFC (UK)	Operates national laboratories at six research facilities across the United Kingdom. Works with partner organization to build and operate national research and innovation campuses, based around national laboratories.	Provides funding for facility and infrastructure development, research programs, and operation of national laboratories.	Provides researchers with access to STFC-funded research infrastructure.	National research and innovation campuses based around national laboratories promote academic and industrial collaboration.	First roadmap is currently under development.

Source: (Gov. of Australia, 2010, 2017, 2018; BMBF, 2013, 2015; Wissenschaftsrat, 2014; Danish Agency for Science, 2015; ESFRI, 2016, 2018a; STFC, 2016, 2017a, 2017b, 2018; CFI, 2017a; NSF, 2017, 2018; UFM, 2019)

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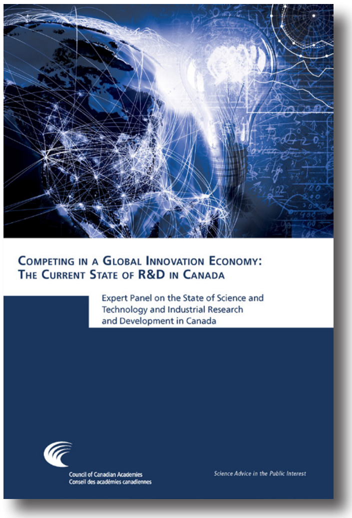

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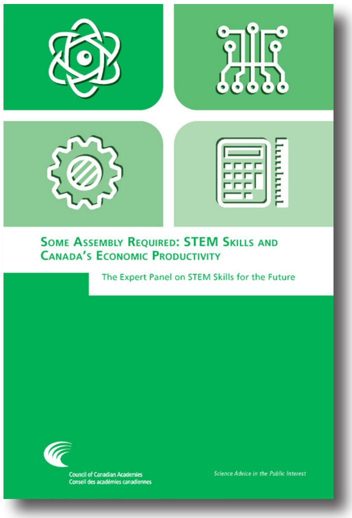

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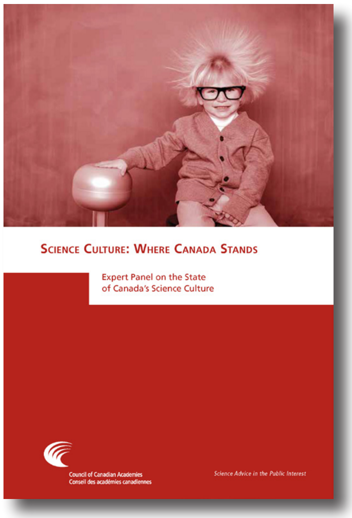

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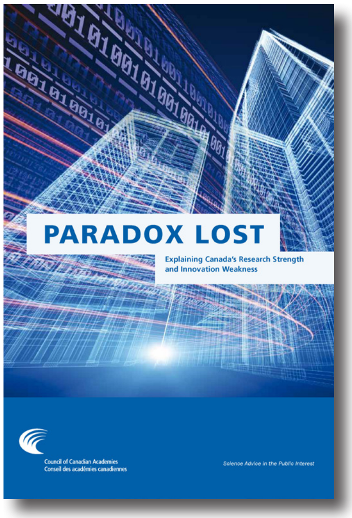

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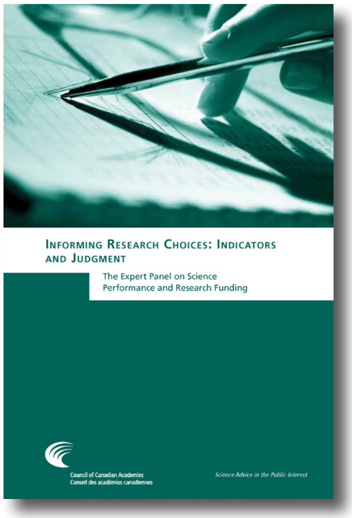

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