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Knowledge Systems for Material Sustainability

by

Akos Kokai

A dissertation submitted in partial satisfaction of the

requirements for the degree of

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in

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in the

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of the

University of California, Berkeley

Committee in charge:

Professor Alastair Iles, Chair
Professor Christine Rosen
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Dr Megan Schwarzman

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Abstract

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Professor Alastair Iles, Chair

Making systems of production sustainable will require deep technological and societal change. This dissertation explores several facets of the relationships between scientific knowledge, society, and “green design”—a set of approaches for eliminating harmful chemical substances from material technologies. This is an interdisciplinary investigation based in science and technology studies (STS), drawing from scholarship in the sociology of knowledge and resource management, information studies, and design studies.

An overarching challenge in green design is effectively cultivating and mobilizing scientific knowledge to enable technical change. This dissertation asks what systems could produce, test, verify, and organize scientific knowledge in ways that better meet the needs of a growing community of green design practitioners, advocates, and decision-makers. Scientific communities are increasingly turning to systems of shared and collectively governed knowledge resources—or knowledge commons. Using in-depth case studies I explore emerging knowledge commons in the domain of chemicals and environmental health. I investigate how a commons can be formed and sustained in this complex and politically contested arena; and whether (or how) such a commons can function as a stable site for producing “socially robust knowledge”—knowledge that has been tested and accepted as valid by a wide range of stakeholders.

At the same time, the politics of green design are structured by dominant systems of knowledge and technological development, in which civil society is largely oblivious to the risks of material design choices and unable to actively participate in shaping alternatives. With a case study of the building sector, I examine how mobilizing science to inform green design necessarily involves making political and value-laden choices, even though these are rarely debated as such. Extending my analysis to the case of nanotechnology, I argue that green design should become more participatory—providing pathways for society to consciously shape material technologies for sustainability.

To Cris: for all you gave back to the universe.

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Many people have contributed to this dissertation. Chapter 2 represents a collective effort in many ways: I thank co-authors Ann Blake, Michel Dedeo, and Tom Lent; and I thank the Healthy Building Network (HBN)—especially Sarah Gilberg, Larry Kilroy, and Jon Stavis—for making the Data Commons project possible. Alastair Iles and Chris Rosen helped create and re-create Chapter 4 over several iterations, while Chapter 5 would not exist without Alastair's vision and guidance.

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Chapter 1

Introduction

The material consequences of industrial activity have become defining features of our world, as well as critical concerns for the sustainability of our society. Chemical contaminants are ubiquitous in the global environment and in human bodies, and they are likely to remain present and exert their effects for many generations into the future. Although pollutants are everywhere, their aggregate impacts create obvious environmental health disparities that follow the lines of social, economic, and racial inequality (Lerner 2010). The problem of toxic substances—their production and use in manufacturing processes, materials, and products, leading to widespread impacts on ecosystems and public health—is a societal challenge as immense as climate change, and one that garners attention from scientists, policy-makers, and activists internationally (United Nations Environment Programme 2013; United Nations Environment Programme 2019). The issue is not new: it is now more than half a century since Rachel Carson raised widespread public concern about the harmful effects of chemical pesticides with her publication of *Silent Spring* (1962), and a quarter century since Colborn and colleagues popularized the science of endocrine-disrupting chemicals with *Our Stolen Future* (1996). Still, chemical pollution continues to erode the integrity and resilience of global ecosystems (Diamond et al. 2015). Peoples' exposure to chemicals in everyday environments and workplaces contributes significantly to the global burden of disease (Attina et al. 2016). For example, Grandjean and Bellanger (2017) estimate that the social costs of environmental chemical exposures currently exceed 10% of the global gross domestic product. Despite scientific advances in understanding chemical risks, we have not detoxified the world (Boudia and Jas 2014).

Perhaps, as some scholars argue, this is because the governance of toxic substances is a "wicked problem" (Allen 2013): it has multiple interdependent causes and undefined boundaries that cut across social, political, and organizational divisions. Wicked problems challenge our typical problem-solving approaches because they are embedded within society, and therefore call for societal change (Rittel and Webber 1973; V. A. Brown, Harris, and Russell 2010). There may be no single identifiable resolution to the toxics dilemma, but rather a range of approaches that could interact or conflict with each other. For example, public policy reform, technical innovations, social and cultural shifts, and large-scale transitions in the structure of the material economy could all play important roles—and each face many barriers. As such, all pathways that we might imagine toward an environmentally sustainable and socially just system of material production are likely to be partial, incomplete, or compromised. With this in mind, the work that follows should be seen as fundamentally limited: I address only a narrow slice of the possibilities for change.

This dissertation concerns itself with efforts to protect human and ecological health through the intentional design of safer material technologies. In my shorthand, "green design" refers to a set of approaches that aim for the *redesign* of chemicals, materials, products, and industrial processes such that harmful substances are eliminated or substituted with benign alternatives. This includes the work of diverse groups across society: scientists and engineers advancing green chemistry (Anastas and Warner 1998; Woodhouse and Breyman 2005; Iles 2013) or developing technical tools to inform safer chemical substitution (Toxics Use Reduction Institute 2006); architects and designers creating environmentally benign products and built spaces (McDonough and Braungart 2002; Goodwin Robbins et al. 2019); policy-makers designing programs to drive the development and uptake of safer alternatives (Geiser 2015; Solomon, Hoang, and Reynolds 2019); and social movements concerned with the effects of material technologies (D. J. Hess 2007; Iles 2007). More specifically, I focus on the systems of producing, verifying, and organizing scientific knowledge that underpins green design efforts. I explore several facets of the relationships between scientific knowledge, green design, and society, highlighting challenges and opportunities for enabling transitions to material sustainability.

One crucial set of challenges has to do with how society can more effectively cultivate and mobilize scientific knowledge for green design. Scientific evidence, concepts, and analytical tools are essential to identify hazardous substances and to evaluate potential safer alternatives (e.g., Lavoie et al. 2010; Voutchkova, Osimitz, and Anastas 2010). But scientific knowledge is not always available to decision-makers, and it does not always provide clear answers. Scientists recognize significant gaps in knowledge about chemical hazards and human exposures (Judson et al. 2009; Egeghy et al. 2012). A vast number of industrial chemicals have been marketed globally, with estimates ranging up to 350 000 substances (Wang et al. 2020); but most of these substances have not been characterized as to their health effects (Geiser 2015). The knowledge gaps are partly a result of public policy and intellectual property regimes operating since the 1970s (M. P. Wilson and Schwarzman 2009; Scruggs, Ortolano, et al. 2014). Furthermore, questions of chemical toxicity often call for difficult interpretation of data that are uncertain, incomplete, or in flux due to an evolving understanding of toxic effects (Gee 2006). In public policy arenas, scientific evidence about the health effects of particular chemicals is contentiously debated when economic interests are at stake (e.g., Vogel 2013).

Green chemists, engineers, and designers seek reliable scientific tools (Zimmerman and Anastas 2015; Malloy et al. 2017) with which to move beyond the decision paralysis that has characterized traditional risk-based regulation—the endless analysis of whether a problem is bad enough, and knowledge good enough, to take action (O'Brien 2000). But they still face uncertainties and unknowns. Moreover, green design practices are still rooted in a chemical knowledge system that evolved together with 20th-century institutions and which, despite its flaws, continues to shape how we understand chemical hazards (Boudia, Creager, et al. 2018; Hepler-Smith 2019) and how we put knowledge into action (Liboiron, Tironi, and Calvillo 2018). This dissertation therefore asks what kinds of systems could produce, test, and mobilize scientific knowledge in ways that better meet the needs of a growing community of green design practitioners, advocates, and decision-makers.

Another set of challenges has to do with ensuring that society equitably benefits from "green" technological transitions. Proponents of green chemistry emphasize the importance of design as an opportunity to consider and prevent environmental health impacts as early as possible in the development of technical systems. For McDonough and Braungart, "design is a signal of intention" (2002, p. 9); for Anastas and Zimmerman, "if a chemical contains a hazard that is not intended, it is a design flaw" (2019, p. 6551). These views dictate that chemists and designers should take responsibility for protecting public health and the environment. But they tacitly assume a model of technological development where design decision-making takes place within firms and research labs, driven by technical expertise yet constrained by corporate or institutional financial interests, without much support or scrutiny from civil society—unless damaging effects are later discovered. This dissertation confronts the possibility that such a model is itself part of the wicked problem of toxic substances.

In a world where reliance on technical expertise has led to the proliferation of risks in everyday life (Beck 1992), science has been forced to become more sensitive to uncertainties and to the varying social contexts in which it operates (Nowotny, Scott, and Gibbons 2001). Social movements increasingly challenge the authority of scientists and technologists (D. J. Hess 2016). Environmental justice movements made up of organized and knowledgeable groups—women, indigenous people, local citizens, and so on—have raised concerns about the impacts of industrial chemicals on their lives (e.g., Lyons and Illig 2007; Hoover et al. 2012; Kozlowski and Perkins 2015). These citizens' concerns have proven to be scientifically and politically credible (e.g., Iles 2007), which suggests that the dominant processes of chemical and material design lack foresight and fail to integrate an analysis of equity and distributional justice. Even "green" technologies can have inequitable social and environmental effects; green design choices often involve hidden trade-offs between different benefits and harms, such as renewable energy or non-toxic materials (Mulvaney 2019). How can green designers legitimately take on the responsibility that they seem eager to accept?

Grappling with these questions, this dissertation proposes and explores opportunities for social and technical change—within and beyond green design. My starting point is the recognition that the dilemmas I have just outlined call for changing how scientific knowledge about chemical hazards is produced, verified, and distributed; how science enters into processes of design; and how design takes place. Although it is focused on the subject matter of chemicals and materials, this dissertation is an interdisciplinary investigation based in science and technology studies (STS), drawing from scholarship in the sociology of knowledge and resource management, information studies, and design studies. Three key ideas have inspired this research and the possibilities it explores: knowledge commons, socially robust knowledge, and the politics of green design.

1.1 Knowledge commons

The notion of “the commons” is both old and new, and potentially one of the most generative ideas of our time. A commons is a system of resources collectively owned and governed by a community of people who also benefit from its use (Bollier 2014). Commons have deep historical roots in the ways that people have organized themselves to sustain shared agrarian lands, forests, fisheries, and other biophysical resources (Ostrom 1990)—and, conversely, in the separation of people from their means of agrarian production in the enclosure of land commons (Polanyi 1944; Caffentzis 2013; Linebaugh 2014). Knowledge, in its many forms, is also a resource. A knowledge commons, according to Frischmann et al. (2014a, p. 3), is “the institutionalized community governance of the sharing and, in some cases, creation, of information, science, knowledge, data, and other types of intellectual and cultural resources.”

The commons plays an important role in many accounts of social, economic, and environmental transformation, ranging from the 18th-century enclosure movement to the many new ways in which commons are reemerging and potentially generating new transformations in response to global problems (Bollier 2014; Linebaugh 2014). Scholars increasingly recognize knowledge commons as important sites of global cultural production (Benkler 2006), as well as being vulnerable to new forms of enclosure through intellectual property rights (Lessig 2004; Boyle 2008). Especially in the past two decades, knowledge commons have materialized in many scientific and technological fields to counter trends in present-day enclosures of science and technology. Open source software (e.g., GNU/Linux) is the best-studied case of knowledge commons (Schweik and English 2012). Wikipedia, Creative Commons, open science, open access science databases, crowd-sourced science, and many others are also becoming prominent (e.g., Nielsen 2012; Mansell 2013; Bartling and Friesike 2014; Bouchout Declaration 2014). More recently, medical knowledge commons have emerged, in which physicians, researchers, patients, governments, and companies jointly share research into genomes, diseases, and therapies (Lucchi 2013; Cook-Deegan and McGuire 2017; Bollinger et al. 2019).

In science and technology fields related to sustainable energy and materials, commons-based initiatives are emerging in response to a perceived lack of access to information, gaps in transparency, and the existence of “information silos” (e.g., National Renewable Energy Laboratory 2020; REEEP 2020). In Europe and the United States, networks of governments, firms, and NGOs have begun to support initiatives for open and collaborative management of knowledge in the development of safer chemicals and materials (e.g., Lissner and Romano 2011; Interstate Chemicals Clearinghouse 2014; eNanoMapper Consortium 2020). The motivation appears to be that knowledge commons can improve stakeholders’ access to data and tools that are critical for evaluating and reducing the environmental health impacts of chemicals, and can also facilitate broader multi-stakeholder participation in tackling difficult problems (Geiser 2015).

This dissertation explores emerging knowledge commons in the domain of chemicals and environmental health. Specifically, I focus on forms of knowledge that enable scientists and decision-makers to substitute hazardous chemicals and materials with safer alternatives (Toxics Use Reduction Institute 2006; Zimmerman and Anastas 2015). Chemical alternatives assessment (CAA) refers to techniques for comparing the characteristics of substances to select the safest option, and to identify data gaps and further research needs (Lavoie et al. 2010; Harrison and Hester 2013; National Research Council (US) 2014). Chemical hazard assessment (CHA) refers to techniques for systematically evaluating the types and severity of harm a substance might cause, as well as evaluating the strength of evidence and the sources of uncertainty in the data (Heine and Franjevic 2013). These two sets of techniques are related, with CHA informing and being a necessary tool for CAA (Geiser 2015, p. 257). Are there knowledge commons in which CHA and CHA knowledge are being produced and distributed? What kinds of technical arrangements, institutions, communities, and social processes make up these commons? How are they sustained, and what challenges do they face? Critically, how do these commons shape the production and validation of knowledge for green design?

Chapter 2 describes the processes of constructing a chemical knowledge commons through an NGO-led effort, in which I participated along with my colleagues Ann Blake, Michel Dedeo, and Tom Lent. The Chemical Hazard Data Commons (or "Data Commons") was a collaborative initiative managed by the non-profit Healthy Building Network (HBN) and designed to address the knowledge needs of chemical alternatives assessment. The practices of CAA involve systematic analyses of chemical hazards and life cycles, and the CAA practitioner community has faced a lack of appropriate information infrastructure and functional tools to enable a diverse set of stakeholders to engage in CAA. In a domain characterized by top-down regulatory approaches and private-sector initiatives, the Data Commons project represented a novel, collaborative approach to provide these missing resources. It framed the problem as a collective challenge and emphasized building shared intellectual and technical capacity. The Data Commons ultimately provided free, publicly accessible chemical hazard data and new tools for understanding it, selected and constructed according to the practitioner community's priorities and criteria as much as possible. However, the project faced challenges in encouraging community participation and aggregating community expertise to produce new knowledge.

1.2 Socially robust knowledge

Generating and acting on scientific evidence about chemical health impacts is a contested terrain that has been shaped by political struggles over the regulatory control of toxic substances. This is partly because policy processes for evaluating and controlling chemicals often generate high scientific uncertainty and indeterminacy, making political decision-making and the interpretation of science extremely difficult to separate from one another (Jasanoff 1987; Jasanoff 1990; Sarewitz 2004). At the same time, the design of public policies and the practice of "regulatory science" has produced major gaps and biases in chemical knowledge (e.g., Schwarzman and M. P. Wilson 2009; Gross and Birnbaum 2017). Seeing these flaws, a growing number of civil society actors have entered the chemical knowledge arena to challenge the assumptions, methods, data sources, and standards of evidence favored by the dominant regulatory-industrial regime. Environmental non-government organizations (NGOs) and health social movements, for example, have emerged as credible experts in their own right (Iles 2007; Shamasunder and Morello-Frosch 2015).

Could this diversification of expertise in the chemical knowledge arena benefit society's capacity to respond to the challenges of material sustainability? Some STS scholars have suggested that science can indeed be strengthened by being openly challenged. Nowotny, Scott, and Gibbons (2001) introduced the idea of "socially robust knowledge," referring to knowledge that is accepted as valid and authoritative by multiple, diverse constituencies. They proposed that socially robust knowledge is a new form of "reliable knowledge." To be socially robust, knowledge must not only pass scientific and technical tests of reliability but also social tests of reliability—such as proving its applicability to particular decision-making contexts, scrutinizing the assumptions and framing narratives upon which it is built, and assessing the credibility and authority of those who contribute to it. Nowotny (2003) suggests that social robustness is about processes: it is made possible by the real-world testing and iterative modification of knowledge, and by the participation of an "extended" peer group that encompasses many different kinds of expertise in an ongoing dialogue.

Intense "scientized" public debates surrounding many critical environmental issues—not just chemicals, but climate change and agricultural biotechnology—would seem to highlight the need for socially robust knowledge as a necessary foundation for reasoned collective action. But what kinds of systems—what arrangements of knowledge-making methods, institutions, and people—could actually enable the iterative, participatory processes of testing and validation? This dissertation builds on more recent scholarship elaborating the idea of socially robust knowledge (e.g., Iles 2013) by considering what it would look like in practice and connecting the concept to empirical observations in the field of chemical knowledge. How could emerging forms of scientific knowledge—which aim to make green chemistry, safer chemical substitution, and sustainable material design possible—also become socially robust? What is the role of commons in generating socially robust knowledge?

In Chapter 3, I follow an extended peer community of scientists, advocates, and decision-makers, arguing that a multifaceted knowledge commons is emerging through their interrelated efforts to understand chemical hazards and how to reduce them. I describe a CHA knowledge commons as a network of resources linked by flows of knowledge and mutually productive relationships. As they grapple with how to advance green chemistry and safer chemical substitution, participants in the CHA commons are engaging collectively in building and testing knowledge—for example, developing chemical hazard assessment methodologies, tools, data sources, and standards by which to evaluate "green" products. They are establishing and defending new practices (such as chemical hazard assessment and alternatives assessment); sharing data and expertise across institutional and organizational boundaries; and finding alignment among actors with diverse interests—and around scientific questions that are often subject to disagreement and debate.

As an in-depth case study, I present an analysis of a more clearly-coalesced knowledge commons existing inside the broader CHA knowledge network: the case of GreenScreen for Safer Chemicals, an open-source methodology for chemical hazard assessment. I ask whether and how this emerging commons can function as a stable site for producing socially robust knowledge. To investigate this, I study how commons-produced knowledge about chemical hazards, assessment methodologies, and tools becomes legitimate and authoritative for participants in the CHA knowledge network—including a varied community of knowledge users. I examine how the institutions and social protocols of the GreenScreen commons—such as peer review processes and conflict resolution mechanisms—can either help make knowledge more socially robust, or alternatively can close off or prevent extended peer review. My analysis reveals a commons that is "nested within" (Bollier 2014) dominant institutions and information infrastructures, such as global molecular information systems and (most of all) intellectual property rights regimes. These are profoundly influential background conditions, which deeply structure the kinds of knowledge that the commons produces and the patterns of collective knowledge production that the CHA knowledge commons supports.

1.3 Politics of green design

By linking the analysis of knowledge commons to socially robust knowledge, this dissertation addresses the relationships between participatory modes of production and the politics of scientific knowledge. Chapters 4 and 5 extend this theme to the analysis of how green design manifests and materializes these politics. Extensive research in STS has shown that technical systems are not politically neutral, but have real effects on social structure and power relations (e.g., Winner 1980; Benjamin 2019). Scholars have argued that technology should be "democratized" (Sclove 1995; Kleinman 2000) and that society needs new institutions and capacities to govern emerging technologies that present social and environmental risks (Guston and Sarewitz 2002; Barben et al. 2007). At the same time, technological design reflects pervasive societal influences, even though we may be oblivious to these influences operating in practice (e.g., Bijker and Law 1992; MacKenzie 1998; Woodhouse and Patton 2004). STS research has analyzed how values and politics enter design, and how design can "materialize" social inequities (Nieusma 2004; Woodhouse and Patton 2004; Nieusma 2011).

Examining the technological politics of green design raises questions about the agency of both designers and civil society. Designers—understood broadly to include everybody from chemists and materials scientists to consumer product designers and architects—make highly consequential choices involving material selection, formulation, specification, and production. These design choices to a large extent determine the environmental health impacts of materials, products, and built environments. Yet designers have limited and imperfect knowledge about how exactly to reduce those impacts. They have even more limited ways of influencing the larger network of industrial technological choices that contribute to harm, because these are part of a socio-technical structure that is impervious to deep changes. If green designers are attempting to reshape technical systems toward sustainability and environmental justice, how exactly they do this—using what knowledge, assumptions, norms, and values—is of critical importance to all of us, whose lives and health will be affected by the resulting designs. Yet there are few opportunities for members of society to learn about or participate in green design decision-making. For example, scientists in the field of green chemistry have typically maintained minimal or skeptical relations with civil society organizations (Woodhouse and Breyman 2005), developing their research largely by following entrenched structures of research funding and dominant framings of policy issues (Maxim 2018).

This dissertation addresses two questions that are central to the politics of green design. First, how do political and value-laden choices enter green design by way of scientific tools and knowledge resources? Second, how could processes of green design be reshaped, providing pathways for society to consciously "signal its intentions" for material sustainability? What would it take to recruit pluralistic societal participation in technological design?

Chapter 4 investigates the emergence of "green design tools" as a new response to the dilemmas that designers face in reducing and avoiding chemical hazards. Using the green building movement as a case study, this chapter examines how environmental health advocates, scientists, and consulting firms are stepping in to provide designers with new tools—including science-based assessment methods, standards, databases, and software—intended to help structure and inform decision-making in sustainable design. With co-authors Alastair Iles and Christine Rosen, I present a novel investigation of the important role that green design tools play in giving designers new forms of influence while mediating how designers' values are translated into actual design choices. Tool makers embed their own values and politics into the construction of the tools, which function as "black boxes" (Latour 1987)—their internal operations are understood as less important than their outputs for informing sustainable design. Examining controversies about the scientific validity of particular green design tools, we argue that they are rooted in value conflicts and tensions in the politics of chemical knowledge. This suggests that transparency about values and politics among tool developers and users could strengthen the legitimacy and credibility of green design tools.

But could citizens actually have a role in shaping the design of greener materials? What can they contribute to the design process, if anything, and how? Chapter 5 examines the development of nanomaterials as a "hard case" of a complex and expert-driven technical system in which civil society has struggled to exercise governance. This chapter builds on the new concept of "materials sovereignty"—the right of people to use and be surrounded by environmentally benign, non-toxic, and renewing materials in their everyday lives. As a rights-based approach, materials sovereignty may help change the politics of governing materials by giving social movements greater traction in changing industrial production. With co-author Alastair Iles, I present an analysis of key elements that are central to achieving materials sovereignty. Our analysis is based on reviewing several strategies through which social movements have attempted (with limited success) to influence the development of nanomaterials, and on closely examining a set of participatory pathways through which social movements could intervene more directly into material design. These pathways—participatory technology assessment, collaboration with industry, and co-design—involve significant institutional and organizational challenges in practice. We find that materials sovereignty requires, among other key elements, creating multi-directional flows of information and agency concerning materials. Knowledge commons, therefore, could be one way of bringing about the conditions for society's informed participation in green design.

1.4 Methods

This study interweaves a variety of research methods and data sources, focusing on qualitative data collected from interviews, participant observation, and document analysis. Chapter 3 includes a more detailed description of methods that informed the overall study.

To summarize, I conducted 35 semi-structured interviews with respondents selected for their involvement in collaborative knowledge efforts relevant to chemicals and environmental health. The interviews were conducted using an interview guide designed to address empirical questions about commoning and knowledge production (Appendix A). The interview data informed my analysis of chemical knowledge commons (Chapters 2 and 3) as well as green design tools (Chapter 4).

I participated in the planning and development of the Chemical Hazard Data Commons (Chapter 2), serving as a core organizational member and providing technical assistance. I also participated in the broader community concerned with CHA and CAA knowledge and practices: I served on the GreenScreen Science Advisory Committee from 2017–2020; I attended meetings of the Business-NGO Working Group for Safer Chemicals and Sustainable Materials, the Second International Symposium on Alternatives Assessment (2018), as well as virtual workgroup meetings and presentations. None of my participation involved any compensation or remuneration. My notes from participatory work primarily contributed to Chapters 2 and 3.

I compiled and analyzed public documents pertaining to a range of chemical knowledge resources, tools, and initiatives. Document analysis contributed to all of the research in this dissertation, but I leverage these data sources much more heavily in my analysis of green design tools (Chapter 4) and interventions in nanotechnology design (Chapter 5).

I conducted content analysis on all data sources using ATLAS.ti (2020).

1.5 Summary

Throughout this dissertation, I have attempted to develop a clear picture of how and why knowledge matters for material sustainability. Knowledge resources, communities, infrastructures, information flows, and the protocols that govern them all shape the possibilities for bringing about a socially and ecologically just transformation of our material economy. Together, my three key themes—knowledge commons, socially robust knowledge, and the politics of green design—form an analytical lens through which I aim to elucidate and perhaps make some contribution toward strengthening the role of science in such a transformation.

Chapter 2

Building shared information infrastructure for chemical alternatives assessment

Akos Kokai, Ann Blake, Michel Dedeo, and Tom Lent[1]

The substitution of hazardous substances with safer alternatives is being driven by policy pressures and business demands. As a result, scientific techniques for chemical alternatives assessment (CAA) have been established and communities of practice are emerging. Interest in safer chemical substitution is widely shared throughout a range of stakeholder groups across science, industry, public policy, and advocacy. Yet there is an unmet need for intentionally designed public information infrastructure to support the highly knowledge-intensive nature of CAA. We report here on the process of developing the Chemical Hazard Data Commons, an experimental project intended to support a diverse community of practitioners by providing publicly accessible chemical hazard data and tools for understanding it. In an arena where market forces and regulatory regimes have largely failed to generate the necessary knowledge, this project represents a novel application of a commons-based approach emphasizing building shared intellectual and technical capacity for CAA. The Data Commons—now a part of the related Pharos Project—includes an online portal providing simultaneous access to many different sources of information and enabling effective interactions with it. Foremost among these interactions are search and retrieval of hazard information about chemical substances, uniform display of the most relevant information,

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[1] We wish to acknowledge Sarah Gilberg, Larry Kilroy, and Jon Stavis, who designed and developed the information systems and software for HBN's Pharos and the Data Commons. We also acknowledge the HBN Materials Research Team for their work on researching and compiling the building product-related chemical information that is included in Pharos. The Data Commons project received funding from the Forsythia Foundation, the Lisa & Douglas Goldman Foundation, the John Merck Fund, and the JPB Foundation.

and the ability to automatically screen substances against consistent and transparent hazard-based criteria. We describe the motivation for the project and report on the principles and key considerations that guided its design as a participatory information infrastructure. We present our approach to organizing chemical information; the process of community engagement and planning; and how we constructed the system to provide functional tools. We discuss the outcomes of the project and highlight important challenges—such as fostering active participation and planning for long-term governance. With this article, we hope to inform future efforts for the collaborative development of knowledge resources for chemical alternatives assessment.

2.1 Introduction

The persistent problem of toxic substances in our industrially transformed environment cannot be solved using the same approach that produced it. Material and product design often fails to consider human and environmental health; manufacturers typically aim to comply with regulatory requirements or—at most—to avoid limited “red lists” of the most harmful substances. These approaches fail to respond to early indicators of harm, and do nothing to guide the development of safer alternatives. Risk assessment and management strategies, when invoked, favor minimizing risk by managing exposure to toxics rather than through the design of inherently safer material technologies.

Faced with these dilemmas, decision-makers are increasingly seeking a different path. New strategies for protecting public health and the environment are gravitating toward the paradigm of alternatives assessment (O’Brien 2000; Ashford 2005)—a problem-solving approach that encourages minimizing harm by comparing several possible options and incorporating a wide range of knowledge, seeking to facilitate decision-making despite uncertainty. The goal of using alternatives assessment is to enable the informed substitution of hazardous chemicals and materials with safer alternatives (Toxics Use Reduction Institute 2006; Zimmerman and Anastas 2015). This goal has been integrated into a wide range of efforts in policy, design, engineering, and business. Chemical alternatives assessment (CAA) refers to techniques for comparing characteristics of substances to select the safest option, and to identify data gaps and further research needs (Lavoie et al. 2010; Harrison and Hester 2013; National Research Council (US) 2014). Chemical hazard assessment (CHA) refers to techniques for systematically evaluating the types and severity of harm a substance might cause, as well as evaluating the strength of evidence and the sources of uncertainty in the data (Heine and Franjevic 2013). These two sets of techniques are related, with CHA informing and being a necessary tool for CAA (Geiser 2015, p. 257).

Scaling up CAA requires developing information resources and tools to address key knowledge challenges. A growing range of professionals—such as designers, engineers, and architects—find themselves facing demands to make informed decisions about chemicals (Scruggs 2013; Logan 2016). This could bring great diversity of thought to one of the major sustainability challenges that we face as a society. At the same time, decision-makers face practical challenges in obtaining, evaluating, and operationalizing information about chemicals and their health impacts. Data about chemical substances—their hazard traits, technical uses in products, and sources of human exposure—are often insufficient due to a lack of scientific research and public disclosure (M. P. Wilson and Schwarzman 2009). Existing data may come from numerous disparate sources with varying standards of organization and interpretation. Many decision-makers engaged with chemical substitution problems aren't experts in chemistry and toxicology, or they don't have the organizational capacity to access and use detailed information about chemicals. Using CAA therefore tends to be technically demanding, resource-intensive, and costly.

Much duplicative work has been done in the parallel efforts of firms, government agencies, and non-governmental organizations to satisfy the interrelated knowledge needs of many stakeholders. There are dozens of different guidelines, ecolabels, chemical "red lists," and databases, but they lack consistency and mutual compatibility. The high cost and proprietary nature of professional chemical hazard assessment services create barriers to accessing and distributing much of the most actionable and valuable knowledge. As a result, decision-makers may find that there are several tools to address the same problem, but few ways to share information, access a pool of existing knowledge, or reconcile inconsistencies and contradictions between different resources.

Taken together, this array of challenges and systemic inefficiencies motivated us to work on improving publicly accessible information infrastructure[2] for chemical alternatives assessment. We report here on the development of the Chemical Hazard Data Commons, a project intended to support a diverse community of practitioners by providing publicly accessible chemical hazard data and tools for understanding it. This project represents a novel application of a collaborative, commons-based approach, and the first effort to create an open, participatory information infrastructure for CAA. In an arena where decades of adversarial policymaking and activism around toxic chemicals have produced intensely contested scientific knowledge, the Data Commons approach emphasizes the value of shared information resources and collective capacity-building. The project aimed to elicit knowledge, expertise, and collaborative peer-review from its participants. The project, led by US-based NGO Healthy Building Network (HBN), began in 2013 and concluded in 2019 with the integration of the Data Commons' newly developed tools and resources into HBN's ongoing Pharos Project (Healthy Building Network 2019d). Pharos, which is accessible online with free user registration, now serves the intended purpose of the commons: a publicly accessible resource for the chemical alternatives assessment community (Healthy Building Network 2020b).

We do not claim that the work reported here is, or will be, the single or best realization of its goals. Rather, we hope to contribute to a larger ongoing enterprise—the collaborative development of knowledge resources to support CAA.

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[2] Infrastructure refers to information technologies that provide services, such as web-based software and databases. It also refers to information systems themselves, and the technical, conceptual, and social agreements that they embody, which serve to enable and coordinate work across many people at once (Bowker and Star 1999).

2.2 Overview of the Data Commons project

The Chemical Hazard Data Commons project aimed to freely and openly provide robust, collaboratively-curated information resources for CAA. We intended to do this by compiling, organizing, and linking together existing publicly available information using open standards; developing online tools for making use of this wide array of information; and coordinating community efforts to increase the knowledge base available to participants and to the public. In essence, the commons has two key elements: networked knowledge resources and a community, bound by common principles, that collaborates to support the development, improvement, and assessment of these resources.

A central component of the commons is a web-accessible library of hundreds of thousands of chemicals with known hazards categorized in terms of 22 specific human and ecological health endpoints (see Table 2.1). Hazard information is drawn from over 40 authoritative sources representing rigorous assessments of scientific evidence, and from other publicly available sources such as professional hazard assessment reports, health studies, and community-vetted datasets. Information about the functional uses[3] of substances is drawn from government and industry sources, along with other relevant information—including physicochemical properties, industrial releases, and "preferred" lists of safer substances. Tables 2.2, 2.3, and 2.4 include representative examples of data sources (for a full list, see the Pharos system documentation: Healthy Building Network 2019a). The system is searchable by chemical names, synonyms and identifiers[4] as well as by keywords indicating product categories and functional use. All data from external resources are integrated or linked in a transparent way, such that users can easily access the sources of cited information.

Besides serving as an up-to-date reference source and knowledge repository, the Data Commons was designed as a practical tool to support CAA. The online system provides rich hazard profiles for chemical substances and classes, and it enables side-by-side comparisons between substances on the basis of hazard. It also provides a screening tool to identify known high-hazard substances based on aggregated information sources. The technical basis for organizing, evaluating, and presenting hazard information is derived from the GreenScreen for Safer Chemicals, an open-source method for chemical hazard assessment developed by Clean Production Action and widely recognized throughout the CAA practitioner community (Heine and Franjevic 2013; Clean Production Action 2020b). GreenScreen's rich underlying technical framework ensures that chemical hazard profiles can be evaluated systematically and compared on an endpoint-by-endpoint basis, making it a valuable standard for CAA. Incorporating elements of the GreenScreen framework into the Data Commons allows the system itself to perform some of the knowledge management and computation work that is involved in applying the GreenScreen method.

Finally, the Data Commons was designed as a place for community interaction around CHA and CAA topics. Discussion forums enable a lively exchange of ideas and expertise,

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[3] "Functional use" refers to functions which a substance may perform in a product or formulation, such as oxidant or plasticizer (Tickner et al. 2015).

[4] Including CAS Registry Number, IUPAC InChI and InChIKey, SMILES, and PubChem CID.

with users posting questions and answers on a variety of technical, policy, and other issues. Discussion posts can be linked to specific chemical substance records, allowing users to "annotate" the information presented in the commons. Collaborative projects intended for community participation also have their own forums. These current forms of community interactivity are a first step toward building a living, community-managed knowledge hub.

2.3 Background and rationale

The Data Commons was driven by the needs of a community of people who practice CHA and CAA. The knowledge users and producers that we refer to as *practitioners* include a range of people with research, design, and decision-making roles in policy, business, and advocacy contexts. They have a variety of professional roles, such as: advocates analyzing chemical production and use; government scientists researching substances or products for regulatory or administrative decision-making; consultants and chemical "profilers" doing background work to support detailed chemical or product sustainability assessments; company staff who manage chemical use in manufacturing and supply chains; and designers researching the material hazards of products and materials.

In consultation with this practitioner community we identified a number of key problems, outlined here, which motivated our efforts to build the Data Commons (Lent, Kokai, et al. 2014).

Knowledge challenges

Historically, many kinds of knowledge that are now recognized as crucial for CHA and CAA have been under-produced, contested, and carefully guarded by industry and governments. This includes scientific data about chemical properties, hazards, human exposures, environmental emissions, and the specific ways that chemicals are used in industry and consumer products. This is partly a result of the public policy and intellectual property regimes operating throughout the 20th century. For a long time, industrial chemical manufacturers had neither requirements nor incentives to test chemicals for toxicity, and they have claimed much of what is known as trade secrets—cutting off the flow of information to the public domain and even to downstream businesses (M. P. Wilson and Schwarzman 2009; Scruggs, Ortolano, et al. 2014). Scientists have found significant gaps in knowledge about chemical hazards and human exposures (Judson et al. 2009; Egeghy et al. 2012), and intellectual property rights continue to obscure much of the regulatory data collected by public agencies (Gilbert 2016; Schwarz and Denison 2018b). Toxicity data may exist for many chemicals but are mainly circulated among industry, private labs, and government agencies. Similarly, information about how chemicals are used—in what products and for what functions—is largely kept confidential or collected only in proprietary databases.

There are many publicly available *sources* of information about chemicals, but also many barriers to their use. One of the project goals was to make these public sources more useful to decision-makers. Individually, each of these sources generally covers only a small proportion of the chemicals in commerce, and each source typically provides only a very limited kind of knowledge (for example: identifying substances associated with one type of health hazard, out of many). Techniques for CAA require practitioners to retrieve and organize many diverse sources and heterogeneous forms of scientific and technical data. Publicly available data sources—such as government lists, databases, and scientific literature—are numerous and appear in an array of digital formats without any consistency. These separate "data silos" are not easily accessible and searchable as a whole. Gathering, transforming, and integrating such information into comprehensive and searchable datasets is tedious and resource-intensive. The underlying data are constantly being updated, making the task a never-ending maintenance process.

A related problem is the lack of standardization and compatibility between information systems, tools, and other resources for chemical alternatives assessment. For example, there are many ways to define and categorize hazards; many ways to describe the functions of chemicals within products or formulations; and different ways to integrate diverse types of data into evaluative frameworks (Harrison and Hester 2013; Jacobs et al. 2016). For non-experts, this makes it difficult to select, interpret, and compare information. In general, inconsistencies between systems make them less interoperable and less cohesive as a toolbox of knowledge resources for CAA (a problem that has led to efforts for "harmonization," for example in the building industry: Heine, Kausch, et al. 2013; Bobenhausen 2016). Similarly, there has been a tendency for database- and tool-building efforts to proliferate rather than converge. For example, multiple organizations have more or less duplicated each other's work in compiling and organizing public chemical hazard information, or producing lists of chemicals of concern—including government agencies, NGOs, product design companies, and firms offering the resulting information resources as for-profit services (Stone and Delistraty 2010; Scruggs 2013).

Examining all these issues in a discussion paper written at the outset of the Data Commons project, we concluded that there was a need for "more efficient, affordable, effective, and consistent" tools for chemical hazard assessment (Lent, Kokai, et al. 2014). The knowledge challenges we have highlighted make CHA and CAA costly and resource-intensive, setting up barriers to safer chemical substitution. If information infrastructure could more thoughtfully and effectively meet the needs of the practitioner community, then these costs and barriers could be reduced.

Chemical hazard data as a commons

We framed our work as building a commons, focusing on how the community of chemical alternatives assessment practitioners can build more effective ways to use, manage, and share knowledge. A commons is a collectively-owned resource, managed or produced by the community of people who also benefit from its use (C. Hess and Ostrom 2007; Bollier 2014). In a science/policy arena that doesn't typically encourage collaboration, the commons invites us to pursue collective solutions. While no single resource can satisfy all stakeholders' knowledge needs, what if many independent resources could interoperate smoothly? What if disparate information sources were linked, eliminating the redundant work of compiling them? What if many sources of data could be understood together under a common framework, enabling more consistent and comprehensive approaches to hazard assessment and alternatives assessment? What if people from a range of historically separate stakeholder groups (such as product designers and NGOs) could collaboratively develop the intellectual and technical capacity to advance CAA?

A commons approach could reinforce the collaborative ethos of the practitioner community. Already, many people and organizations contribute to making knowledge and tools available to support better decision-making about chemicals—and, likewise, many people and organizations benefit from this knowledge. A commons, by design, can harness the collective expertise and effort of many individuals and organizations. In imagining the Data Commons as a participatory and community-driven project, we took inspiration from open-source software commons (Schweik and English 2012) and from numerous contemporary ideas that highlight the generative results of participatory knowledge communities: peer production (Benkler 2006), user-centered innovation (von Hippel 2006), and networked science (Nielsen 2012).

The commons framing also reinforces a widely-held principle central to effective chemicals policy and product stewardship: that information about the toxicity and environmental hazards of chemical substances should be publicly available in reliable and accessible forms (e.g. Guth, Denison, and Sass 2007; Geiser 2014; Lent and Stamm 2019). Put another way, everyone who uses or makes decisions about chemical substances has the *right to know* if there may be health risks, and how to reduce those risks. This principle is enshrined in, for example, the Dubai Declaration on International Chemicals Management (United Nations Environment Programme 2006, p. 9); California's Proposition 65, which was passed by 2/3 of the state's voters in 1986 (OEHHA 2015); and the U.S. Emergency Planning and Community Right-to-Know Act, which created one of the most effective information-based regulatory regimes for pollution prevention (United States Congress 1986; Fung and O'Rourke 2000). There is real and strong demand from a diverse array of stakeholders for relevant and credible scientific knowledge that can inform safer chemical substitution (Scruggs and Ortolano 2011). Finally, chemical hazard information is basic scientific knowledge and arguably should be considered a public good (Stiglitz 1999)—in one way or another, it is part of a global common pool of knowledge that should be available for new science and innovation to build upon.[5]

Project history

The concept of a chemical hazard data commons emerged from the work of participants in a 2012 conference called Building a Chemical Commons, organized by BlueGreen Alliance,

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[5] Indeed, as a result of the work of many research organizations, there is already a much broader information commons of web-enabled chemical data resources, mostly centered on biosciences and computational chemistry fields (for a holistic view, see Murray-Rust et al. 2011).

Clean Production Action, and the Lowell Center for Sustainable Production.[6] These participants included government agency staff, academics, environmental consultants, labor union representatives, consumer product manufacturers, philanthropic funders, and environmental NGOs. One outcome of this conference was the Commons Principles for Alternatives Assessment (BizNGO 2013), a consensus statement of the role of CAA in safer substitution. Subsequently, a Data Commons working group formed to pursue one of three streams of work originating from the conference—the others focusing on developing CAA methods and organizing the community of practice. Healthy Building Network (HBN) secured funding from the Forsythia Foundation to carry out an initial scoping project to explore what it would take to develop a chemical data commons. Begun in 2013, this project resulted in a set of discussion papers (Lent, Kokai, et al. 2014; Lent 2014a; Blake 2014; Lent 2014b; Kokai, Lent, and Dedeo 2014). HBN has since led the development of the Data Commons, supported by the funding sources listed at the end of this article.

Initial development of the Data Commons' web and data infrastructure by HBN began after collecting feedback on the discussion papers (Healthy Building Network 2014a; Healthy Building Network 2014b). In 2016–2017, HBN invited 175 participants to join a pilot project in which they could use an early development version of the Data Commons and give feedback through a community survey (Healthy Building Network 2016). The systems and data were then developed continuously, with ongoing use and testing by this initial group. In 2017, the commons was opened to the public; development has continued since then. Approximately 1500 users registered before the Data Commons was merged into the Pharos Project, which itself has several thousand users.

2.4 Design of the Data Commons

We aimed to overcome pervasive "information silos," enable simultaneous access to many different sources of information, and facilitate more effective user interactions with those combined sources. Foremost among these interactions are: search and retrieval of relevant chemical hazard information; clear and succinct display of the information most relevant to hazard assessment; and the ability to automatically screen a substance—or many substances simultaneously—against consistent and transparent hazard-based criteria. Furthermore, the system would have to be broadly accessible to a wide range of users, participatory, and able to sustain a community.

Hazard as an organizing principle

Organizing principles dictate how resources—such as data and visualized information—are intentionally arranged to enable particular kinds of interactions (Glushko 2013). For example, chemical identity is an organizing principle of chemical information systems, meaning

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[6] The conference was organized by Charlotte Brody (BlueGreen Alliance), Mark Rossi (Clean Production Action), and Joel Tickner (University of Massachusetts, Lowell Center for Sustainable Production).

that those systems may enable retrieving, categorizing, and comparing information by substance.[7] Chemical hazard is an organizing principle of the Data Commons information system. This is fundamental to how it can support CAA, and sets it apart from other public information systems in the domains of chemistry, sustainability, and environmental health sciences.

Hazard—the potential for a chemical substance to harm human or environmental health—encompasses multiple "endpoints" (outcomes) for a variety of species and systems. Accordingly, information system design should reflect this complexity (Lavoie et al. 2010; Whittaker and Heine 2013; Jacobs et al. 2016). At the same time, the system should make indicators of hazard understandable for users with a range of expertise in CHA. For example, users should be able to distinguish between chemicals of high, moderate, and low concern; they should be able to tell why substances may be of concern (i.e. for what hazard properties and endpoints) and based on what specific evidence. Furthermore, users should be aware of uncertainties and gaps in the evidence of hazard. In other words, the system should provide varying levels of data interpretation, using consistent and transparent methods.

Realizing this design calls for a number of elements: a taxonomy of hazard endpoints, systematic ways to evaluate and represent the severity of hazard and the strength of scientific evidence across endpoints, and ways of classifying the overall level of hazard for a substance. Several existing chemical assessment frameworks provide these elements: the GreenScreen for Safer Chemicals (Clean Production Action 2020b), the Globally Harmonized System (United Nations 2019), the US EPA Safer Choice Criteria (US Environmental Protection Agency 2012), and the Cradle to Cradle Certified Material Health Assessment Methodology (Cradle to Cradle Products Innovation Institute 2019). These frameworks are comparable and interrelated, but we chose to adopt the GreenScreen as an underlying organizing system for hazard data.[8] The taxonomy of hazard endpoints is shown in Table 2.1. GreenScreen was selected for its "open-source" and peer-reviewed technical methodology; evaluative system that provides substance-level and endpoint-level indicators of hazard; and widespread adoption across government, industry, research, and advocacy communities—especially in our practitioner community. Furthermore, GreenScreen includes a widely used protocol called the GreenScreen List Translator (GSLT), for identifying high-hazard substances based on information from authoritative lists, such as those included in the Data Commons (Table 2.2).

The GreenScreen framework became the information infrastructure that shaped the Data

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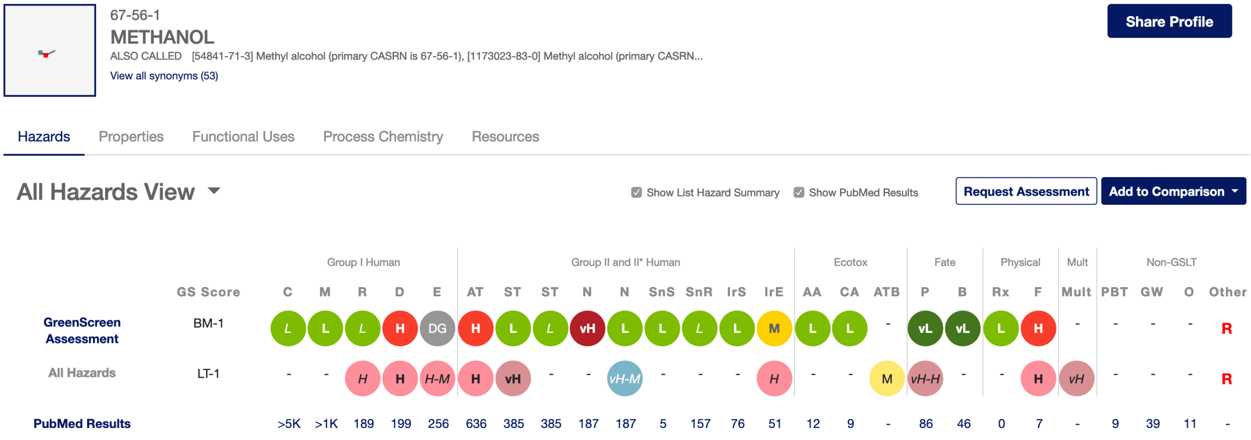
[7] This seemingly self-evident principle conceals a complex and historically contingent answer to the question of what makes "one" substance unique (Hepler-Smith 2019). The Data Commons identifies chemical substances using Chemical Abstracts Service Registry Numbers (CASRN), PubChem Compound identifiers (CID) (S. Kim et al. 2016), SMILES molecular representations (Weininger 1988), and IUPAC International Chemical Identifiers (InChI) (Heller et al. 2013).

[8] In principle, the commons could have been designed to use multiple hazard classification and evaluation frameworks in tandem. Using the same set of hazard data, the system could translate between frameworks to accommodate user preferences. The Pharos Project currently takes this approach, allowing users to choose between multiple "views" of hazard information.

Commons' selection, organization, interpretation, and visual display of hazard data. Each substance profile presents an interactive hazard summary table (Figure 2.1) that shows an overall substance-level hazard score, as well as the endpoint-specific indicators that underlie that substance-level score. The endpoint-specific indicators use consistent visual conventions to communicate characterizations of hazard levels, data availability (or data gaps), and strength of evidence. If a full GreenScreen assessment is publicly available for the substance, then its results are shown, including the GreenScreen Benchmark score (a roll-up of the full assessment). If there is no public full assessment, then the table shows endpoint-specific hazard levels determined from authoritative public data sources using the GSLT protocol, as well as the overall GSLT score for the substance. Extending this paradigm to enable more useful interactions for CAA practitioners, the Data Commons also provides a hazard comparison tool. Users can create, share, import, and export customized sets of substances for automated screening and side-by-side comparison—the hazard profiles are displayed together in a matrix that enables comparative analysis of safer alternatives and data gaps (Figure 2.2).



67-56-1

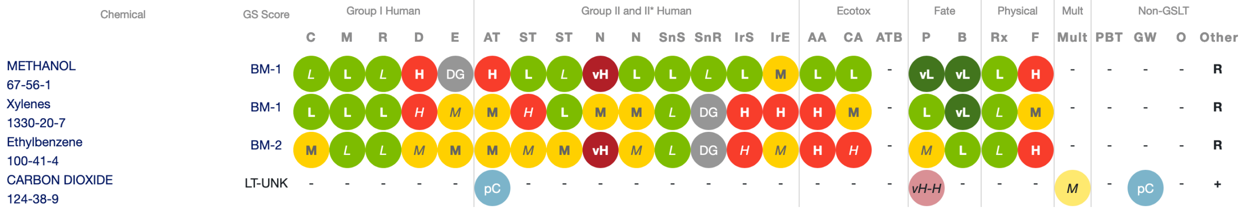
METHANOL

ALSO CALLED [54841-71-3] Methyl alcohol (primary CASRN is 67-56-1), [1173023-83-0] Methyl alcohol (primary CASRN...

View all synonyms (53)

		Group I Human					Group II and II* Human									Ecotox			Fate		Physical		Mult	Non-GSLT			
	GS Score	C	M	R	D	E	AT	ST	ST	N	N	SnS	SnR	IrS	IrE	AA	CA	ATB	P	B	Rx	F	Mult	PBT	GW	O	Other
GreenScreen Assessment	BM-1	*L*	L	*L*	H	DG	H	L	*L*	vH	L	L	*L*	L	M	L	L	-	vL	vL	L	H	-	-	-	-	R
All Hazards	LT-1	-	-	*H*	H	*H-M*	H	vH	-	-	*vH-M*	-	-	-	*H*	-	-	M	*vH-H*	-	-	H	*vH*	-	-	-	R
PubMed Results		>5K	>1K	189	199	256	636	385	385	187	187	5	157	76	51	12	9	-	86	46	0	7	-	9	39	11	-

Figure 2.1: Hazard summary table displayed in the Pharos substance profile for methanol



Chemical	GS Score	Group I Human					Group II and II* Human									Ecotox			Fate		Physical		Mult	Non-GSLT			
		C	M	R	D	E	AT	ST	ST	N	N	SnS	SnR	IrS	IrE	AA	CA	ATB	P	B	Rx	F	Mult	PBT	GW	O	Other
METHANOL 67-56-1	BM-1	*L*	L	*L*	H	DG	H	L	*L*	vH	L	L	*L*	L	M	L	L	-	vL	vL	L	H	-	-	-	-	R
Xylenes 1330-20-7	BM-1	L	L	L	*H*	*M*	M	*H*	L	M	M	*L*	DG	H	H	H	M	-	L	vL	*L*	M	-	-	-	-	R
Ethylbenzene 100-41-4	BM-2	M	*L*	*L*	*M*	M	M	*M*	M	vH	*M*	*L*	DG	*H*	*M*	H	*H*	-	*M*	L	*L*	H	-	-	-	-	R
CARBON DIOXIDE 124-38-9	LT-UNK	-	-	-	-	-	pC	-	-	-	-	-	-	-	-	-	-	-	*vH-H*	-	-	-	*M*	-	pC	-	+

Figure 2.2: A hazard comparison table in Pharos

Incorporating functional use

Knowing the specific technical role or purpose a substance serves in a material, product, or manufacturing process is essential for identifying feasible technological alternatives (Tickner et al. 2015). We aspired to provide well-organized functional use information alongside hazard information in the Data Commons. However, the CAA practitioner community lacks a standard for describing or categorizing the functional uses of chemicals. Instead, we found that there are many diverse and incommensurate systems for categorizing functional uses, including industry-specific vocabularies and regulatory classification systems (Blake 2013; Blake 2014).

In the Data Commons, we understand functional use as determined by varying sets of chemical properties in a wide range of technological contexts, for which no single overarching classification system is necessarily appropriate. For example, researchers at the US EPA integrated many sources of data on chemical ingredients in consumer products to produce CPDat, a database that links thousands of chemicals to a harmonized set of functional use categories (Dionisio, Phillips, et al. 2018). While CPDat provides an excellent source of information (and is used in the Data Commons), it still emphasizes certain consumer product sectors and therefore certain types of functions—is not a "universal" classification system for functional use. For functional use descriptors, we therefore adopted a tagging-based system that is able to include terms from many data sources (see Table 2.3) even if they are based on conceptually disparate systems. This is in contrast to how hazard is understood, where the use of a single classification system enables consistent comparisons.

Compiling and linking data

Rather than serving as a container of information, the Data Commons was designed as a portal that makes accessible information from many sources. Using the paradigm of linked data (Heath and Bizer 2011), the system consumes and integrates data from several high-quality open chemical data sources and provides links for users to navigate directly to specific records in the source systems. This allows the system to tap into a rich, distributed landscape of chemical information without reproducing the work or taking on the costs of providing and maintaining all of that information directly. Examples of linked data sources are included in Table 2.4. For example, physical property data and molecular structure graphics displayed in the Data Commons are drawn from PubChem. Hazard summary tables include linked scientific literature searches for each specific substance-endpoint combination via PubMed, showing the number of hits and enabling users to instantly delve into the search results (see Figure 2.1). Because these elements are dynamically generated, they are always up-to-date in relation to the resources they reference.

Yet, much of the publicly available information relevant for CAA cannot easily be collected from open data sources. A central part of the Data Commons was borrowed from (and is still part of) HBN's Pharos project: the Chemical and Material Library (CML), which compiles and cross-references hazard associations from authoritative public-domain sources such as those in Table 2.2 (for full documentation, see Healthy Building Network 2019a). This compilation takes substantial effort: HBN curates and regularly updates the library from government and scientific sources that encompass a great variety of original publication formats.

Leveraging open standards and frameworks

Open standards and frameworks play important roles in CAA: promoting consistency in how science is used to inform decisions, and ensuring mutual compatibility of work products and practices in the field. The Data Commons was designed to both leverage and reinforce open standards to support CAA. Two notable examples are the GreenScreen for Safer Chemicals (discussed above) and the Health Product Declaration (HPD). HPD is an open standard for disclosure and communication of the material content and associated hazards of building materials (HPD Collaborative 2020a), which has been instrumental in extending material hazard considerations into sustainable design in the building sector. As detailed above, the Data Commons employs GreenScreen to organize information; but it also helps to operationalize the GreenScreen method by automatically computing the GSLT score for any chemical. This is possible because the system integrates all of the data sources that the GSLT protocol requires for hazard evaluation. Similarly, the Data Commons was designed to support the use of HPD by integrating all "priority hazard lists" referenced in the hazard screening component of the standard, thus giving manufacturers and designers the ability to instantly evaluate chemical and product hazards as specified by the standard.

In collaboration with Clean Production Action, the Data Commons has also contributed to new standards intended to make list-based hazard screening more consistent, including standards for updating screening list databases and for interpreting the hazard properties of groups and classes of chemicals.[9]

Community engagement and knowledge sharing

When we first articulated the idea of the Chemical Hazard Data Commons, we understood it as "both a tool-building project and a community-building project" (Lent, Kokai, et al. 2014). A global community of experts and practitioners was already engaged in collective work to make chemical information actionable for CAA. For example, organizations in North America and Europe—such as ChemSec and the Business-NGO Working Group for Safer Chemicals and Sustainable Materials—were already working to advance CAA across government, business, and advocacy sectors. The role we envisioned for the Data Commons was to link this community together with shared and interactive resources that filled key knowledge needs.

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[9] For example, the GreenScreen List Translator automator update policy (Clean Production Action 2017) and the GreenScreen chemical groups policy (Clean Production Action 2018a; Healthy Building Network 2020a).

In an effort to build the commons, we engaged an initial core group of people who expressed high interest in the project goals, sought to create opportunities for knowledge sharing and collaboration, and set up a basic framework for fostering and governing community interactions. We reached out to professionals located primarily in the US and Europe, and representing approximately 40 organizations in the following sectors: (1) government agencies involved with chemical assessment, regulation, or public chemical information services; (2) NGOs and labor unions active on environmental health issues; (3) academic institutions; (4) firms and independent consultants in the chemical hazard assessment consulting sector; and (5) companies in the manufacturing and retail sectors. Throughout the development of the Data Commons, over 50 community members had direct input into the design and priorities of the commons at the scoping stage via discussions, interviews, and written comments on the discussion papers (Healthy Building Network 2014a; Healthy Building Network 2014b). Over 100 community members helped to shape the early development of the web system through their responses to a detailed online survey, pilot testing, and participation in the development of the infrastructure (Healthy Building Network 2016). The resulting system design reflected our thinking and the feedback we received from participants.

We included online discussion forums, intending for these to facilitate knowledge sharing among the commons participants who have diverse professional backgrounds; they include chemists, toxicologists, and environmental health scientists, but also engineers, public health practitioners, civil servants, architects, and industrial designers. Given this heterogeneity, simply inviting open discussion among participants seemed like a good starting point. Discussion threads are organized into broad categories of topics and tagged with detailed topic descriptors, and they can be linked to specific substance data records.

Actively facilitating and coordinating collaborative efforts among participants was a more ambitious design goal. Such efforts could include working together on new knowledge resources or collectively evaluating scientific evidence about chemical hazards. Designing systems to foster direct collaboration between participants remains a priority for future development of the commons. Still, we did include some elements (currently included in Pharos) that were intended to provide opportunities for collaborative work. For example:

- Substance comparison sets can be shared—publicly or among limited groups—for collaborative curation, discussion, or CAA work.
- Discussion forums include special sections dedicated to ongoing collaborative projects.
- Participants can signal their demands for full GreenScreen assessments of particular chemicals by clicking a "Request Assessment" button, which allows the system to aggregate community interest in developing new knowledge.

Governance

According to David Bollier (2014), "a commons is *a resource + a community + a set of social protocols.*" Social protocols are what govern the processes of sharing and management through which the commons can provide ongoing benefits to the community (Frischmann, Madison, and Strandburg 2014b). We made several key decisions about these social protocols, or the governance of the commons.

In the Data Commons, governance relates to what participants *bring in.* To the extent that anyone can actively contribute knowledge, ideas, and discourse, they have an influence on what others can take away from the commons. We identified two potential problems[10] to which the Data Commons could be vulnerable: false contributions of knowledge, such as misleading claims or inaccurate data; and discourse that seeks to undermine the goals, methods, or practices of CAA. Both of these problems have precedents in the often contentious public discourse around chemical safety and risk.

Whereas CAA seeks to reduce harm by substituting toxic substances with safer alternatives, the dominant industry and government discourse in chemicals policy is based on the idea of acceptable risk—a notion that emerged as a compromise between industry interests and public health protection in the conflicted history of environmental policy-making (Boyd 2012). As exemplified by contemporary controversies about substances like bisphenol A and glyphosate, representatives of the chemical industry have historically used scientific discourse to advocate for the use of data, technical criteria, and assumptions that make health risks seem more acceptable (Vogel 2009; Montenegro de Wit and Iles 2015). The science and methods of CAA appear to be under scrutiny from advocates of risk-based approaches (Palmer 2016). For example, after the publication of the Commons Principles for Alternatives Assessment (BizNGO 2013), a coalition of industry advocates created their own competing set of completely different principles a year later (American Chemistry Council 2014). It was reasonable to anticipate that the participatory features of the Data Commons could also be used to undermine the goals of safer chemical substitution.

To address these potential problems, we instituted the following basic governance mechanisms, which set boundaries on what kinds of knowledge and discourse can be contributed to the commons and expectations about how people should conduct themselves as participants.

- A Code of Conduct (COC), which all participants must agree to (Healthy Building Network 2019b). The COC provides guidelines for how community members should participate, and a standard to which community members can hold each other (see below). It also defines sanctions that can be brought against participants who violate the code, as well as an appeals process.

- Terms of Service (TOS), which contain official rules and the consequences of breaking them in precise legal language (Healthy Building Network 2019c). These rules may be invoked in cases of clear and severe breach of the community guidelines set out in the COC.

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[10] Beyond these specific problems, any system on the internet is vulnerable to more general problems like spam (unwanted content) and intellectual property liabilities (e.g. a user posts the entire text of a copyrighted article in a comment).

- Technical systems and requirements to support the social protocols set out in the COC and TOS. Site registration is required before contributing content, enabling the commons administrators to identify and address any offenses. Users with administrative privileges also have control over contributed content.

The norms and guidelines expressed in the COC represent what we viewed as reasonable basic principles that our community would readily accept and abide by—such as being considerate, respectful, constructive, and avoiding advertising or political campaigning. The COC generally posits that the Data Commons should be used for reasoned discussion of science pertaining to CAA, and codifies those concepts via a mission statement and conflict of interest (COI) guidelines. The mission statement links the goals of the Data Commons to the concepts of hazard assessment and alternatives assessment, and Data Commons participants are asked to recognize and support it:

> The mission of the Chemical Hazard Data Commons is to advance science, policy, and business efforts to identify hazardous substances through chemical hazard assessment and find safer substitutes through alternatives assessment. We aim to do this by developing community-accessible tools and information resources. Your engagement in this project should be grounded in your support of these goals. (Healthy Building Network 2019b)

Establishing a shared understanding of the meaning and value of these concepts addresses the contested nature of the field of alternatives assessment as a science/policy field. While the Data Commons community thrives on open, constructive criticism of methods and science, we wanted it to be clear that actively undermining these goals is an unwelcome form of participation.

The COC also asks participants to be transparent about potential COI. A COI may arise when someone contributes to the Data Commons on a topic that has bearing on their own financial interests or those of their affiliates. We did *not* seek to discourage participants with COI from contributing, because there are potential COI situations where participation would still be highly valuable—for example, users who work with companies seeking to commercialize safer substances and products. Rather, we ask for awareness and transparency of COI so that the community can understand the full context of all the information in the commons.

2.5 Discussion

The design considerations and development process reported here represent our efforts to plan, initialize, and formally constitute a knowledge commons for chemical hazard assessment. Although this is still a partially realized and evolving project, it has already produced a valuable public resource at the same time as it has surfaced some important challenges and limitations.

Outcomes

Feedback from a wide range of Data Commons participants indicates that the project has yielded a valuable and novel public resource. By enabling easy access and reference to the most commonly needed information and tools, the Data Commons benefited practitioners across the field of chemical alternatives assessment. It was the first open-access system to link information about chemical substances with hazard properties in a consistent way—thus facilitating direct comparisons between substances on the basis of hazard—and also to link substances to functional use classifications. The development of the Data Commons provided two particularly useful functions for chemical assessors: automated chemical screening using the GreenScreen List Translator protocol, and hazard-based comparisons. Having free access to these resources has been particularly helpful for public-sector and civil society organizations, small enterprises (such as environmental consultants), and educational institutions, because they may not have access to equivalent paid services. Several academic and NGO research projects have reported using the Data Commons as a resource. It has also helped green chemistry education: for several years, students at the University of California, Berkeley have used the Data Commons (and Pharos) to learn and carry out CAA in real applied projects (Schwarzman and Buckley 2019).

Moreover, participants can join or interact with a community of practice, and keep themselves updated on developments in the community or broader field. The Data Commons has hosted a variety of discussions and debates in an open forum—now continued in Pharos. Some of our participants have noted that the Data Commons consolidated, and in some cases replaced, previous informal person-to-person channels for knowledge sharing. One of the collaborative efforts initiated in the Data Commons—the systematic identification of substances belonging to known hazardous chemical classes, mentioned above—became a significant and thoroughly-debated ongoing project involving multiple organizations (Healthy Building Network 2020a). To date, HBN staff have collaborated with various organizations to integrate findings from their projects into the commons, making participants among the first to benefit from the work. This has resulted in new information resources being incorporated into the system, such as data about chemicals found in plastic packaging materials (in collaboration with Food Packaging Forum: Groh et al. 2018) and hard-to-find regulatory agency documents obtained via FOIA requests (in collaboration with the Natural Resources Defense Council).

Challenges

The experimental participatory project begun by the Data Commons leaves many opportunities for advancement, and its development faced a number of challenges—particularly in the areas of fostering participation and collaboration, and planning for long-term governance and viability.

Participation and collaboration

Ideally, the Data Commons could productively harness some of the community's attention, directing a little effort from many participants toward collective tasks. The commons is designed to do this by enabling multi-directional interactions like commenting on resources, asking and answering questions, or contributing to open projects. However, as a new entrant into the field of tools and collaborative practices for chemical alternatives assessment, the commons faced a paradox in which potential participants would be more likely to engage if there were already more engaged participants. Even after several years, most participants seemed to prefer using the Data Commons as a tool rather than to interact with others in an active exchange. Providing tools was indeed one of the goals of the commons, but it does not reflect the full participatory ambition of the project.

Another part of the aspirational vision of the Data Commons was to aggregate community expertise to accelerate progress on shared goals—such as improved CAA tools, methods, and data. We imagined, for example: collaboratively-authored summaries of scientific studies on substances of interest, or community peer-reviewed methods for filling data gaps in chemical assessments. The CAA community already engages in a number of collaborative efforts, such as tackling shared methodological problems.[11] We hoped to extend collaborative practices into the realm of data. There are many excellent precedents for collective work in knowledge commons, such as open-source software (Schweik and English 2012), Wikipedia (Benkler 2006), and new scientific research practices that Nielsen (2012) refers to as "networked science." For these networked efforts to be successful, there must be self-sustaining participatory systems that efficiently direct the attention and expertise of participants where it is most needed and best matched to their individual interests and skills. For example, very large projects can be coordinated through modular organization, or incrementally accomplished through many accumulated "microcontributions"—also known as crowdsourcing (Nielsen 2012).

Initializing active collaborations in the Data Commons has been challenging, and crowdsourcing of data resources has generally not occurred. For example, an earlier version of the Data Commons included a shared library of scientific citations and public domain documents to which users could contribute—but few did, and it was eventually discontinued. Two main factors may explain these challenges. First, the commons has not yet evolved sufficiently effective mechanisms to harness the attention and efforts of the community. We could have actively guided and facilitated engagement, which would have come with significant organizational and resource demands on HBN. Instead, we relied to a large extent on the online platform itself to foster participation. But discussion forums enable only a limited form of interaction, whereas coordinating the collaborative review of a dataset (for example) may require dedicated staff time and far more specialized software tools. In other words, the design and implementation of the participatory infrastructure is still incomplete. Second, there may not be sufficient incentives or appropriate opportunities for participants to get more involved. For example, prospective participants may feel that a project's possible out-

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[11] For example, through formally organized working groups consisting mostly of volunteer participants.

comes are not worth their time, that it could get done anyway without their input, or that they can't participate because the project is too technically demanding. Ideal collaborative projects would be those that present a compelling shared benefit and that are easy for many participants to contribute to. Identifying such projects should be a priority for future development of the commons.

Creating a hazard assessment commons

One hope was that the Data Commons could aggregate community resources by producing and distributing a significant number of new GreenScreen hazard assessments. A GreenScreen assessment is a highly valuable work product requiring considerable toxicological knowledge and effort. The vast majority of GreenScreen assessments is produced by a handful of companies with vetted expertise and capacity (Clean Production Action 2020e). Many of these chemical profilers are part of the Data Commons user community, and there was a considerable level of interest in leveraging the commons to "scale" CHA practice.

Nevertheless, facilitating the commons-based production of chemical hazard assessments remains a significant challenge. First, CHA is highly demanding work regardless of the resources provided by the Data Commons. It requires dedicated professional effort and associated expenses. Second, to recover the high costs of CHA, profilers restrict the redistribution of their work using copyright. These intellectual property arrangements are in tension with the commons-based intention to pool assessments for collective re-use—and more generally with the open access goals of the Data Commons project. Some profiler organizations, ToxServices and NSF International, have collaborated to release a limited number of assessments into the public domain, but they cannot be expected to make all of their work freely available.

One approach for creating a common pool of chemical assessments is to abandon open access and switch to a more limited form of sharing that is supported by subscription fees. A newly emerging project, ChemForward (ChemForward 2020), is pursuing this strategy. Another approach is to generate an open-access pool of assessments by funding profilers to work on a set of substances regarded by the community as high priority for assessment. This approach has not been realized, but still holds promise given the high financial stakes of new chemicals regulations (e.g. California Department of Toxic Substances Control 2020b) that may require industry to switch to safer alternatives for certain substances in major product categories.

Long-term governance

Another challenge to be faced by the Data Commons is its governance and maintenance in the long term. Part of the rationale for creating a Data Commons was that no single organization could support all of the information needs of the community. Yet, due to the particular circumstances of organizational capacity and philanthropic funding streams, there is currently a single organization (namely the Healthy Building Network) endeavoring to manage and sustain the commons. One consequence of this is that the project has been conceived and executed largely in a US-centric context, privileging Anglophone resources and audiences despite the global nature of the broader community.

At a minimum, sustaining the Data Commons involves development and maintenance of essential infrastructure (software, servers, databases, etc.), financially supporting a free public-access resource, and providing a basic level of coordination for the affairs of the community (e.g., assigning administrative privileges and duties to volunteers). These responsibilities could in principle be shared among a group of organizations and individuals, but there are currently no arrangements for allocating or distributing them in the long term. Likewise, the challenge of long-term financial support may require shifting from philanthropic funding models to community contributions or other models.

2.6 Conclusions

We developed the Chemical Hazard Data Commons to fill a need for public information infrastructure to support chemical alternative assessment practice. More fundamentally, we developed the Data Commons as an experiment in collective capacity-building for safer chemical substitution—as an alternative to continued reliance on regulatory and market drivers to furnish this information infrastructure.

The design of the Data Commons considers how chemical hazard information should be organized so that it can be retrieved and used in meaningful ways, particularly through the lens of frameworks and standards prevalent in the practitioner community. These design considerations contributed to the development of new tools and functions based on aggregated and linked data. The commons was also designed to enable interactions among community members, with the aspirational goal of facilitating rich multi-directional flows of knowledge among a diverse set of producers and users of chemical hazard information.

This development process represents a novel application of a collaborative, commons-based approach, and the first effort to create an open, participatory information infrastructure for CAA. In an arena where decades of adversarial policymaking and activism around toxic chemicals have led to intense contestation of scientific knowledge, the Data Commons approach emphasizes the value of shared information resources and collective capacity-building.

The development of the Data Commons, now merged into the ongoing Pharos Project, has yielded an open-access resource available online at https://pharosproject.net/. The commons exists for members of a global community interested in CAA, and serves as a tool and a space for exchanging knowledge and expertise. We welcome participation in the commons itself, as well as constructive criticism of our efforts to design and formally constitute the commons. While this project is unlikely to singlehandedly solve most of the problems that motivated it, we hope that it will not be the last of its kind. We present our work, and the challenges we encountered, so that our experience may benefit future efforts.

Table 2.1: Taxonomy of hazard endpoints used in the Chemical Hazard Data Commons

Grouping	**Endpoints**
Group I human	Carcinogenicity
	Mutagenicity
	Reproductive toxicity
	Developmental toxicity
	Endocrine activity
Group II human (single exposure)	Acute mammalian toxicity
	Systemic toxicity/Organ effects, single exposure
	Neurotoxicity, single exposure
	Eye irritation
	Skin irritation
Group II* human (repeated exposures)	Systemic toxicity/Organ effects, repeated exposures
	Neurotoxicity, repeated exposures
	Respiratory sensitization
	Skin sensitization
Ecotoxicity	Acute aquatic toxicity
	Chronic aquatic toxicity
	Terrestrial ecotoxicity
Physical hazard	Flammability
	Reactivity
Environmental fate	Persistence
	Bioaccumulation
	Persistent bioaccumulative toxicants (PBT)
	Global warming Ozone depletion

Table 2.2: Representative chemical hazard and restricted substances information sources included in the Chemical Hazard Data Commons

Title	**Hazard endpoints**	**Source**
GreenScreen hazard assessments	All	Various (primary sources)
IARC Monographs on the Evaluation of Carcinogenic Risks to Humans	Carcinogenicity	International Agency for Research on Cancer
IRIS Carcinogen assessments	Carcinogenicity	US Environmental Protection Agency, Integrated Risk Information System Database (IRIS)
EU Priority Endocrine Disruptors	Endocrine activity	European Commission, EU Community Strategy for Endocrine Disruptors
AOEC Exposure Codes - Asthmagen List	Respiratory sensitization	Association of Occupational and Environmental Clinics
EU Scientific Committee on Consumer Safety - Fragrance Allergens	Respiratory sensitization	European Commission
GHS classifications published by national-level agencies	Multiple endpoints	Multiple sources, including the European Chemicals Agency and the Governments of Japan, Denmark, New Zealand, Korea, Malaysia, and Australia
Stockholm Convention - Persistent Organic Pollutants	PBT	United Nations Environment Programme, Stockholm Convention on Persistent Organic Pollutants
IPCC Global Warming Chemicals	Global warming	Intergovernmental Panel for Climate Change (IPCC) Third Assessment Report (2001)

Table 2.2: Representative chemical hazard and restricted substances information sources (continued)

Title	**Hazard endpoints**	**Source**
Ozone-Depleting Substances (ODS) Class I & Class II	Ozone depletion	US Environmental Protection Agency
Substitute It Now (SIN) List	Multiple endpoints	International Chemical Secretariat (ChemSec)
Substances restricted under REACH	Multiple endpoints; Restricted substances list	European Chemicals Agency
RoHS Annex II	Restricted substances list	European Commission

Table 2.3: Representative sources of functional use information included in the Chemical Hazard Data Commons

Title	**Source**
CosIng Cosmetic Ingredient Database	European Commission
REACH Registered Substances: Article Categories	European Chemicals Agency
Hazardous Substances Databank (HSDB)	US National Institutes of Health
Safer Chemical Ingredient List (SCIL)	US Environmental Protection Agency
US EPA Registered pesticides	US Environmental Protection Agency
Chemical and Products Database (CPDat)	US Environmental Protection Agency
HBN Common Products Database	Healthy Building Network

Table 2.4: Representative linked data sources included in the Chemical Hazard Data Commons

Title	**Source**	**Type of data**
PubChem	US National Institutes of Health	Physical properties, molecular structure graphics
ChemIDplus	US National Institutes of Health	Physical properties, synonyms
Hazardous Substances Data Bank	US National Institutes of Health	Literature summaries
PubMed	US National Institutes of Health	Literature search results
CompTox Chemistry Dashboard	US Environmental Protection Agency	Synonyms, database IDs
ToxCast Dashboard	US Environmental Protection Agency	Toxicity data
Toxics Release Inventory	US Environmental Protection Agency	Pollution and waste (USA)
REACH Registration Dossiers	European Chemicals Agency	Manufacturer-submitted data (EU)
OECD eChemPortal	Organisation for Economic Co-operation and Development	Various
International Toxicity Estimates for Risk (ITER)	Toxicity Excellence for Risk Assessment (TERA)	Toxicity data

Chapter 3

Emerging commons: Socially robust knowledge in green chemistry?

In the challenging context of chemical governance and technological sustainability transitions, many constituents are advocating for "green chemistry" approaches that involve substituting toxic substances with safer alternatives. A broad array of scientists, NGOs, businesses, and public administrators are increasingly intervening in the contested field of regulatory science and chemical knowledge. As they grapple with how to advance green chemistry and safer chemical substitution, they are engaging with collective knowledge challenges: establishing and defending new practices such as chemical hazard assessment; sharing data and expertise across institutional and organizational boundaries; and finding alignment among actors with diverse interests. By following an extended peer community engaged with these challenges, I argue that a multifaceted knowledge commons is emerging through their interrelated efforts to understand chemical hazards and how to reduce them—although it is nested within dominant information infrastructures and intellectual property regimes. I present a case study of a knowledge commons based on GreenScreen, an open-source methodology for chemical hazard assessment. I ask whether, and how, this emerging commons can function as a stable site for producing socially robust knowledge, and how the commons may become legitimate and authoritative—both for its own participants and for external actor groups. How the processes of "commoning" play out in the contested chemicals policy arena is of great interest for efforts to develop knowledge commons that are motivated by other socially complex environmental issues.

3.1 Introduction

The problem of "regrettable substitution" demonstrates the fallibility of existing science and policy systems for controlling toxic substances (Zimmerman and Anastas 2015). For example, in California, automotive break cleaner products once contained chlorinated solvents;

although they were introduced as a replacement for ozone-depleting CFCs (US Environmental Protection Agency and ICF Consulting 2004), they generated hazardous waste and formed dioxins in the environment. Regulators banned these products in the 1990s, and the industry switched to an alternative solvent mixture that ultimately harmed many auto repair workers by permanently numbing and weakening the muscles in their limbs (M. P. Wilson, Hammond, et al. 2007). This neurotoxic blend was later phased out in the early 2000s and replaced with a substance that can cause cancer and reproductive toxicity (California Department of Health Services 2004). Policy-makers, environmental health advocates, product designers, and business managers are increasingly recognizing that to avoid these types of regrettable substitution requires decision-makers to better understand the hazards of chemicals and their potential alternatives (Scruggs 2013; Geiser 2015). To enable the informed substitution of toxic substances with safer alternatives, these actors need knowledge of the human health and environmental hazards of chemicals, as well as techniques to integrate hazard information into practical decision-making contexts. Enabled by the techniques of chemical hazard assessment (CHA) and chemical alternatives assessment (CAA) (Lavoie et al. 2010; Harrison and Hester 2013; National Research Council (US) 2014), safer chemical substitution can be part of a proactive approach to break through the "inertia" of chemicals policies that have lagged in identifying and controlling hazardous substances (Krimsky 2017).

However, scientific knowledge about the environmental health effects of chemicals is not always available and does not always provide the advice needed for safer chemical substitution. Extensive STS research on chemicals policies has examined "regulatory science"—the norms, procedures, and information infrastructures that government agencies, scientists, and regulated industries have developed to politically legitimize highly uncertain and indeterminate scientific knowledge (Jasanoff 1990; Boudia and Jas 2013; Boudia and Jas 2014). Regulatory knowledge systems privilege establishing direct, isolated relationships between health effects and individual molecular substances, industrial activities, or polluted localities—while they overlook much of the complexity of chemical life cycles (Boudia, Creager, et al. 2018; Hepler-Smith 2019). The processes and politics of regulatory science have led to chemical knowledge being unevenly produced and unevenly distributed (M. P. Wilson and Schwarzman 2009; Scruggs, Ortolano, et al. 2014), as well as being vulnerable to deconstruction in endless debates among competing interests. As a result, decision-makers face considerable practical challenges in obtaining, evaluating, and operationalizing information about chemicals and their health impacts.

In contrast with this pattern of destructive interference by competing interests, some stakeholders are beginning to engage in collective efforts to generate and mobilize knowledge for creating safer products and materials. Multi-stakeholder collaborative initiatives, such as the Chemical Hazard Data Commons (Chapter 2), are explicitly taking on the goal of providing shared knowledge resources for a growing community of CHA and CAA practitioners. At the same time, this community is producing a heterogeneous network of chemical substitution resources—such as chemical assessment methodologies, open standards, and databases—each building on the others' efforts. I argue that a knowledge commons is emerging around the science and practices of CHA through the efforts of multiple varied actors. A knowledge commons refers to a system of collective production or management of knowledge shared among a community (C. Hess and Ostrom 2007; Frischmann, Madison, and Strandburg 2014a). The commons could provide significant opportunities to generate new knowledge that existing regulatory systems have failed to produce. But given the complexities and contentious politics of chemical toxicity, how can this CHA commons effectively produce knowledge that both meets the needs of chemical substitution decision-makers and is accepted as valid by a wide range of stakeholders?

The concept of socially robust knowledge (SRK) may help elucidate processes of knowledge production in domains that are politically contested, like chemical hazards. According to Nowotny, Scott, and Gibbons (2001), knowledge is socially robust if it is accepted as valid and authoritative by multiple, diverse constituencies. Nowotny (2003) suggests that social robustness is about processes: it is made possible by the real-world testing and iterative modification of knowledge, and by the participation of an "extended" peer group that encompasses many different kinds of expertise in an ongoing dialogue. With many critical environmental issues mired in intense "scientized" public debate (climate change being a prime example), science that has actually been tested and agreed upon by diverse societal actors could be a critical, but missing, foundation for reasoned collective action. In contrast to regulatory science, SRK would seem to provide a way out of the endless political arguments over chemical risks, potentially helping to resolve the political choices and value judgments underlying how to interpret toxicological and epidemiological data (Fernández Pinto and Hicks 2019, see also Chapter 4). It may also crystallize greater pressure on governments to intervene with regulation and on industry to make chemicals and materials that are truly safer.

How could emerging forms of CHA knowledge—which aim to make safer chemical substitution possible—become socially robust? Their participatory institutions, real-world contexts, and interactive processes suggest that knowledge commons may be sites for the production of socially robust knowledge. The chemical knowledge domain is a particularly good case for testing this hypothesis, because its entanglement with dominant regulatory knowledge systems and institutions provides a well-studied background against which to observe the norms, politics, and choices of participants.

As an in-depth case study, I present an analysis of a knowledge commons centered on the GreenScreen for Safer Chemicals, an open-source methodology for chemical hazard assessment. I ask whether and how this emerging commons can function as a stable site for producing socially robust knowledge. To investigate this, I study how commons-produced knowledge about chemical hazards, assessment methodologies, and tools becomes legitimate and authoritative for commons participants and a varied community of knowledge users. I examine how the institutions and social protocols of the GreenScreen commons—such as peer review processes and conflict resolution mechanisms—can either help make knowledge more socially robust, or alternatively can close off or prevent extended peer review. My analysis reveals a commons that is "nested within" (Bollier 2014) dominant institutions and information infrastructures, such as global molecular information systems and (most of all) intellectual property rights regimes. These are profoundly influential background conditions, which deeply structure the kinds of knowledge that the commons produces and the patterns of collective knowledge production that the CHA knowledge commons supports.

3.2 Theorizing chemical knowledge commons

This study links theoretical elements from three areas of scholarship: knowledge commons, the politics of knowledge about chemicals in the environment, and the politics of scientific expertise—drawing heavily on the concept of socially robust knowledge. Each of these areas of scholarship addresses processes of knowledge-making from quite different perspectives. Yet they intersect on the key questions of who can participate in making and evaluating knowledge; and how knowledge, actors, and their interactions are ordered and governed by institutions and norms.

Knowledge commons

A commons refers to a system of resources collectively owned and equitably shared among a community that is also responsible for its management. Much extensive study of natural resource commons stems from the work of Ostrom (1990), whose institutional analysis and development framework highlights the importance of how actors organize themselves and generate rules to govern collective action in shaping the economic outcomes of commons.[1] Knowledge is also a resource—whether it be research data, medical literature, agricultural practices, or software—but with important differences from biophysical resources that affect the possibilities and challenges for the governance of knowledge commons (C. Hess and Ostrom 2007). For example, while knowledge is non-depletable and non-rivalrous (i.e. one actor's use does not subtract from others' use), it can be undersupplied. People can be excluded from access to knowledge through the assertion of intellectual property (IP) rights, or from participation in knowledge production through barriers associated with expertise, labor, or funding.

A knowledge commons is not synonymous with free or open access to knowledge. Scholars in sociology and law have conducted extensive analyses of how knowledge commons operate, such as the predominantly biomedical case studies presented by Frischmann et al. (2014a) and the in-depth study of open-source software commons conducted by Schweik and English (2012). This scholarship reveals that knowledge commons vary greatly in how and why participants engage, how membership is defined, and how access and contribution are governed. In particular, the notion of "openness" in knowledge commons is more complex than simply the conditions of access to information. Frischmann et al. (2014a, p. 28-30) point out that openness has both resource and community dimensions. For knowledge resources, openness

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[1] The so-called "tragedy of the commons"—more accurately, the "tragedy of open access without rules"—is only one of many possible scenarios, and is far less common in reality than in the popular neoliberal imagination (see Ostrom 1990).

refers to the ways of interacting with resources that prospective users are afforded—such as the ability to view, modify, add, copy, or transform. Resource openness has to do with how and to what degree these capacities are regulated by imposing barriers—physical, legal, technological, and so on—and who has control over them. Community openness refers to "the extent to which there are criteria for or barriers to membership or participation in the creation or innovation processes that a knowledge commons is intended to support" (Frischmann, Madison, and Strandburg 2014a, p. 29-30). How these criteria or barriers arise is likewise relevant to understanding how and to what degree a knowledge commons is "open." In summary, openness is not a binary attribute of knowledge commons but a variable set of characteristics.

The commons plays an important role in many scholars' accounts of social, economic, and environmental transformation. A prominent historical strand is the enclosure of the land commons in Britain, or the separation of people from their means of agrarian production, beginning in the 18th century (e.g., Polanyi 1944; Caffentzis 2013; Linebaugh 2014). At the same time, these scholars draw attention to new ways in which commons are reemerging and potentially generating new transformations in response to global problems. Bollier (2014) suggests that the commons as a paradigm has under-appreciated popular relevance and "holds great promise for reinventing dysfunctional governments and reforming predatory markets." He draws attention to the importance of social practices and processes by which participants form and sustain commons—"commoning"—suggesting that these are integral to how and why people value commons. Boyle (2008) underscores the continued existence and societal value of knowledge commons in particular. He argues that a "second enclosure movement" is taking place around knowledge commons as industries and policy-makers increasingly privilege stronger protection of private IP rights. This trend increasingly curtails the availability of the public domain, a global commons (including ideas, scientific theories, culture, and so on) that serves as a vital resource for technical and cultural innovation. Boyle points out that IP rights regimes profoundly shape the governance of technology: stronger IP rights typically go hand-in-hand with the diminishing freedom of citizens to make consequential choices about technical systems that affect their lives. Benkler (2006) and Lessig (Lessig 2004) advance this point further, arguing that the collective production of knowledge, technology, and culture is critical to social and economic justice.

The intersection of knowledge, IP, and technological governance is highly relevant to chemicals. Industrial chemical pollution is present throughout the global environmental commons, contaminating human bodies even before birth (President's Cancer Panel 2010). Many sources of exposure to chemicals are products or materials used in everyday life (Dionisio, Frame, et al. 2015). Yet there is little public access to knowledge about the chemical makeup, life cycles, and health hazards of chemical substances used in consumer products (e.g., Steinemann, MacGregor, et al. 2011) and in industry more broadly (e.g., Maule et al. 2013). This is in large part because the default stance of policy-makers is that such information is private IP or confidential business information. Far-reaching trade secret protection obscures public capacity to identify and regulate chemicals of concern (M. P. Wilson and Schwarzman 2009; Schwarz and Denison 2018a), and hinders safer chemical substitution within the private sector by preventing the flow of chemical knowledge in supply chains (Scruggs and Ortolano 2011). Although not all chemical knowledge is proprietary, the entrenched practices of corporate confidentiality and the legal regimes that support them are part of a "background environment" (Frischmann, Madison, and Strandburg 2014a) that influences any commons where chemical knowledge is included, referenced, or produced. This accords with Bollier's (2014) observation that "commons tend to be nested within other systems of power and institutional relationships, and therefore are not wholly independent."

Chemical knowledge politics

The making of knowledge about chemical impacts on health is a contested terrain that has been shaped by political struggles over the regulatory control of toxic substances. The policy processes for evaluating and controlling chemicals routinely open up areas of high scientific uncertainty and indeterminacy. As a result, political decision-making and the interpretation of science become extremely difficult to separate from one another (Sarewitz 2004). Jasanoff (1987; 1990) has shown how government agencies, scientists, and regulated industries argue over the interpretation of scientific data and findings in adversarial legal and regulatory processes in the US. These arguments often involve attacks on the validity and credibility of animal tests and epidemiological studies (e.g., Michaels 2008). As such, "regulatory science" has developed a set of norms, procedures, and protocols that influence greatly how chemical health impacts are studied and understood (Boudia and Jas 2013; Boudia and Jas 2014). The dominant regulatory framing of chemical issues in terms of risk assessment and risk management is another deeply ingrained part of the "background environment" of CHA knowledge production, even as the emerging norms and practices of safer chemical substitution aim to resist this framing (see Chapters 2 and 4).

The design and practice of regulatory systems are flawed—or at best imperfect—and have produced major gaps and biases in chemical knowledge. For example, many governments institute only minimal requirements for industry to generate chemical safety data (Guth, Denison, and Sass 2007)—and as discussed above, the US government protects much of these data as confidential business information. Narrow ways of understanding, prioritizing, and legitimizing chemical knowledge (e.g., Frickel and Edwards 2014) have failed to take into account new scientific evidence that reveals a much more complex, interrelated, and unpredictable field of chemical exposures and harms than policy-makers ever anticipated (Schwarzman and M. P. Wilson 2009; Gross and Birnbaum 2017). Furthermore, the priorities and assumptions of scientific research on chemical pollution are shaped by dominant societal interests, creating areas of "undone science" (Frickel, Gibbon, et al. 2010).[2] Safer chemical substitution is one example: pervasive data gaps in chemical toxicity information make it much more difficult to pursue alternative approaches to chemical governance, such as evaluating several potential replacements for a chemical of concern to identify inherently

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[2] More insidiously, as Libioron et al. (2018) argue, regulatory science can perpetuate power imbalances through its definitions of environmental harm and its protocols for legitimizing evidence.

safer technologies. As a result, substitutes can perversely perpetuate the risks that drove their introduction (as is the case with chemical replacements for BPA: Eilebrecht et al. 2019). In short, regulatory science systems have failed to generate adequate knowledge to effectively and equitably protect human and environmental health.

Yet, at the same time, an astounding array of chemical and toxicological information has been accumulated and organized into databases, registries, inventories, and archives as a result of regulatory and industrial activity. Hepler-Smith (2019) has traced the development of information infrastructures within US public- and private-sector institutions. He argues that "molecular bureaucracy" is "the global complex of legal structures, administrative procedures, regulatory lists, information systems, and nomenclature conventions that render toxic environments tractable to regulatory politics on a molecule-by-molecule basis." By ordering vast amounts of chemical knowledge in a kind of inescapable—but arbitrary—totality, this infrastructure has shaped the possibilities, actions, and even imaginations of policy-makers and scientists, often with poor outcomes for environmental governance. As a case in point, the very notion of safer chemical substitution fits so easily into the molecule-by-molecule logic that alternative terms like "functional substitution" (Tickner et al. 2015) need to be used to remind practitioners that "drop-in" chemical replacements are not the only way. Molecular bureaucracy shapes the building of new digital information systems through the requirements of interoperability and "sideways compatibility" (Bowker and Star 1999). Molecular bureaucracy highlights the fact that information infrastructure is not merely a technical attribute of knowledge resources, but can be a profoundly influential background condition for an entire knowledge commons.

Socially robust knowledge

Recognizing these failures, a growing number of societal actors are entering the chemical knowledge arena and challenging the assumptions, methods, and epistemic authority of the dominant regulatory-industrial regime. For example, Iles (2007) uses the case of phthalates in children's toys to explore how environmental health NGOs emerged in the 2000s as knowledge-makers in their own right, through testing—and changing—the standards of evidence and data sources regulators use to understand how and why substances in consumer products pose a threat to public health. Similarly, organizations within environmental health and justice movements have become active participants in producing and mobilizing biomonitoring studies, which track the presence of industrial chemicals in human bodies. Shamasunder and Morello-Frosch (2015) examine how these scientists have entered debates about the interpretation of human biomonitoring data alongside industrial, regulatory, and academic scientists, reframing the issue of chemical body burdens in terms of "toxic trespass" and advancing interpretations that call for urgent policy action. These NGOs and social movement actors are intervening in the making of regulatory science—something that industry scientists and managers have long done, but on a much larger scale, with markedly different tactics and power relations (Markowitz and Rosner 2003; Michaels 2008).

At their core, these struggles have much to do with the politics of scientific expertise. Traditionally, epistemic authority has been associated with "expert" scientists and regulators, with "lay" citizen actors being seen as "non-expert" and thus lacking credibility. STS scholars have long studied the social and political processes that community groups, environmental advocates, and other "outsiders" must navigate to gain credibility as valid knowledge-holders in debates about chemical and environmental justice issues (e.g., Corburn 2005; Ottinger and Cohen 2011; Ottinger 2013).

Arguably, diverse forms of expertise are exactly what is needed in debates about substituting toxic chemicals—debates characterized by high scientific uncertainty and real consequences for protecting environmental health. Funtowicz & Ravetz (1993) argued that policy-relevant science dealing with complex and uncertain issues or having high societal stakes—what they called "post-normal science"—is fundamentally different from traditional applied science, which relies on well-understood systems and has few immediate social consequences. As such, they proposed that post-normal science requires new quality-control processes: to be considered valid, it requires "extended" peer review. In extended peer review, researchers must respond not only to scientific experts but to a broader range of stakeholders—including non-scientists and people affected by environmental issues, technologies, or policy decisions—who can make their own assessments of validity. In this framework, chemical substitution is post-normal science. Yet, in practice, the debates about chemicals do not perform the function of extended peer review, as they never seem to reach a resolution point. This leaves knowledge users no better off, and leaves scientific knowledge still vulnerable to deconstruction and delegitimization. For example, Scruggs and Ortolano (2011) found that business decision-makers interested in pursuing safer chemical substitution were often left confused and unable to take action in situations where "NGOs, government authorities, and chemical producers may reach different conclusions about a chemical's hazards."

Some STS scholars have suggested that science can be strengthened by being openly challenged. Nowotny, Scott, and Gibbons (2001) introduced the idea of "socially robust knowledge," referring to knowledge that is accepted as valid and authoritative by multiple, diverse constituencies. In other words, in addition to passing scientific and technical tests of reliability (such as experimental reproducibility and statistical validity), knowledge also passes social tests of reliability to be considered valid beyond scientific communities. These may include testing knowledge for applicability to particular decision-making contexts, scrutinizing the assumptions, values, or framing narratives upon which it is built, and continually reevaluating the credibility and authority of those who contribute to making or testing knowledge. The concept of socially robust knowledge (SRK) seems particularly apposite to knowledge domains that are politically contested, like chemicals and environmental health. In contrast to extended peer review, SRK looks at a range of tests and processes used in multiple arenas including courts, legislatures, policy agencies, and the broader public.

More recently, STS scholars have elaborated this concept. For example, Hinchliffe et al. (2014) used case studies of cooperative research projects concerning food, water, and biofuel issues to evaluate the capacity of multi-stakeholder participatory research to generate knowledge that is socially robust. Iles (2013) studied the epistemic politics of green chemistry in the US and considered what socially robust knowledge may actually look like in practice. He argued that while green chemistry experts have generally not engaged with many societal stakeholders, emerging policy initiatives in the state of California could provide opportunities for generating socially robust knowledge—if policy-makers could devise new institutions to enable societal input and evaluation of chemical technologies.

There are three key aspects of how socially robust knowledge could be made:

- First, it is tested for validity in real-world settings, outside of traditional scientific contexts. In the knowledge domain of chemical substitution, businesses in product sectors downstream from the chemical industry may be highly relevant settings for testing knowledge because they are also potential "users" of chemical knowledge generated by NGOs, regulators, consultants, and other actors.
- Second, it is made and tested by an "extended" peer group, encompassing many different kinds of expertise. In other words, socially robust knowledge does not just rely on one single source of authority to be valid. This factor aligns with the general trend, highlighted above, of many varied constituencies entering the chemical knowledge field. In a knowledge commons, this means that a diversity of knowledge-holders must be engaged in producing and peer reviewing knowledge, with social protocols that enable them to establish their credibility. Importantly, this also requires a range of actors to have access to the knowledge in question, to be able to verify or contest it.
- Third, it is produced through iterative and participatory processes involving frequent testing and revision. SRK is not static; as with all scientific knowledge, it is always provisional and incomplete. However, making and re-making SRK requires "a permanent dialogue between scientists and diverse 'others' in society" (Nowotny, Scott, and Gibbons 2001). This can include multi-centered and multi-directional flows of information (Iles 2013).

Building on these theoretical elements, this study explores whether and how a green chemistry knowledge commons could serve as a new site for the production of socially robust knowledge. As a means of producing valuable shared knowledge resources, the commons could provide significant opportunities to generate fresh knowledge that existing regulatory systems have failed to produce. With diverse multi-stakeholder participation, the commons may be able to "do" some "undone" science—such as developing socially robust ways to evaluate environmental justice concerns normally excluded from analyses of chemical risks. As a collaborative space woven from participatory processes, the commons could provide infrastructural conditions for multi-directional information flows and facilitate extended peer review. The commons may also provide opportunities to reshape or loosen the structuring forces that have made regulatory science narrow and reductionist. Here, how the commons mediates controversy and contestation, negotiating tests of validity and legitimacy for "commoned" knowledge, is central to its robustness.

3.3 Methods

I studied the knowledge domain of chemical hazard assessment (CHA) to search for potential cases of knowledge commons. This domain has fairly wide multi-stakeholder participation and generates shared knowledge resources relevant to green chemistry. My investigation focused on the following empirical questions:

1. The ontology of commons knowledge. How are knowledge commons constituted—particularly in socially contested contexts—and who participates in them?
2. Socially robust knowledge. Do knowledge commons, in fact, help make and stabilize socially robust knowledge with regard to their content? What tests and criteria are developed to do so, who applies these, and to what effect? What are the consequences?
3. Legitimacy. Can a knowledge commons establish its legitimacy and authority for actor groups both inside and outside the commons, and if so, how? To what extent do commons seek to engage the larger industry, IP, and regulatory science institutional contexts in which it may be nested?
4. Epistemic and social/environmental justice. What are the politics of expertise within the knowledge commons? Can a commons change who is regarded as expert vis-à-vis prevailing structures of knowledge production? Whose knowledge is being included or excluded?

I approached these questions by collecting and analyzing qualitative data from interviews, participant observation, and documents.

I conducted 35 semi-structured interviews with respondents selected specifically because of their involvement in the formative development of knowledge commons in the domain of chemicals and their environmental health hazards.[3] They were mostly women who are doing the hard work of bringing science into decision-making for sustainable production and consumption. Many of them habitually raise the same questions that I am asking; they wonder about how they can solidify their commons, what social protocols they need, and how to relate to larger institutions. The interviews were conducted using an interview guide designed to address my empirical questions about commoning and knowledge production (see Appendix A).

I participated in a core group of people organizing the Chemical Hazard Data Commons project (see Chapter 2 of this dissertation), thereby taking part in its design. I provided technical assistance in developing information infrastructure, helped set policies for the commons, and helped collect and analyze stakeholder feedback. I worked intensively on a sub-project associated with the commons: trying to solve the "chemical groups" issue that I describe

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[3] Respondents included 16 employees of environmental NGOs, 10 from government agencies, 6 from industry firms, 5 from consulting firms, and one from an academic institution. This study conforms to CPHS Protocol Number 2016-02-8368.

later, in collaboration with the US-based NGOs Healthy Building Network (HBN) and Clean Production Action (CPA). I took part in a community webinar presentation in which the CHDC organizers presented the commons in depth when it publicly launched.

I also participated in the broader community concerned with mobilizing chemical hazard information for safer substitution. I served on the GreenScreen Science Advisory Committee from 2017–2020. I attended two meetings of the Business-NGO Working Group for Safer Chemicals and Sustainable Materials (BizNGO; 2014 in San Francisco and 2018 in Berkeley) and the Second International Symposium on Alternatives Assessment (2018 in Sacramento). I also attended virtual workgroup meetings and online presentations by the providers of particular chemical substitution information resources, for example, the ChemSec's Marketplace and the ZDHC Chemicals Module.

Finally, I compiled and analyzed documents pertaining to the formation/development, management/governance, and community/participation for a range of shared knowledge resources and initiatives within the field of safer chemical substitution. For example, the CHDC effort began with the authoring of several white papers that outline its potential design, community norms, and connections with the prevailing IP landscape. The CHDC organizers collected stakeholder feedback on these papers. Later, HBN also surveyed approximately 100 members to determine their priorities for the development of the commons; the results of the survey were compiled for publication back to the community. All of these public documents were part of my analysis. I conducted content analysis on all data sources using ATLAS.ti (2020).

3.4 Are knowledge commons emerging in CHA?

A broad array of scientists, NGOs, businesses, and public-sector organizations are increasingly participating in producing and using knowledge focused on safer chemical substitution, which is based on the scientific approaches of chemical hazard assessment (CHA) and chemical alternatives assessment (CAA). Regulators and the chemical industry still play major roles in shaping the "universe" of chemical substances and materials available in commerce—through regulatory science, rule-making, and their design and production choices. But a wide range of downstream industry sectors that use chemicals in their products or operations—such as cleaning products, electronics, textiles, building products, and retail, to name a few—are actively taking on safer chemical substitution problems themselves (Scruggs 2013). As a result, chemical decision-making and governance increasingly takes place in industrial design, engineering, institutional purchasing, standard-setting, and other non-regulatory settings. Interested groups, such as environmental health advocates and industry associations, therefore seek to influence chemical decision-making outside of government institutions by participating in the development of CHA knowledge systems. In short, the chemical substitution arena includes multiple societal constituencies with diverse interests and motivations who are producing, evaluating, and using chemical knowledge.

Table 3.1: Types of knowledge resources

Resource type	**Description**	**Examples**
Data resource	Chemical, toxicological, environmental, and regulatory databases; other sources of information relevant to CHA	Pharos; SIN List; Subsport; PubChem
Method	Methods for chemical hazard assessment	GreenScreen for Safer Chemicals; C2C Material Health Assessment Methodology
Standard	Standards that define elements of hazard assessment or communication	Globally Harmonized System (GHS); Health Product Declaration (HPD)
Certification	Certification programs for product sustainability that include CHA elements	Cradle to Cradle Certified; US EPA Safer Choice ecolabel
Profiler	Entities, such as consulting firms, that produce CHA knowledge using methods and data	ToxServices; NSF International; Gradient; Scivera
Policy	Chemicals policy programs that leverage other CHA resources	REACH (EU); California Safer Consumer Products Program
Platform	Products and services that provide CHA knowledge and coordinate multiple business functions	Scivera Lens; ToxFMD; ChemForward

A heterogeneous array of knowledge resources make up what I refer to broadly as CHA knowledge, as summarized in Table 3.1. Toxicological and epidemiological data generally drive regulatory understandings of chemical risks, along with data about industrial production, human exposures, environmental releases, and the physical properties of substances. Collections of such data exist in the form of databases, inventories, scientific publications, and so on. However, these data are often incomplete and uncertain, not pointing to a clear conclusion and subject to differing interpretations by scientific experts. Many decision-makers face challenges in obtaining, interpreting, and using scientific data about chemicals to inform safer substitution (see Chapter 2 of this dissertation). As a result, they rely on a further array of resources that serve to make sense of scientific knowledge by organizing, selecting, and aggregating data to generate more actionable forms of knowledge about chemical hazards. For example, standards like the Globally Harmonized System (GHS) (United Nations 2019) play an important role in codifying agreements about the definitions of health effects and in structuring the production and evaluation of scientific evidence. CHA methods—formalized procedures for organizing and interpreting chemical and toxicological information (Harrison and Hester 2013)—enable practitioners to produce chemical assessments and other decision aids that are readily applicable in chemical substitution contexts. Businesses and NGOs are providing many of these knowledge resources and integrating them into professional services, software systems, and online platforms.

These resources are hybrids of scientific knowledge, policy, and interpretive reasoning. As such, CHA knowledge can embody stable agreements among stakeholders, or it can be controversial and contested. For example, CHA methods and standards include criteria and thresholds for delineating safety from harm, classification systems for different types of health hazards, guidance for selecting test methods or weighing evidence, and lists of known harmful substances. These evaluative systems and protocols are integral to the production and stabilization of CHA knowledge in a domain where there are many possible ways of interpreting uncertain and incomplete scientific data to arrive at conclusions (Jacobs et al. 2016). This also means that CHA knowledge is political, enfolding value-laden assumptions and perspectives into knowledge resources that are effectively used as tools for selecting safer chemicals, materials, and products (see Chapter 4 in this dissertation). The politics of CHA knowledge and how it is produced are highly relevant to understanding whether and how knowledge can be made socially robust.

CHA knowledge is being produced in increasingly "networked" ways: that is, through many interrelated efforts by otherwise independent and diverse stakeholders. The actors that I have followed in the landscape of CHA knowledge are engaged in developing and using a variety of heterogeneous knowledge resources, among which many interactions and relationships exist. In many cases these resources build on one another, refer to each other, or maintain interoperability. To illustrate this pattern, I will in this chapter highlight a specific knowledge resource: a methodology for comparative chemical hazard assessment called the GreenScreen for Safer Chemicals, developed by the US-based NGO Clean Production Action (Clean Production Action 2020b). The authors of GreenScreen cite as "normative references" two key resources on which the methodology is fundamentally based: the GHS (United Nations 2019) and the US EPA's Safer Choice methodology for chemical alternatives assessment (US Environmental Protection Agency 2012). In turn, dozens of other CHA knowledge resources reference or build on GreenScreen in a variety of ways, to the extent that it has become inseparable from a broader CHA knowledge infrastructure. Figure 3.1 shows a partial and incomplete map of CHA knowledge resources and relationships among them, focusing on resources with a relationship to GreenScreen (which therefore occupies a central place in the graph).

This network of interrelated knowledge resources has some key characteristics of a knowl-

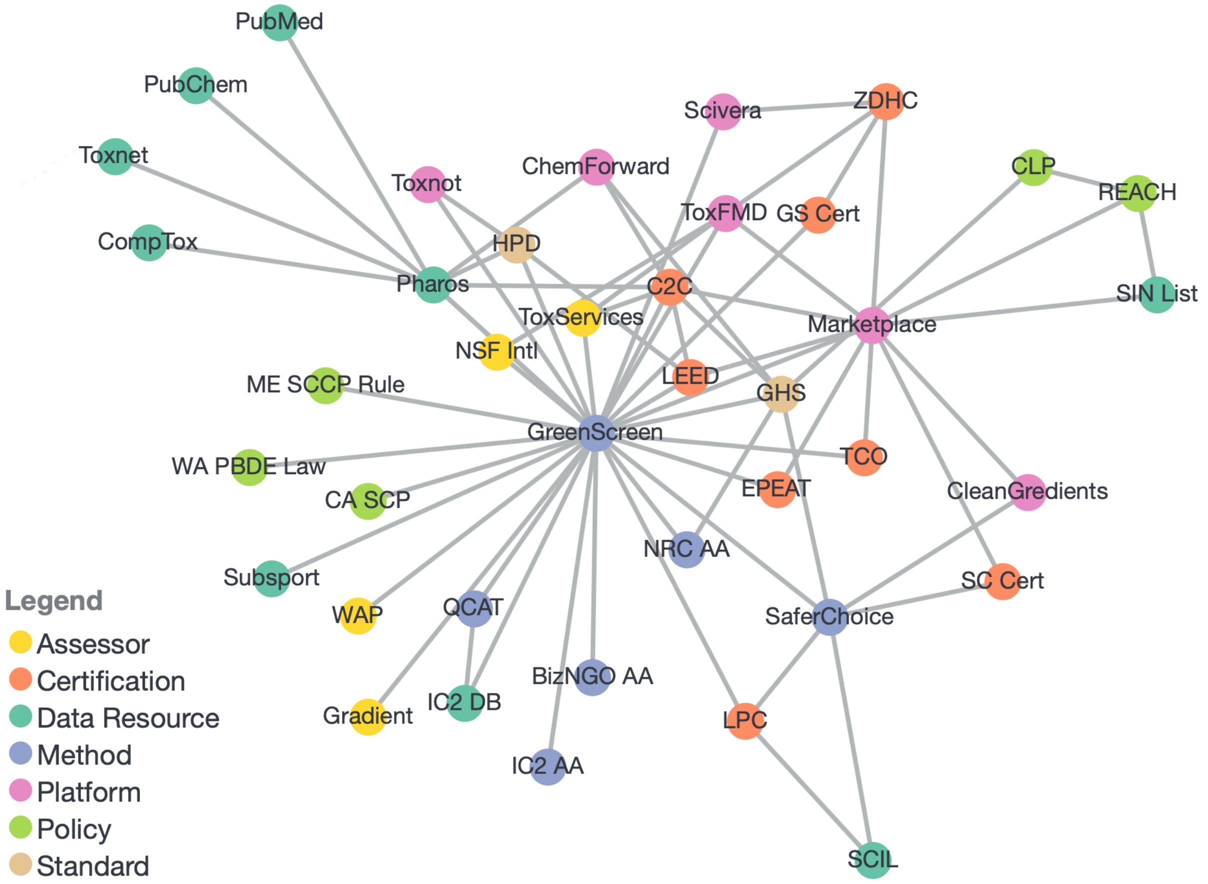

Figure 3.1:

Partial network graph of knowledge resources for safer chemical substitution[4]

edge commons. Through this network, shared resources are being generated, propagated, governed, and used in practice by a community of actors concerned with safer chemical substitution. This includes several forms and instances of shared knowledge—such as assessment methods and open-access databases—that are effectively “common property.” For some of these knowledge resources, like the GreenScreen and Cradle to Cradle CHA methodologies, the broader community has had direct input on scientific matters during the processes of development. Table 3.2 summarizes the community’s access to several categories of CHA knowledge resources and what kinds of actors contribute to producing them. In highlighting the shared resources in this network, I am contrasting its commons-like aspects against the pervasive institutional background of intellectual property restrictions and corporate confi-

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[4] All data underlying the graph are included with this dissertation as supplementary information. Additionally, an interactive version of this figure can be accessed at https://kaios.net/research/network/.

dentiality. There is a massive "shadow" of proprietary chemical knowledge that private-sector actors control through intellectual property rights, which is not included in this network of shared resources.

The point is that there is wide knowledge sharing based on communal norms even though the actors do not necessarily have recognizable formal institutions for governance that might encourage it. Instead, an informal knowledge commons is arguably emerging through a number of overlapping collective efforts nested within the larger knowledge network. Some of these efforts are in fact formally-constituted "sub-commons" (such as the Chemical Hazard Data Commons was until late 2019; see Chapter 2) or have formal institutions to govern knowledge production and sharing (namely, GreenScreen, discussed below).

Table 3.2: Resources in the emerging CHA knowledge commons

Resource type	**Access**	**Provision**	**Examples**
Assessment methodologies	Shared	NGOs and government agencies, sometimes with input from other stakeholders	GreenScreen and derivative methods; EPA Safer Choice; Cradle to Cradle assessment methodologies
Certifications and standards	Shared	NGOs, firms, and governments	Open access: GHS, Health Product Declaration, GreenScreen Certified
Data resources	Shared	NGOs, firms, and governments	Pharos; Toxnot; SIN List; PubChem
Chemical assessments	Mostly private, some shared	Chemical assessors, platforms	Open access: Pharos and IC2 collections of GreenScreen assessments; Partially open access: ToxFMD database; Private access (platform): Scivera

Political economy of CHA knowledge

If a CHA knowledge commons is indeed emerging, our empirical study suggests that its "community" shares some overarching goals even though participants may have diverging interests. The actors I followed align substantially on the idea that chemical hazard assessment makes sense as a basis for addressing the toxic impacts of industrial production, and that CHA should be more widely used in practice. The actors generally realize that they, or the other stakeholders in the community, face many of the same knowledge challenges when it comes to safer chemical substitution. Many actors are motivated to solve those challenges through some form of collective action—such as generating missing but needed resources, reducing duplicated effort by allowing those resources to be shared, and creating standardized ways of coordinating collective work (i.e., one of the functions of information infrastructure: Bowker and Star 1999).

But there is also a diverse and sometimes conflicting mix of goals and interests, which reflects the heterogeneous makeup of the CHA knowledge arena as well as its politics and institutional setting. Actors do not necessarily agree on the specific forms of action and pathways for industrial change that CHA knowledge production is supposed to enable. For instance, several NGOs advocate for "transparency" of chemical knowledge. Groups like HBN[5] and Environmental Defense Fund argue that sustainable and just transitions to safer chemicals can only happen if all stakeholders can understand and critically evaluate the scientific basis of decision-making. In other words, shared CHA knowledge can be a way for societal actors to intervene in industry and regulation, perhaps holding them accountable (Fung and O'Rourke 2000; Fortun 2004). This narrative goes hand-in-hand with cross-cutting information interventions (O'Rourke 2005, see also Chapter 4) aiming to make CHA knowledge available to a wide array of stakeholders, and a strategy of producing open-access knowledge resources as public goods.

In contrast, many organizations are focusing instead on driving safer chemical substitution through an internal transformation of industry. This involves making CHA knowledge resources that can mesh with the interests and decision-making needs of the private sector. Some NGOs and a number of firms are deploying CHA knowledge services—including, for example, toxicological assessment and data management for tracking chemicals in products.[6] These services can be integrated into existing processes of corporate chemical governance, while protecting proprietary IP and confidential business information (e.g. through non-disclosure agreements). Together with this diversity of interests and approaches, the broader CHA community lacks agreement on institutional arrangements regarding intellectual property. There are unsettled questions about how the community should produce CHA

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[5] For instance, HBN's Pharos Project was originally intended to reveal previously inaccessible knowledge about chemicals in building products to architects.

[6] Such services collect and compile information about every chemical constituent, furnish comprehensive assessments performed by certified toxicologists, screen the products for compliance with safety regulations and ecolabels, and report results to their clients. Scivera Lens and the ToxFMD Screened Chemistry Program are two examples.

knowledge and how, or among whom, CHA knowledge should be shared.

These tensions are critical for understanding how a CHA knowledge commons might (or might not) generate socially robust knowledge. Perhaps the clearest case of a CHA knowledge commons that embodies these tensions and contradictions is the GreenScreen for Safer Chemicals.

3.5 GreenScreen: Institutions and knowledge production

The case of GreenScreen illustrates how institutions structure knowledge production in the emerging commons. The GreenScreen method encapsulates an array of technical elements and interpretive logic for assessing chemical hazards. It includes lists of recommended data sources, a taxonomy of hazard endpoints, systematic criteria to evaluate and classify the severity of hazard and the strength of scientific evidence across endpoints, ways of classifying the overall level of hazard for a substance, and conventions for documenting and communicating CHA knowledge. When GreenScreen is applied by trained practitioners, it can produce a broadly understandable indicator of how hazardous (or safe) a given substance is to human and environmental health—namely, assigning a score on a 4-step scale from highest concern (Benchmark 1) to lowest concern (Benchmark 4). I discuss GreenScreen in greater detail in Chapters 2 and 4.

Initially, GreenScreen was developed as an extension of regulatory science. The original authors, Dr. Lauren Heine and Dr. Mark Rossi of Clean Production Action (CPA), created GreenScreen as a method to identify safer chemical alternatives to brominated flame retardants—a need that was motivated by regulations in Washington State, USA (Washington State Department of Ecology 2008; *An Act Relating to Flame Retardants* 2013). GreenScreen 1.0 was based on existing standards and methodologies, but its main conceptual innovation was the Benchmark system—an attempt to answer the question of how to systematically identify *safer* chemicals. Rather than focusing on identifying hazards in an ad hoc fashion, GreenScreen provided uniform indicators of hazard and enabled direct comparisons among substances to select the safest alternative. GreenScreen has since evolved from a one-off example of a CHA policy application into a standalone methodology that is widely recognized as technically and socially credible. It has effectively become embedded in a variety of standards, practices, and tools, and is even referenced in some US state policy programs (see Figure 3.1). It is a boundary object—"those objects that both inhabit several communities of practice and satisfy the informational requirements of each of them" (Bowker and Star 1999). According to Heine, this was not the original goal. She and several other respondents referred to GreenScreen as a "brand," evoking a sense of something widely recognized even by those who do not fully understand it:

> Maybe, while these methodologies don't have to be a brand, people will make brands from the methodology... Because that's the way these things grow, I

> think. Like any open standard, it gets integrated into things... It becomes a building block.

The CHA knowledge community quickly began to adopt GreenScreen to new uses, and its evolution was spontaneous, as Heine describes:

> One of the cool things about GreenScreen was that putting it out there, I didn't invent all this stuff. People started using it in really creative ways, and it was really neat to see it evolve. I wasn't like this mastermind who knew all the answers. I was just following the thread... It's really the cleverness of other people seeing an opportunity to use a tool.

For example, Helen Holder at Hewlett-Packard became an early champion of the methodology and began applying it for material selection in the electronics industry (Holder et al. 2013). Eventually CPA expanded their focus to include developing GreenScreen into a robust standard for CHA. This widespread adoption as a "building block" demonstrates that the methodology has been tested in practice and that it "works"—it generates knowledge of real utility to decision-makers. Passing such tests of applicability in context is one of the key characteristics of SRK.

GreenScreen's broad credibility is also a result of the community and institutions that have made it so—in particular, its commons-like institutions. When I asked members of the CHA knowledge community why they used GreenScreen or incorporated it into systems of their own, they consistently cited its scientific credibility and linked this credibility to the fact that the methodology is publicly available ("open-source") and has been peer-reviewed by an international group of scientific, government, industry, and NGO experts. If GreenScreen appears to exhibit the key characteristics of SRK—real-world applicability, extended peer review, and participatory development—this has been made possible through deliberate institutional arrangements that involve the CHA community in dynamic processes of knowledge-making.

Institutionalizing extended peer review

GreenScreen's evolution has been shaped by institutional arrangements that CPA set up, which enabled them to engage an extended community of expert contributors and practitioners. The development of GreenScreen beyond version 1.0 involved recruiting, structuring, and governing this community—initially by Heine, and later by CPA's Shari Franjevic. They convened committees of volunteer experts drawn from the green chemistry, environmental health, and toxicology communities to deliberate on the technical details of the method, its application in practice, and the overall direction of the program. Over time, a considerable amount of external input—from other environmental NGOs, government and industry scientists, and academics—has been channeled into the program through these formal mechanisms as well as through informal collaboration. Heine characterizes these collaborative processes as "a bunch of smart people figuring it out together."

Thus, GreenScreen has arguably been subjected to "extended peer review" (Funtowicz and Ravetz 1993; Iles 2013). The initial technical committee was selected by Heine using a "snowball" process in which she asked experts to recommend others who might participate. In principle, it was broadly open to anyone who had the technical skill and know-how—meaning that it was limited to scientific experts. The GreenScreen methodology itself—and all of its technical criteria, protocols, and guidance—have always been publicly available, meaning that it is open to inspection, criticism, and deconstruction. Under the oversight of CPA, GreenScreen also periodically goes through formal peer review processes between versions (for example, before the publication of version 1.2 in 2011; it is currently in version 1.4). These processes involve international participation from a broad range of stakeholders, including other environmental NGOs that had been critical of earlier versions. CPA also continuously accepts feedback through its advisory committees, as well as through community channels and individual communications. Thus, GreenScreen is not only "open" in terms of a resource access policy (anyone can read the methodology) but is also institutionally open to iterative challenge, modification, and improvement.

GreenScreen has also very much developed "in the context of its application." The practicing toxicologists who are the most frequent direct users of the GreenScreen method—chemical assessors or "profilers"—play a critical role in identifying and resolving implementation challenges and developing best practices to refine the method. For example, Dr. Margaret Whittaker and her firm ToxServices are long-standing GreenScreen practitioners and contributors. Testing in practice has led to improvements in how the methodology evaluates inorganic substances and polymers. These processes of real-world testing and revision are central to how the GreenScreen method has become socially robust.

Epistemic authority and intellectual property

GreenScreen knowledge production is governed by a combination of transparency rules, expert authority, and intellectual property rights. These institutions shape the possible ways that CHA knowledge can be produced, verified, and tested by the community. GreenScreen is "open-source" in the sense that anyone can apply the method, as long as they have the necessary skills and data resources (chemical databases, toxicological studies, etc.).[7] This implies a decentralized pattern of knowledge production, with GreenScreen assessments potentially being made in a wide variety of organizations, by many different actors, and for any purpose. Using a combination of legal mechanisms, CPA has taken care to maintain the accessibility and openness of the GreenScreen method, and also to maintain a consistent form of *verifiability* across all GreenScreen assessments. They consider this necessary for protecting against potentially false or erroneous results, misrepresentations of how the method was applied, or fraudulent uses that might damage GreenScreen's credibility as a

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[7] Making an analogy between GreenScreen and open source software may not be entirely accurate and is not my goal. Still, it is worth pointing out the "openness" of the GreenScreen method in principle, as contrasted with the much more closed and proprietary ways in which it is used. This evokes both the practices and the ideological conflicts around free and open source software (Kelty 2008).

de facto standard.[8] Importantly, CPA's legal terms allow profilers to own copyright for the GreenScreen assessments that they produce. GreenScreen practitioners are not obligated to contribute their assessment work to the CHA knowledge commons, thus potentially limiting its growth.

CPA's knowledge-governing institutions have taken two parallel yet quite different approaches to ensure the validity or verifiability of GreenScreen assessments. First, using transparency: according to the GreenScreen Terms of Use, "GreenScreen assessments may be shared publicly only if access to the full report and supporting data are provided" (Clean Production Action 2019). This requirement enables effective vetting and community review of GreenScreen assessments that are made public. But in the vast majority of cases, there is no transparency required because GreenScreen assessments are not intended to be shared publicly—rather, they are used internally by the organizations that produce them, or shared between profilers and clients as part of a business relationship. A second and arguably more important set of institutional arrangements aims to ensure validity by positioning CPA as a trusted central authority. CPA has implemented training and accreditation programs through which they recognize "authorized practitioners" and "licensed profilers"—individuals and organizations that have been vetted and legally licensed by CPA to provide GreenScreen assessment (Clean Production Action 2020e). These are mostly consulting firms and industry employees, but a few of them are staff in environmental heath NGOs. If a business entity wants to use GreenScreen assessment results in any official communications or claims—such as certifying products with ecolabels—the assessments must be performed by authorized or licensed profilers (Clean Production Action 2020a).

The accreditation of GreenScreen practitioners provides a form of authoritative review that effectively replaces transparency and community peer-review, enabling GreenScreen knowledge to be made credible while remaining proprietary. By using licensed profilers, for instance, firms can get the benefits of using a community-validated CHA methodology with the institutional "sign-off" of its creators, but without disclosing their chemical-specific knowledge to the community. Clients can also choose to have GreenScreen assessments verified by a third party (or by CPA in some cases), strengthening the public assurance that the hazard assessment has been privately validated. At the same time, profilers generally claim copyright on the assessments that they produce. Making CHA knowledge private IP, rather than open-access by default, is arguably what enables firms like ToxServices and NSF International to earn income for their services, which after all involves much skill and careful work.

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[8] One example is that GreenScreen assessments have an expiration policy. They are considered invalid after 5 years, because CPA anticipates that the scientific data and perhaps even its own assessment methods may change, possibly invalidating older conclusions.

3.6 Testing CHA knowledge

If GreenScreen and its institutions and community constitute a knowledge commons, then how its attributes shape the testing and validation of knowledge is central to whether that knowledge might become socially robust. To probe this, I examine two cases of controversies or challenges to CHA knowledge, and how those challenges were resolved. In the first case, experts disagreed over hazard assessment results, engaging in a deeply technical debate. To resolve this, CPA invoked a formal conflict resolution process that they have prescribed. In the second case, some community members attempted to expand CHA knowledge in the commons, based on new interpretations of what was previously "settled" knowledge. This new knowledge production needed to be verified by the community before being accepted.

Disputed chemical assessments: Experts disagree

Given that toxicological and environmental data about chemicals are often incomplete and uncertain, the possibility that experts may disagree on hazard assessments is widely recognized in the community. The decentralized pattern of knowledge production that an "open-source" method like GreenScreen supports would seem to further encourage a proliferation of different assessments and conclusions about the same substances. This would simply continue the debates about indeterminate chemical knowledge.

In 2013, ToxServices conducted a GreenScreen assessment of the plasticizer diisononyl cyclohexane-1,2-dicarboxylate (DINCH), and the assessment was publicized as part of an academic report on safer alternative plasticizers (M. Becker 2013). The maker of that chemical, BASF, disputed the assessment. At issue was a single endpoint: endocrine activity. The profiler had assessed a "moderate" level of endocrine activity, but BASF strongly disagreed and provided detailed technical arguments and data supporting a "low" hazard level for endocrine activity (BASF 2013). This endpoint was the key factor determining whether the overall Benchmark score for DINCH would be 2 or 3, an important distinction. The parties to the conflict could not agree on a technical basis for resolving these incompatible interpretations. Such disagreements do not happen frequently, according to Whittaker, but they can sometimes reach an impasse:

> There are certain instances where we've just had to agree to disagree. [On] our interpretation of specific studies, or the absence of endpoints that should have been looked at in certain studies—in certain cases we've just had to say we're not going to agree upon a Benchmark score, or on the interpretation of a certain study. I've just learned, in the long run, that's just the way it goes.

The conflict over the assessment of DINCH activated CPA's "Benchmark Review Process" (Thorpe 2017), a formal conflict resolution protocol—another GreenScreen policy meant to ensure the validity or verifiability of GreenScreen assessments.[9] Using external experts, and with CPA acting as a neutral mediator, they used this protocol to reach a conclusion and produce a "harmonized" assessment that both parties must adopt. Each GreenScreen assessment involved must be amended to note and reflect the Benchmark Review. Institutionally, conflicts over GreenScreen assessments are treated as disagreements between experts—the broader community is not consulted or involved in any way. The validity of the final harmonized assessment is ostensibly assured by the process itself, the participants, and CPA's mediation. Given the stakeholders involved, it is not surprising that the entire process is designed to be compatible with corporate confidentiality. In this particular case, the harmonized assessment and Benchmark score for DINCH are not publicly available.

New interpretations of settled science: Chemical groups

Many CHA knowledge resources have incorporated elements of the GreenScreen, but perhaps the most commonly used element is the GreenScreen List Translator (GSLT). This is a screening protocol that identifies known high-hazard chemicals using "authoritative lists," or public data sources that are widely considered useful and valid for hazard identification (Clean Production Action 2020c, see also Chapter 2). For example, it uses the World Health Organization's IARC classifications of human carcinogenic potential (among other authoritative sources) to evaluate the cancer hazard endpoint. Authoritative lists and their interpretation as hazard information are considered to be "settled" knowledge by the community of GreenScreen users. For example, by accepting the GSLT methodology, these knowledge users also accept that if a substance has been classified by IARC as a "Group 1" carcinogen, then in the absence of any other evidence, it should be understood to have a high level of concern for cancer. GSLT codifies community-vetted interpretations of many scientific and regulatory information sources, enabling the practical re-use of many different sources of information within the framework of CHA. Moreover, community chemical data systems, like HBN's Pharos, enable users to access computer-generated GSLT scores for thousands of chemicals (see Chapter 2).

However, what was not settled (or even widely known) in the development of GSLT was that translating authoritative lists into consolidated chemical databases occasionally required expert judgments or challenging interpretations of which molecular substances are associated with which hazards. Scientists at HBN realized that there were gaps in how the GSLT methodology was being used to automatically screen chemicals through databases of authoritative lists. Pharos and other software tools (such as the commercial tool Toxnot) were not interpreting regulatory lists carefully and precisely enough when it came to defining groups of chemicals—such as "mercury compounds." As a result, these widely used online tools were failing to associate some substances with known hazards.

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[9] It is not only CPA and the GreenScreen method that struggle with conflicting results from profilers. The Cradle to Cradle Certified assessment program, the US EPA Safer Choice program, the CleanGredients program, and the ChemForward platform all have conflict resolution processes.

HBN started developing ways to fill in these "machine knowledge" gaps by systematically reinterpreting all of the authoritative lists of chemical *groups* and turning them into much larger lists of *individual* chemicals. This was necessary because Pharos, like many other data systems used in CHA, is built on the infrastructure of the CAS Registry: a de facto global standard chemical information system, which generally associates data with identifiers corresponding to unique molecular substances. HBN was tying to work around the shortfalls of a dominant chemical information infrastructure, so that it could be more successfully adapted to the goals of environmental health protection (Hepler-Smith 2019). This was done in an effort to improve some of the shared knowledge resources that the CHA community uses frequently.

However, this led to a situation where different data systems were operationalizing conflicting interpretations of the same regulatory lists. In turn, the users and developers of a range of standards and ecolabels that depend on automated GSLT scores began to notice that this information was changing in some cases, as "new" hazards became associated with chemicals in their data systems. Opening up settled knowledge had destabilized other resources in the network, and the community noticed new inconsistencies (ironically, even though they had not previously noticed the knowledge gaps).

To avoid continuing conflicts, CPA and HBN started an effort to standardize the interpretation of the chemical groups using community peer review. The aim was to make sure that this chemical grouping method would be accepted and considered as rigorous as the GreenScreen method itself. They organized several online presentations and discussions about the "chemical groups issue," which solicited community feedback on the chemical and toxicological basis for assigning molecular substances to "groups" with common hazard properties as well as practical considerations of how the community could agree on interpretations of chemical groups. CPA and HBN initiated a technical peer review of the chemical lists and groups, recruiting a small group of 4–5 volunteer chemistry experts from the CHA community, myself included. Together, these reviewers examined a sample of 80 different chemical groups drawn from authoritative lists. Each reviewer combed through lists of hundreds or thousands of individual substances that HBN had identified as belonging to each group, and compared these sets of substances against the scientific documentation of the groups provided by the authoritative sources. They discussed inconsistencies or problems with the methods or interpretations. Ultimately, the peer review process concluded after two years, having produced iterative improvements—but no major challenges—to the data analysis and interpretation methodology put forth by HBN. This work on identifying substances in chemical groups has become a standard (Clean Production Action 2018a) that is now also used by Toxnot to ensure that the data systems implementing the GSLT protocol are mutually consistent.

Legitimizing CHA knowledge

Based on how these controversies were resolved (Table 3.3), it appears that CHA knowledge is being verified either by subjecting it to community-defined tests of validity, or through formal conflict-resolution processes. In each case, the process of verifying new or contested knowledge is shaped by an institutional setting—the available rules and protocols—and by the possibilities that this setting offers to actors. In controversies over GreenScreen assessments, this includes the Benchmark Review Process, which is designed to manage disagreements by convening small groups of experts, as well as rules that protect the IP of all parties and keep the controversy within this closed group. Thus, the verification of GreenScreen assessments is likely to proceed via private vetting by an authoritative expert group. While there could also be community peer-review of GreenScreen assessments, this would only happen if the assessment in question were openly shared, or it would require modifications to the Benchmark Review Process.

Table 3.3: Two examples of contested knowledge and tests of validity in the CHA commons

	Disputed GreenScreen assessment	**Chemical groups in authoritative lists**
What is challenged	Chemical assessment conclusion; interpretation of toxicity data	Refining established methodology; reinterpreting settled knowledge
Challengers	Chemical company & profiler	NGO & standards groups
Formal protocol	Yes – Benchmark Review	No – new review process created
Mediator	CPA (formal)	CPA & HBN (informal)
Open process	No	Yes
Who participated	Only challengers, mediator, neutral experts	Toxicologists & chemists from community
Result	Harmonized assessment (confidential)	Ongoing peer review; new open standards created

These cases also reveal the community's expectations and demands about CHA knowledge and what characteristics it should have to be considered valid. Many stakeholders in the knowledge network express a demand for CHA knowledge to converge on clear conclusions about individual substances. Yet hazard assessment and classification conclusions are contingent on expert judgments and interpretations of uncertain data. The developers of CHA methodologies—not only GreenScreen, but also Cradle to Cradle Certified and US EPA Safer Choice—recognize that expert toxicologists can disagree in their conclusions. For a number of reasons, this is universally seen as a systems problem that needs to be minimized and managed for the CHA project to move forward. This is even stated as a matter of policy in the GreenScreen Terms of Use: "Only one GreenScreen Benchmark score from a Certified assessment may be assigned to a single chemical" (Clean Production Action 2019).

The demand for “one chemical, one score” comes from the ways that this community uses and exchanges knowledge. From the perspective of non-expert decision-makers, for example, they want to be assured that CHA assessment conclusions are reliable: that a competitor cannot simply hire a different consultant to get a different, more convenient answer. Furthermore, conflicting assessments of the same chemical could destabilize the many ways that GreenScreen assessment results are used as input to many other community knowledge resources—for example, in determining whether commercial products meet ecolabel requirements. Having conflicting conclusions underwritten by the GreenScreen methodology could also undermine the method as a boundary object: it could no longer be relied on as a standardized unit of meaning that transparently summarizes “the science” of chemical hazard in a way that is understandable to diverse stakeholders. Finally, the demand for “one answer” is ingrained in the information infrastructure of the CHA community, which privileges forms of knowledge that can be organized and sorted according to the identities of specific molecular substances. In some ways, the “one chemical, one score” policy allows the comparatively small CHA knowledge community to maintain interoperability with the massive industrial and regulatory “molecular bureaucracy” (Hepler-Smith 2019).

3.7 Socially robust knowledge?

How, and to what degree, is there socially robust knowledge being produced through the CHA knowledge commons? Based on the above empirical data and analysis of how the community produces, tests, and verifies knowledge, some limited and preliminary comparisons are possible between theory and observation. Table 3.4 summarizes these comparisons, looking at two kinds of “commoned” knowledge: the GreenScreen method and the chemical hazard assessments produced by using it. Theory suggests that socially robust knowledge is tested in the real world, produced and reviewed by an extended peer community, and produced through an iterative and participatory process.

The GreenScreen method itself appears to be an example of socially robust knowledge, with some caveats. It has withstood multiple social tests in a range of real-world contexts: it has been in the hands of an extended expert community since its inception; it has been applied numerous times in everyday design practice; and has gone through iterative, participatory modification to strengthen it. However, significant questions remain about the breadth and diversity of the knowledge community that has participated in developing and vetting GreenScreen. Representatives from a broad range of organizations have participated, including academics, governments, manufacturing companies, and environmental NGOs. However, the active participants have been mostly scientific and technical experts in toxicology and chemistry. Despite active debates about the technical details of the methodology and an iterative approach to including community input, it does not appear that this commons is deeply reconfiguring the politics of expertise. Actors who might provide additional rigorous challenges to the knowledge—such as health practitioners and representatives of an array of social movements focused on environmental health and justice—have not yet participated.

They may not see a clear way to evaluate the knowledge from their standpoint, because the entire CHA commons is currently framed in terms of producing reliable knowledge to design and select safer chemicals in industrial contexts—and is tightly focused on ways of understanding the toxicity of individual substances, as opposed to a more diverse range of human health, ecological, and social effects. The GreenScreen may be "socially robust" but only in a narrow sense. It is telling that most of the challenges to CHA knowledge production have come from the chemical industry, not from NGOs or social movements. As such, these challenges reflect the particular commercial interests of chemical companies.

Table 3.4: How commons attributes affect social characteristics of CHA knowledge

Socially robust knowledge	**GreenScreen method**	**GreenScreen assessments**
Tested in the real world	Yes; Enabled by community access to method and widespread use	Yes; but only among actors with direct access to assessments
Extended peer community	Yes; Enabled by open access but bounded by required scientific expertise	Possible but rare; Limited by lack of institutions and by protocols that protect private IP
Iterative, participatory testing & modification	Yes; Enabled by open access, institutions and protocols in method development	No; Limited by protocols that protect private IP; Limited by access to chemical hazard assessments

On the other hand, the knowledge produced using the GreenScreen method is not necessarily subjected to the same tests and iterative processes, and does not appear to have the same characteristics of socially robust knowledge. GreenScreen assessments are mostly produced and verified within closed groups of stakeholders, due to the IP-driven political economy of chemical knowledge. Institutions governing the verification of this type of knowledge support private vetting between experts rather than enabling or supporting community review. As a result, extended peer review is only possible informally and only if assessments have been made public. The lack of transparency around proprietary GreenScreen assessment practices may be closing off the possibility of CHA knowledge to become thoroughly socially robust. But arguably this outcome may seem to have very little importance to many of the stakeholders involved when it comes to judging the validity of GreenScreen knowledge. Because they are primarily technical and scientific experts who work within supply chain contexts, they may not see the need for more inclusive and participatory input, or for broader strengthening of public knowledge about chemicals.

Some users of CHA knowledge do pay close attention to the technical details and judgments that profilers make (such as evaluating the weight of evidence for hazard classifications). But several profilers and community members indicated that they believe the greatest demand from industry decision-makers is for "summary" hazard information (such as Benchmark scores) that can be used as decision aids without examining their technical details and evidentiary basis. Furthermore, GreenScreen knowledge is mostly used in contexts where decision-making does not need to be publicly justified at the chemical level. This could change, for example, if laws require businesses to submit publicly-accessible assessments to approve product sales. The California Safer Consumer Products (SCP) regulation provides a partial model for how this could happen (State of California 2012; Solomon, Hoang, and Reynolds 2019). SCP targets a limited number of "priority" chemicals and products already on the market, and requires their producers to submit alternatives analyses—including chemical hazard assessments—for agency review through an online information system (California Department of Toxic Substances Control 2017; California Department of Toxic Substances Control 2020a). Members of the public can read and comment on the analyses while the agency decides on its regulatory response. However, businesses may redact confidential information, and they are not required to use a systematic and transparent methodology like GreenScreen.

3.8 Commons dilemmas

The question of whether GreenScreen assessments should be a more publicly accessible form of knowledge touches on underlying tensions in the CHA community over the role of knowledge and social institutions in industrial change. A project by the NGO Environmental Defense Fund (EDF) serves as an example of these tensions. As a demonstration of how comprehensive hazard assessment can inform decision-making in chemical design and selection, EDF published and discussed the results of GreenScreen assessments for several commercially-used preservatives (Environmental Defense Fund 2017). The assessments were performed by ToxServices and made freely available as part of the project. In its report,

> EDF calls for the creation of an independent chemicals assessment clearinghouse that would provide comprehensive, structured, transparent, and comparable health and safety assessments of chemicals in a centralized, web-accessible repository. Operational standards would be established for qualifying assessors to develop and contribute assessments to the clearinghouse, ensuring quality assurance, and updating assessments to reflect the most current science—all with an eye toward producing assessments that are meaningful, actionable, and credible to actors along the supply chain. (Environmental Defense Fund 2017, p. 34)

In effect, EDF is proposing a CHA commons governed according to many of the same institutions and practices that exist around GreenScreen—but centralized, accessible, transparent, and "independent." The report's recommendations suggest that industry decision-makers would be the main stakeholders in the provision of CHA knowledge resources to inform chemical and product design, but EDF emphasizes the importance of "greater public access to chemical health and safety information" to enable comprehensive assessment work (Environmental Defense Fund 2017, p. 35). Discussing the report with me, lead author and EDF senior scientist Dr. Jennifer McPartland further emphasized the importance of public transparency of CHA knowledge in general, and specifically for building the credibility of chemical assessment conclusions:

> If somebody tells me that a chemical is a Benchmark 2, I have to take that at face value unless I can see the actual underlying analysis that was done to reach that conclusion. And because two well-meaning toxicologists can look at the same chemical and come up with different hazard characterizations, that makes it all the more important to have access into the work that was actually done.

The idea that there must only be one assessment result for each chemical may only stand up to societal testing if full information is publicly provided.

Yet, despite considerable community discussion of intentionally forming a CHA commons (e.g. the Chemical Hazard Data Commons discussion papers in 2014; see Chapter 2), the vision has proved challenging to realize. The main challenges, and how they relate to the production of socially robust knowledge, can be understood in terms of collective action dilemmas that knowledge commons are vulnerable to as a function of their institutions, community, and other characteristics. Three particular types of dilemmas are most relevant: the underproduction of knowledge resources in the commons, the privatization of knowledge, and pollution of knowledge.

One of the main challenges has been devising satisfactory institutional and economic arrangements to make more chemical assessments of particular substances openly available. "Underproduction" refers to this shortfall. Evaluating substances using GreenScreen or comparable methods is costly and resource-intensive, so the problem can be seen as a classical "underproduction of public goods" situation. The actors within the community that are most interested in producing public goods through the commons have also been the least able to create incentives for knowledge producers to do this. In an effort to support the commons, some profilers (notably ToxServices and NSF International) and some firms (Hewlett-Packard) have made some of their work publicly available for free. Some NGOs, like EDF, have funded and then publicized limited sets of chemical assessments. But neither of these models has yet been sustained or grown to a significant extent. Instead, CHA knowledge production occurs in a private-sector dominated market, which fails to aggregate the broader community's desire to know more about the chemicals that are being assessed.

By "privatization" I refer to the pattern of CHA knowledge being generated as private IP inaccessible to the community, whereas knowledge resources from the broader commons (such as the GreenScreen method) are being leveraged to produce this knowledge. Privatization is a result of both the institutional context of IP rights around chemical information, and the economic position of chemical profilers and private-sector service providers. This is not necessarily the same as "enclosure" or "appropriation," because already-existing knowledge resources are not being taken away. Rather, it is a corollary of underproduction: the knowledge that is not being produced as common resources is instead being produced as private property.

A third dilemma is how to institute effective systems and processes to validate CHA knowledge in the commons. This relates to the collective action problem of pollution—the degradation of a knowledge commons through unwanted contributions (C. Hess and Ostrom 2007, p. 61). Pollution of a chemical knowledge commons could include the manipulation of knowledge, the production of false or conflicting data, or "negative knowledge" that is considered disruptive by the community (Frickel, Gibbon, et al. 2010). For example, actors approaching the CHA knowledge community from an industry background rooted in risk assessment have occasionally tried to insert risk-based principles for evaluating chemical safety,[10] which conflict with the fundamental basis of hazard assessment (see Chapters 2 and 4 of this dissertation).

More frequently, it is mundane instances of conflicting chemical hazard assessment conclusions—even if they arise from legitimate differences in the interpretation of hazard data—that can "pollute" the commons. As discussed above, this contradicts community expectations about CHA knowledge and violates the GreenScreen Terms of Use. The GreenScreen Benchmark Review Process is one example of a quality-control system that addresses this, but it is not necessarily the only possible system. Community peer-review processes similar to those that produced the GreenScreen methodology could be adapted or expanded to resolve isolated conflicts between CHA conclusions. This would most likely require a clearly defined process with a definite conclusion and an authoritative actor (such as CPA) to make the process effective.[11]

These dilemmas affect the capacity of the CHA commons to produce socially robust knowledge. Privatization limits the ability of a sufficiently broad peer community to test, challenge, or verify knowledge. Institutional choices about how to assure the validity of CHA knowledge—such as by community review or by authoritative vetting—shape who can evaluate knowledge, and whose expertise will be taken into account. The epistemic politics of making these choices is at the heart of what makes knowledge socially robust.

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[10] According to Whittaker, this happens because GreenScreen is increasingly being applied to industry products and ingredients "that have always been formulated and selected and regulated under a risk-based paradigm." When hazard assessment indicates a high potential for harm, industry often responds by contesting CHA knowledge with claims that, "from a risk point of view, this is a safe chemical."

[11] Kelty (2008) has described how collaborative decision-making processes in open-source software development sometimes result in convergence on a favored technical solution, but sometimes result in a "fork" where two or more diverging approaches continue to exist, fragmenting both the community and the software project. In the collaborative review of CHA conclusions, this would most likely be considered an undesirable result, signifying a return to endless debate.

3.9 Institutional innovations

Recognizing these dilemmas, several groups have initiated or proposed alternative institutions and economic models for more effectively "commoning" CHA knowledge. While these institutional innovations are only now being tested, how they are constructed will likely affect the outcomes of the commons in terms of producing socially robust knowledge.

Collaborative funding

A number of NGO and business actors have proposed collaboratively funding chemical assessments. If a group of stakeholders can pool significant financial resources, then they can share the expense of hiring profilers to generate GreenScreen assessments for a selected set of substances. This could be, for example, one thousand substances that are used in large quantities in the stakeholders' respective industries or jurisdictions. Collaborative funding would leave the dominant IP institutions and economic structures untouched, adding only a new degree of collaboration between stakeholders who are knowledge users. Public policy could, in principle, drive this kind of collaboration: in the European Union, for example, the REACH regulation (European Commission 2006) required companies manufacturing or importing the same chemical substance to organize themselves into a "substance information exchange forum" (SIEF) with the aim of collectively generating the toxicological data needed to register that substance (Biedenkopf 2015; European Chemicals Agency n.d.[b]). Still, companies may fail to collaborate effectively for a number of reasons: they may have competing interests (Gubbels-van Hal and Pelkmans 2009) or, without policy drivers, they may not be able to identify a set chemicals that is relevant to all of them. Furthermore, the notion of collaborative funding typically leaves out of the equation the fact that hazard assessments need to be regularly updated as data and scientific tools evolve, meaning that costs will need to be incurred over and over again.

This model appears to have limited potential to generate knowledge that meets the broader demands—or the epistemic tests—of the community. Due to the financial resources and IP involved, collaborative funding is most likely to happen through private business consortia (as it does in REACH SIEFs). However, some have suggested—and even attempted[12]—an open "crowdfunding" model in which community members could make small financial contributions that would be aggregated toward assessing whichever substances they choose. While crowdfunding could potentially draw significant resources to the assessment of high-profile substances (for example, glyphosate or BPA), Whittaker pointed out to me that "a crowd won't know what chemicals are used in a supply chain." In other words, selecting which specific substances to assess requires that actors already have enough insider knowledge to understand where more knowledge is needed, and this funding model does nothing to solve the underlying lack of transparency in manufacturing industries.

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[12] Toxnot, an online chemicals management platform, launched in 2016 with a campaign to crowdfund GreenScreen assessments.

Platforms

Rather than waiting for interested actors to pool their resources and purchase assessments on a chemical-by-chemical basis, an increasingly significant approach is for profilers to pool the knowledge that *they* generate and offer access to whole collections of CHA knowledge to limited groups of subscribers, in controlled ways. Such chemical knowledge "platforms" are rapidly emerging, providing hazard assessment "as a service."[13] These approaches can potentially enable more actors to pay lower fees to access a larger body of CHA knowledge, by achieving economies of scale and spreading assessment and maintenance costs over many subscribers. Thus, they address the economic issues that lead to the underproduction of CHA knowledge.

I refer to such initiatives as *platforms* because they share a number of features with digital services businesses, such as streaming media platforms. They are systems of closely linked knowledge products and services, which provide additional value by coordinating multiple functions. These services and functions may include chemical data management, supply-chain information tracking, compliance checking for regulatory or eco-certification requirements, and the ability to organize chemical information together with product specifications. Importantly, platforms include organizational and technological mechanisms for protecting the IP of clients—for example, ensuring that one clients' product chemical ingredients are not disclosed to other clients. Scivera, the company that pioneered this model, provides a variety of tools and services specific to business chemicals management as part of an offering that includes access to a digitally curated knowledge base of chemical assessments. More recently, two GreenScreen profiler firms—ToxServices and NSF International—began offering access to their shared ToxFMD database of chemical assessment knowledge as a subscription service (ToxServices LLC 2019). The new non-profit organization ChemForward, which aims to expand access to CHA knowledge, is building a repository of profiler-contributed chemical assessments and offers subscriptions to "chemical alternatives assessment portfolios" (ChemForward 2020).

How these various platform initiatives alter IP and access arrangements is a key factor in whether they can contribute to the production of socially robust CHA knowledge. It is too soon to tell, but there is at least a possibility that platforms or other collaborative initiatives might unsettle some of the IP institutions governing chemical knowledge. Offering CHA knowledge in the form of whole databases rather than individual reports is an incremental shift, lowering barriers to knowledge about individual substances while maintaining the confidentiality of proprietary formulations and products. For instance, as of 2018, the ToxFMD Database offers a free subscription level that gives users access to full GreenScreen assessments for all substances that were assessed as Benchmark 1—the most hazardous category. Whittaker explained that they are providing these particular assessments for free "because everyone wants to know, what are the Benchmark 1 [chemicals], but nobody wants to pay

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[13] Or to use economic terminology, organizations are offering CHA knowledge as "club goods" (C. Hess and Ostrom 2007).

for it."[14] But the overall goal is not necessarily to provide open-access public goods. A knowledge commons, after all, is not synonymous with open access: it can mean sharing knowledge as common property within a bounded community. The question is how these platforms will draw the boundaries.

While they may be effective in solving the underproduction dilemma, platforms might not ease community tensions around the privatization of knowledge. By encouraging more and more new CHA knowledge to be generated within these specific and ultimately proprietary arrangements—in the absence of any open-access alternative—the platform business model would seem to *increase* the trend of privatization. The fact that platforms may compete with one another for a larger share of the community's knowledge production and participation could potentially divide the commons into privatized fragments. This is not to say that platform operators are seeking to dominate a market for proprietary chemical knowledge. They see themselves as part of a broader knowledge community, but at the same time they have economic interests and legal obligations that are sometimes aligned with and sometimes at odds with community constituents. For example, while the ToxFMD Database offers free Benchmark 1 chemical assessments, all of their assessments are provided under copyright restrictions. Whittaker emphasized that this arrangement is meant to ensure economic fairness to the organizations involved, and at the same time to obviate and discourage the informal circulation of copied hazard assessments—which pollutes the commons with out-of-date and unreliable information.

How these platforms will approach the verification and "quality control" of CHA knowledge will also be central to whether they can produce socially robust knowledge. Peer review and conflict resolution within individual organizations (e.g. Scivera) or among business and NGO partnerships (e.g. ToxFMD, ChemForward) is not necessarily equivalent to an extended group of experts, or community peer review. Among community members, CHA platforms are generally seen as "business-to-business solutions" rather than community information infrastructures. They could conceivably integrate community review mechanisms to a limited degree—just as they can offer limited degrees of public access. But how this would work in practice is unclear, and the same tensions between community and private knowledge are likely to surface. Can a platform be a commons—an intentional cultivation of shared knowledge? Or is it necessarily a service, privileging a one-way asymmetric flow of information?

Leverage points outside the commons

There are possibilities for institutional change outside of the actors who directly produce and use hazard assessments. An extensive network of actors, resources, and relationships (only partially visualized in Figure 3.1) may afford new means of encouraging the production and socially robust validation of chemical knowledge. One approach is for governments to require

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[14] Arguably, accessing the details of Benchmark 1 chemical assessments may represent much a lower economic value to clients than the Benchmark 2–4 chemicals, which are not as highly hazardous and therefore more relevant for safer substitution.

and fund the production of comprehensive, open-access CHA knowledge. However, for this knowledge to become socially robust, government intervention would also need to leave intact—and even strengthen—the participatory institutions and processes of the knowledge commons. It is an open question whether this could be done without subsuming CHA into the domain of regulatory science.

Another strategy is to motivate product manufacturers to supply the necessary resources for producing and openly publishing open-access chemical assessments. This could occur through market-based governance: a network of certifications, ecolabels, and environmentally preferred purchasing programs links manufacturers' chemical choices to possible market advantages for their products—although the effectiveness of these links has not been empirically established (Geiser 2015, Ch. 7). Many of these ecolabels and product sustainability standards already involve the production and use of chemical hazard assessments. These programs could—as Shari Franjevic suggested to me—institute a requirement that for products to be certified as "green," CHA knowledge must be contributed to the public domain. Product makers, not chemical profilers, would take on the economic costs. The Cradle to Cradle Certified program, for example, already includes many of these elements, except that—like other certification programs—it is designed to enable an evaluation of specific products, not to produce public knowledge about chemical substances. As such, hazard information is organized, summarized, and published only in connection with certified products (e.g., Cradle to Cradle Products Innovation Institute 2020). The underlying chemical assessments are currently owned by the independent profilers that produce them and are not made public—and therefore are not open to community review. Furthermore, existing product sustainability standards are designed to protect supply-chain confidential business information—for example, the Health Product Declaration Open Standard allows manufacturers to disclose hazardous ingredients while keeping their chemical identity secret (HPD Collaborative 2018, see Chapter 4). Thus, to potentially produce SRK, product certification programs would need greater institutional openness and a capacity to move beyond what is currently a one-directional flow of knowledge from profilers to customers.

These possibilities are merely ideas, and they are untested. Systems analysts use the metaphor of "leverage points" to express the idea that small changes at certain points may produce large shifts in the overall outcomes of a system. Meadows (2008, pp. 145–165) cautions that in many systems, the leverage points—the most effective places to intervene—are not easy to identify; and if found, it is often unclear which way to push the "levers" and difficult to predict what will happen. Regulatory and market interventions into knowledge networks may be leverage points, but how should they be leveraged? I can only offer these ideas as mere clues for future experiments in the governance of chemical knowledge.

3.10 Conclusions

A knowledge commons is arguably emerging through the interrelated efforts of many stakeholders to substitute hazardous chemicals with safer alternatives. Its outlines are blurry, and it is characterized by partial agreements and overlapping relationships in a network of heterogeneous knowledge resources. A tension between public and private knowledge pervades the community's efforts to build commons institutions and practices. Yet this community has been instrumental in developing technical capacity for safer chemical substitution and inserting chemical hazard assessment into a wide range of decision-making contexts—including business practices and public policies. The GreenScreen method is a prototypical example of "commoned" CHA knowledge, and it in turn fosters further knowledge production in a decentralized commons. GreenScreen's broad credibility and stability across multiple contexts of application is a commons effort, and it exhibits key characteristics of socially robust knowledge.

Like many knowledge commons, this one is vulnerable to dilemmas related to the underproduction, privatization, and pollution of community knowledge. Community members and organizations have had to make institutional choices about who can access, use, and produce knowledge; who can test, challenge, and evaluate knowledge; and whose expertise will be taken into account. The epistemic politics of these choices is at the heart of what makes knowledge socially robust—or not. This nascent knowledge commons is emerging against the background of an industry backed by powerful intellectual property institutions and deeply ingrained information infrastructure. Its knowledge community lacks actors and institutions with sufficient potency to escape a politics of chemical knowledge that is based in confidentiality and reductionist analysis of harm on a molecule-by-molecule basis. The commons does not have any way of opening up private knowledge to community scrutiny. As a result, even the community's socially robust tools (such as GreenScreen) cannot easily produce socially robust chemical knowledge. The institutions that produced GreenScreen—open access, community peer review, and iterative participatory validation—cannot be replicated in the assessment of individual substances.

This study, although it is limited and cannot be generalized, suggests that knowledge commons can be sites for the production of socially robust knowledge. However, this depends critically on the openness of the commons—of its knowledge resources, community, and processes of knowledge production and validation. This openness, in turn, is shaped by institutional choices that may be constrained or compromised by the background conditions in which the commons exists.

Chapter 4

Green design tools: Building values and politics into material choices

Akos Kokai, Alastair Iles, and Christine Meisner Rosen

Green design tools are emerging as a new response to the dilemmas that architects and designers face in preventing the toxic impacts of building construction. Environmental health advocates, scientists, and consulting firms are stepping in to provide designers with new tools—including science-based assessment methods, standards, databases, and software—intended to help structure and inform decision-making in sustainable design. We argue that green design tools play an important but largely uninvestigated role in giving designers new forms of influence while mediating how designers' values are translated into actual design choices. Tool makers embed their own values and politics into the construction of the tools, which function as "black boxes"—their internal operations are understood as less important than their outputs for informing sustainable design. Using the green building movement as a case study, we consider three tools for selecting environmentally benign materials: the GreenScreen for Safer Chemicals, Pharos, and the Health Product Declaration. Examining controversies about the scientific validity of green design tools, we suggest that they are rooted in value conflicts and tensions in the politics of chemical knowledge. Transparency about values and politics among tool developers and users could strengthen the legitimacy and credibility of green design tools.

4.1 Introduction

An architect consults the manufacturer's documentation about an energy-efficient fiberglass window that she is about to select for her latest green building project. Apparently the window sealant contains a solvent called toluene—a chemical name that sounds vaguely familiar, perhaps because it's also an air pollutant emitted by petrochemical refineries in her local area. As a building product, the window has "green" credentials: it meets the environmental criteria of the highly-regarded Living Building Challenge, a sustainable building certification program. But could it be toxic? Curious, she logs into a community website for architects concerned with safer materials and asks her colleagues for advice. Sure enough, toluene is linked to reproductive, developmental, and neurological toxicity from chronic low-level exposures—even though it does not appear on some of the many corporate "red lists" of chemicals to avoid in buildings. Should she be concerned? If she specifies this energy-saving window in her design, will it slowly release small quantities of toluene into the air that the building occupants breathe?

Architects and designers face dilemmas about how to attend to the harmful effects of the industrial materials that make up the built environment. As in our partly-fictional example, they must navigate multiple incomplete and sometimes contradictory forms of environmental health knowledge. Even if well-informed, "green" design choices aiming to protect health and the environment frequently involve trade-offs between different impacts. For example, building materials and construction practices introduced for energy-efficiency gains have had the unintended consequences of exposing building occupants to worse indoor air quality (Steinemann, Wargocki, and Rismanchi 2017) and construction workers to substances that endanger their health (Guo et al. 2017). After decades of awareness that building materials can emit pollutants that affect human health, knowledge of these effects and how to effectively reduce them is still emerging (White and Pyke 2016; Dodson et al. 2017; Zimmer and Ha 2017). Moreover, designers have limited ways of influencing the larger network of technological choices in the industrial materials system that contribute to environmental health harm, because these are often part of a socio-technical structure that is impervious to deep changes.

Green design tools are emerging as a new response to these dilemmas, and as an effort by a number of groups to reshape the material economy by intervening in design work. Environmental health advocates, scientists, and consulting firms are stepping in to provide designers with new tools to help them make informed decisions about the material consequences of their work (Goodwin Robbins et al. 2019). We use the term design broadly to encompass all aspects of the intentional development of material technologies, products, industrial processes, and built environments. Design involves work by scientists, engineers, product designers, company managers, architects, builders, and so on (Woodhouse and Patton 2004; Woodhouse and Breyman 2005). Green design tools include knowledge resources, science-based assessment methods, standards, databases, and computer programs that are all intended to help structure and inform decision-making in sustainable design. We focus on design tools that address the human and environmental health hazards of building materials, because this has been a particularly active area of tool-building.

We argue that green design tools play a key role in mediating whether and how designers' values are translated into actual design choices; and at the same time, they embed the perspectives, values, and politics of their developers. Green design tools extend designers' agency to intervene in the materials system by offering new capabilities to discriminate between potential material choices—for instance, based on evaluating and comparing their toxicity. What is less evident is how such tools mediate decision-making about materials in design processes by summing up toxicological and environmental knowledge in databases and algorithms, and by translating into actual designs choices about what risks and impacts to prioritize. Green design tools therefore function as "black boxes" that enfold complex scientific and interpretive work in ways that are not visible to their users, and that reflect the values, priorities, and assumptions of their makers.

In constructing design tools, tool developers may inadvertently limit the ability of users to learn about chemical issues or critically appraise how the industrial chemicals/materials system might be different. This makes green design tools vulnerable in ways that echo many of the problems of regulatory science. When green design tools are contested, controversies that appear to be about their scientific validity may instead be rooted in tensions between implicit value judgments and interpretations of chemical knowledge. We argue that all possible ways of evaluating toxic harm involve value judgments, and that the prevalent discourse about hazard-based design tools misses this point. Ultimately, selecting a given tool is itself a value judgement. To strengthen the legitimacy and credibility of green design tools, we suggest that designers and tool developers should be aware of and transparent about the values and politics built into the tools.

4.2 Values and politics in chemical knowledge

Value-based decision-making permeates the production of scientific knowledge about chemicals. Jasanoff (1990) argues "regulatory science" is a hybrid of policy and scientific knowledge. The regulatory science that developed together with twentieth-century environmental policy has come to define and dominate understandings of how toxic substances cause harm, such as by positing the existence of acceptable risks and safe levels of exposure (Boudia and Jas 2013). The concept of risk is central to how regulatory regimes have sought to reduce and manage chemical pollutants without eliminating their industrial sources (Boyd 2012; Boudia 2014). Risk refers to measures of harm that express the probability and magnitude of health effects on human populations. Risk is commonly understood as a function of hazard (the inherent potential of a substance to cause harm), exposure, population vulnerability, and other factors—which can in principle be quantified using the tools and techniques of risk assessment.

How values influence the use of science in risk assessment and management is particularly relevant to green design tools. Assessing chemical risks for regulatory purposes calls for interpretation of scientific evidence typically characterized by high uncertainty, data gaps, and incomplete or evolving understanding of toxic effects. To act on such evidence, researchers and decision-makers must resort to value judgments, interpretation of extant chemical knowledge, and ethical reasoning where the evidence is insufficient. For example, recent research examines the social, political, and economic influences on regulatory agencies' risk assessments for determining acceptable levels of perfluorinated chemicals in drinking water (Cordner et al. 2019). Douglas (2000; 2009) identifies many legitimate and necessary, yet value-laden, methodological choices in toxicology and risk assessment. These include setting thresholds of statistical significance, classifying borderline experimental results (e.g. as normal or abnormal tissue samples), selecting appropriate models or assumptions for extrapolating quantitative dose-response relationships, and accepting or rejecting hypotheses about cause-effect relationships. These interpretive choices are often contested in contentious debates pitting the protection of public health against industry's economic interests (e.g. concerning the safety of BPA: Vogel 2013). Rather than dismissing regulatory science as "political," this scholarship critically foregrounds the role of values and value conflicts in evidence-based democratic policy-making (Fernández Pinto and Hicks 2019). For example, policy-makers can choose to adopt the precautionary principle as a guide for decision-making in the face of scientific uncertainty, although this has been recognized mostly in hindsight (European Environment Agency 2001; European Environment Agency 2013).

Yet existing environmental policies have failed to prevent the permanent pollution of the biosphere (Boudia and Jas 2014), and the dilemmas policy-makers face suggest even greater challenges when it comes to making and using tools to inform green design. The chemical knowledge systems of industrial and regulatory science—which privilege establishing direct, isolated relationships between individual molecular substances, industrial activities, polluted localities, and health effects—have been unable to grasp the complex reality of industrial materials in the environment, with their many social and biophysical relations (Murphy 2017; Boudia, Creager, et al. 2018; Hepler-Smith 2019). Unexpected interactions, lengthy timescales or confounding delays between cause and effect, ubiquitous presence, and the sheer scale of global pollution have again and again challenged established regulatory-scientific models and definitions of harm (Liboiron 2016). Endocrine-disrupting chemicals, which invalidated key science/policy assumptions about health effects at low doses, are a case in point (Bergman et al. 2013). Policy-makers' reductionist compartmentalization of the world and our inattention to residual categories—"matter that is not supposed to matter" (Boudia, Creager, et al. 2018)—has backfired, creating environmental health inequalities and institutionalizing ignorance. The technocratic politics of uncertainty and risk is just one facet of a deeper "toxic politics" (Liboiron, Tironi, and Calvillo 2018) where power relations are structurally embedded into how toxic harm is understood and acted upon (or ignored) through systems of scientific knowledge and governance.

Can green design tools exert a political agency of their own, and if so, can it counter the prevailing toxic politics? In Winner's (1980) analysis, technologies are political because specific technical arrangements can have real effects on the ordering and structuring of society. The processes of technological development are in turn shaped by a multitude of systemic biases, such as unequally distributed power to make value-laden technical choices, which can lead to arrangements that structurally favor some interests over others. STS scholars have extended this analysis to investigate how social values and politics enter design, with or without conscious decisions by designers and participation by society (Nieusma 2004; Woodhouse and Patton 2004). Scientific tools are technical artifacts, and early STS research has explored how they are constructed and stabilized in scientific laboratory practices (Clarke and Fujimura 1992).

However, there has been little attention to technical tools used by designers. Liboiron has linked Winner's insights to the politics of scientific tools, in her account of developing an environmental monitoring device that attempts to resist asymmetries in power and agency between local communities, polluting industries, and academic institutions (Liboiron 2017). Green design tools (as we will describe below) are more like scientific information systems; STS scholarship has shown how such systems can privilege particular sets of values and perspectives (Bowker and Star 1999; Bowker 2000). Tool developers in scientific fields increasingly make use of algorithms to help automate information retrieval and classification and inform decision-making. Current research raises serious concerns about the ability of developers to attend to the social agency of algorithms, particularly the ways that they can enact systemic oppression by amplifying racial biases associated with their inputs, outputs, or contexts of application (Gianfrancesco et al. 2018; Noble 2018; Benjamin 2019). Green design tools are unlikely to exhibit the same forms of social bias—but they may instead reproduce the uneven politics of chemical knowledge.

4.3 Green design tools in the building sector

Green design tools are knowledge resources that can inform decision-making in architecture and building engineering by enabling the prospective assessment of environmental impacts of designs and ultimately the selection of materials and products that are safer for human health and the environment. Many resources can function as design tools in green building, including assessment methods, rating systems, certification standards, databases, and computer programs (Haapio and Viitaniemi 2008; Zuo et al. 2017). These tools address many aspects of building design and construction ranging from the choice of products and materials to the operation and maintenance of buildings. Green building has traditionally focused much more on assessing and reducing energy and resource use than on the environmental health hazards of materials (Goodwin Robbins et al. 2019). Existing design tools reflect this focus, with architects and engineers until recently lacking actionable information to guide sustainable material selection (Franzoni 2011). Tools do exist for reducing the life cycle impacts of chemical substances in industrial processes (e.g., Bare 2011) and for reducing chemical toxicity at the molecular level (Faulkner et al. 2017), but these tools are too removed from building design to be realistically applicable. We therefore focus on green design tools that address chemical hazards and have been made accessible to building designers.

A variety of non-profit organizations and private-sector firms develop green design tools in response to perceived gaps (or business opportunities) in industry decision-making. Some NGOs active in environmental health and policy advocacy, like the Sweden-based ChemSec and the US-based Healthy Building Network (HBN), seek to influence industry practices, markets, and supply chains—to favor safer chemicals and materials—by furnishing the tools that industry and government have failed to develop by themselves.[1] To make design tools,

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[1] For an example outside the green building sector: one of ChemSec's tools is the Substitute It Now (SIN) List, a database that companies use to identify and avoid substances that are likely to face future EU

these organizations cultivate scientific and technical expertise among their staff, as well as partnerships with industry actors and experts. Indeed, many NGOs that make tools also have close financial ties with businesses: some generate income from consulting or contract services; others, like the Health Product Declaration Collaborative, are supported entirely by industry partners (HPD Collaborative 2020c). A range of commercial firms also develop for-profit green design tools and market them as products or services that can also help businesses outsource some of the work of green design. For example, the US-based company Scivera provides software platforms and services for toxicological assessment, business data management, and product stewardship. Designers in the apparel industry use Scivera's tools to inform their chemical and material selections, such as selecting safer textile finishes and dyes (Rinkevich 2018). All of these tool makers situate their work in a project to change industries, and they can be seen as participants in the "alternative industrial movements" of green building and green chemistry (Woodhouse and Breyman 2005; D. J. Hess 2007).

Green design tools share two broad functional characteristics. First, these tools organize and make sense of the information that is needed to understand the material health consequences of design choices. They identify information requirements (for example, by collecting, or instructing users how to collect, detailed knowledge of a product's chemical makeup), and they guide users to select the most relevant information. Second, they provide a means to measure success or failure in some aspect of green design. Tools typically include ways of interpreting data to enable assessments (e.g. technical criteria for safety), and ways of integrating and summarizing these assessments to produce decisions aids (for example, a rating system for material health hazards). Tool developers may use knowledge from several scientific disciplines—such as environmental chemistry, toxicology, exposure science, and epidemiology—to construct green design tools, but this is no simple matter. Available scientific knowledge is typically incomplete, having significant gaps and many sources of uncertainty. Furthermore, the many dimensions of environmental health impacts means that harm, or safety, cannot be reduced to simple metrics like efficiency ratios or numeric scores.

Three distinct but interrelated green design tools have become instrumental in green building: the GreenScreen for Safer Chemicals, HBN's Pharos, and the Health Product Declaration Open Standard. We analyzed these tools to understand how values and politics inform the technical choices made in their development. We interviewed professionals involved in the development and use of these tools to investigate the goals and underlying principles of the tools, the processes of their development, and how they are put into practice by designers.[2]

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regulatory controls because of their hazard properties (ChemSec 2019a).

[2] We interviewed 33 professionals involved in the development and use of green design tools, focusing on tools used in the building sector but also including tools that more generally address chemical hazard. We collected relevant documentation of tools themselves (such as publications, presentations, technical specifications, guidance, and licenses or terms of use). We conducted content analysis on these data using ATLAS.ti.

GreenScreen for Safer Chemicals

GreenScreen is an open methodology for multi-endpoint chemical hazard assessment developed by the US-based organization Clean Production Action (2020d). GreenScreen, described in detail by Heine and Franjevic (2013), can be used to systematically compare different chemical substances, based on their hazard properties. The methodology uses scientific evidence to classify hazards from "very low" to "very high" across twenty categories of human and environmental health effects. It then uses criteria and a decision logic to summarize those hazards in an overall rating on a scale from highest concern (Benchmark 1) to lowest concern (Benchmark 4). GreenScreen is not a piece of software or a service: human practitioners must carry out the work of conducting the assessment and generating the full GreenScreen report along with these hazard indicators. Once that is done, however, the GreenScreen Benchmark scores provide a simple, understandable indicator; designers use them to identify hazardous chemicals in products and materials and to select safer substances. Through the Benchmark system, its decision logic and algorithms, GreenScreen enfolds complex assessment criteria and logic in simple pieces of information that can be communicated between scientists, designers, suppliers, and other actors.

Performing a GreenScreen assessment requires knowledge of toxicology and chemistry, and it involves retrieving, organizing, and evaluating complex sets of chemical and toxicological information. In contrast, applying the Benchmark score in green design does not necessarily require any knowledge of how the scoring works. GreenScreen also includes a simpler methodology called GreenScreen List Translator (GSLT), which can be used to judge whether or not a chemical is already known to be of high concern. This is done by applying an algorithm based on the full GreenScreen criteria and using existing publicly available chemical assessments, which have been published by government and scientific sources that the GreenScreen developers consider to be authoritative (Clean Production Action 2020c). Software tools such as Pharos (described below) have automated this process, making GSLT Benchmark scores immediately available for all chemicals online. However, GSLT scores are less informative than full GreenScreen assessments because they do not involve the open-ended and potentially far deeper assessment process that practitioners carry out.

Pharos

Pharos is a web-based tool that provides curated information about chemical substances from a large number of public sources, including information about toxicity, industrial use, and independently researched information about the chemical makeup of over a hundred categories of building products (Healthy Building Network 2020b). Architects and designers use Pharos to inform building product selection with detailed knowledge of chemical composition and hazards. The US-based organization HBN originally developed Pharos as an information intervention (Kokai and Iles 2020) into the building products market: HBN believed that if designers could easily learn about the material hazards and environmental impacts of specific building products, they could more clearly express the green building sector's market preferences for safer products to manufacturers.

Pharos presents information about building products in ways that are accessible to designers—for example, using the construction industry's MasterFormat classification system to refer to generic types of products—but reframes products and materials through the lens of their health hazards and chemical relationships. Users can quickly discover whether a particular type of building product contains toxic substances by looking at a "roll-up" summarizing the most hazardous of its known chemical contents. Pharos also highlights chemicals that may be indirectly related to the product, as manufacturing inputs or trace impurities. In this sense, the developers of Pharos are encouraging designers to attend to the "matter that is not supposed to not matter" (Boudia, Creager, et al. 2018) that traditional regulatory systems ignore.

Pharos has broadened its scope beyond the building industry to serve as a more general reference tool for understanding chemical hazards. Part of this broadening has been an adoption of the GreenScreen as an information infrastructure: Pharos presents hazard information graphically, organized using the concepts and categories provided by the GreenScreen system; it also computes GSLT scores and provides a repository of publicly-available full GreenScreen assessments of chemical substances.

Health Product Declaration Open Standard

The Health Product Declaration (HPD) is a standard for communicating the chemical makeup and associated environmental health hazards of building products, developed by the US-based organization HPD Collaborative (2020a). Manufacturers complete HPD documents describing their products, which are then distributed to architects, designers, and commercial clients along with traditional marketing information. Designers then use these manufacturer declarations to understand and compare the material hazard properties of each product. The HPD standard requires manufacturers to disclose all known health hazards attributable to chemicals ingredients, as understood using the GreenScreen Benchmark system and using a set of "priority lists" designating chemicals of concern. However, manufacturers have some flexibility to choose how thoroughly they disclose chemical ingredients.[3] All information from HPDs is collected in a public repository, which designers can access for free.

4.4 Creating agency in green design

The structure and organization of the industrial materials system strongly shape the possibilities for sustainable design. Designers seeking to reduce the life-cycle environmental health impacts of buildings must trace those impacts back to *building product* design and manufacture, from there to the design and manufacture of industrial *materials*, and ultimately to the

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[3] HPD is not the only building product transparency standard. The Declare label (International Living Future Institute 2019) performs a similar function, but has less stringent requirements for hazard disclosure.

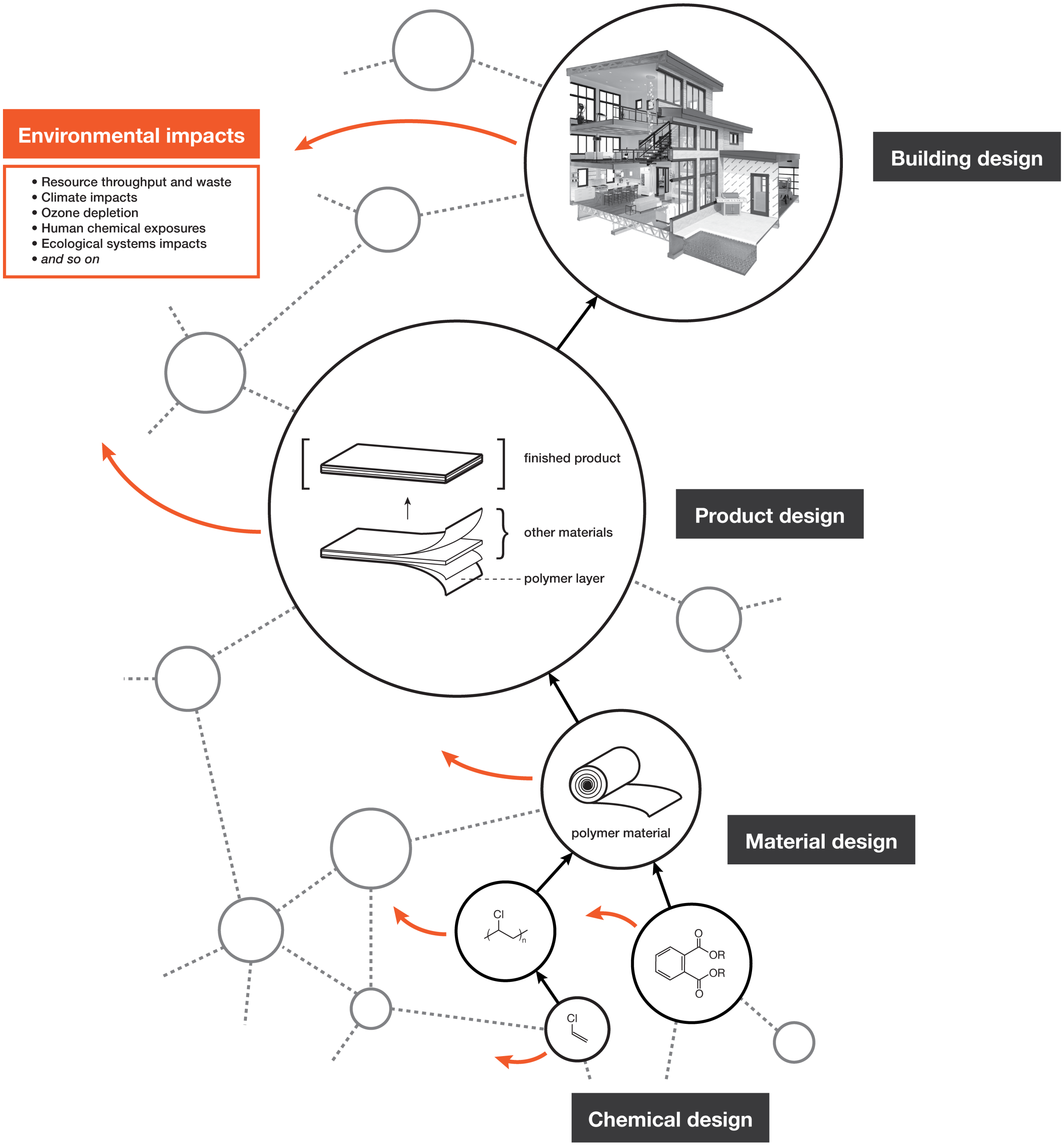

Figure 4.1:

Environmental impacts result from a multi-layered network of relationships in the industrial materials system[4] level of *chemical* design and production (Figure 4.1). Designers face barriers in exerting their influence through this multi-layered network of technical and social relationships. The industrial materials system imposes what Dean Nieusma calls “agency-structure tensions” that function to preserve the status quo against the efforts of interventionist designers (Nieusma 2004). These include dominant social assumptions about what designers should know and care about, as well as the dominant economic incentives of clients, product manufacturers, and chemical suppliers.

Green building designers must push back against these structuring forces. Green design tools help them to exert new forms of influence through the materials system, while also mediating that influence in subtle ways. By using these tools, designers can make technical demands on products, materials, and their manufacturers in ways that were not previously possible.

First, tools give designers the capacity to access information about the chemical makeup and health hazard properties of building products. Over the past decade, green building advocates and firms have increasingly promoted greater “transparency” in building products, contending that chemical ingredients should be tracked, evaluated, and disclosed by product manufacturers so that designers can choose less hazardous products (Geiser 2014). But achieving transparency is a struggle, because manufacturers rarely know or even try to collect chemical and toxicological details about the materials they buy from their suppliers. In the US, no regulations have required full disclosure of product compositions or full toxicological testing of chemicals. Instead, long-standing industry norms of trade secrecy have inhibited the flow of information through supply chains (Scruggs and Ortolano 2011).

The HPD Open Standard has helped create the limited transparency that now exists, despite these deeply ingrained industrial norms and knowledge gaps. In 2014, a number of major design firms began demanding that manufacturers submit HPDs as a precondition for considering their products in new projects (Weeks 2013). A major driver for adopting of the HPD standard is the widely-used LEED green building rating system.[5] In 2014, LEED added a few “material health” credits that reward building projects if they use products with fully disclosed chemical ingredients, or products that are documented to avoid certain high-hazard chemical ingredients (US Green Building Council 2019). The HPD public repository now contains over 4600 declarations (HPD Collaborative 2020b), but industry experts estimate that this represents a “only a fraction of the tens of thousands of building product variants” on the market (Goodwin Robbins et al. 2019).

Second, green design tools enable designers to insert knowledge from chemical and environmental health sciences into their work practices. Whereas the chemistry of building materials has historically been opaque and off-limits to architects and interior designers, it now seems to be increasingly part of the territory in which they practice design. The archi-

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[4] This figure is available under a Creative Commons Attribution-Share Alike 4.0 International License at https://kaios.net/assets/materials-system.png. The figure contains an architectural rendering by Wikimedia Commons user Skieridaho, used under a Creative Commons Attribution-Share Alike 4.0 International License. Original image available at: https://commons.wikimedia.org/wiki/File:3D_Home_Cut-Away_.png

[5] For a review of green building rating systems, see Doan et al. (2017).

tecture firm Perkins+Will developed one of the early and conceptually simple design tools in the industry: the P+W Precautionary List. Perkins+Will (2019) selected a set of substances of concern in collaboration with external scientific experts. The P+W Precautionary List still serves as a reference point for the firm's designers about chemicals that should be avoided in buildings, and it is one of several so-called "red lists" circulated throughout the industry. Many designers now deploy several green design tools—including GreenScreen, HPD, Pharos, and others—as part of a growing suite of knowledge resources. These resources enable them to interrogate the makeup of products and materials and to expose potential health hazards.[6]

Green design tools that expand transparency are performing a political function. They seek to redistribute some knowledge and power from industry actors—who previously held exclusively authority over material design—to designers. Through these tools, designers now have the ability to make demands of those actors and to hold them accountable, at least in limited ways.

This can take the form of new information flows and feedbacks between designers and manufacturers, in which designers are able to exert new (albeit indirect) forms of influence. According to one informant, the process of completing an HPD can sometimes trigger manufacturers to re-evaluate the product design: they may rather substitute or eliminate a GreenScreen Benchmark 1 ingredient, than disclose the high hazard that it presents. To some extent, then, the market preferences of the green building sector are being transmitted through the use of disclosure mechanisms like HPD, with their intervening layers of interpretation. In a more common scenario, designers are unsatisfied with how little they still understand about product hazards based on the information manufacturers provide.[7] Designers often reach out to manufacturer representatives and engage them in a dialogue to fill gaps in the environmental health knowledge about the product. They use their own independent research—as well as knowledge gained from other green design tools—to investigate and push back on manufacturers' lack of transparency or dubious claims, persuading representatives to track down more detailed information. Designers described essentially *educating* manufacturer representatives about why questions of chemical hazard are important.[8]

By making scientific knowledge and analytical frameworks available to designers, the tools mediate whether and how designers' values are translated into technical choices. Most architects interested in safer materials rely heavily on the outputs and interfaces of green

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[6] Speaking about the resistance she and her colleagues faced from clients, manufacturers, and other actors in the building industry, one architect highlighted the importance of having these scientific knowledge resources available to back up her decision-making authority, despite her own understanding of their limitations.

[7] In using the HPD standard, manufacturers can choose a high reporting threshold for chemical ingredients (e.g., 1% as opposed to 0.01%); they can avoid listing potential trace impurities, and they can keep chemical names confidential (as long as the hazards are disclosed). Many product makers choose to satisfy only minimal requirements.

[8] In one poignant account of such a dialogue, a sales representative became aware that the product they were marketing contained a toxic substance that had previously contaminated their own family's drinking water.

design tools to inform decisions: chemical "red lists," Benchmark scores, product ratings, and other decision aids. Some designers go beyond merely using the tools, cultivating their individual and organizational expertise in the larger scientific and political issues of environmental health. For example, some architects have set up "material health labs" within their firms to study the details of building product chemistry. People from design and engineering professions have engaged in lengthy discussions about chemical risks on the Pharos Project's online forum. They are motivated to attend to issues of occupational chemical exposure, material life cycles, and residual manufacturing impurities because they want to reduce ubiquitous chemical exposures. Still, most architects tend to accept the tools' results as authoritative, without delving further into just how these results were derived.

Green design tools are thus intermediaries in the mechanism by which designers take the responsibilities indicated by an ethics of material health and sustainability. Tools enable designers to operationalize values such as precaution, prevention of harm, and environmental justice—and translate these into making technical demands on products, materials, and their manufacturers.

4.5 How tools embed values

In addition to acting as the technical intermediaries for designers operationalizing an ethic of sustainable materials, green design tools also embed the perspectives, values, and politics of their developers. Our review of the chemical knowledge arena serves as a starting point for examining how this happens. Design tools, like regulatory science, assemble scientific evidence and policy framings to generate advice on highly uncertain questions, on which science itself may not necessarily offer the possibility of a clear conclusion (Jasanoff 1987; Jasanoff 1990). Likewise, both rely on constructing systems of definitions, conceptual models, and information infrastructures (Bowker and Star 1999) to ensure that the work of environmental protection can be coordinated. But this inevitably involves a narrowing of the many possible ways of knowing chemicals and their toxicities (Hepler-Smith 2019), choices about which aspects of a complex reality to attend to and which to leave out of the equation (Boudia, Creager, et al. 2018), and power relations embedded in all of these aspects (Liboiron, Tironi, and Calvillo 2018).

Design tools are sites of analysis, calculation, and discernment about the possibilities for health and sustainability. Green design tools intentionally package chemical knowledge systems, with all their assumptions and contingencies, into simple interfaces and outputs. According to several tool developers, users demand simple and uniformly understandable indicators of chemical hazard. Developers prefer to make tools that are practically useable and immediately applicable: using a green design tool should be straightforward, not requiring users to fundamentally rethinking the issues that the tool addresses—perhaps not even requiring a full understanding of how the tool works. Even if their methods are transparent, green design tools often effectively function as a "black box" that enfolds complex scientific and ethical reasoning out of sight of their users.

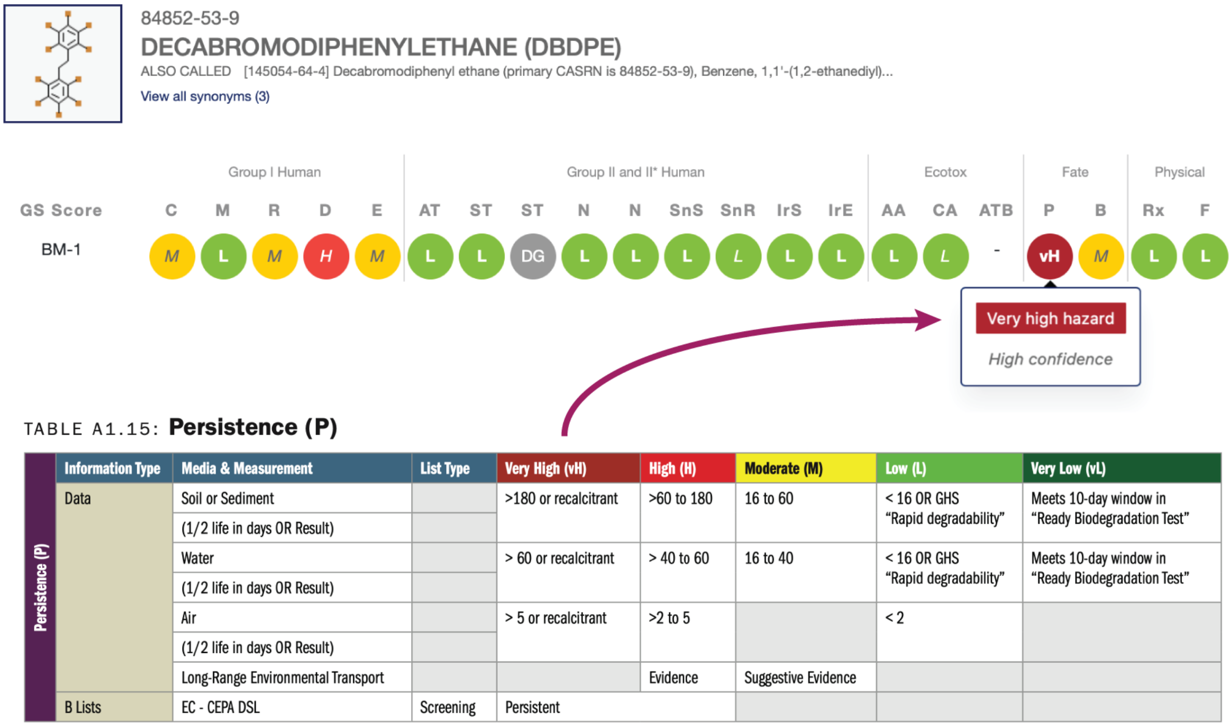
Constructing green design tools involves developers making a range of value-laden choices and introducing chemical knowledge politics into what may later appear to be a purely technical apparatus. First, all design tools are built on a set of core assumptions. These include value-based priorities and goals (such as reducing the toxic content of products, or occupational exposures), as well as possible design solutions such as product selection, chemical substitution, or risk management. These assumptions strongly influence what scientific and technical principles are then used to construct the tool. Pharos, for example, aims to help designers eliminate chemicals of concern throughout the full life cycle of building products—including products as well as their associated manufacturing processes and ultimate wastes. Pharos therefore uses hazard, or the inherent potential for a substance to cause harm, as the key organizing principle for measuring "healthy" or environmentally benign design. This is just one way to define what is "safe," and it competes with the more dominant concept of risk—which, as a function of both inherent chemical hazard and human or environmental exposure, can theoretically be reduced by controlling exposure without reducing inherent hazard.

Second, green design tools integrate technical elements—data, metrics, categories, and criteria—to distinguish between design options based on the available scientific evidence. Values necessarily play a role in putting these elements into place. Tool developers must choose what kinds and sources of data (toxicological test methods, databases, computational models, etc.) are relevant and appropriate to evaluating environmental health impacts. They may set evidentiary thresholds to decide when sufficient scientific data exists to warrant a classification of harm (Douglas 2009). Classification systems are commonly used to "sort out" and weight the many varied kinds of harm that might be controlled or prevented through design: cancer, reproductive toxicity, bioaccumulation, and so on. This can involve judgments about whether certain health effects are sufficiently important or well-understood to evaluate as part of a policy program or a product design process. For example, GreenScreen largely follows the United Nations' Globally Harmonized System (GHS) in specifying what health and environmental effects should be evaluated, and what kinds of evidence should be considered (United Nations 2019). But it adds several health endpoints that GHS excludes. In particular, GreenScreen addresses endocrine disruption, which growing—but highly incomplete and uneven—scientific evidence suggests can harm human development and reproduction. While increasingly recognized as a problem by European regulators, endocrine disruption has been heavily contested by industry and industry-funded scientists, and somewhat neglected by US policy-makers (Bergman et al. 2013).

Third, design tools contain assumptions, contingent decision rules, and other mechanisms that enable them to generate results under conditions of uncertainty and ignorance. In practice, most chemicals in commerce lack complete, detailed, and accurate information about their health hazards, their potential worker exposures, their end-of-life fate, and so on. Pervasive gaps in scientific knowledge about chemical hazards and exposures are well-documented (Judson et al. 2009; Egeghy et al. 2012). Tool developers must decide how they identify, handle, and expose these uncertainties. For instance, the GreenScreen method dictates how to account for missing data in a chemical hazard assessment (Clean Production Action 2018b, p. 79). The method permits larger data gaps in some kinds of health effects, reflecting both value judgments (e.g., chronic effects are elevated over acute effects) and pragmatic considerations (because some health effects, like endocrine disruption, are important but rarely studied). In the GreenScreen method, missing data is set to translate into a higher overall hazard assessment (a lower Benchmark score). In other words, unallowable data gaps are considered equivalent to evidence of potential harm. This embeds a precautionary bias into the tool that users may not realize exists.

Finally, for tools to be useful to designers, they must be configured to meaningfully distinguish between "good" and "bad" attributes of designs, materials, and substances. To do so, developers interpose multiple layers of interpretation in order to move from scientific evidence to actionable decision aids. This interpretation typically works by inserting evaluative criteria and decision logics into the tool that generate scores, ratings, or indicators. The GreenScreen method has two parallel systems of evaluative criteria: one system distinguishes between between low, moderate, or high levels of *concern* for each of the 18 hazard endpoints, and another appraises the level of *confidence* in the scientific evidence used (see Figure 4.2).

The GreenScreen Benchmark system further distills the levels of concern for those 18 hazard endpoints into a single Benchmark score that designers can use to evaluate the substance in question. This is done through a decision logic that explicitly prioritizes certain combinations of hazard properties to judge the overall level of concern. For example, substances are automatically scored as Benchmark 1 if they have a "high" level of concern in any of the Human Health Group I endpoints: cancer, mutagenicity, reproductive toxicity, developmental toxicity, and endocrine activity. These endpoints represent chronic human health effects, and GreenScreen emphasizes them because of the potential for severe irreversible effects on people from long-term low-level exposures—in contrast to other human endpoints, such as acute skin and eye irritation, or ecological effects such as aquatic toxicity. The Benchmark system's logic and assumptions have been scientifically peer reviewed and are fully exposed to users in principle. In practice, users may not be aware that this information exists or be able to gauge its technical validity. The Benchmark system is meant to help designers by systematically identifying substances that fit certain patterns of hazard properties thought to be concerning. Yet this is not the only conceivable way of summing up hazard information. Scientists, regulators, and chemical industry actors can certainly raise objections over the value judgments that tool developers make. Is prioritizing a few chronic human health effects justified? What about ecosystem health, or occupational exposure scenarios where acute hazards may be far more critical? In principle, design tools can include any kind of algorithm that weighs different types of evidence and environmental health impacts to produce an aggregate indicator or decision aid. The critical point is that trade-offs and value judgments are unavoidable.



84852-53-9

DECABROMODIPHENYLETHANE (DBDPE)

ALSO CALLED [145054-64-4] Decabromodiphenyl ethane (primary CASRN is 84852-53-9), Benzene, 1,1'-(1,2-ethanediyl)...

View all synonyms (3)

	Group I Human					Group II and II* Human									Ecotox			Fate		Physical	
GS Score	C	M	R	D	E	AT	ST	ST	N	N	SnS	SnR	IrS	IrE	AA	CA	ATB	P	B	Rx	F
BM-1	M	L	M	H	M	L	L	DG	L	L	L	L	L	L	L	L	-	vH	M	L	L

Very high hazard

High confidence

TABLE A1.15: **Persistence (P)**

	Information Type	Media & Measurement	List Type	Very High (vH)	High (H)	Moderate (M)	Low (L)	Very Low (vL)
Persistence (P)	Data	Soil or Sediment		>180 or recalcitrant	>60 to 180	16 to 60	< 16 OR GHS “Rapid degradability”	Meets 10-day window in “Ready Biodegradation Test”
		(1/2 life in days OR Result)						
		Water		> 60 or recalcitrant	> 40 to 60	16 to 40	< 16 OR GHS “Rapid degradability”	Meets 10-day window in “Ready Biodegradation Test”
		(1/2 life in days OR Result)						
		Air		> 5 or recalcitrant	>2 to 5		< 2	
		(1/2 life in days OR Result)						
		Long-Range Environmental Transport			Evidence	Suggestive Evidence		
	B Lists	EC - CEPA DSL	Screening	Persistent				

Figure 4.2: A screenshot from Pharos showing the GreenScreen hazard summary table for the chemical DBDPE; superimposed: the GreenScreen criteria for persistence (Clean Production Action 2018a, p. 61)

4.6 Chemical knowledge controversies

Controversies about chemical knowledge can reveal more clearly how values are embedded in design tools. Even controversies that supposedly involve only technical questions are, under the surface, often rooted in tensions between different value judgments that tool developers make—which may or may not mirror those that users would favor. Value conflicts may arise in connection with environmental health and design problems such as:

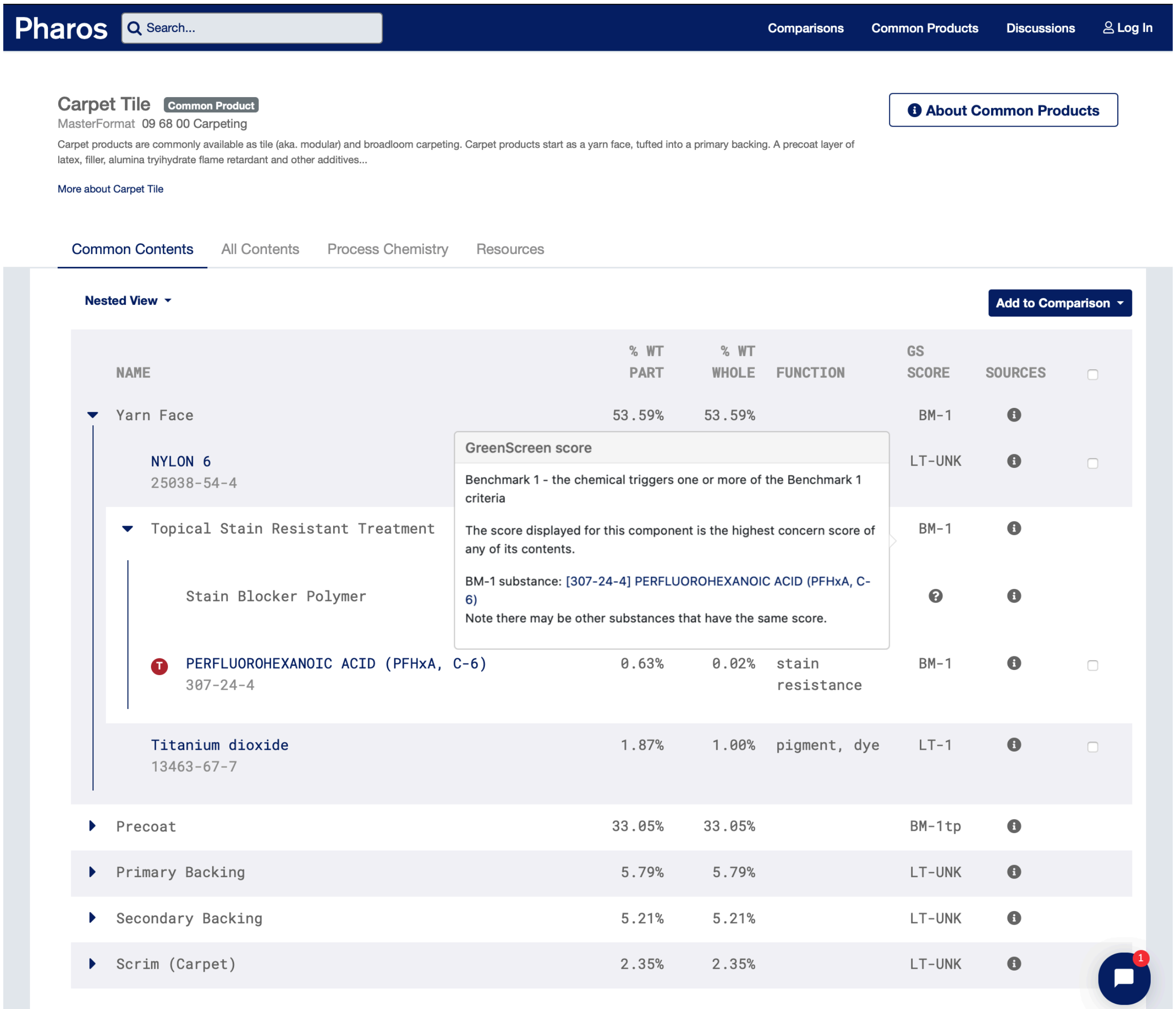
- What it means to protect health: are there acceptable levels of exposure and risk of toxic effects? Should there be no acceptable levels?
- Where to draw system boundaries: Whom should designers have the greatest responsibility to protect? For example, should they emphasize impacts on customers over workers or ecosystems?
- Sustainability paradigms: What design goals and strategies are most beneficial in attaining “sustainability?” How is sustainability defined, and by whom?

One particularly contentious issue relates to the outcomes that should be achieved by using design tools. Put simply, should hazard reduction or risk reduction prevail as the most desirable strategy to improve the environmental health performance of buildings? Take, for example, the Pharos hazard analysis of generic carpet tile product, shown in Figure 4.3. This product has a stain resistant treatment containing C-6, a chemical of high concern (GreenScreen Benchmark 1) at a level of 0.02% by mass. Based on this ingredient, what should designers do? Must they avoid the product outright because it is inherently hazardous, or can they justifiably calculate that the exposure—and hence risk—will be relatively low? If they can take the latter course, then the risk to whom—the building occupants, the construction workers, the manufacturing workers, or the people living around the factory?

The use of GreenScreen, Pharos, and HPD in green building design reflects an underlying assumption by tool developers that *hazard avoidance* by designers is the most effective strategy to follow. The developers of Pharos deliberately chose to emphasize the hazard properties of a substance over its exposure potential, even if the chemical is present at trace levels or if it is only used during manufacturing and is not present in the final product. This is because they wanted designers to understand how their choices map onto a broader industrial system of chemical manufacturing that affects workers and frontline communities, not just building occupants. Making hazard the central focus shifts attention to why the product contains a hazard at all. Manufacturers are more likely to encounter demands to change or eliminate the product based on hazard avoidance.

In contrast, some scientists, companies, and chemical industry associations challenge the use of hazard-based design tools, arguing that environmental health impacts must be understood in terms of *risk*. They contend that GreenScreen and Pharos are flawed tools because these do not consider the magnitude of human exposure to chemicals, which might radically change the risk associated with their use. If a chemical is used at very low levels or is not widely used, then its risk will be minimal—even if it is hazardous. Finding ways to reduce exposure, then, might suffice. For example, designing a product to contain the toxic substance from being released, or training workers in safe use practices could diminish exposure. Two studies funded by the American Chemistry Council (a trade association) exemplify this argument. These studies compare between chemical assessment tools and conclude that hazard-based tools are incomplete because they “lacked the capability to evaluate risk based on exposure” (Gauthier et al. 2015), and of questionable appropriateness because they involve “value judgments” (Panko et al. 2017). In response, the makers of GreenScreen and Scivera Lens pointed out technical and methodological flaws that largely invalidated the conclusions, but did not specifically respond to the claims of value bias (Palmer 2016). Yet, as many scholars of toxicology and chemical knowledge have argued, determining dose-response relationships and analyzing exposure patterns involve making many assumptions (e.g. Douglas 2009; Greggs et al. 2019). Thus risk-based evaluations are just as value-laden as their hazard counterparts. The incompleteness and partiality of scientific knowledge is a fundamental issue on which STS can provide at least some insight: the most appropriate response is humility (Jasanoff 2007).

Even if the hazard approach is favored, it can still be seen as limited in its dominant



Carpet Tile Common Product

MasterFormat 09 68 00 Carpeting

Carpet products are commonly available as tile (aka. modular) and broadloom carpeting. Carpet products start as a yarn face, tufted into a primary backing. A precoat layer of latex, filler, alumina tryihydrate flame retardant and other additives...

More about Carpet Tile

NAME	% WT PART	% WT WHOLE	FUNCTION	GS SCORE	SOURCES	☐
Yarn Face	53.59%	53.59%		BM-1	ⓘ	
NYLON 6 25038-54-4				LT-UNK	ⓘ	☐
Topical Stain Resistant Treatment				BM-1	ⓘ	
Stain Blocker Polymer				?	ⓘ	
T PERFLUOROHEXANOIC ACID (PFHxA, C-6) 307-24-4	0.63%	0.02%	stain resistance	BM-1	ⓘ	☐
Titanium dioxide 13463-67-7	1.87%	1.00%	pigment, dye	LT-1	ⓘ	☐
Precoat	33.05%	33.05%		BM-1tp	ⓘ	
Primary Backing	5.79%	5.79%		LT-UNK	ⓘ	
Secondary Backing	5.21%	5.21%		LT-UNK	ⓘ	
Scrim (Carpet)	2.35%	2.35%		LT-UNK	ⓘ	

GreenScreen score

Benchmark 1 - the chemical triggers one or more of the Benchmark 1 criteria

The score displayed for this component is the highest concern score of any of its contents.

BM-1 substance: [307-24-4] PERFLUOROHEXANOIC ACID (PFHxA, C-6)

Note there may be other substances that have the same score.

Figure 4.3: Pharos hazard analysis of carpet tile

form, namely appraising individual substances within a single product. Some practitioners and chemicals scholars argue this is a fundamentally reductionist perspective that overlooks the manifold complexities of how chemical substances move through a world of physical, ecological, and social relations (Liboiron 2016; Murphy 2017; Boudia, Creager, et al. 2018). An alternative view could, then, frame hazard avoidance as beneficial only if it reduces the aggregate life-cycle health impacts of the industrial systems involved. This critiques the system boundaries set by design tools, like HPD, which establish the product itself as the unit of analysis. For example, a business official from a major building product manufacturer told us that substituting a hazardous chemical with a safer alternative may not amount to a significant systems-level change, especially if the alternative material is "made in the factory right next door, owned by the same company, in Cancer Alley in Louisiana." Moreover, this substitution may create even worse environmental health effects depending on the accompanying changes to the supply chain. One way that such unintended harm might happen is if a hazardous but recycled material is replaced with a less-hazardous but primary petrochemical-based material whose use contributes to climate change and air pollution.[9]

This more inclusive standpoint implies that single-chemical hazard properties may not be the most relevant organizing principle for constructing green design tools. Instead, population-level disease burdens, distributive justice, or greenhouse gas emissions may be more relevant. But this shift in system boundaries raises further value tensions between the many categories and *scales* of environmental health impacts that tool developers and building designers might consider. It also raises difficult questions regarding regarding whether values and chemical knowledge choices should be embedded into a tool's operations, or should be kept open-ended for designers to ponder and choose according to their own preferences. Should designers be expected to use tools to analyze the global impacts of every decision? Which parts of the industrial system should tools take for granted, and what should be left up to designers to imagine? Where does scientific analysis end and design intervention begin?

Many other value and knowledge choices permeate design tools. But designers may be oblivious to the decision-making that happens "behind the tool." They may not fully realize that they are depending on results that reflect the "defaults" that developers have built into the tool. They may also not understand they can consider a range of chemical concerns or even alternative framings.

4.7 Conclusions

Exposing the values and chemical politics of green design tools opens important questions concerning the agency of designers to intervene in an unsustainable and unjust materials system, and on what ethical basis. It is almost inevitable that the more designers and engineers try to comprehensively address environmental impacts, the more trade-offs they will need to make between incompatible approaches—trade-offs that require operationalizing some value preferences at the cost of others. How can designers weigh these trade-offs? What ethical basis do they have for setting priorities? Green design tools can quietly impose the ethical perspectives of their creators, rather than those of users, regulators, or even the public, to the extent that they implicitly encourage particular ways of prioritizing outcomes—such as elevating the apparent "greenness" of individual products over systemic sustainability and environmental justice. This process does not invite public debate or scrutiny, even though NGO staff may help produce the tools. Extensive social scientific evidence suggests technical experts can view environmental issues or risks quite differently from the public (e.g. Savadori

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[9] Similarly, the goals of material hazard avoidance can be at odds with the goals of creating a "circular economy" based on closed-loop material cycles (Goldberg 2017).

et al. 2004). Values can thus be subtly and deeply embedded in the way the tool constructs assessments of problem-solving options.

In effect, green design tools have become a new "black box" species (Latour 1987). Their internal operations are understood as less important than their outputs for informing sustainable design. Nonetheless, this approach can generate environmental and social problems that are disguised by a sustainability imprimatur. That a design tool is intended to be "green" does not mean that it is, in fact, green in its real effects. Yet, advocates—both NGOs and industry—are inserting these tools into voluntary standards, certifications, regulations, and government policies, to incentivize and reward designers for using them and to grow the market for green building materials and products. Without critical, thoughtful use, design tools can become de facto standards (Busch 2011) that are embedded into a variety of industrial and government practices. Like "molecular bureaucracy" (Hepler-Smith 2019), they can narrow possibilities without people noticing. They can become part of the invisible infrastructure that everyone takes for granted, or yet another part of the structural constraints that limit designers' agency. In some ways, this is the goal: to integrate green design practices everywhere. In other ways, it can mean perpetuating policy failures—like the serial substitution of "bad actor" chemicals with new, unknown, and unconsidered harms (Geiser 2015)—and it can enable specific groups (industry, NGOs, governments) to push forward their particular approaches and interpretations without challenge.

As long as green design tools have their underlying assumptions, algorithms, and data properly interrogated in a transparent way, they can play a valuable role in addressing the distributed harms of a toxic world. The process of developing tools needs to be open and participatory to those who are using the tools, and to those whose lives and health will be affected by the resulting designs.

Chapter 5

Materials sovereignty: Pathways for shaping nanotechnology design

Akos Kokai and Alastair Iles[1]

People in contemporary industrial societies encounter countless novel materials that did not exist previously, many of which present risks to health and environment. In this article, we build on the concept of "materials sovereignty" as the right of people to use and be surrounded by environmentally benign, non-toxic, and renewing materials in their everyday lives. As a rights-based approach, materials sovereignty may help change the politics of governing materials. We suggest that social movements that explicitly base interventions into design on materials sovereignty may be better able to gain traction in changing industrial production. We consider the case of nanotechnology as a particularly challenging field for social movement intervention. We review several pathways that have been used by social movement organizations in attempts to influence the development of nanomaterials, but which have met with limited success. We more closely examine three participatory pathways through which social movements could intervene more directly into material design: participatory technology assessment, collaboration with industry, and co-design. We identify three key elements of materials sovereignty: participatory knowledge systems, which create multi-directional flows of knowledge and agency; the embedding of citizen voices into design processes; and building accountability systems. Of the pathways we examine here, co-design appears to be the most promising from a theoretical and ethical perspective, but there remain significant institutional and organizational challenges for bringing it into practice.

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[1] This chapter has been published as a peer-reviewed article (Kokai and Iles 2020).

5.1 Introduction

Industrial societies face difficult quandaries in deciding how to deal with emerging materials, from teflon to bioplastics. Novel materials promise new capabilities and functions, including greater sustainability. Yet their use may result in harm to ecological and human health, or worsen economic inequality across societies. From perfluorinated compounds to flame retardants, seemingly "safe" industrial chemicals have turned out to harm reproduction and development in human bodies (Harremoës et al. 2013; Lanphear 2017). Despite observing early warnings of these effects, corporations and governments have allowed problematic chemical uses to proliferate, while people have remained oblivious to the fact they are being exposed without their knowledge and permission. Do citizens have a role in helping shape the design and use of materials? What can they contribute to the design process, if anything, and how? What might be needed for more diverse voices to be represented in the development of material technologies?

To investigate such questions, we consider a class of materials that has emerged in the last 20 years: nanotechnologies, or substances designed with features at very small scales roughly between the molecular and the cellular (Ramsden 2011). Examples include carbon nanotubes, titanium dioxide, and quantum dots. Their use in everyday consumer products is expanding rapidly and in relatively unseen ways. Nanomaterials may present novel risks to workers involved in production, to vulnerable populations, or to ecosystems. However, enormous uncertainty exists in estimating these risks because of how much is still unknown about nanomaterial use and hazards (Lai et al. 2018).

Nanomaterials present a challenge for citizen involvement in design. Engineering nanomaterials is a technically esoteric domain. Developing them—and scaling up to production capacity—entails sophisticated chemistry, quantum physics, material informatics, and manufacturing technologies. Furthermore, the global material production system ranges across large geographical, temporal, economic, and cultural distances between the designers of materials and the people using them or being exposed to their effects (Princen 2002). As a consequence, there is little feedback from societal actors into the design process, except through market demand and legal liability (Nieusma 2011). Companies primarily use economic and market analysis to decide whether to insert nanomaterials into their products. It would appear, then, that only scientists and corporate managers can legitimately decide on introducing this new class of materials into society, because they hold the requisite knowledge and expertise. In theory, material scientists can apply green chemistry principles to develop nanomaterials that are benign to human health and the environment (Anastas and Warner 1998; Hutchison 2008). In practice, very few actors in the nanotechnology industry are realizing these principles, mostly because they are not being held accountable by societies for their decisions. Yet nanomaterials are still at an early, if rapidly evolving, stage of development: intervention now could result in risk reduction later (van Broekhuizen and Reijnders 2011).

Multiple civil society organizations are now striving to influence the development of nanotechnology. Together, they are attempting to build a new social movement around making nanomaterials safer, at a time when the technologies are still emerging—their forms still in flux, open to change. This did not happen with earlier generations of industrial chemicals, leading to what sociologists Woodhouse and Patton (2004) have described as technological somnambulism: societies sleepwalking through the rapid, unmonitored growth of the modern industrial chemical system, oblivious to the environmental and social costs of new substances. However, social movements have historically had only partial success in influencing technological fields (D. J. Hess 2005; D. J. Hess 2007).

We suggest that social movements can invoke what we call "materials sovereignty" as a basis for active intervention into the development of material technologies. Akin to food sovereignty, people can seek to create and assert rights to have a say in what materials are used in their products. But what materials sovereignty means, who can effectively invoke it, and its implementation in practice are uncertain. We use the challenging case of nanotechnology to begin fleshing out the concept of materials sovereignty, by comparing different pathways through which diverse voices could be incorporated (via social movements) into the design of new materials. The prevailing approach sees nanotechnology design processes as occurring largely within private firms and universities, even though they still reflect pervasive societal influences (Woodhouse and Patton 2004). Investment, research funding, business models, regulations, intellectual property rights, and consumer culture are all examples of social systems that help determine how nanotechnologies take shape. The unintended consequences of technologies are often the result of not intentionally exercising "anticipatory" social governance over technologies (Barben et al. 2007). In contrast, we suggest, social movements may push for particular scientific research priorities, public policy interventions, or business practices to ensure that potentially risky technologies develop in ways that reflect broader public interests.

5.2 Materials sovereignty and social movements

We define materials sovereignty as the right of people to use, and be surrounded by, environmentally benign, non-toxic, and renewing materials in their everyday lives. The concept of materials sovereignty has a parallel in food sovereignty, a fast-coalescing discourse and practice in the food system worldwide (Wittman, Desmarais, and Wiebe 2010; Claeys 2012; Claeys 2015). Materials are diverse and pervasive in everyday life: they include plastics, metals, wood, stone, ceramics, and bone. In contemporary societies, people encounter countless chemical products that did not exist previously. Materials sovereignty builds on, but also goes beyond, the extensive STS literature on democratizing technology (e.g., Sclove 1995; Kleinman 2000; Woodhouse and Patton 2004). It emphasizes the role of *sovereignty* in potentially changing the politics of chemicals and other materials in a context where decades of democratization discourse have struggled to transform the terrain on which design and production happen.

Materials sovereignty is arguably emerging through an array of new demands and actions taken by consumers, citizens, indigenous peoples, scientists, and NGOs that are centered on making materials safer. Examples include the NGO campaigns occurring in the United States to mobilize consumers to boycott cosmetics that contain phthalates and baby bottles that carry bisphenol A (Geiser 2015). Communities in West Virginia and Minnesota have organized against DuPont and 3M Corporation respectively to stop their drinking water from being polluted with perfluorinated chemicals (Kozlowski and Perkins 2015). European mothers have had their bodies tested for the presence of synthetic chemicals, such as flame retardants, in connection with the passage of the REACH law that transformed chemical controls in 2006 (Lyons and Illig 2007). Indigenous peoples have linked the issues of sovereignty, self-determination, and human rights to struggles against chemical pollutants that contaminate their air, water, and food (Downie, Fenge, and Inuit Circumpolar Conference 2003; H. Selin and N. E. Selin 2008; Hoover et al. 2012). They have brought human rights petitions in international fora to demand the reduction of air pollutants that endanger climate stability in the arctic (Watt-Cloutier 2015). Many of these efforts center on chemicals but others address metals and wood. While still far from being a settled "constitutional" norm, the concept of materials sovereignty helps gather these disparate efforts into a cohesive form.

Materials sovereignty is rooted in human and democratic rights. Under this framework, people have the right, for example, to say they want products designed without endocrine disrupting chemicals—and made readily available, at affordable costs. Across millions of workplaces and households globally, people have the right to reject being exposed to harmful substances present in the consumer products, technologies, and infrastructures they use (c.f. Dinham and Malik 2003; Westra 2008; D. G. Arnold 2010). They have the right to be free from building up a body burden of industrial chemicals through their lifetime (Hoover et al. 2012). They also have a right to say that materials should be sourced or manufactured without causing environmental degradation and damage to human health (e.g., not made from ore mined with destructive methods). This harm could occur directly to consumers through using products; it could also be felt indirectly through the spread of chemical contamination from factories and products around the planet (Lerner 2010). Implicitly, therefore, people have the right to intervene in the materials production system in order to assure their health and well-being; and to have the precautionary principle implemented in chemical design, business decisions, and government policies where feasible (Kerns 2001).

Many institutional, legal, knowledge, and political elements are necessary to support the capacity of people to exercise their right to use non-toxic and renewing materials. For example, people may need readily accessible knowledge about material ingredients and manufacturing; the science of chemical toxicity, ecological impacts, and body burdens; and the alternative safer materials that manufacturers could potentially use (Lambert et al. 2003). In turn, more protective laws, chemical testing and evaluation regimes, biomonitoring surveys, and readily searchable open-access databases may be needed to generate and provide such knowledge to the public. People may also need epistemic political changes in policy-making and scientific institutions that enable their local and societal expertise to be more widely recognized and used (Iles 2007; Iles 2013). They may need the re-configuration of chemical manufacturing systems to allow engagement with designers and corporate decision-makers.

Ultimately, materials sovereignty calls for attention to how the entire materials production system is built and operated—including research, design, regulation, and other forms of technological decision-making. In contrast with the rights framework of environmental justice, which attends to the effects of the industrial material system on people, materials sovereignty is about the construction of that system itself. Under this sovereignty, designers and industry can no longer unilaterally decide to introduce new materials or products without facing, and responding adequately to, societal scrutiny. Instead of leaving sovereignty to the makers of technologies, such as Apple or Dow Chemical, people have the social authority to decide *because* they are exposed to harmful substances and may face substantial risks; and because the environment more generally is heavily burdened with chemical pollutants that endanger human reproduction and development.

In this paper we focus on how the formation and work of social movements can influence material design, potentially incorporating diverse voices into the governance of materials. Social movements are networks or coalitions of people, organizations, and communities who come together around a shared goal or ethical position—such as eliminating toxic chemicals from human bodies, or calling on energy companies to leave fossil fuels in the ground (Tilly 1978; Schlosberg 2004; Woodhouse and Breyman 2005). These movements represent collective voices raised from within civil society—the larger public existing alongside government and private-sector institutions. They may play particularly influential roles in catalyzing civil society responses to environmental and social problems, as in the Civil Rights era of the 1950s–1970s. Yet social movements may not always be cohesive (Della Porta and Diani 2006). They can contain many strands with internal philosophical contradictions and political competition. They can be more democratic than the political system they work through or seek to change, but they can also lack democracy. A few particularly powerful organizations or individuals can hold outsized control over their direction. In short, the human frailties of social movements should not be forgotten.

Research on social movements reveals that they can have complex and influential roles in scientific and technological change. Analyzing social movements that focused on transforming the harmful effects of major industries, Hess (2007) has shown that they can be "generative"—influencing, promoting, or spreading alternative technological designs—rather than merely opposing industry. Hess theorizes social movements' impacts on technological fields as the incorporation and transformation of civil society demands or proposals into industrial systems. This often results in significant changes in the systems as well as the actors involved, although the original demands are usually only partially satisfied; the goals of the movement itself may be changed through the process. One key way that social movements intervene in technological designs is by identifying alternative research priorities that have been neglected, and demanding new science that might lead to the desired innovations or socio-technical change (Frickel, Gibbon, et al. 2010; D. J. Hess 2016).

For social movements to do this, they do not necessarily need to be mobilized around specific technological fields. Studies of health social movements organized around illnesses like asthma and breast cancer have shown how they can intervene in research agendas and public policy around environmental and occupational health by acting as “boundary movements” (P. Brown, Morello-Frosch, and Zavestoski 2011). These movements engage strategically in both challenging and collaborating with scientists, redefining the boundaries of scientific knowledge, expertise, and authority. In the case of social movements organized around the health risks of consumer products, highly specialized activist organizations have crystallized out of the movement and developed considerable technical and analytical expertise that NGOs traditionally have not been associated with (Iles 2007). Social movements can therefore mobilize a variety of scientific and political resources that have relevance to material design. This is why we focus on social movements as actors that could be instrumental in introducing materials sovereignty into the technological politics of nanomaterials.

5.3 A brief overview of nanotechnology issues

Nanotechnology is a broad category of technologies that involve engineering and manipulating materials at extremely small dimensions, typically 1–100 nanometers (Ramsden 2011). At this scale, matter manifests physical, chemical, and biological phenomena not usually observed at larger scales where ordinary physical forces predominate. Nanomaterials offer novel physical, optical, and electronic properties that make them attractive for a variety of technological applications. Examples include carbon nanotubes, graphene sheets, quantum dots, and dendrimers. Many nanomaterials are nanoscale versions of common chemicals, such as silver or titanium dioxide. While nanoparticles occur naturally, we focus on materials that scientists, engineers, and manufacturers intentionally design and synthesize for use in consumer products.

Research suggests that normally benign substances can be toxic as nanoscale particles. Their small size means they can move around bodies readily and their large surface area-to-volume ratio makes them chemically and biologically reactive. A growing body of toxicological evidence suggests that nanomaterials present risks to human and environmental health (Gupta and Xie 2018). Researchers have identified many adverse health effects from nanoparticles in experimental studies. These include respiratory diseases, cardiovascular inflammation, reproductive and developmental toxicity, and immune system effects (Zhang et al. 2014). Carbon nanotubes have been shown to cause pulmonary fibrosis, an irreversible lung disease (Pacurari et al. 2016). Many mechanisms of toxicity are being explored, but one of the most significant is the production of reactive oxygen species within living tissues. This can damage DNA and disrupt the work of mitochondria, the tiny energy-producing organelles found in every cell (Jain et al. 2018).

Nanomaterials have rapidly entered consumer product manufacturing chains. In 2006, the Woodrow Wilson Center’s Project on Emerging Nanotechnologies (PEN) began tracking the use of nanomaterials across many product categories, cataloguing thousands of products as they entered the market in their Consumer Product Inventory (Vance et al. 2015). Personal care products, cosmetics, and sunscreens comprise 29% of the total product inventory as of 2019; clothing products make up an additional 12% (Project on Emerging

Nanotechnologies 2019). People apply these products to their bodies directly, making human exposure to nanoscale ingredients almost certain (Katz, Dewan, and Bronaugh 2015). Moreover, nanomaterials may become riskier by intentional choices made in their design and formulation. In personal care products, nanoparticles are often specifically engineered to more effectively penetrate the skin (Katz, Dewan, and Bronaugh 2015). Many products also include "permeability enhancers," substances that help active ingredients enter the skin (Mihranyan, Ferraz, and Strømme 2012). Since people tend to use multiple personal care products on a daily basis, they may be exposed to many interacting sources of nanomaterials.

Manufacturers are bringing new materials into the market with little awareness amongst consumers, lax regulatory oversight, and negligible input from society as to whether the material is desirable (Bennett and Sarewitz 2006). With very few exceptions, governments around the world rely on the same laws and regulations designed to govern industrial chemicals, drugs, and consumer products without giving special consideration to nanomaterials (Lai et al. 2018). Manufacturers have operated with very little transparency: some companies advertise the presence of nanoscale ingredients in products—even if the information they provide is incomplete (Vance et al. 2015)—while other companies make misleading claims or simply avoid disclosing that their products contain nanomaterials (S. Becker 2013). Public consciousness of nanotechnology is still in the formative stages, even after 20 years of scientific research and debates amongst policy-makers over what to do about possible risks. Survey studies conducted by scholars and policy institutes since the early 2000s reveal a consistent pattern: for example, a meta-analysis in 2009 showed a largely uninformed, mostly undecided, yet optimistic public (Satterfield, Kandlikar, et al. 2009).[2] More recent studies have demonstrated that public views of nanotechnology are still highly malleable and context-dependent (Satterfield, Conti, et al. 2013; see also van Giesen, Fischer, and van Trijp 2018, for a review).

As a rapidly emerging new class of materials, nanotechnology is still in an early era of industrial development, when intervention in design choices could greatly improve environmental and health outcomes. Nanotechnology R&D decision-making remains opaque and confined to a relatively exclusive set of industry and scientific actors. A number of social movement efforts have already occurred to attempt to shape the introduction of nanomaterials into everyday consumer products. But simply following traditional activist strategies does not appear to work particularly well, given strengthening industry power and consolidation. Materials sovereignty could give social movements more political traction and authority, by asserting health and environmental rights in pressing for systemic change in design.

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[2] 51% of respondents in 11 different studies in North America, Europe, and Japan reported knowing nothing about nanotechnology. Studies that asked respondents to weigh the perceived benefits and risks of nanotechnology consistently showed a prevalence (by about three-fold) of people seeing greater benefits versus greater risks; however, a significant proportion of respondents (almost half on average) were unsure (Satterfield, Kandlikar, et al. 2009).

5.4 Pathways for social movements to exercise materials sovereignty

How can social movements can intervene at strategic points in the materials system to shape the design of nanotechnologies? To exercise materials sovereignty, social movements must understand, and act on, a complex industry in which agency in design decision-making is unevenly distributed. Within the ecosystem, certain agents have more concentrated power over how nanotechnologies are developed, and deliberately exercise this power.

In innovation networks, for example, investors who allocate financial resources for nanotechnology research can set agendas and priorities, or choose to support one possible vision of technology over others. Trends in funding can influence academic research programs, or corporate management—which in turn directly controls R&D within firms. Likewise, companies that dominate a given market sector have greater opportunities to introduce precedent-setting new designs. In industry chains, some companies may function as gate-keepers to supply or distribution networks; some retailers greatly influence which manufacturers get access to large consumer markets. Within companies, groups of designers, scientists, and business executives hold power over deciding what materials to use in making a product, and where and how to source these materials. Some institutional structures, such as laws and regulations, are also highly influential. In comparison, consumers, citizens, and environmental NGOs have historically not been part of the materials development and product design processes. Their values and arguments have mostly been excluded until the past 20 years.

Social movements, then, can direct their influence at the agents and structures that have the greatest potential to yield change. Systems analysts use the metaphor of *leverage points* to capture the idea that small changes at certain points may produce large shifts in overall system behavior (Meadows 2008, pp. 145–165). Leverage points are effective places to intervene in a system. What are the most effective places to intervene in the nanotechnology system, and how can social movements use them to achieve their goals? The work of environmental, consumer, and health groups to identify valuable leverage points in what is still a novel, nascent, and fast-evolving industry has already yielded a diverse set of possible pathways, as seen in Table 5.1.

We briefly review the direct action, policy activism, and market mobilization strategies, discussing how social movements have experimented with these approaches and appraising their success to date in shaping nanomaterials. We pay attention to how materials sovereignty has been, or could be, integrated into these strategies. In the subsequent section we turn to the three remaining pathways that are our main focus: participatory technology assessment, collaboration with industry, and co-design.

Table 5.1: Pathways for intervening in nanotechnology

Pathway	**Mechanism**	**Examples**
Direct action and civil resistance	Demonstrate and enact opposition to nanotechnology research and deployment; raise public awareness	Anti-nanotech activists in Europe
Policy activism	Influence government regulations that play an important role in shaping technological design, manufacturing, and commercialization	NGOs advocating for product labeling laws and chemicals policy reform
Market mobilizations	Mobilize consumers to send market signals to technology developers, enabled by increased consumer knowledge and systems of corporate accountability	Skin Deep Cosmetics Database; campaigns about nano sunscreens; Campaign for Safe Cosmetics
Participatory technology assessment	Engage citizens in public deliberation about emerging technologies; allow citizens to participate in the governance of technological systems	National Citizens' Technology Forum (US); Project on Emerging Nanomaterials (US)
Collaboration between social movements and industry	Partner with companies to gain "inside" influence and insert social movement concerns into design processes	EDF-DuPont Nano Risk Framework
Co-design/Participatory design	Open the technological design processes to direct participation by representatives from affected groups in civil society	Collaborative On-site Technology Exploration

Direct action and civil resistance

Social movements can act directly against new technological developments, attempting to physically stop research and design from proceeding. Inspired by successful protests against GMO field trials in Britain and France, a small number of civil resistance actions in Europe have targeted nanotechnology specifically.

One example is the effort in the early 2000s by the French group Grenoble Opponents to Necrotechnology (OGN) to oppose a new nanotechnology research center, Minatec, being built in Grenoble. OGN was critical not only of the risks of nanotechnologies to environmental and social well-being, but of how a complex of industrial, government, and military interests has controlled nanotechnology research. Activists in Grenoble tried many tactics to stop Minatec's inauguration (OGN 2006). During the construction of the facility, activists occupied a crane in an attempt to stop the project. In 2006, OGN activists hurled insults and eggs at a reception for scientists celebrating the opening of Minatec; they occupied regional government buildings to protest the use of public funds to invest in the research center. They distributed magazines posing as official public education materials that contained scenarios of alarming nanotechnological interventions in daily life. Finally, activists disrupted a public forum on "Science and Democracy," organized by the local government, which OGN viewed as deceptive and hypocritical—"a talk show ... aiming at making us accept decisions which had already been taken" (OGN 2006). OGN's views on nanotechnology have likely been shaped by multiple movements worldwide, which are concerned with the relationships of material technologies to health, human-ecological sustainability, economics, and power. OGN's actions ultimately did not stop Minatec, which today is an "international hub for micro and nanotechnology research" (Minatec 2016). Moreover, OGN failed to influence the design of nanomaterials more broadly.

Policy activism

Social movements often make demands for the reform or creation of public policy to force industrial change, such as activism around alternative energy and toxic waste in the US (D. J. Hess 2007; D. J. Hess 2010). Social movements can also aspire to engage in producing and debating policy-relevant scientific knowledge so that they can intervene in regulatory and policy-making processes or influence the risk assessments that government agencies do—often through the work of specialized professional organizations that develop in connection with the social movement (Iles 2007; P. Brown, Morello-Frosch, and Zavestoski 2011).

Many environmental NGOs and labor groups have therefore issued detailed calls for new or revised regulations (e.g., European Trade Union Confederation 2008; European Trade Union Confederation 2010; European Environmental Bureau et al. 2014) or mounted legal challenges (e.g., Center for Food Safety 2015) to push governments to control nanomaterials more effectively. Among numerous demands, calls for mandated product labeling schemes for nano-ingredients have received the most extensive consideration and debate by governments, NGOs, industry, and researchers. Labeling is one way to provide some information about nanomaterials to consumers at the point of purchase. Recent EU laws governing cosmetics and biocides require manufacturers to disclose nanoscale ingredients on product labels using the word "(nano)" and institute nano-specific requirements for safety screening and authorization (European Commission 2017; European Chemicals Agency n.d.[a]). In the US, no laws yet require products to be labeled as regards the use of nanotechnology.

Consumer mobilizations through the market

Social movements can aim to mobilize citizens into campaigns, pressuring corporations to produce consumer goods using safer and healthier materials. Much evidence supports the idea that consumer behavior (or perceptions of demands) can influence manufacturers and retailers to change their business strategies, product designs, sourcing decisions, and operations (O'Rourke 2005; Hall 2006; Gulbrandsen 2006). Manufacturers may find lucrative incentives in responding to, or foreseeing, consumer demands: they may not want to lose market share or risk damage to their brand reputation. Companies could also sell products at premium prices and create new markets for safe products. Numerous cases of effective consumer pressure include the electronics, seafood, apparel, and forestry product sectors (O'Rourke 2005). Consumers may express their pleas through multiple, sometimes mutually reinforcing means: boycotting a brand or company, telling a company about their concerns, joining a social media campaign stigmatizing the firm, preferentially buying eco-labeled products, or lobbying governments for regulation.

Consumer demands may eventually feed back into research, design, and production. This may happen if firms identify these demands as pertinent to their financial and market performance. In response, they may pursue new design goals—even if incremental ones like removing specific chemicals of concern—with the expectation of increased market share. This can be a proactive approach based on foresight, or a reaction to negative publicity and stagnant sales. Either way, companies may end up redesigning their products, or requesting specific reformulations from their suppliers. This hypothetical market mechanism is a feedback loop that connects product design, consumers' expressed preferences, and the actual market performance of products—which is connected back to product design. The potential leverage of consumer mobilizations comes from driving this feedback loop to make product design as responsive as possible to consumer demands.

In the nanotechnology arena, consumer information campaigns and campaigns directed against brands and visible companies have been the most prominent to date.

Informing consumers

A common strategy is to provide information about chemical risks to consumers to allow them to evaluate products more critically and potentially change their buying behavior, thus sending signals to manufacturers and retailers. Information provision can occur in several ways: through NGO reports and press releases; through digital media and online resources; and through voluntary or mandated product labeling and eco-certification. Environmental Working Group's Skin Deep Cosmetics Database (Environmental Working Group n.d.) allows consumers to search for and evaluate products based on EWG's analysis of the ingredients and their associated health effects, and includes limited information about nanoscale ingredients. Several other NGOs have engaged in consumer knowledge interventions around nanotechnology in personal care products specifically. Between 2006 and 2009, Friends of the Earth (FoE) published three reports warning consumers of the potential health risks of nanomaterials in personal care products (Friends of the Earth 2006), presenting summaries of relevant scientific research, and arguing for a precautionary approach (Friends of the Earth 2009). They guide consumers in choosing nanomaterial-free products and recommend that citizens express their concerns to manufacturers and to the US FDA (Friends of the Earth 2007).

NGOs are providing these resources to mitigate an information asymmetry in the market: manufacturers do not reliably reveal nanomaterial content, and in general, they publicly disclose as little as possible about the ingredients of their products. If they voluntarily make any information public, they do so for marketing reasons. Product makers have made advertising claims about how nanotechnology enhances their products with special functions, especially in the cosmetics and textile sectors. But in terms of leveraging the feedback between consumer demands and product design, consumer knowledge interventions have generally failed to shape how consumers perceive differences between products on the basis of their design. They have relied on relatively uncoordinated and weak outreach by NGOs to consumers. They have also relied on a diffused campaign strategy that aimed broadly across product sectors, rather than targeting market leaders who would have the greatest power to translate consumer demand into changes in design, supply chains, and industry norms.

Targeting companies

Instead of trying to reach consumers, social movements can target brands and their supply chains directly. Since the mid-1990s, NGOs have organized many campaigns that invoke the threat of consumer activism against companies and brands. An example of a market campaign centered on chemical health impacts is the Campaign for Safe Cosmetics (CSC) (Safe Cosmetics Action Network n.d.). Beginning in 2006, the US-based chapter of FoE —a founding member of the Campaign for Safe Cosmetics—led its own campaign targeting nanomaterials in sunscreens and cosmetics (Friends of the Earth n.d.). In letters to 128 sunscreen manufacturers, FoE demanded information about the nanomaterial content of their products, and warned about the potential health risks of untested nanomaterials. Most companies refused to reply; FoE published the responses that they received from the nine manufacturers who answered that their products do not contain any nanomaterials. FoE has cited this very poor response rate as evidence that consumers are not adequately informed of, nor protected from, the risks of nanomaterials in products. However, it is unclear to what extent FoE's nano-specific campaign was integrated into the broader strategies of the CSC, and whether it benefitted from the CSC's effective consumer and business outreach strategies. Relatively few social movement efforts have aimed at supply chains to shape nanomaterial design and use.

5.5 Appraising existing approaches

Social movement efforts focused on the leverage points discussed above have not led to systemic change in how nanomaterials are designed and incorporated into everyday products. Resistance tactics have failed to dismantle the nanotechnology industry: in many forms, it continues to develop over the objections of civil society opponents. Industry can find it easy to depict certain forms of civil resistance as ill-informed, thereby dismissing the concerns being raised. The localized concerns of activists in France did not make a strong connection to nanotechnology as a global phenomenon for social movements to oppose, perhaps because of the many subtle and invisible ways in which it is being deployed. Perhaps, if highly public actions were mobilized in multiple, strategically chosen locations simultaneously—creating a coordinated front of resistance[3]—activists could potentially have created new accountability from industry and government, or forced greater interaction between researchers and concerned citizens.

Policy advocacy does not appear to have radically altered the regulation and governance of nanomaterials; social movements have not succeeded in using public policy to make nanotechnology researchers and designers accountable and responsive to their concerns (D. J. Hess 2010). The degree of government control over the material economy—even its power to manage the health risks of materials on the market—is a deeply contested political issue, in which social movement activists must face off against powerful industry lobbies. In a global political economy that has grown more neoliberal in its culture since 1980, the default approach to introducing new technologies is now to let the market "decide".[4]

Consumer mobilizations represent an attempt by social movements to harness market forces proactively. But can market mechanisms really enable social movements concerned about nanomaterials to exercise their materials sovereignty? There are historical examples of consumers leading companies to redesign products through their user resistance, adaptation of products to their own preferences, and expression of values (Kline 2002; Oudshoorn and Pinch 2003; McCarthy 2007). On the other hand, there are many difficulties with relying on mass consumer power. Consumers can only choose among already-existing alternatives, reflecting their exclusion from pre-market design and innovation. Moreover, consumers' ability to meaningfully exercise choice is impaired by poor and inaccessible information about the health and environmental risks of nanomaterials, or about what materials are actually in products. For example, despite some attention by environmental NGOs to nanomaterials in consumer products, the tendency has been for companies to simply manage consumer perceptions. Analysis in 2009 showed that some cosmetics makers, who previously vigorously

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[3] This strategy has been used by organizations such as 350.org and Fridays for Future on the issue of climate change.

[4] Although market decision-making itself is complex: Polanyi (1944) pointed out that markets typically rely extensively on laws.

endorsed their products as nano-enhanced, had reduced or stopped this publicity for the same products (EurActiv 2009). The reasons are unknown, but may have little to do with changes in product formulation: manufacturers may be responding to NGO campaigns by hiding the presence of nanomaterials in their products. In 2012, FoE Australia successfully pressured a sunscreen maker to admit that their 'non-nano' product included nanoparticles (Friends of the Earth Australia 2012).

Many dimensions of industrial production are structurally impervious to market influences. Materials production chains are often complex, geographically dispersed, and feature numerous, anonymous contract manufacturers (Smith, Sonnenfeld, and Pellow 2006). Clothes and electronics exemplify these chains. Substances used in intermediate stages in the supply chain, produced as by-products, or sold between businesses, are invisible to consumers even though they affect workers and the environment. Because these materials are not identifiable in connection with specific products, brands, or companies, it is virtually impossible to launch a market-based campaign against them (O'Rourke 2005).

More fundamentally, market-based campaigns transfer the work of health and environmental protection from industry and government onto individual consumers (Maniates 2001), but consumers may have little influence over systems-level outcomes that emerge from the workings of markets. Market incentive structures tend to focus design in ways that benefit consumers with the greatest economic and social power—a tendency that can "materialize inequity" in the development of nanotechnologies just as it has in other sectors (Nieusma 2011). Shoppers may not mobilize in a concerted way that is strong and focused enough to achieve systemic change in industrial production (O'Rourke 2012). In a political economic system that fails to cultivate communal knowledge-making about products, people may identify with consuming, comfort, and materialism as their core values. As a result, truly *collective* consumer demands for health and environmental protection—for meaningful input into product design—have been sporadic and feeble (Szasz 2007; Dauvergne and Lister 2012).

Appraising these pathways in terms of creating materials sovereignty, they have tended to fall short. They rely on social movements exerting a weak and diffuse influence on technological design through many structural and institutional layers. We now turn to a deeper examination of participatory processes, which we argue hold greater promise.

5.6 Participatory pathways

What might be possible if social movements could participate more directly in processes that shape technological design? Instead of being passive recipients of knowledge, or being asked to sign off on knowledge, how could civil society and technoscientists collectively produce knowledge—a higher level of participation (Pretty 1995)? In this section we look more deeply into three further pathways: participatory technology assessment, collaboration with industry, and co-design. We discuss how they might enable more meaningful social-movement-driven change in nanotechnology based on materials sovereignty. We discuss a collaboration between the DuPont chemical company and the Environmental Defense Fund (EDF) to create a framework for more environmentally and socially responsible development of nanomaterials in industry. Then, we explore the concept of participatory design, or co-design, using examples of participatory community development and community-led "exploration" of nanotechnology. We discuss how co-design practices could be applied in highly technical fields like nanotechnology to advance materials sovereignty.

Research on social movements suggests some general mechanisms by which collaborative and participatory interventions could happen. Intervention in the design of nanomaterials could follow a pathway like what Hess describes for alternative industry movements—such as those advocating zero-waste manufacturing and green buildings—which do not necessarily achieve a fundamental restructuring of socio-technical systems (D. J. Hess 2016). Social movement organizations could work across the boundaries of science, building ties with collaborators "inside" scientific and industrial research communities and eventually gaining the capacity to influence research agendas—or even to fund and carry out research projects that they help to design. Following a pattern seen in health social movements (P. Brown, Morello-Frosch, and Zavestoski 2011), social movements can strategically develop ties to technoscientists who feel an ethical responsibility to develop safer and more sustainable technologies. These scientists could potentially join with NGOs to provide needed expertise in design and hazard reduction. Or, social movements could engage in partnerships with companies or research labs that design and produce nanomaterials for commercial applications. Either way, the goal would be to influence design decision-making in consequential ways that might lead to materials sovereignty.

Participatory technology assessment

Instead of exerting leverage via market, regulatory, or industry mechanisms, social movements can attempt to intervene in the societal infrastructure through which technologies are introduced and governed. Considerable shaping of new technologies occurs through public and private investment in research—the measures that governments, universities, and large companies take to promote and advance new areas of science and technology. Social movements could try to intervene in processes of institutional agenda-setting and oversight regarding nanotechnology, specifically by influencing the analysis and reasoning about the proposed or imagined benefits, risks, and ethical implications.

Technology assessment (TA) refers to processes of inquiry into the societal implications—including risks, opportunities, and broader goals—of emerging areas of science and technology. Historically developed as a function of national-level governments, a range of TA approaches have been tested in the past several decades (Schot and Rip 1997; Guston and Sarewitz 2002). TA aimed to add a dimension of foresight to public decision-making, so that governments can potentially intervene in shaping new technologies toward desired outcomes. Traditional TA is centered on independent expert analysis—for example, setting up government bodies of experts that hold public hearings and seek input from selected witnesses (Owens 2012; Federation of American Scientists n.d.). In contrast, participatory technology assessment (PTA) refers to methods and activities that aim to be more democratic by eliciting the informed views of citizens or formally integrating public deliberation into the TA process. Examples of such processes include consensus conferences and scenario workshops, which have been used in Denmark since the late 1980s (Andersen and Jæger 1999). Increasingly, a range of organizations besides national governments are undertaking various forms of PTA: academics, NGOs, research consultancies, think tanks, and citizen groups.

Can technology assessment be a mechanism for people outside of research and design—including social movements—to engage in such a broader discussion of the possibilities, goals, and visions of nanotechnology? Social movements could intervene in the processes of technology assessment, using them or working to change them. They can seek recognition as legitimate participants—alongside companies, scientists, and government bureaucrats—in the processes of inquiry, foresight, and long-term decision-making that shape technological systems. Participating in TA would afford social movements some influence over the human values and ethical positions that are brought into these processes. They could also seek to develop new institutions for multi-directional dialogue, through which citizens and lay publics can have greater input into setting broad policy directions for nanotechnology, and into product design processes more directly. In theory, this is a key leverage point: materials sovereignty could be embedded into the complex of policies, regulations, corporate governance, and scientific practice.

Public engagement

Questions of public engagement in the development of nanotechnology have attracted much attention in government and social sciences research. In the early 2000s, major governmental research organizations in the US, UK, and EU made recommendations or commitments to include public engagement as part of nanotechnology development strategies,[5] motivating a period of experimentation with PTA in which dozens of public engagement processes were convened. Efforts were made to incorporate public engagement "upstream" in nanotechnology development (Wilsdon and Willis 2004). Several sources provide summaries of these diverse initiatives (Gavelin, R. Wilson, and Doubleday 2007; Strandbakken, Scholl, and Stø 2013; Guston 2014; Foley, Wiek, and Kay 2017). Critically, public engagement exercises have shown that ordinary citizens are able to articulate well-reasoned positions on nanotechnology issues, which often relate to materials sovereignty. If they are given opportunities to educate themselves and overcome the barrier of gaining technical knowledge about nanotechnology, people demonstrate a significant capacity to reason about its social and political dimensions.

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[5] For example, in the US, the 21st Century Nanotechnology Research and Development Act of 2003 required that the national R&D program ensure "ethical, legal, environmental, and other appropriate societal concerns… are considered during the development of nanotechnology" by various means, including "public input and outreach… by the convening of regular and ongoing public discussions, through mechanisms such as citizens' panels, consensus conferences, and educational events" (United States Congress 2003). In the UK, public engagement was recommended by the Royal Academy of Engineering (Royal Society and Royal Academy of Engineering 2004).

They often want to be better informed—demanding the production and communication of greater knowledge, more studies of health and social impacts—and to become more involved in the making of nanotechnology (Schomberg and Davies 2010). For example, American participants in a deliberative forum on nanotechnology and human enhancement expressed a range of concerns grounded in individual rights balanced with the safeguarding of the collective good (Philbrick and Barandiaran 2009). They emphasized the importance of directing nanotechnology research toward meeting pressing social needs, rather than following agendas dictated by profit motives, authorities, or desires for a luxurious life.

Still, efforts to promote public engagement with science and technology harbor complex problems, as highlighted by numerous scholars (Stilgoe, Lock, and Wilsdon 2014). There remains a tendency for experts in government, science, and industry to treat citizens simply as passive recipients of information, and to "correct" public misunderstandings of science and technology issues (Jasanoff 2005). Experiments in PTA have likewise struggled to break down divisions between experts and "lay" publics, with some supposedly participatory processes effectively reenacting an outdated model of one-way science communication (Petersen and Bowman 2012). Furthermore, institutionalized processes that bring together citizens, scientists, and policy-makers often fail to acknowledge or balance power relations among these groups (van Oudheusden 2011). Even if social movements with technically competent representatives participate, the resulting dialog may reproduce the dominant framing assumptions and discourses that already prevail among scientific experts and policy-makers—intentionally or not. An effort to create broad consensus and a mutually-agreeable plan of action may instead serve to silence social movement views that go against the dominant political framework. If the framing assumptions of PTA are set in advance, then citizens and social movements lose important opportunities to intervene in making the technological agenda. A public engagement program on nanotechnology in France achieved precisely this outcome. In 2009–2010, the French government convened panels of experts for a series of public debates on nanotechnology issues. However, the debates were criticized by activists and even opposed by civil society organizations that had relevant expertise (C. Arnold 2010; Bensaude-Vincent 2012). In their view, none of the fundamentally important questions were being opened to debate—such as the potential encroachment of nanotechnologies on private life. Protests escalated around the debates, eventually causing some of them to be cancelled.

NGO-led technology assessment

Government and academic sponsorship of public engagement activities has arguably not amounted to a deep reconfiguration of the role of citizens in shaping new technologies—even in Europe, where PTA has supposedly been institutionalized (Bensaude-Vincent 2012). If governments are not adequately performing the functions of technology assessment despite persistent advocacy, then another strategy for social movements is to create alternative, non-governmental organizations to take the lead for this work. A few NGOs have indeed leveraged TA in the ways that we outlined above: pushing for and getting involved in PTA, or taking up technology assessment initiatives themselves. Important critiques have come from the Canada-based activist group, ETC Group, which has been highly active in international legal and political arenas pertaining to agricultural, biological, and environmental technologies (ETC Group 2016). ETC Group was among the first civil society organizations to raise doubts about nanotechnology, and as a result, has played an influential role in framing political dialogue (ETC Group n.d.). The group has argued that there are no existing systems of governance capable of guiding the potential transformations that nano- and biotechnologies might bring to natural, technical, and socio-economic systems. In response to the history of unprecedented corporate consolidation of power in the agricultural biotechnology sector, ETC Group advocates a strongly precautionary position, calling for a worldwide moratorium on nanotechnologies until the dilemmas of governance and risks are solved. As part of a solution, they advocate for creating institutions of democratic technology assessment (ETC Group 2003).

In the US, where citizen participation in technology assessment has lagged behind Europe (Sclove 2010), non-governmental groups have lobbied the federal government to adopt participatory nanotechnology governance, or even generated multi-directional dialogue processes on their own. One such group, the Loka Institute, successfully advocated for including public engagement and PTA elements into the US National Nanotechnology Initiative (NNI), a major nanoscience funding program (Loka Institute 2013). Loka has since criticized the US government for failing to fund and implement meaningful programs of public engagement. Another group, the Project on Emerging Nanotechnologies (PEN) at the Woodrow Wilson Center in Washington DC, worked in the vein of TA from 2005 onwards. Spanning the boundaries of government, academia, industry, and civil society, PEN performed several public-interest functions related to critically framing nanotechnology issues and introducing them to ever broader constituencies (Michelson 2013). While the organization never aimed to be politically “neutral,” PEN did not join environmentalist movements in their activism or lawsuits against the government. Instead, PEN chose to instigate cross-cutting channels of communication that allowed social movements, government, and industry to exchange their knowledge more effectively. Despite these important achievements, PEN remained a small entity funded by sympathetic foundations; its budget and activities appear to have dwindled since 2012, reflecting a lack of longer-term stability. Moreover, PEN did not have direct input into manufacturer and designer practices, nor did it created wide-ranging public participatory processes beyond opinion surveys.

Moving beyond assessment

Can PTA approaches enable greater materials sovereignty? While expressing an ambition to foster democratic processes in the development of new technologies, many PTA approaches are geared toward researching or experimenting with how public engagement can be promoted. To date, the trials in participatory assessment tend to be highly academic or bureaucratic in practice. They are usually one-off, small-scale, and institutionally fragile. They do not seek to create new conduits for social movements to directly influence the deliberations of companies and designers when making new materials. They sidestep questions of how to bind such actors to the choices and authority of citizens. Corporations responsible for the commercialization of nanomaterials are conspicuously absent from participatory and democratic dialogues. Given the potency of corporate power, civil society actors are understandably reluctant to include companies in their fora. However, this means that there are no mechanisms to include societal (not consumer) voices in product design processes.

Collaboration with industry: the Nano Risk Framework

Can social movement organizations attempt to collaborate with industry directly? While corporations regularly engage in voluntary initiatives aimed at environmental and social responsibility, public participation is usually absent from these (Muldoon and Nadarajah 1999). Social movements therefore face a challenge of aligning corporate interests with their own to a sufficient degree to develop stable and productive partnerships. To do this, they may need to find particularly receptive companies and internal advocates within them. Even so, collaborators may face dual pressures from industry and from the movement if they have conflicting goals and interests—pressures that may compromise the possibilities for change.

In 2007, DuPont was a major chemical company involved in designing and commercializing nanomaterials (it has since merged with Dow Chemical and subsequently reorganized again). The company entered a seemingly unlikely partnership with EDF, a non-profit group that advocates strongly precautionary approaches to regulating chemicals and nanomaterials. As a social movement organization, EDF has cultivated technical competence among its staff and maintained close involvement with businesses.[6] In the late 2000s, the two organizations worked together to create a joint framework for structuring decision-making in organizations that conduct nanomaterial research and design (Environmental Defense Fund n.d.[b]). The Nano Risk Framework (NRF)[7] "offers guidance on the key questions an organization should consider in developing applications of such materials, and on the critical information needed to make sound risk evaluations and risk management decisions" (Environmental Defense–DuPont Nano Partnership 2007, p. 7).

The NRF is a system for organizing and tracking certain prescribed practices in the context of R&D involving any nanomaterial. It divides these practices into six steps and provides extensive guidance on each, borrowing in many respects from paradigms of chemical risk assessment, risk management, and life-cycle thinking. The six steps are as follows:

1. Describing the material and its applications. This includes the material's origins and characteristics, as well as how it is used, in what quantities, and why it is being used.

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[6] For example, in 2017, EDF funded detailed hazard assessment studies on sixteen chemicals used as preservatives in consumer products, and made the results public to provide a basis for further research in safer alternatives (Environmental Defense Fund 2017)—effectively conducting research that industry should itself be doing.

[7] This project is no longer active, but the NRF is still available online (Environmental Defense Fund n.d.[b]).

2. Generating sufficient information about the material's physical properties, health effects, environmental fate, and exposure potentials throughout its life cycle. Here, the NRF includes a detailed protocol for addressing data gaps and uncertainties in a precautionary manner.

3. Evaluating risks, including characterization of the data gaps, uncertainties, and assumptions.

4. Assessing risk management options, and developing a risk management plan.

5. Deciding on the organization's course of action pertaining to this nanomaterial. This involves deliberative analysis of the information produced in the preceding steps by a review team. It may result in the identification of problems, data needs, or new priorities. The organization must make and implement short-term decisions, engage in long-term planning, and plan when to revisit their conclusions in the future. Decisions made here are to be extensively documented and shared as broadly as possible.

6. Cycle through the framework, periodically reviewing decisions and adapting them in light of new knowledge.

The framework interlocks with typical corporate product development processes, i.e., systems of "milestones as a product moves through basic R&D, prototyping, pilot testing, test marketing, and finally to full-scale commercial launch" (Environmental Defense–DuPont Nano Partnership 2007, p. 14). The responsibilities for implementing various parts of the NRF likewise fit naturally within a hierarchical leadership structure. The information gathering and evaluative steps of the NRF (i.e., steps 1–4) are likely to be performed in small technical teams working on a discrete project within the firm. Step 5, however, introduces a broader "review team" and gives them the opportunity to reflect on a new technology and influence the R&D processes that will take the project to its next milestone. DuPont and EDF recommend going through multiple iterations of the entire NRF whilst developing a single nanotechnological application, to ensure that this review process contributes substantially to the ultimate design.

The participatory potential of the NRF hinges on who is included in the review team and what actual influence the review process has. According to DuPont and EDF, "the review team facilitates interactions that might never occur if left to informal processes" (Environmental Defense–DuPont Nano Partnership 2007, p. 78), because it intentionally assembles a cross-functional group of leaders for the critical assessment stage. The framework recommends including a workforce representative, as well as experts on safety, legal, manufacturing, and administrative aspects. These roles may be filled by people within the firm, or by external partners. Besides convening review teams, the NRF requires documenting the rationale for decision-making in each feedback cycle, and specifies an "output worksheet" format for encapsulating all of the relevant types of information to be documented. Moreover, the NRF recommends sharing these review results with successively broader groups of stakeholders and audiences as a product moves toward commercialization—even if it is a limited, guarded disclosure to protect the firm's R&D investments.

The NRF can be seen as a constructive intervention by one member of a social movement into the scientific and methodological process of risk assessment in corporate nanotechnology R&D. By helping to set the guidelines, protocols, baseline assumptions, and organizational priorities for nano-risk assessment and management, EDF has—to some extent—imprinted on the framework its own ethical understandings of how science should be used to protect environmental health. However, so has DuPont: the NRF does not venture very far from the chemical industry's established positions on matters of risk. In fact, through the very strategy of partnering with industry, EDF did not act as a representative of the broader social movement concerned with nanotechnology (Krabbenborg 2013).[8] EDF has been seen as an outlier in its eagerness to compromise with industry (Leber 2016). A group of 20 environmental NGOs, including FoE, Greenpeace, and ETC Group, publicly rejected the NRF (D. J. Hess 2010). They did not see collaboration with industry on a voluntary initiative as an ethically tenable substitute for societal oversight.

Still, a variety of corporations, industry associations, government agencies, and NGOs have reviewed and "endorsed" the NRF, and three organizations have implemented it in their own practices (Environmental Defense Fund n.d.[a]). DuPont used it to guide and track the development of nanomaterials in three cases, sharing the output worksheets with the public and with the US EPA. A greater number of firms—namely General Electric, Procter & Gamble, Lockheed Martin, and Lloyd's—have chosen to incorporate elements of the NRF into their own practices. Which elements they used, and to what extent they implemented provisions for stakeholder participation and transparency, remains unclear.

Can such a voluntary initiative enable social movements to exercise materials sovereignty over how nanomaterials are developed? In principle, the DuPont-EDF framework can embed citizen perspectives into the heart of the design process—something that has been missing from the majority of experiments with increasing societal oversight. The framework can also create direct accountability between a company and its chosen civil-society representatives, provided that they are willing and able to play this role. Nonetheless, efforts to infuse participatory processes into intact hierarchies of corporate authority and expertise face inherent challenges.

One key critique of the Nano Risk Framework is that it does not provide an *adequate* participatory approach to addressing the potential health risks of nanomaterials. It does not contribute to creating new multi-directional dialogue between designers and social movements, maintaining instead a traditional linear vision of technology development in which

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[8] This case highlights a crucial (and often ignored) point: the people and organizations most active within social movements may or may not be representative of the people they purport to speak for. NGOs frequently claim moral and political authority because they stand for the interests of their constituencies (Wapner 2002). They may aggregate the resources of people who otherwise lack the time and capacity to participate in an issue. Yet, NGO staff may make decisions and express views that do not necessarily reflect the experiences, priorities, and values of those who are supporting them through memberships. NGOs and movements can also lack democracy: a few particularly powerful individuals can control their direction.

"stakeholders" are involved mostly at the end. The Loka Institute, an US-based NGO working to develop participatory technology assessment, publicly expressed "disappointment ... about the relatively slight attention in the framework to the urgency of directly involving the general public and workers—whose livelihoods and safety are most at stake—in assessing and reducing nano risks" (Loka Institute 2007). The cross-functional review teams that comprise the main mechanism of high-level analysis and evaluation would very likely be drawn from a limited group of elite insiders, dominated by high-ranking company staff and experts. Even if the review team were eventually broadened to include outside stakeholders—such as community representatives or citizen panels—the closed, specialized group developing the product will have already carried out their own evaluation of risks and assessment of risk management options (steps 3 and 4 of the framework). These risks and options will be framed and selected in advance of the broader review. Similarly, as a new technological application takes shape and approaches its market-ready state, its fundamental design will become markedly less responsive to influence by outside contributions. Finally, the firm's communication with public and other stakeholders is conceptualized as one-way "transparency" rather than multi-directional engagement.

Second, the NRF focuses too narrowly on the environmental fate, toxicity, and exposure issues of nanomaterials, lacking an entry point for questions of materials sovereignty. Even if practitioners are addressing the entire product lifecycle, this is still narrow because it does not consider the broader relationships of the technology to social systems. The functions of a nanomaterial—the practical reasons for using a material—are established and documented in the first step of the NRF, presumably within a purely technical scope. There is no attention to why the material is being used, in a wider sense. Who needs it, and who stands to benefit from its use? Might particular applications of nanotechnologies affect individual autonomy, privacy, or economic empowerment?

The NRF may be adept at assessing the toxicological risks of materials, but it does not equip organizations with tools for asking questions of equal or perhaps greater concern to social movements. The NRF authors recognize that they built the framework with a focus on their own limited areas of expertise, and invite others to develop ways of addressing broader issues (EDF-DuPont, 2007, pp. 12–13). To date, there have been no further efforts from within the NRF network to connect the framework to other civil society dialogues. This situation simply underscores the need for public participation. It is not that the available technical expertise is too limited; the deficiency is rather an unwillingness within powerful institutions of research, design, and development to broaden the discussion of organizational goals and visions for nanotechnologies.

Co-design approaches

How can we advance models of technological governance that are more multi-directional, directly shape the design process, and hold industry and scientists accountable for their choices? We suggest that approaches based on co-design, or participatory design, offer one way toward strengthening the capacity of social movements to exert their materials sovereignty. Participatory design encompasses several strands of theory and practice in the overarching spirit of citizen involvement in the design of objects, spaces, and technological systems (Schuler and Namioka 1993; Sanoff 2008; Simonsen and Robertson 2013). A rich variety of techniques can be used to realize co-design—including dialogue, deliberation, storytelling, participatory mapping, and many other methods of eliciting and sharing knowledge. Co-design has been applied in a range of domains including health information systems, architecture, urban planning, and education. One prominent strand of participatory design originated in the context of Scandinavian labor movements responding to the computerization of manufacturing work, and asserting their rights to be involved in the development of technologies that affect workers' livelihoods. This rights-based framing resonates with our current framing of materials sovereignty.

Co-design holds promise as a way to assert materials sovereignty, because it fundamentally recognizes that citizens should have opportunities to question and shape the basic directions of technological design. In the case of nanomaterials, such questions might include: What are the goals of developing specific nanomaterials or nano-enabled products? Are these goals truly best served by nanotechnologies, or would non-nano alternatives be preferable? What technical functions are desirable—or superfluous? How are nanotechnologies being introduced, and how can we monitor their effects in the world? Are nanomaterials actually being designed to be safer? Do systems exist to recycle nanomaterials securely? What values are missing from green nanoscience—or from the larger social discourse on nanotechnology? Citizen involvement in design can lead to criticisms of the agendas and framing assumptions of technologists, and this is something that many scientists and company staff fear because they imagine public opposition as a barrier to innovation. Materials sovereignty implies that citizens should indeed have a degree of decision power that includes the right to refuse nanotechnologies based on their informed participation—or refusal to participate—in co-design. Yet this can actually be useful to technology developers, since early public engagement could diagnose issues that may arise later in the form of even stronger opposition or regrettable harm, after flawed technical systems have been allowed to develop (e.g., Harremoës et al. 2013). Co-design would seem to present the most potent leverage point for social movements to intervene in an industry that is only beginning to consider whether nanotechnologies are really delivering their promised benefits to society.

Co-design can also play an instrumental role in creating technological alternatives, which social movements can then advance through the process of incorporation and transformation theorized by Hess (2007). Shaping technological fields through social movement action has typically involved the making and use of technological objects that can compete with incumbent systems—objects such as functional prototypes, alternative designs, and visions of alternative socio-technical systems; objects that can be shown to "work." Taking two of Hess' historical examples: alternative energy movements advocated for solar and wind technologies on the basis of existing technical artifacts that were already being developed and commercialized. In contrast, 20th century social movements opposing the toxic hazards of industrial manufacturing were largely focused on ways to reduce exposure through waste management, leaving industry to pursue (or not) more "upstream" technical innovations like product and process redesign (D. J. Hess 2007). Even now, the limited development of safer alternative *chemicals* is almost wholly pursued by the chemical industry and academic researchers, with NGOs contributing expertise mainly in the assessment of alternative technologies.[9] This highlights the need for co-design to create alternative nanotechnologies: new technological objects that social movements could advance together with research programs and startup firms, to eventually challenge or displace the incumbent forms of nanotechnology that they find problematic. It could even make social movement participants "users" of innovative nanotechnologies that "materialize" (Nieusma 2011) the forms of equity and sustainability that they demand.

A particularly relevant group of scientists and engineers for social movements to collaborate with would be those already engaged in a professional movement sharing some of the same goals—i.e., materials that are benign by design. Green chemistry, articulated in the 1990s as a set of principles for chemists (Anastas and Warner 1998), is one such movement. It is now an established research field with dedicated peer-reviewed journals, conferences, and professional networks. Broadly, the practices of green chemistry aim to reduce waste, pollution, resource use, and toxicity in chemicals throughout their life cycles. At the University of Oregon, James Hutchison has applied green chemistry principles to nanotechnology, coining "green nanoscience" to describe his work (Hutchison 2008). Hutchison and colleagues call on scientists to develop design strategies, informed by nanotoxicology, for making new nanomaterials that are inherently non-toxic and environmentally benign (Gilbertson et al. 2015). Nonetheless, social movements cannot assume that they will find allies among green nanoscientists, just as manufacturers should not assume that they can engineer all nanomaterials to be safe. These scientists may form a new disciplinary field and a movement in their own right, but maintain minimal or skeptical relations with civil society organizations—as seems to be the case with green chemistry (Woodhouse and Breyman 2005; Maxim 2018).

However, "green" technology fields have tended to develop in a technocratic manner rather than adopting participatory design practices (Howard 2004). This is particularly true in the design of "sustainable" synthetic materials—as exemplified by green chemistry, which has developed largely following entrenched structures of research funding and dominant framings of policy issues (Maxim 2018). As we have noted, many aspects of how chemicals and nanomaterials are designed present structural and cognitive challenges to intervention and participation by civil society. Social science scholars have urged that design processes should incorporate intentional input from civil society, with the same level of attention as is given to the contributions of technical professionals (Woodhouse and Patton 2004). But they have largely left open the questions of how this can be accomplished, especially when advanced materials require highly interdisciplinary and technical expertise. Dean Nieusma (2011) presents a detailed analysis of how and why nanotechnology should incorporate participatory design to address the problem of materialized inequity—in which technological

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[9] Environmental NGOs and government agencies, as well as various consumer product firms, have worked together on developing methods for the assessment of safer chemical alternatives (such as Lavoie et al. 2010). But the alternative molecules are typically new products developed by the chemical industry in response to regulatory pressure (e.g. Harmon and Otter 2018).

design creates, reinforces, or fails to counteract systems of oppression. Intentionally shaping nanotechnologies to be socially equitable must proceed on multiple fronts simultaneously, requiring "a combined effort by nanotechnology experts, representatives of the social groups subjected to materialized inequities, and policy makers committed to experimenting with new decision-making protocols" (Nieusma 2011). Policy-makers and nanotechnologists need to actively seek out and institutionalize the involvement of said social groups, with technology designers paying particular attention to groups whose needs would be ignored or undermined by relying on market signals alone to shape design. Once identified, these civil society representatives must be invited to participate with in the work of universities, agencies, firms, and other actors that "translate" nanomaterials out of labs and into society.[10] However, Nieusma is unclear about what the specific roles and capacities of these representatives would be in technological design, besides providing their perspectives in a general sense. He is also unclear on how the representatives would actually contribute to design processes and what the practical challenges might be.

What elements might be needed to make co-design effective as a pathway for social movements to achieve materials sovereignty? The implications of Nieusma's analysis for co-design are clear on one point: it must entail "systematically reconsidering who participates in nanotechnology decision making and on what terms" (Nieusma 2011). This means reshaping the distribution of decision-making power and epistemic authority. How can this be done? Although we are not focusing on methodological issues specifically, looking at how co-design might happen in practice is critical for investigating the overarching question that we pose. There are many examples to follow in the practice of participatory design (Simonsen and Robertson 2013), but examples of co-design approaches being applied in nanotechnology are very few. Most efforts to involve citizens in this field have focused on deliberation about macro-level social and ethical issues, rather than the particulars of technological applications. Still, some academics are experimenting with bringing nanoscientists and representatives of civil society together in participatory ways. We will look at two examples that provide possible models for nanotechnology. One example deals with nanoscience specifically, while the other example is about sustainable infrastructure and energy systems—we include it because it exemplifies several important features that we would like to highlight and relate to nanomaterial design. After briefly discussing these example, we will turn to the needs and challenges for participatory pathways.

Nanotechnology in urban sustainability

Researchers at the Center for Nanotechnology in Society at Arizona State University (CNS-ASU) have approached participatory design by working at the intersection of nanotechnology and urban development (Wiek, Foley, and Guston 2012; Wiek, Guston, et al. 2013). An approach reported recently by Foley, Wiek, and Kay (2017) deploys co-design principles with notable attention to the particular challenges of engaging citizens in nano-design. Their

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[10] The term "translate" is quoted here from Nieusma (2011) but also recalls the sense of Latour (1987).

approach, called “collaborative on-site technology exploration” (COTE), situates participatory technology assessment practices within citizen-guided walking tours of urban neighborhoods. Representatives of local citizen groups lead small groups of nanoscientists and citizens through parts of the city, exploring specific social challenges faced by local communities, and discussing how nanotechnologies might play a role (or not) either in solving or exacerbating the problems. These challenges are identified through partnerships between the COTE facilitators (university researchers) and civil society organizations. Likewise, potential nanotechnologies of relevance are identified in collaboration with the participating scientists. In the COTE engagements reported by Foley and colleagues, the participants considered the challenges of energy vulnerability, public health impacts of chronic diseases, and water contamination in the US city of Phoenix. The participants readily linked these challenges to broader systemic problems, and some lines of “exploration” led to later interventions having to do with nanotechnology while others did not. Even if COTE participants fail to identify relevant and workable nano-solutions to high-priority problems, that in itself is a valuable learning outcome and an insight for scientists and technology designers.

This co-design approach has several aspects that suggest a potential for integrating materials sovereignty. First, intentional steps are taken to destabilize conventional configurations of power between technoscientists and “lay” citizens. By locating the exercise in the urban environment rather than in labs or conference rooms, and by giving civil society participants the role of guides, COTE aims to put all of the participants on the same level of epistemic authority. Indeed, it is designed to encourage humility in the scientists who find themselves not only on an equal footing, but on the home turf of urban residents. Second, the COTE model sets up much needed interactions between the disparate knowledges of citizens and technoscientists—although not without difficulty. The facilitators must intentionally orchestrate and mediate these interactions, while also fostering multi-directional dialogue and learning rather than a simple exchange of information. For example, facilitators at CNS-ASU helped prepare the citizen guides by briefing them on the nanoscience topics that they had identified as relevant. Scientist participants were likewise familiarized with the problem framings of urban challenges. These knowledges may not resolve or coalesce, but rather meet in an unpredictable and generative dialogue, as the facilitators “attempt to reconcile the ways of knowing and making sense of the complex urban challenges and nanotechnologies” (Foley, Wiek, and Kay 2017). Furthermore, the encounter might invite reflection in each participant on their “own values and other people’s normative positions regarding fairness, moral claims, harms and risks, and value conflicts (or trade-offs).”

Sustainable infrastructure in a tribal community

Although this second example of co-design does not address nanotechnology, several of its features contribute to our analysis of how co-design can enable social movements to seek materials sovereignty. In a recent UC Berkeley-based participatory study, Ryan Shelby led a team that explored the potentials of co-design through a project in partnership with the Pinoleville Pomo Nation (PPN), a Native American tribe in Northern California (Edmunds et al. 2013). The project sought to meet community-identified needs for renewable energy and culturally appropriate housing infrastructure, which would replace existing natural gas systems and prefabricated homes. The underlying principle of the engagement was that community members "are considered to be experts on their needs and therefore should co-design solutions with designers and engineers... The voice and point of view of the user community is at the forefront" (Shelby, Perez, and Agogino 2012, p. 801). It is up to the community whether they will accept the solutions that the co-design process has produced.

The PPN participants engaged in collective story-telling over how they defined a sustainable way of life. They shared their previous history of negative experiences with US government officials and academic researchers. Supported by a technically expert PPN employee, David Edmunds, participants from both UC Berkeley and PPN generated graphic concepts for the design of self-sufficient housing, water, and energy systems, via multiple rounds of workshops. This co-design approach contrasted with conventional technology-driven approaches to sustainability, in which "little or no time is spent on understanding the needs of the Native American communities and building trust" (Shelby, Perez, and Agogino 2012, p. 796).

In an iterative process that combined ongoing community participation with technical analysis and design activities performed by UC Berkeley students, community members oversaw the design, engineering, and construction aspects of the project. For example, Berkeley researchers would build several prototype building models based on community input, and bring them back to the tribe (Edmunds et al. 2013). Tribe members would critique these models and imagine how the buildings might fit into their life. They would have materials at hand to make their own models. The PPN-Berkeley partnership yielded locally situated and culturally sensitive designs, which were constructed on-site, and led to further sustainable development efforts in the community. Importantly, the co-design process did not rest on any prior, unquestioned assumptions of what constitutes sustainability. Nor did it require participants to arrive at any definite conception of sustainability. Rather, the focus was on understanding the values underlying design. As a result, the value of cultural sovereignty was understood to be profoundly intertwined with ecological sustainability. The tribe could not be sustainable without also having cultural self-determination.

5.7 Needs and challenges for participatory change

What principal elements are needed to provide participatory pathways to materials sovereignty? And what are the main challenges to meeting these needs? Based on our review of participatory pathways, including theory and experimentation in public engagement with nanotechnology, we propose that three overarching elements are central to achieving substantive materials sovereignty. We present these elements, their components, and associated challenges as a hypothesis to guide future research in materials sovereignty. We summarize the following sections in Table 5.2.

Table 5.2: Needs and challenges for materials sovereignty

Key elements	Challenges
Participatory knowledge systems • Knowledge sharing, collaboration, and commons • Enable complex and multi-directional dialogues between knowledges • Epistemic humility	• Cognitive constraints of citizens and designers • Gaps in knowledge • Epistemological, methodological, and political tensions • Citizens' independent time and resources • Organizational resources
Embedding civil societies into the design process • Upstream engagement with publics • Intentional inclusion of citizen representatives • Practical mechanisms for engagement	• Accessibility of upstream R&D processes • Appropriate selection of representatives from civil society • Corporate behavioral norms • Organizational capacity for engagement
Building broad-based accountability systems • New or reinforced social norms • Policies giving more power to citizens • Institutionalized societal oversight	• Industry power and commercial incentives • Weak existing institutions • Political climate favoring deregulation and free markets

Participatory knowledge systems

Materials sovereignty requires creating multi-directional flows of information, knowledge, and agency—in other words, participatory knowledge systems—centering on materials. Conventional models of the public understanding of science rely on drawing lines between technical experts and lay people, between scientific/technological and popular/experiential knowledge, between policy-makers and citizenries (Jasanoff 2005). Such models assume that lay people are passive recipients of knowledge radiating from technical experts, and that scientific and technological developments flow linearly into policy-making. By contrast, numerous cases of citizen science and socially robust knowledge-making attest to the potential capacity of lay people to contribute significant expertise on environmental issues (e.g., Nowotny 2003; Corburn 2005; P. Brown, Morello-Frosch, and Zavestoski 2011). People not only need to be informed, they need to be empowered to be knowledge-making agents in their own right.

Developing participatory knowledge systems will require addressing the cognitive challenges and barriers that various actors face. Citizen groups will need technical expertise to be able to participate in the assessment and co-design of material technologies—to evaluate material design issues, and to judge alternative designs. Successful efforts to intervene in industrial environmental activities, from pollution prevention at chemical plants to toxics reduction programs, have often entailed citizen groups working with scientists and engineers who volunteer to help or who are paid as consultants. Such experts can help bridge the large knowledge gaps that citizens have regarding industrial operations. Finding experts willing and able to collaborate with social movements as the leaders can be challenging, as can finding ways to finance the use of those experts. Bringing in technical experts who do not share the goals and values of movements can undermine the pursuit of real change (Ottinger 2013). Mobilized citizens can sometimes feasibly develop enough familiarity with technical knowledge to be able to participate in knowledge-making. For example, AIDS disease activists in the US acquired enough expertise in clinical pharmaceutical research to insist on their equal involvement in co-designing drug trial protocols (Epstein 1996). Other citizen science examples can be seen in design for pollution monitoring (Rey-Mazón et al. 2018) and agricultural technologies (Bishaw and Turner 2008). Academic institutions and NGOs can contribute to "building capacity" (Guston 2014) for public participation around nanomaterial issues. Nonetheless, few citizens have thus far had the time, resources, or interest to develop particular expertise in green nanotechnology that could inform actual design choices. The lack of active public interest is evident in the gap between people's largely uninformed and malleable views about nanotechnology on the one hand, and the nuanced understandings and critiques that citizens develop while participating in "capacity-building" PTA exercises on the other (e.g., Guston 2014). If it appears that people don't care, this may be because they are poorly informed and resourced to do so.

Even within expert knowledge communities, technology designers face substantial cognitive and technical barriers to developing safer materials. For example, green nanoscience calls for even more highly specialized technical knowledge than already is involved in nanomaterial design. Designers must more carefully characterize the physical and toxicological properties of their materials, among other challenges (Harper et al. 2011). Yet there is a lack of information that would enable them to do so, and corporations are not obliged to generate environmental data on nanomaterials. Green nanoscientists will also need to choose which environmental impacts and risks are most important to reduce, but few ethical or policy guidelines exist to govern their thinking. This underscores all the more why participatory knowledge sharing can improve design outcomes.

One way to work toward participatory knowledge systems is through practices of sharing and collaborative creation of knowledge—the development of knowledge commons (C. Hess and Ostrom 2007). These might include databases, libraries, or informal networks for sharing knowledge. Some starting points already exist to develop knowledge commons about nanomaterials and their health, environmental, and social dimensions. An international network of nanoscientists and toxicologists has collaboratively developed an information system called eNanoMapper (Kilic et al. 2016), which enables the publication and open sharing of scientific data about the environmental health effects of nanomaterials. While eNanoMapper makes important contributions to the capacity of scientists to share knowledge and assess nanomaterial health risks using agreed-upon standards and conceptual agreements, it primarily addresses expert rather than civil society knowledge needs. Taking a different approach, researchers at CNS-ASU have begun assembling a range of knowledge resources about nanotechnology applications in city environments, creating the online database NICE (Center for Nanotechnology in Society 2019). They were able to leverage this database in their facilitation of COTE engagements on urban nanotechnology issues (Foley, Wiek, and Kay 2017). Of course, these efforts demand significant investments of organizational resources and citizens' time (Kleinman, Delborne, and Anderson 2011).

Participatory knowledge systems must enable complex and multi-directional dialogues between knowledges—and for this, scientists and designers must exercise epistemic humility. For example, in the PPN-Berkeley partnership, researchers made efforts to catalyze new information flows within the tribal community while allowing the tribe to maintain decision-making authority regarding building materials, design, and renewable energy technologies. The designers were willing to communicate across what can be profound epistemological, political, methodological, and language divides in transdisciplinary work (Lélé and Norgaard 2005). Both the community and researchers were open to learning from each other, treating each other with mutual respect. The COTE methodology also requires this willingness. Epistemic humility is needed (Jasanoff 2003), especially in science and engineering, where no single knowledge predominates. Likewise, efforts to build shared knowledge resources—like databases and product standards—should be participatory themselves, recognizing the capacity of information systems to embed and codify values (Bowker 2000).

Embedding civil society in design processes

Material sovereignty demands embedding civil society representatives into the design process. Instead of keeping design practices enclosed, societal actors need ways to directly and authoritatively communicate their values into materials design (Howard 2004; Woodhouse and Patton 2004). Technical experts, in turn, must be willing to allow lay people and social movements to define the values and needs that are embedded into a material or product. This needs to occur "upstream" in the design process, at points where technological applications are still coalescing and before path-dependencies set in (Wilsdon and Willis 2004). Working through the market, for example, may be circuitous: can companies actually learn about social preferences from buying patterns? Can citizens truly overrule design choices already made and rendered as manufactured products? For direct engagement to exist, civil society actors must be regarded as epistemically and socially legitimate fellow participants in the design process. They cannot be seen as token representatives of diverse social voices. New institutions and social norms need to develop through which material design can only have legitimacy if it has included civil society review.

But who are civil society "representatives," and how should they be selected—and by whom? This is one of the most difficult challenges to address in imagining co-design as a broadly applicable strategy and pathway to materials sovereignty. Nieusma (2011) points out that unlike traditional examples of participatory design integrating user input, nanomaterial design should also consider the wide range of *affected non-users* of the materials, such as people exposed to pollution or otherwise impacted by the introduction of specific technologies. Seeking a broad set of participants is therefore of critical importance. This includes equitable representation of the diversity of civil society—in terms of gender, disability, race, class, and other dimensions—which is likely to be challenging with co-design methods that typically involve only small groups of participants. We suggest that another important aspect of representation, especially as concerns materials sovereignty, is the intentional inclusion of representatives of social movement groups that have organized around focal interests—such as local community pollution, product-specific issues (e.g. nanomaterials in cosmetics), or other technology issues. As *mobilized publics* (2007), these groups may have clearly articulated concerns and demands that would be much more difficult to elicit from representatives selected from the general public. On the other hand, co-design processes cannot be allowed to be overrun by self-nominated representatives of industrial or political interest groups.

The legitimate selection of co-design participants may require new organizational functions not usually associated with technological design. For example, CNS-ASU facilitators needed to identify and invite civil society organizations into an ongoing dialogue, before inviting specific representatives to serve as COTE guides. Similarly, they partnered with scientists and engineers who were interested in engaging with broader challenges in their research. This required extensive research, outreach, and relationship-building on the part of the facilitators. In short, co-design requires a clear recruitment strategy and significant organizational capacity and credibility to implement it. Given the innumerable private-sector design processes happening at any given time, how such processes could be institutionalized and financed at a larger scale is one of the question that future research in co-design needs to address.

For civil society and social movement concerns and knowledges to be embedded into design, practical mechanisms—like co-design or PTA techniques—are needed to facilitate encounters and interaction with designers. This requires nanotechnologists to be accessible to the people whose lives are affected, but this requires them to be willing to cede some of their structurally-accorded power and privilege. Pragmatic approaches like those used in COTE—taking scientists and designers outside of labs and conference rooms, letting citizens lead them for a while—might be effective, if they can be institutionalized. Indeed, rather than design occurring purely inside industrial laboratories, nanotechnologists could venture out into community spaces to share their potential ideas via prototypes for feedback. Companies and research institutes could internalize citizen perspectives by developing new design tools and protocols that incorporate broader evaluation alongside traditional performance criteria and toxicity data. Such practices would contravene long-held industry norms of secrecy, competition, and intellectual property. Nonetheless, such behavioral norms are arguably obsolete in an era of proliferating ecological and human health degradation.

Accountability systems

Finally, realizing materials sovereignty would require building a broad-based accountability system for assuring actual practice. As Hess has observed, social movements aiming to influence industry rarely achieve their goals fully, instead becoming "caught up in a more complex dance of partial success and cooptation" (2007, p. 236). Corporations can readily promise to make their materials safer, only to make compromises in design, or ultimately subside into their familiar profit-seeking culture. They must be made accountable for their materials choices. Similarly, scientists and government regulators may be at a distance from the populations whose lives they are affecting. Weber (2003) suggests that accountability is "a system, or set of mechanisms designed to make sure promises are kept, duties are performed and compliance is forthcoming." In other words, a substantive standard can be defined, and then accountability can be assured through assessing whether that standard is being met, enforcing performance, and imposing sanctions. Some empirical evidence suggests that corporations are more likely to adopt ethical design choices if they face questioning from citizens about their rationale, or when governments require rigorous, highly public tracking of progress in making materials safer (Geiser 2015). New institutions and laws may be required to support a web of accountability relationships that can work more effectively in complex materials production systems.

How might co-design happen in institutional terms? If designers are, in fact, willing to accept and work with the other elements of materials sovereignty, accountability systems may be created jointly with civil society participants and may rely on conventional social norms—such as academic standards of research conduct. The Berkeley researchers working with PPN were held accountable for their design choices, and for including tribe members in the process, through rolling report-backs and presentations of prototypes for feedback. They were sensitive to how power was distributed across their team and throughout the R&D process (see also Schattman et al. 2014). Another possibility is that green nanoscientists and designers may develop a vested interest in the participatory process itself, either through incentives for research funding or through their own ethics and politics. Like the computer scientists who eventually originated the free software movement, nanotechnologists could develop a "moral and technical order" of collaboration and sharing with society (Kelty 2008). If the history of free software is any indication, though, such an order might be fragile and easily commodified by companies.

Public policy changes may be needed to institutionalize accountability in technological design. One way might be for government to mandate that new nanotechnologies or nanoproducts can only be approved if authentic citizen engagement has occurred. This could take the form of participatory technology assessment structures that enable people to collaborate with designers in their many locations within start-ups, large multi-national corporations, and university institutes. Decentralized, site-specific organizations could be created to facilitate dialogue with social movements. Using taxes on the ecological and health effects of materials, governments could fund open access to technical expertise—as well as new institutions for participatory research (e.g., Woodhouse and Breyman 2005). Governments could give citizens the power to require design changes, or new development could be held up or even vetoed through lawsuits or product suspensions against companies. All proposals that depend on asserting government power over the private sector, of course, face serious challenges in the current neoliberal political climate. Finally, civil society can seek accountability through careful and sustained oversight of nanomaterial issues in a global forum—a collective form of participatory technology assessment—as Jasanoff and colleagues have argued should be instituted for human gene editing technologies (Jasanoff and Hurlbut 2018).

Much of the preceding discussion has been exploring the premise that social movements' goals can include changing the design of nanomaterials, in the vein of "sustainable materialism" (Schlosberg 2019). But we also recognize that the goal of some social movements may, in fact, be full resistance to nanotechnology—and perhaps also resistance to the attendant material cultures of consumption and corporate control. Materials sovereignty could still form the basis for such demands, and all of its key elements could contribute to an "informed refusal" (Benjamin 2016) of nanotechnology. That is: an alternative vision of just and sustainable material systems *without* nanotechnology should be open to social movements and societies.

5.8 Conclusions

Nanotechnologies in many ways exemplify emerging technologies that could cause an array of ecological and health damages, if they are not designed with sustainability in mind. Yet we face fundamental problems in governing such emerging technologies. Green nanotechnology is now being developed as a way to make nanomaterials safer through rational design, but nanotechnologists do not uniformly recognize any obligation to attend to societal concerns and only limited obligations to address environmental health and safety issues (Corley, Y. Kim, and Scheufele 2015; Johansson and Boholm 2017).

Against this background, the new concept of materials sovereignty is arguably emerging in the practices of social movements for health. Materials sovereignty is the right of people to use, and to be surrounded by, environmentally benign, non-toxic, and renewing materials in their everyday lives. In this paper, we have begun to sketch how and why materials sovereignty matters in the governance of emerging technologies. We suggest that social movements using the idea of materials sovereignty can bridge between technological designers and ordinary citizens. Far from the passive audiences that surveys portray, citizens are likely to be feeling disempowered because of their lack of agency and lack of access to information about the (nano)materials present throughout their environments, workplaces, homes, and bodies. The relatively few instances of participatory citizen analysis of nanotechnology suggest this.

In this paper, we have examined how materials sovereignty might be achieved in the case of nanotechnologies by targeting leverage points within the industrial materials system. We have discussed five examples of such pathways: direct resistance; market-based approaches; policy activism; participatory technology assessment; voluntary partnerships between industry and NGOs; and co-design approaches. We have analyzed these pathways in terms of their theoretical and practical contributions to materials sovereignty. Based on this analysis, we identified three key elements of materials sovereignty: participatory knowledge systems creating multi-directional flows of knowledge and agency; the embedding of citizen voices into design processes; and building accountability systems.

We conclude that most of the pathways we have analyzed are lacking as regards one or more of these elements. Still, we suggest that all of the pathways are essential to realizing materials sovereignty; they are not mutually exclusive and they can complement each other. Co-design appears to be the most promising pathway from a theoretical and ethical perspective, but there remain significant institutional and organizational challenges for bringing it into practice.

Therefore, further research and experimentation is needed to determine whether co-design processes can intervene effectively in materials design. To begin with, action-research projects—such as Arizona State University's COTE endeavor—can gather scientists, citizens, NGOs, and companies together in structured experiments to develop safer nanomaterials for specific uses. Such projects can evaluate mechanisms to assure that citizen and social movement participants are fully representative, and test practical methods for enabling dialogue and sharing of power between civil society actors and designers. They can make it more "normal" for civil society to be directly part of materials development. These projects can also be used to seed, and gradually expand, a shared infrastructure for recruiting participants, pooling and financing accessible technical expertise, and making designers accountable for their choices. Based on the results, governments may need to enact laws that mandate participatory design as a precondition for marketing new materials.

As social movements increasingly apply pressure on multiple leverage points in the global materials system, we hope that our analysis may help guide strategies to maximize the beneficial effects of interventions in technological design. Materials sovereignty can provide a way to integrate societal perspectives into material design for the benefit of humans and ecosystems.

Chapter 6

Conclusions

At some level, this dissertation is motivated by a hope for green design—technological design that attends to human and ecological health—to open new pathways toward a sustainable material economy. Yet it is far from given that this hope can be realized. My aim, therefore, has been to critically inform green design efforts by exploring how they relate to science and society—and in doing so, to contribute to interdisciplinary environmental research in the vein of STS scholarship.

If green designers can learn anything from STS, it is to step back and examine the "habits of thought" (Jasanoff 2003) that permeate knowledge, tools, infrastructures, and practices. Extensive STS research (e.g., Jasanoff 2004) has shown that scientific knowledge and technical systems develop in reciprocal, mutually generative relationships with social and political systems. Sheila Jasanoff (2003) describes the dominant pathways of development as "technologies of hubris," which strive for the prediction, control, and management of risks. An example of a technology of hubris is the regime of legal, administrative, and industrial arrangements that aims to protect workers from exposure to cancer-causing substances—but only to a level where the number of cancer cases can be quantified and deemed to be "acceptable" (Boyd 2012); and where the risk calculation is based on workers' exposure to each substance by itself, even if they are exposed to mixtures of cancer-causing agents (Callahan and Sexton 2007). This regime is shaped by a way of thinking and knowing (e.g., "acceptable risk") that permeates through science, technology, business, policy, and law in the materials arena. Taken together, these approaches leave humanity and the environment vulnerable when decision-makers fail to anticipate emergent harm, fail to see the "design flaws" in complex systems, or fail to act on uncertain and incomplete indicators of harm already taking place (e.g., European Environment Agency 2001; European Environment Agency 2013).

In contrast to this dominant regime, Jasanoff articulates a need for institutions and habits of thought that can bring greater wisdom to the governance of science and technology:

> Today, there is a need for 'technologies of humility' to complement the predictive approaches: to make apparent the possibility of unforeseen consequences; to make

> explicit the normative that lurks within the technical; and to acknowledge from the start the need for plural viewpoints and collective learning. (Jasanoff 2003, p. 240)

Epistemic humility, for Jasanoff, means attending to how problems are framed, what dimensions of social and environmental vulnerability must be accounted for, and how risks and benefits are distributed throughout society. It also means grappling with how society can integrate knowledge and understanding for the governance of technology—in a complex world where we tend to create many partial knowledges and contradictory understandings.

Is green design, despite its goals and hopes, a "technology of hubris?" While the alternatives assessment paradigm may offer an alternative to risk assessment that is better suited to participatory and precautionary decision-making (O'Brien 2000), is this necessarily so in its current application to chemical substitution? What can we make of CHA's somewhat abstract standards of safety that are quite narrowly construed, almost exclusively in terms of mammalian toxicology? What of the narrow system boundaries that we set when we seek to define "sustainable" products, buildings, or chemicals—what about the larger effects of industrial systems, or the inevitable trade-offs that trouble most design choices? I cannot answer this question here in depth—I pose it as a strong provocation for future research and reflection. But I could paraphrase much of this dissertation as investigating what it would take to make green design a "technology of humility." Here I draw two overarching conclusions, summarizing the challenges and opportunities they highlight for green design.

6.1 Knowledge systems matter

How do we know whether our technological choices are "safe"—biophysically, ecologically, socially and economically? In the prevailing science/policy view, resolving this dilemma demands more and more data about chemical toxicity, deeper visibility into material production systems and chemical life cycles, and greater methodological capacity for analyzing health and environmental impacts (Geiser 2015). In other words, we are justifiably focused on what we need to know, and how much we still must learn or discover, to answer critical questions of health and sustainability.

Looking beyond this often technocratic stance, this dissertation suggests that we should also give systematic attention to *how* we know—what "habits of thought" we bring to generating knowledge and action in a complex world. This dissertation has empirically explored systems for producing, organizing, testing, and mobilizing chemical knowledge: from the intentional design of the Chemical Hazard Data Commons to the spontaneous evolution of the GreenScreen knowledge commons; from the community peer-review of chemical hazard assessment methods to the encapsulation of those technicalities (and politics) into green design tools, and the deployment of those tools through a network of standards, practices, and institutions. Rather than focusing on the facts, methods, and tools themselves, my investigation has been about the systems, processes, and structures through which they exist.

These "knowledge systems" matter because they shape the pathways of action that knowledge makes possible. This is evident in how green chemistry information systems maintain compatibility with an entrenched chemical-by-chemical view of toxic impacts—a view that legitimizes continuing to ignore the reality of chemical mixtures and the dynamic, multi-causal reality of environmental hazards. The science and tools of chemical alternatives assessment, including the Data Commons and GreenScreen, do little to interrupt or diverge from this dominant regulatory-scientific paradigm. As a result, connections with other environmental health knowledges and strategies are more difficult for green chemists, policy-makers, and alternatives assessment practitioners to make—for example, where the organizing principle is not chemical substances but places, bodies, or complex material systems such as plastics (Liboiron 2016) and waste (ChemSec 2019b; O'Neill 2019).

Furthermore, my research makes the case that green design knowledge systems should become more participatory and democratic. For example, the highly privatized political economy of chemical hazard assessment knowledge is one way that civil society actors—consumers, social movements, and many NGOs—are excluded from making and using science, and from the technical conversations around green chemistry. This, and other barriers, closes off participatory pathways such as public accountability systems, citizen science, and co-design—which could potentially help drive industrial transitions in the chemistry of everyday products and materials. To open up these possibilities, green design should actively invite pluralistic knowledges and diverse approaches—but with humility, and with a recognition that no one community and no single knowledge system can encompass all possible pathways for changing the global material economy.

With this in mind, it is worth revisiting the disclaimer with which I first introduced "green design" as a fundamentally limited, primarily technological approach to sustainability. The problem-solving strategies I have examined in this dissertation share a common systems frame that also prevails in environmental policy: materials matter, but material culture does not (see Felt 2019; Schlosberg 2019). The idea of safer chemical substitution, for instance, is premised on stable notions of chemicals, materials, products, and in some cases services (Tickner et al. 2015) existing within an unchanged system of economic production/consumption. These notions fail to take into account how that economic system could itself be transformed, through structural and cultural change, to enable entirely different kinds of sustainability transitions that also reduce chemical pollution (O'Rourke and Lollo 2015). The point is that to practice humility, it is critical to be aware of what frames green design takes for granted, because these determine what systemic changes are *not* being pursued.

6.2 The commons: Transformative or compromised?

What is the role of the commons in green design and in pathways to socio-technical change? This dissertation offers two parallel accounts of how knowledge commons are emerging as sites for the collaborative production and mobilization of chemical knowledge: first, as a collectively-organized effort to provide open-access knowledge resources (the Data Commons project); and second, as an emergent knowledge network in which participants actively generate, test, and revise the shared knowledge resources that support their independent knowledge-making (the case of GreenScreen). My most significant empirical finding comes from the latter case: that the commons appears to be producing the GreenScreen methodology as a form of socially robust knowledge. Whether this claim can be generalized to other knowledge commons will be up to further research, which must significantly extend what I have done here.

What emerges from these accounts is a picture of chemical knowledge commons that are potentially transformative but "compromised." As a technical resource and as an intervention to make knowledge more accessible and actionable, the outcomes of the Data Commons project have great value and utility. But the project focused almost exclusively on technical and infrastructural innovations, without creating new institutional and economic arrangements involving chemical profilers. As a result, the Data Commons was not successful in changing the entrenched background conditions of CHA knowledge production. The GreenScreen commons, by providing a successful open-access methodology, supports the economic interests of private-sector profilers—but at the expense of enclosing the resulting knowledge-making processes within proprietary IP arrangements and exclusive business models that limit the potential of CHA knowledge to propagate further into the public sphere. The commons participants, including chemical profilers and the makers of GreenScreen, see these outcomes and would prefer to change them. However, between the immediate practical realities of CHA and the community tensions around openness and transparency, there appear to be limited possibilities for change. Each actor feels powerless to behave differently on their own.

But is settling for a compromised commons really the only way, or is this actually a collective action trap? As I interviewed green design knowledge-makers, it was clear that many of them are searching for ways to change this system. They are experimenting to find the right "business model"—the right combination of market drivers, access arrangements, payment schemes, and long-term funding plans—to solve the supply and demand problems of chemical hazard assessment and provide more knowledge to the public. An innovative market-based solution cannot be ruled out, nor can solutions based on collaborative funding consortia. Supplying public-domain chemical knowledge may yet call for government intervention—beyond what already exists in leading policy programs like REACH and California's SCP—and with it, institutionalized public support. The point is that systems can, after all, be changed. It takes not only ingenuity, but collective action.

If knowledge commons continue to emerge around green design, it may be because they fulfill a communally shared need. However preliminary and incomplete, my findings in the case of GreenScreen support the hypothesis that a knowledge commons—and an extended expert community—can serve as an essential proving ground for working through scientific, practical, and political challenges endemic to chemical and material issues. Tom Lent, former Policy Director of HBN, provided a clear example of this when he described how the motivation to pursue a commons-based approach grew out of HBN's experience developing

Pharos:

> As we went down the path of trying to evaluate things through chemical hazard analyses, we learned about the limits of hazard lists and the gaps remaining in that [approach]... We started to identify all the challenges that we would need to solve if this was really going to be the "perfect" or even "really good" tool, to close all the [gaps]. As we understood the magnitude of what needed to be done, we quickly came to realize that doing this on our own was always going to be a challenge, and that figuring out how to recruit or bring the world together to collaborate and help us solve these problems would be a useful venture.

6.3 Future work

My findings suggest some paths for further work. First, there are several additional cases that I did not have time to include in this study, such as CleanGredients (GreenBlue 2020), the Clean Electronics Production Network (Green America 2020), the evolving ChemForward initiative (ChemForward 2020), and the textile industry's ZDHC Roadmap to Zero Programme (ZDHC Foundation 2020). These cases could form the basis for an extended comparative case study. More critically, this dissertation has generated hypotheses linking knowledge commons to transformation of the social governance of technology: through socially robust knowledge (which deserves further investigation), but also through participatory knowledge systems that have yet to be described and conceptualized. Could the commons generate greater public awareness, attention, and capacity to engage in participatory technological design? Or bring together diverse constituents under the rubric of rights-based claims to a healthy environment—providing a pathway to materials sovereignty?

While this document marks the end of my doctoral work, I expect to grapple with these questions for some time into the future—even if it is through applied research, information infrastructure design, or policy development. I hope the questions I have raised here will provide some inspiration for other scholars, scientists, designers, or activists interested in remaking the way we make knowledge.

Bibliography

Allen, Jennifer H. (2013). "The Wicked Problem of Chemicals Policy: Opportunities for Innovation". In: *Journal of Environmental Studies and Sciences* 3.2, pp. 101–108. DOI: 10.1007/s13412-013-0117-0.

American Chemistry Council (2014). *Manufacturing Coalition Announces Principles for Effective Alternative Assessments.* URL: http://www.americanchemistry.com/Media/PressReleasesTranscripts/ACC-news-releases/Manufacturing-Coalition-Announces-Principles-for-Effective-Alternative-Assessments.html.

An Act Relating to Flame Retardants (2013). In collab. with Sharon Nelson and Andy Billig. URL: https://app.leg.wa.gov/billsummary?BillNumber=5181&Chamber=Senate&Year=2013.

Anastas, Paul T. and John C. Warner (1998). *Green Chemistry: Theory and Practice.* Oxford; New York: Oxford University Press.

Anastas, Paul T. and Julie B. Zimmerman (2019). "The Periodic Table of the Elements of Green and Sustainable Chemistry". In: *Green Chemistry* 21.24, pp. 6545–6566. DOI: 10.1039/C9GC01293A.

Andersen, Ida-Elisabeth and Birgit Jæger (1999). "Scenario Workshops and Consensus Conferences: Towards More Democratic Decision-Making". In: *Science and Public Policy* 26.5, pp. 331–340. DOI: 10.3152/147154399781782301.

Arnold, Cathy (2010). *Blogging from France: Science and Public Debate.* URL: https://asunow.asu.edu/content/blogging-france-science-and-public-debate.

Arnold, Denis G. (2010). "Transnational Corporations and the Duty to Respect Basic Human Rights". In: *Business Ethics Quarterly* 20.03, pp. 371–399. DOI: 10.5840/beq201020327.

Ashford, Nicholas A. (2005). "Incorporating Science, Technology, Fairness, and Accountability in Environmental, Health, and Safety Decisions". In: *Human and Ecological Risk Assessment: An International Journal* 11.1, pp. 85–96. DOI: 10.1080/10807030590919918.

ATLAS.ti Scientific Software Development GmbH (2020). *ATLAS.ti: The qualitative data analysis & research software.* URL: https://atlasti.com/about-atlas-ti/.

Attina, Teresa M. et al. (2016). "Exposure to Endocrine-Disrupting Chemicals in the USA: A Population-Based Disease Burden and Cost Analysis". In: *The Lancet Diabetes & Endocrinology.* DOI: 10.1016/S2213-8587(16)30275-3.

Barben, Daniel et al. (2007). "Anticipatory Governance of Nanotechnology: Foresight, Engagement, and Integration". In: *Handbook of Science and Technology Studies, Third Edition*. Ed. by E J Hackett et al., pp. 979–1000.

Bare, Jane (2011). "TRACI 2.0: The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts 2.0". In: *Clean Technologies and Environmental Policy* 13.5, pp. 687–696. DOI: 10.1007/s10098-010-0338-9.

Bartling, Sönke and Sascha Friesike, eds. (2014). *Opening Science*. Cham: Springer International Publishing. URL: http://link.springer.com/10.1007/978-3-319-00026-8.

BASF (2013). *BASF Corporation Comments on Final GreenScreen Assessment of Hexamoll DINCH*. URL: https://greenchemistryandcommerce.org/assets/media/images/Publications/BASF%20comments%20on%20final%20GreenScreen%20assessment%20of%20Hexamoll%20DINCH.pdf.

Beck, Ulrich (1992). *Risk Society: Towards a New Modernity*. Theory, Culture & Society. London; Newbury Park, California: Sage Publications. 260 pp.

Becker, Monica (2013). *Chemical Hazard Assessments of Alternative Plasticizers for Wire & Cable Applications*. Green Chemistry and Commerce Council (GC3). URL: https://greenchemistryandcommerce.org/assets/media/images/Publications/Pilot%20Project%20Full%20Report%20Oct%202%20-%20final.pdf.

Becker, Sean (2013). "Nanotechnology in the Marketplace: How the Nanotechnology Industry Views Risk". In: *Journal of Nanoparticle Research* 15.5, pp. 1–13. DOI: 10.1007/s11051-013-1426-7.

Benjamin, Ruha (2016). "Informed Refusal: Toward a Justice-Based Bioethics". In: *Science, Technology, & Human Values* 41.6, pp. 967–990. DOI: 10.1177/0162243916656059.

— (2019). "Assessing Risk, Automating Racism". In: *Science* 366.6464, pp. 421–422. DOI: 10.1126/science.aaz3873.

Benkler, Yochai (2006). *The Wealth of Networks: How Social Production Transforms Markets and Freedom*. New Haven: Yale University Press.

Bennett, Ira and Daniel Sarewitz (2006). "Too Little, Too Late? Research Policies on the Societal Implications of Nanotechnology in the United States". In: *Science as Culture* 15.4, pp. 309–325. DOI: 10.1080/09505430601022635.

Bensaude-Vincent, Bernadette (2012). "Nanotechnology: A New Regime for the Public in Science?" In: *Scientiae Studia* 10 (Special Issue), pp. 85–94. DOI: 10.1590/S1678-31662012000500005.

Bergman, Åke et al. (2013). "The Impact of Endocrine Disruption: A Consensus Statement on the State of the Science". In: *Environmental Health Perspectives* 121.4, a104–a106. DOI: 10.1289/ehp.1205448.

Biedenkopf, Katja (2015). "EU Chemicals Regulation: Extending Its Experimentalist REACH". In: *Extending Experimentalist Governance? The European Union and Transnational Regulation*. Ed. by Jonathan Zeitlin. Oxford University Press.

Bijker, Wiebe E. and John Law, eds. (1992). *Shaping Technology/Building Society: Studies in Sociotechnical Change*. Cambridge, Mass.: MIT Press.

Bishaw, Zewdie and Michael Turner (2008). "Linking Participatory Plant Breeding to the Seed Supply System". In: *Euphytica* 163.1, pp. 31–44. DOI: 10.1007/s10681-007-9572-6.

BizNGO (2013). *The Commons Principles for Alternatives Assessment: Addressing Chemicals of Concern to Human Health or the Environment.* URL: http://www.bizngo.org/alternatives-assessment/commons-principles-alt-assessment.

Blake, Ann (2013). "Examining Existing Systems for Functional Use Categorization".

— (2014). *Chemical Hazard Data Commons Working Paper: Finding Alternatives through Categorizing Functional Use.* URL: https://s3.amazonaws.com/hbndatacommons/ChemDat-WorkPaper-FunctionalUse.pdf.

Bobenhausen, Catherine (2016). "Harmonization in Green Building: Tools for Assessing Chemical Hazards in Building Products". In: *The Synergist* (April 2016). URL: https://synergist.aiha.org/201604-harmonization-in-green-building.

Bollier, David (2014). *Think like a Commoner: A Short Introduction to the Life of the Commons.* Gabriola, British Columbia: New Society Publishers. 197 pp.

Bollinger, Juli M. et al. (2019). "What Is a Medical Information Commons?" In: *The Journal of Law, Medicine & Ethics* 47.1, pp. 41–50. DOI: 10.1177/1073110519840483.

Bouchout Declaration (2014). *The Bouchout Declaration for Open Biodiversity Knowledge Management.* URL: http://www.bouchoutdeclaration.org/declaration/.

Boudia, Soraya (2014). "Managing Scientific and Political Uncertainty: Environmental Risk Assessment in a Historical Perspective". In: *Powerless Science? Science and Politics in a Toxic World.* Ed. by Soraya Boudia and Nathalie Jas. The Environment in History 2. New York: Berghahn, pp. 95–112.

Boudia, Soraya, Angela N.H. Creager, et al. (2018). "Residues: Rethinking Chemical Environments". In: *Engaging Science, Technology, and Society* 4, p. 165. DOI: 10.17351/ests2018.245.

Boudia, Soraya and Nathalie Jas, eds. (2013). *Toxicants, Health and Regulation since 1945.* Studies for the Society for the Social History of Medicine no. 9. London: Pickering & Chatto. 193 pp.

— eds. (2014). *Powerless Science? Science and Politics in a Toxic World.* The Environment in History 2. New York: Berghahn. 280 pp.

Bowker, Geoffrey C. (2000). "Biodiversity Datadiversity". In: *Social Studies of Science* 30.5, pp. 643–683. DOI: 10.1177/030631200030005001.

Bowker, Geoffrey C. and Susan Leigh Star (1999). *Sorting Things out: Classification and Its Consequences.* Cambridge, Mass.: MIT Press.

Boyd, William (2012). "Genealogies of Risk: Searching for Safety, 1930s-1970s". In: *Ecology Law Quarterly* 39.4, pp. 895–987. DOI: 10.15779/Z38QG3T.

Boyle, James (2008). *The Public Domain: Enclosing the Commons of the Mind.* New Haven: Yale University Press. 315 pp.

Brown, Phil, Rachel Morello-Frosch, and Stephen Zavestoski (2011). *Contested Illnesses: Citizens, Science, and Health Social Movements.* Berkeley: University of California Press.

Brown, Valerie A., John A. Harris, and Jacqueline Y. Russell (2010). *Tackling Wicked Problems through the Transdisciplinary Imagination.* London; Washington, DC: Earthscan. 312 pp.

Busch, Lawrence (2011). "The Private Governance of Food: Equitable Exchange or Bizarre Bazaar?" In: *Agriculture and Human Values* 28.3, pp. 345–352. DOI: 10.1007/s10460-009-9210-0.

Caffentzis, George (2013). *In Letters of Blood and Fire: Work, Machines, and the Crisis of Capitalism.* Oakland, California: PM Press. 288 pp.

California Department of Health Services (2004). *Aerosol Cleaner Use in Auto Repair (HESIS Fact Sheet).* URL: https://www.cdph.ca.gov/Programs/CCDPHP/DEODC/OHB/HESIS/CDPH%20Document%20Library/aerosol.pdf.

California Department of Toxic Substances Control (2017). *Alternatives Analysis Guide, Version 1.0.* URL: https://www.dtsc.ca.gov/SCP/upload/AA-Guide-Version-1-0_June-2017.pdf.

— (2020a). *CalSAFER.* URL: https://calsafer.dtsc.ca.gov/.

— (2020b). *Safer Consumer Products (SCP).* URL: https://dtsc.ca.gov/scp/.

Callahan, Michael A. and Ken Sexton (2007). "If Cumulative Risk Assessment Is the Answer, What Is the Question?" In: *Environmental Health Perspectives* 115.5, pp. 799–806. DOI: 10.1289/ehp.9330.

Carson, Rachel (1962). *Silent Spring.* 40th anniversary ed., 1st Mariner Books ed. Boston: Houghton Mifflin. 378 pp.

Center for Food Safety (2015). *EPA Agrees to Regulate Novel Nanotechnology Pesticides after Legal Challenge.* URL: http://www.centerforfoodsafety.org/press-releases/3817/epa-agrees-to-regulate-novel-nanotechnology-pesticides-after-legal-challenge.

Center for Nanotechnology in Society (2019). *Nanotechnology in City Environments Database.* URL: http://nice.asu.edu.

ChemForward (2020). *ChemForward.* URL: https://www.chemforward.org.

ChemSec (2019a). *SIN List.* URL: https://sinlist.chemsec.org/.

— (2019b). *The Missing Piece – Chemicals in Circular Economy.* URL: https://chemsec.org/publication/chemicals-business,circular-economy/the-missing-piece/.

Claeys, Priscilla (2012). "The Creation of New Rights by the Food Sovereignty Movement: The Challenge of Institutionalizing Subversion". In: *Sociology* 46.5, pp. 844–860. DOI: 10.1177/0038038512451534.

— (2015). *Human Rights and the Food Sovereignty Movement: Reclaiming Control.* Routledge Studies in Food, Society and Environment. London; New York: Routledge. 197 pp.

Clarke, Adele E. and Joan H. Fujimura, eds. (1992). *The Right Tools for the Job: At Work in Twentieth-Century Life Sciences.* Princeton: Princeton University Press.

Clean Production Action (2017). *GreenScreen List Translator Automator Update Policy (Version 1.0).* URL: http://www.greenscreenchemicals.org/method/method-documents.

— (2018a). *GreenScreen for Safer Chemicals Chemical Groups Policy (Version 1.0).* URL: http://www.greenscreenchemicals.org/method/method-documents.

— (2018b). *GreenScreen for Safer Chemicals Hazard Assessment Guidance (Version 1.4).*

Clean Production Action (2019). *GreenScreen Terms of Use.* URL: https://www.greenscreenchemicals.org/about/greenscreen-terms-of-use.

— (2020a). *Assess Chemicals with GreenScreen.* URL: https://www.greenscreenchemicals.org/assess/assess-gs-details.

— (2020b). *GreenScreen for Safer Chemicals.* URL: https://www.greenscreenchemicals.org/.

— (2020c). *GreenScreen List Translator.* URL: https://www.greenscreenchemicals.org/learn/greenscreen-list-translator.

— (2020d). *GreenScreen Method.* URL: https://www.greenscreenchemicals.org/learn/full-greenscreen-method.

— (2020e). *GreenScreen Professionals & Service Providers.* URL: https://www.greenscreenchemicals.org/assess/gs-professionals.

Colborn, Theo, Dianne Dumanoski, and John Peterson Myers (1996). *Our Stolen Future: Are We Threatening Our Fertility, Intelligence, and Survival? A Scientific Detective Story.* New York: Dutton. 306 pp.

Cook-Deegan, Robert and Amy L. McGuire (2017). "Moving beyond Bermuda: Sharing Data to Build a Medical Information Commons". In: *Genome Research* 27.6, pp. 897–901. DOI: 10.1101/gr.216911.116.

Corburn, Jason (2005). *Street Science: Community Knowledge and Environmental Health Justice.* Urban and Industrial Environments. Cambridge, Mass.: MIT Press. 271 pp.

Cordner, Alissa et al. (2019). "Guideline Levels for PFOA and PFOS in Drinking Water: The Role of Scientific Uncertainty, Risk Assessment Decisions, and Social Factors". In: *Journal of Exposure Science & Environmental Epidemiology* 29.2, pp. 157–171. DOI: 10.1038/s41370-018-0099-9.

Corley, Elizabeth A., Youngjae Kim, and Dietram A. Scheufele (2015). "Scientists' Ethical Obligations and Social Responsibility for Nanotechnology Research". In: *Science and Engineering Ethics*, pp. 1–22. DOI: 10.1007/s11948-015-9637-1.

Cradle to Cradle Products Innovation Institute (2019). *Material Health Assessment Methodology.* URL: https://www.c2ccertified.org/resources/detail/material_assessment_methodology.

— (2020). *Material Health Registry.* URL: https://www.c2ccertified.org/products/mhcregistry.

Dauvergne, Peter and Jane Lister (2012). "Big Brand Sustainability: Governance Prospects and Environmental Limits". In: *Global Environmental Change* 22.1, pp. 36–45. DOI: 10.1016/j.gloenvcha.2011.10.007.

Della Porta, Donatella and Mario Diani (2006). *Social Movements: An Introduction.* Malden, MA: Blackwell.

Diamond, Miriam L. et al. (2015). "Exploring the Planetary Boundary for Chemical Pollution". In: *Environment International* 78, pp. 8–15. DOI: 10.1016/j.envint.2015.02.001.

Dinham, Barbara and Sapna Malik (2003). "Pesticides and Human Rights". In: *International Journal of Occupational and Environmental Health* 9.1, pp. 40–52. DOI: 10.1179/107735203800328867.

Dionisio, Kathie L., Alicia M. Frame, et al. (2015). "Exploring Consumer Exposure Pathways and Patterns of Use for Chemicals in the Environment". In: *Toxicology Reports* 2, pp. 228–237. DOI: 10.1016/j.toxrep.2014.12.009.

Dionisio, Kathie L., Katherine Phillips, et al. (2018). "The Chemical and Products Database, a Resource for Exposure-Relevant Data on Chemicals in Consumer Products". In: *Scientific Data* 5, p. 180125. DOI: 10.1038/sdata.2018.125.

Doan, Dat Tien et al. (2017). "A Critical Comparison of Green Building Rating Systems". In: *Building and Environment* 123, pp. 243–260. DOI: 10.1016/j.buildenv.2017.07.007.

Dodson, Robin E. et al. (2017). "Chemical Exposures in Recently Renovated Low-Income Housing: Influence of Building Materials and Occupant Activities". In: *Environment International* 109, pp. 114–127. DOI: 10.1016/j.envint.2017.07.007.

Douglas, Heather E. (2000). "Inductive Risk and Values in Science". In: *Philosophy of Science* 67.4, pp. 559–579. DOI: 10.1086/392855.

— (2009). *Science, Policy, and the Value-Free Ideal.* Pittsburgh, PA: University of Pittsburgh Press. 210 pp.

Downie, David Leonard, Terry Fenge, and Inuit Circumpolar Conference, eds. (2003). *Northern Lights against POPs: Combatting Toxic Threats in the Arctic.* Montreal: McGill-Queen's University Press. 347 pp.

Edmunds, David S. et al. (2013). "Tribal Housing, Codesign, and Cultural Sovereignty". In: *Science, Technology & Human Values* 38.6, pp. 801–828. DOI: 10.1177/0162243913490812.

Egeghy, Peter P. et al. (2012). "The Exposure Data Landscape for Manufactured Chemicals". In: *Science of the Total Environment* 414, pp. 159–166. DOI: 10.1016/j.scitotenv.2011.10.046.

Eilebrecht, Elke et al. (2019). *Bewertung des endokrinen Potenzials von Bisphenol Alternativstoffen in umweltrelevanten Verwendungen.* Umweltbundesamt, p. 88. URL: http://www.umweltbundesamt.de/publikationen.

eNanoMapper Consortium (2020). *eNanoMapper.* URL: https://www.enanomapper.net/.

Environmental Defense Fund (2017). *Smart Innovation: The Opportunity for Safer Preservatives.* Environmental Defense Fund. URL: http://business.edf.org/smart-innovation-the-opportunity-for-safer-preservatives.

— (n.d.[a]). *DuPont Nanotech Project: Endorsements and Public Impact.* URL: http://business.edf.org/projects/featured/past-projects/dupont-safer-nanotech/dupont-nanotech-project-endorsements-and-public-impact/.

— (n.d.[b]). *DuPont-Safer Nanotech.* URL: http://business.edf.org/projects/featured/past-projects/dupont-safer-nanotech/.

Environmental Defense–DuPont Nano Partnership (2007). *NANO Risk Framework.* Environmental Defense Fund.

Environmental Working Group (n.d.). *Skin Deep Cosmetics Database.* URL: http://www.ewg.org/skindeep/.

Epstein, Steven (1996). *Impure Science: AIDS, Activism, and the Politics of Knowledge.* Medicine and Society 7. Berkeley: University of California Press. 466 pp.

ETC Group (2003). *The Big Down.* URL: http://www.etcgroup.org/content/big-down.

ETC Group (2016). *ETC Group: A Brief History.* URL: http://www.etcgroup.org/content/etc-group-brief-history.

— (n.d.). *Nanotechnology.* URL: http://www.etcgroup.org/issues/nanotechnology.

EurActiv (2009). *Nanotech Claims 'dropped' for Fear of Consumer Recoil.* URL: http://www.euractiv.com/innovation-enterprise/nanotech-claims-dropped-fear-con-news-221915.

European Chemicals Agency (n.d.[a]). *Nanomaterials under Biocidal Products Regulation.* URL: https://echa.europa.eu/regulations/nanomaterials-under-bpr.

— (n.d.[b]). *Working within SIEFs.* URL: https://echa.europa.eu/press/pr-for-siefs.

European Commission (2006). *Regulation (EC) No 1907/2006 of the European Parliament and of the Council of 18 December 2006 Concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH).* URL: http://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1427817884285&uri=CELEX:32006R1907.

— (2017). *Nanomaterials.* URL: https://ec.europa.eu/growth/sectors/cosmetics/products/nanomaterials_en.

European Environment Agency (2001). *Late Lessons from Early Warnings: The Precautionary Principle, 1896-2000.* Ed. by Poul Harremoës. Environmental Issue Report 2001,22. Copenhagen: European Environment Agency. 210 pp. URL: http://www.eea.europa.eu/publications/environmental_issue_report_2001_22.

— ed. (2013). *Late Lessons from Early Warnings: Science, Precaution, Innovation.* EEA Report 2013,1. Copenhagen: European Environment Agency. 44 pp. URL: http://www.eea.europa.eu/publications/late-lessons-2.

European Environmental Bureau et al. (2014). *European NGOs Position Paper on the Regulation of Nanomaterials.* URL: http://www.beuc.org/publications/beuc-x-2014-024_sma_nano_position_paper_caracal_final_clean.pdf.

European Trade Union Confederation (2008). *ETUC Resolution on Nanotechnologies and Nanomaterials.* URL: http://www.etuc.org/sites/www.etuc.org/files/ETUC_resolution_on_nano_-_EN_-_25_June_08_2.pdf.

— (2010). *ETUC 2nd Resolution on Nanotechnologies and Nanomaterials.* URL: http://www.etuc.org/sites/www.etuc.org/files/13-GB_final_nanotechnologies_and_nanomaterial_2.pdf.

Faulkner, David et al. (2017). "Tools for Green Molecular Design to Reduce Toxicological Risk". In: *Computational Systems Pharmacology and Toxicology.* Ed. by Rudy J Richardson and Dale E Johnson. Issues in Toxicology. Cambridge: Royal Society of Chemistry, pp. 36–59. DOI: 10.1039/9781782623731-00036.

Federation of American Scientists (n.d.). *The Assessment Process.* URL: https://ota.fas.org/technology_assessment_and_congress/theassessmentprocess/.

Felt, Ulrike (2019). ""Plastic Governance": Material Culture, Plasticity, and Policy Struggles". In: *Proceedings of 4S 2019.* 4S. New Orleans.

Fernández Pinto, Manuela and Daniel J. Hicks (2019). "Legitimizing Values in Regulatory Science". In: *Environmental Health Perspectives* 127.3, p. 035001. DOI: 10.1289/EHP3317.

Foley, Rider W., Arnim Wiek, and Braden Kay (2017). "Nanotechnology Development as If People and Places Matter". In: *NanoEthics* 11.3, pp. 243–257. DOI: 10.1007/s11569-017-0300-y.

Fortun, Kim (2004). "Environmental Information Systems as Appropriate Technology". In: *Design Issues* 20.3, pp. 54–65. DOI: 10.1162/0747936041423217.

Franzoni, Elisa (2011). "Materials Selection for Green Buildings: Which Tools for Engineers and Architects?" In: *Procedia Engineering* 21, pp. 883–890. DOI: 10.1016/j.proeng.2011.11.2090.

Frickel, Scott and Michelle Edwards (2014). "Untangling Ignorance in Environmental Risk Assessment". In: *Powerless Science? Science and Politics in a Toxic World*. Ed. by Soraya Boudia and Nathalie Jas. The Environment in History 2. New York: Berghahn, pp. 215–233.

Frickel, Scott, Sahra Gibbon, et al. (2010). "Undone Science: Charting Social Movement and Civil Society Challenges to Research Agenda Setting". In: *Science, Technology, & Human Values* 35.4, pp. 444–473. DOI: 10.1177/0162243909345836.

Friends of the Earth (2006). *Nanomaterials, Sunscreens and Cosmetics: Small Ingredients, Big Risks*. URL: http://libcloud.s3.amazonaws.com/93/ce/0/633/Nanomaterials_sunscreens_and_cosmetics.pdf.

— (2007). *Nanotechnology & Sunscreens: A Consumer Guide for Avoiding Nano-Sunscreens*. URL: https://libcloud.s3.amazonaws.com/93/23/9/634/Nanotechnology_and_sunscreens.pdf.

— (2009). *Manufactured Nanomaterials and Sunscreens: Top Reasons for Precaution*. URL: http://libcloud.s3.amazonaws.com/93/14/0/632/Manufactured_nanomaterials_and_sunscreens_reasons_for_precaution.pdf.

— (n.d.). *Nanotechnology and Sunscreens*. URL: http://action.foe.org/content.jsp?key=3060.

Friends of the Earth Australia (2012). *Sunscreen Scandal Questions and Answers*. URL: http://emergingtech.foe.org.au/sunscreen-scandal-questions-and-answers/.

Frischmann, Brett M., Michael J. Madison, and Katherine Jo Strandburg (2014a). "Governing Knowledge Commons". In: *Governing Knowledge Commons*. Ed. by Brett M. Frischmann, Michael J. Madison, and Katherine Jo Strandburg. Oxford; New York: Oxford University Press, pp. 1–43.

— eds. (2014b). *Governing Knowledge Commons*. Oxford; New York: Oxford University Press. 499 pp.

Fung, Archon and Dara O'Rourke (2000). "Reinventing Environmental Regulation from the Grassroots up: Explaining and Expanding the Success of the Toxics Release Inventory". In: *Environmental Management* 25.2, pp. 115–127. DOI: 10.1007/s002679910009.

Funtowicz, Silvio O. and Jerome R. Ravetz (1993). "Science for the Post-Normal Age". In: *Futures* 25.7, pp. 739–755. DOI: 10.1016/0016-3287(93)90022-L.

Gauthier, Alison M. et al. (2015). "Chemical Assessment State of the Science: Evaluation of 32 Decision-Support Tools Used to Screen and Prioritize Chemicals." In: *Integrated Environmental Assessment and Management* 11.2, pp. 242–55. DOI: 10.1002/ieam.1605.

Gavelin, Karin, Richard Wilson, and Robert Doubleday (2007). *Democratic Technologies? The Final Report of the Nanotechnology Engagement Group (NEG)*. Involve. URL: http://www.involve.org.uk/wp-content/uploads/2011/03/Democratic-Technologies.pdf.

Gee, David (2006). "Late Lessons from Early Warnings: Toward Realism and Precaution with Endocrine-Disrupting Substances". In: *Environmental Health Perspectives* 114.S-1, pp. 152–160. DOI: 10.1289/ehp.8134.

Geiser, Ken (2014). *The New Chemicals in Products Information Transparency*. URL: http://insight.gbig.org/the-new-chemicals-in-products-information-transparency/.

— (2015). *Chemicals without Harm: Policies for a Sustainable World*. Urban and Industrial Environments. Cambridge, Mass.: MIT Press. 444 pp.

Gianfrancesco, Milena A. et al. (2018). "Potential Biases in Machine Learning Algorithms Using Electronic Health Record Data". In: *JAMA Internal Medicine* 178.11, pp. 1544–1547. DOI: 10.1001/jamainternmed.2018.3763.

Gilbert, Natasha (2016). "Legal Tussle Delays Launch of Huge Toxicity Database". In: *Nature*. DOI: 10.1038/nature.2016.19365.

Gilbertson, Leanne M. et al. (2015). "Designing Nanomaterials to Maximize Performance and Minimize Undesirable Implications Guided by the Principles of Green Chemistry". In: *Chemical Society Reviews* 44.16, pp. 5758–5777. DOI: 10.1039/C4CS00445K.

Glushko, Robert J. (2013). *The Discipline of Organizing*. Cambridge, Mass.: MIT Press. 539 pp.

Goldberg, Terri (2017). "What about the Circularity of Hazardous Materials?" In: *Journal of Industrial Ecology* 21.3, pp. 491–493. DOI: 10.1111/jiec.12585.

Goodwin Robbins, Lisa J. et al. (2019). "Pruning Chemicals from the Green Building Landscape". In: *Journal of Exposure Science & Environmental Epidemiology*. DOI: 10.1038/s41370-019-0174-x.

Grandjean, Philippe and Martine Bellanger (2017). "Calculation of the Disease Burden Associated with Environmental Chemical Exposures: Application of Toxicological Information in Health Economic Estimation". In: *Environmental Health* 16.1. DOI: 10.1186/s12940-017-0340-3.

Green America (2020). *Clean Electronics for Safer Manufacturing*. URL: http://www.centerforsustainabilitysolutions.org/clean-electronics.

GreenBlue (2020). *CleanGredients*. URL: https://cleangredients.org/.

Greggs, William et al. (2019). "Qualitative Approach to Comparative Exposure in Alternatives Assessment". In: *Integrated Environmental Assessment and Management* 15.6, pp. 880–894. DOI: 10.1002/ieam.4070.

Groh, Ksenia J. et al. (2018). "Overview of Known Plastic Packaging-Associated Chemicals and Their Hazards". In: *Science of The Total Environment*. DOI: 10.1016/j.scitotenv.2018.10.015.

Gross, Liza and Linda S. Birnbaum (2017). "Regulating Toxic Chemicals for Public and Environmental Health". In: *PLOS Biology* 15.12, e2004814. DOI: 10.1371/journal.pbio.2004814.

Gubbels-van Hal, Ineke and Jacques Pelkmans (2009). “Is REACH Going Well?” In: *CEPS Policy Brief* 198. URL: https://papers.ssrn.com/abstract=1513261.

Gulbrandsen, Lars H. (2006). “Creating Markets for Eco-Labelling: Are Consumers Insignificant?” In: *International Journal of Consumer Studies* 30.5, pp. 477–489. DOI: 10.1111/j.1470-6431.2006.00534.x.

Guo, Dennis Fengmao et al. (2017). *Summary of Technical Information and Scientific Conclusions for Designating Spray Polyurethane Foam Systems with Unreacted Methylene Diphenyl Diisocyanates as a Priority Product.* Sacramento, CA: California EPA, Department of Toxic Substances Control. URL: https://dtsc.ca.gov/wp-content/uploads/sites/31/2018/07/SPF-Systems-Summary-of-Technical-Information-2.pdf.

Gupta, Ritu and Huan Xie (2018). “Nanoparticles in Daily Life: Applications, Toxicity and Regulations”. In: *Journal of Environmental Pathology, Toxicology and Oncology* 37.3, pp. 209–230. DOI: 10.1615/JEnvironPatholToxicolOncol.2018026009.

Guston, David H. (2014). “Building the Capacity for Public Engagement with Science in the United States”. In: *Public Understanding of Science* 23.1, pp. 53–59. DOI: 10.1177/0963662513476403.

Guston, David H. and Daniel Sarewitz (2002). “Real-Time Technology Assessment”. In: *Technology in Society.* American Perspectives on Science and Technology Policy 24.1–2, pp. 93–109. DOI: 10.1016/S0160-791X(01)00047-1.

Guth, Joseph H., Richard A. Denison, and Jennifer Sass (2007). “Require Comprehensive Safety Data for All Chemicals”. In: *New Solutions* 17.3, pp. 233–258.

Haapio, Appu and Pertti Viitaniemi (2008). “A Critical Review of Building Environmental Assessment Tools”. In: *Environmental Impact Assessment Review* 28.7, pp. 469–482. DOI: 10.1016/j.eiar.2008.01.002.

Hall, Jeremy (2006). “Environmental Supply Chain Innovation”. In: *Greening the Supply Chain.* Ed. by Joseph Sarkis. London: Springer, pp. 233–250.

Harmon, J. Patrick and Rainer Otter (2018). “Green Chemistry and the Search for New Plasticizers”. In: *ACS Sustainable Chemistry & Engineering* 6.2, pp. 2078–2085. DOI: 10.1021/acssuschemeng.7b03508.

Harper, Stacey L. et al. (2011). “Systematic Evaluation of Nanomaterial Toxicity: Utility of Standardized Materials and Rapid Assays”. In: *Acs Nano* 5.6, pp. 4688–4697. DOI: 10.1021/nn200546k.

Harremoës, Poul et al. (2013). *The Precautionary Principle in the 20th Century: Late Lessons from Early Warnings.* Hoboken, NJ: Taylor and Francis.

Harrison, Roy M. and Ronald E. Hester, eds. (2013). *Chemical Alternatives Assessments.* Issues in Environmental Science and Technology 36. Cambridge: Royal Society of Chemistry. 301 pp. URL: http://doi.org/10.1039/9781849737234.

Healthy Building Network (2014a). *Chemical Hazard Data Commons White Paper Reviewer Commentary.* URL: https://s3.amazonaws.com/hbndatacommons/ChemDat-ContentFeedback.pdf.

— (2014b). *Chemical Hazard Data Commons White Paper Survey Results.* URL: https://s3.amazonaws.com/hbndatacommons/ChemDat-SurveyResults.pdf.

Healthy Building Network (2016). *Community Survey Response Analysis.* URL: https://drive.google.com/file/u/1/d/0ByChXzZXqy9WRWNJTWYweEZldTQ/view?usp=drive_open&usp=embed_facebook.

— (2019a). *Chemical & Material Library (CML) Full System Description.*

— (2019b). *Chemical Hazard Data Commons Code of Conduct.* URL: https://commons.healthymaterials.net/code.

— (2019c). *Chemical Hazard Data Commons Service Terms and Conditions of Use.* URL: https://commons.healthymaterials.net/terms.

— (2019d). *Combining the Powers of Pharos and Data Commons.* URL: https://www.pharosproject.net/merger.

— (2020a). *Compound Group Population Project.* URL: https://pharosproject.net/compound-groups.

— (2020b). *Pharos Project.* URL: https://www.pharosproject.net/.

Heath, Tom and Christian Bizer (2011). "Linked Data: Evolving the Web into a Global Data Space". In: *Synthesis Lectures on the Semantic Web: Theory and Technology* 1.1, pp. 1–136. DOI: 10.2200/S00334ED1V01Y201102WBE001.

Heine, Lauren G. and Shari A. Franjevic (2013). "Chemical Hazard Assessment and the GreenScreen for Safer Chemicals". In: *Chemical Alternatives Assessments.* Ed. by R. M. Harrison and R. E. Hester. Issues in Environmental Science and Technology 36. Cambridge: Royal Society of Chemistry, pp. 129–156. URL: http://doi.org/10.1039/9781849737234-00129.

Heine, Lauren G., Matteo Kausch, et al. (2013). *Material Health Evaluation Programs: Harmonization Opportunities Report.* US Green Building Council, p. 32.

Heller, Stephen et al. (2013). "InChI - The Worldwide Chemical Structure Identifier Standard". In: *Journal of Cheminformatics* 5.1, p. 7. DOI: 10.1186/1758-2946-5-7.

Hepler-Smith, Evan (2019). "Molecular Bureaucracy: Toxicological Information and Environmental Protection". In: *Environmental History* 24.3, pp. 534–560. DOI: 10.1093/envhis/emy134.

Hess, Charlotte and Elinor Ostrom, eds. (2007). *Understanding Knowledge as a Commons: From Theory to Practice.* Cambridge, Mass.: MIT Press. 367 pp.

Hess, David J. (2005). "Technology- and Product-Oriented Movements: Approximating Social Movement Studies and Science and Technology Studies". In: *Science Technology & Human Values* 30.4, pp. 515–535. DOI: 10.1177/0162243905276499.

— (2007). *Alternative Pathways in Science and Industry: Activism, Innovation, and the Environment in an Era of Globalization.* Urban and Industrial Environments. Cambridge, Mass.: MIT Press. 334 pp.

— (2010). "Environmental Reform Organizations and Undone Science in the United States: Exploring the Environmental, Health, and Safety Implications of Nanotechnology". In: *Science as Culture* 19.2, pp. 181–214. DOI: 10.1080/09505430903183697.

— (2016). *Undone Science: Social Movements, Mobilized Publics, and Industrial Transitions.* Cambridge, Mass.: MIT Press.

Hinchliffe, Steve, Les Levidow, and Sue Oreszczyn (2014). “Engaging Cooperative Research”. In: *Environment and Planning A* 46.9, pp. 2080–2094. DOI: 10.1068/a140061p.

Holder, Helen A. et al. (2013). “Hewlett-Packard’s Use of the GreenScreen for Safer Chemicals”. In: *Chemical Alternatives Assessments*. Ed. by R. M. Harrison and R. E. Hester. Issues in Environmental Science and Technology 36. Cambridge: Royal Society of Chemistry, pp. 157–176. URL: http://doi.org/10.1039/9781849737234-00157.

Hoover, Elizabeth et al. (2012). “Indigenous Peoples of North America: Environmental Exposures and Reproductive Justice”. In: *Environmental Health Perspectives* 120.12, pp. 1645–1649. DOI: 10.1289/ehp.1205422.

Howard, Jeff (2004). “Toward Participatory Ecological Design of Technological Systems”. In: *Design Issues* 20.3, pp. 40–53. DOI: 10.1162/0747936041423253.

HPD Collaborative (2018). *HPD 2.1.1 Standard*. URL: https://www.hpd-collaborative.org/hpd-2-1-1-standard/.

— (2020a). *Health Product Declaration Collaborative*. URL: https://www.hpd-collaborative.org.

— (2020b). *HPD Public Repository*. URL: https://www.hpd-collaborative.org/hpd-public-repository/.

— (2020c). *Sponsors*. URL: https://www.hpd-collaborative.org/sponsors/.

Hutchison, James E. (2008). “Greener Nanoscience: A Proactive Approach to Advancing Applications and Reducing Implications of Nanotechnology”. In: *Acs Nano* 2.3, pp. 395–402. DOI: 10.1021/nn800131j.

Iles, Alastair (2007). “Identifying Environmental Health Risks in Consumer Products: Non-Governmental Organizations and Civic Epistemologies”. In: *Public Understanding of Science* 16.4, pp. 371–391. DOI: 10.1177/0963662505059442.

— (2013). “Greening Chemistry: Emerging Epistemic Political Tensions in California and the United States”. In: *Public Understanding of Science* 22.4, pp. 460–478. DOI: 10.1177/0963662511404306.

International Living Future Institute (2019). *Declare Products*. URL: https://living-future.org/declare/.

Interstate Chemicals Clearinghouse (2014). *IC2*. URL: https://theic2.org/.

Jacobs, Molly M. et al. (2016). “Alternatives Assessment Frameworks: Research Needs for the Informed Substitution of Hazardous Chemicals”. In: *Environmental Health Perspectives* 124.3. DOI: 10.1289/ehp.1409581.

Jain, Aditi et al. (2018). “Nanomaterials in Food and Agriculture: An Overview on Their Safety Concerns and Regulatory Issues”. In: *Critical Reviews in Food Science and Nutrition* 58.2, pp. 297–317. DOI: 10.1080/10408398.2016.1160363.

Jasanoff, Sheila (1987). “Contested Boundaries in Policy-Relevant Science”. In: *Social Studies of Science* 17.2, pp. 195–230. DOI: 10.1177/030631287017002001.

— (1990). *The Fifth Branch: Science Advisers as Policymakers*. Cambridge, Mass.: Harvard University Press.

— (2003). “Technologies of Humility: Citizen Participation in Governing Science”. In: *Minerva* 41.3, pp. 223–244. DOI: 10.1023/A:1025557512320.

Jasanoff, Sheila, ed. (2004). *States of Knowledge: The Co-Production of Science and Social Order*. International Library of Sociology. London; New York: Routledge. 317 pp.

— (2005). *Designs on Nature: Science and Democracy in Europe and the United States.* Princeton, NJ: Princeton University Press. 374 pp.

— (2007). “Technologies of Humility”. In: *Nature* 450.7166, pp. 33–33. DOI: 10.1038/450033a.

Jasanoff, Sheila and J. Benjamin Hurlbut (2018). “A Global Observatory for Gene Editing”. In: *Nature* 555.7697, pp. 435–437. DOI: 10.1038/d41586-018-03270-w.

Johansson, Mikael and Åsa Boholm (2017). “Scientists’ Understandings of Risk of Nanomaterials: Disciplinary Culture through the Ethnographic Lens”. In: *NanoEthics* 11.3, pp. 229–242. DOI: 10.1007/s11569-017-0297-2.

Judson, Richard et al. (2009). “The Toxicity Data Landscape for Environmental Chemicals”. In: *Environmental Health Perspectives* 117.5, pp. 685–695. DOI: 10.1289/ehp.0800168.

Katz, Linda M., Kapal Dewan, and Robert L. Bronaugh (2015). “Nanotechnology in Cosmetics”. In: *Food and Chemical Toxicology* 85, pp. 127–137. DOI: 10.1016/j.fct.2015.06.020.

Kelty, Christopher M. (2008). *Two Bits: The Cultural Significance of Free Software.* Experimental Futures. Durham, NC: Duke University Press. 378 pp.

Kerns, Thomas A. (2001). *Environmentally Induced Illnesses: Ethics, Risk Assessment, and Human Rights.* Jefferson, NC: McFarland. 294 pp.

Kilic, G. et al. (2016). “eNanoMapper – A Database and Ontology Framework for Design and Safety Assessment of Nanomaterials”. In: *Toxicology Letters* 258, S118–S119. DOI: 10.1016/j.toxlet.2016.06.1481.

Kim, Sunghwan et al. (2016). “PubChem Substance and Compound Databases”. In: *Nucleic Acids Research* 44.D1, pp. D1202–D1213. DOI: 10.1093/nar/gkv951.

Kleinman, Daniel Lee, ed. (2000). *Science, Technology, and Democracy.* Albany: State University of New York Press. 186 pp.

Kleinman, Daniel Lee, Jason A. Delborne, and Ashley A. Anderson (2011). “Engaging Citizens: The High Cost of Citizen Participation in High Technology”. In: *Public Understanding of Science* 20.2, pp. 221–240. DOI: 10.1177/0963662509347137.

Kline, Ronald R. (2002). *Consumers in the Country: Technology and Social Change in Rural America.* Baltimore, MD: Johns Hopkins Univ Press.

Kokai, Akos and Alastair Iles (2020). “Materials Sovereignty: Pathways for Shaping Nanotechnology Design”. In: *Elem Sci Anth* 8.1 (1), p. 14. DOI: 10.1525/elementa.410.

Kokai, Akos, Tom Lent, and Michel Dedeo (2014). *Chemical Hazard Data Commons Working Paper: Getting Hazard Right through Managing Chemical IDs.* URL: https://s3.amazonaws.com/hbndatacommons/ChemDat-WorkPaper-ChemID.pdf.

Kozlowski, Michelle and Harold A. Perkins (2015). “Environmental Justice in Appalachia Ohio? An Expanded Consideration of Privilege and the Role It Plays in Defending the Contaminated Status Quo in a White, Working-Class Community”. In: *Local Environment*, pp. 1–17. DOI: 10.1080/13549839.2015.1111316.

Krabbenborg, Lotte (2013). “DuPont and Environmental Defense Fund Co-Constructing a Risk Framework for Nanoscale Materials: An Occasion to Reflect on Interaction Processes in a Joint Inquiry”. In: *NanoEthics* 7.1, pp. 45–54. DOI: 10.1007/s11569-013-0167-5.

Krimsky, Sheldon (2017). “The Unsteady State and Inertia of Chemical Regulation under the US Toxic Substances Control Act”. In: *PLOS Biology* 15.12. Ed. by Linda S. Birnbaum, e2002404. DOI: 10.1371/journal.pbio.2002404.

Lai, Racliffe W. S. et al. (2018). “Regulation of Engineered Nanomaterials: Current Challenges, Insights and Future Directions”. In: *Environmental Science and Pollution Research* 25.4, pp. 3060–3077. DOI: 10.1007/s11356-017-9489-0.

Lambert, Timothy William et al. (2003). “Ethical Perspectives for Public and Environmental Health: Fostering Autonomy and the Right to Know”. In: *Environmental Health Perspectives* 111.2, pp. 133–137. URL: http://www.ncbi.nlm.nih.gov/pmc/articles/PMC1241339/.

Lanphear, Bruce P. (2017). “Low-Level Toxicity of Chemicals: No Acceptable Levels?” In: *PLOS Biology* 15.12. Ed. by Linda S. Birnbaum, e2003066. DOI: 10.1371/journal.pbio.2003066.

Latour, Bruno (1987). *Science in Action: How to Follow Scientists and Engineers through Society*. Cambridge, Mass.: Harvard University Press.

Lavoie, Emma T. et al. (2010). “Chemical Alternatives Assessment: Enabling Substitution to Safer Chemicals”. In: *Environmental Science & Technology* 44.24, pp. 9244–9249. DOI: 10.1021/es1015789.

Leber, Jessica (2016). *Why Environmental and Health Groups Are so Torn about Toxic Chemical Reform*. URL: http://www.fastcoexist.com/3060183/why-environmental-and-health-groups-are-so-torn-about-toxic-chemical-reform.

Lélé, Sharachchandra and Richard B. Norgaard (2005). “Practicing Interdisciplinarity”. In: *BioScience* 55.11, pp. 967–975. DOI: 10.1641/0006-3568(2005)055[0967:PI]2.0.CO;2.

Lent, Tom (2014a). *Chemical Hazard Data Commons Working Paper: Facilitating Decision Making with Assessment Summaries*. URL: https://s3.amazonaws.com/hbndatacommons/ChemDat-WorkPaper-AssessmentSummaries.pdf.

— (2014b). *Chemical Hazard Data Commons Working Paper: Speeding & Improving Assessment through Data Sharing*. URL: https://s3.amazonaws.com/hbndatacommons/ChemDat-WorkPaper-DataSharing.pdf.

Lent, Tom, Akos Kokai, et al. (2014). *Toward Safer Products: Accelerating Change with a Chemical Hazard Data Commons*. URL: https://s3.amazonaws.com/hbndatacommons/ChemDat-WhitePaper.pdf.

Lent, Tom and Rebecca Stamm (2019). *The Solution Is Transparency: Public Disclosure of Product Content and Hazard Is Critical to Solving Material Health Challenges*. URL: https://healthybuilding.net/blog/499-the-solution-is-transparency-public-disclosure-of-product-content-and-hazard-is-critical-to-solving-material-health-challenges.

Lerner, Steve (2010). *Sacrifice Zones: The Front Lines of Toxic Chemical Exposure in the United States*. Cambridge, Mass.: MIT Press.

Lessig, Lawrence (2004). *Free Culture: How Big Media Uses Technology and the Law to Lock down Culture and Control Creativity.* New York: Penguin Press. 345 pp.

Liboiron, Max (2016). "Redefining Pollution and Action: The Matter of Plastics". In: *Journal of Material Culture* 21.1, pp. 87–110. DOI: 10.1177/1359183515622966.

— (2017). "Compromised Agency: The Case of BabyLegs". In: *Engaging Science, Technology, and Society* 3, p. 499. DOI: 10.17351/ests2017.126.

Liboiron, Max, Manuel Tironi, and Nerea Calvillo (2018). "Toxic Politics: Acting in a Permanently Polluted World". In: *Social Studies of Science* 48.3, pp. 331–349. DOI: 10.1177/0306312718783087.

Linebaugh, Peter (2014). *Stop, Thief! The Commons, Enclosures and Resistance.* Oakland, California: PM Press. 289 pp.

Lissner, Lothar and Dolores Romano (2011). "Substitution for Hazardous Chemicals on an International Level—The Approach of the European Project "SUBSPORT"". In: *NEW SOLUTIONS: A Journal of Environmental and Occupational Health Policy* 21.3, pp. 477–497. DOI: 10.2190/NS.21.3.l.

Logan, Katharine (2016). "Healthy Materials: Sweating the Small Stuff". In: *Architectural Record* (2016 June). URL: http://www.architecturalrecord.com/articles/11711-healthy-materials.

Loka Institute (2007). *Loka Institute Response to the DuPont/Environmental Defense Nanotechnology Risk Framework.* Letter. URL: http://www.loka.org/Documents/Loka_nano_framework.pdf.

— (2013). *Loka's Advocacy for Public Participation in Federal Nanotechnology Policymaking.* URL: http://www.loka.org/FedNanoPolicy.html.

Lucchi, Nicola (2013). "Understanding Genetic Information as a Commons: From Bioprospecting to Personalized Medicine". In: *International Journal of the Commons* 7.2, p. 313. DOI: 10.18352/ijc.399.

Lyons, G. and P. Illig (2007). "Getting the Message across – WWF'S and ISDE's Perspectives on Communication Strategies to Reduce Exposures to Hazardous Chemicals". In: *Reproductive Health and the Environment.* Ed. by P. Nicolopoulou-Stamati, L. Hens, and C. V. Howard. Environmental Science and Technology Library 22. Springer Netherlands, pp. 297–310. DOI: 10.1007/1-4020-4829-7_14.

MacKenzie, Donald A. (1998). *Knowing Machines: Essays on Technical Change.* Inside Technology. Cambridge, Mass.: MIT Press. 338 pp.

Malloy, Timothy et al. (2017). "Advancing Alternatives Analysis: The Role of Predictive Toxicology in Selecting Safer Chemical Products and Processes: Predictive Toxicology in Alternatives Analysis". In: *Integrated Environmental Assessment and Management* 13.5, pp. 915–925. DOI: 10.1002/ieam.1923.

Maniates, Michael F. (2001). "Individualization: Plant a Tree, Buy a Bike, Save the World?" In: *Global Environmental Politics* 1.3, pp. 31–52. DOI: 10.1162/152638001316881395.

Mansell, Robin (2013). "Employing Digital Crowdsourced Information Resources: Managing the Emerging Information Commons". In: *International Journal of the Commons* 7.2, p. 255. DOI: 10.18352/ijc.395.

Markowitz, Gerald E. and David Rosner (2003). *Deceit and Denial: The Deadly Politics of Industrial Pollution.* Berkeley: University of California Press. 420 pp.

Maule, Alexis L. et al. (2013). "Disclosure of Hydraulic Fracturing Fluid Chemical Additives: Analysis of Regulations". In: *NEW SOLUTIONS: A Journal of Environmental and Occupational Health Policy* 23.1, pp. 167–187. DOI: 10.2190/NS.23.1.j.

Maxim, Laura (2018). "More than a Scientific Movement: Socio-Political Influences on Green Chemistry Research in the United States and France". In: *Science & Technology Studies*, pp. 24–46. DOI: 10.23987/sts.60243.

McCarthy, Tom (2007). *Auto Mania: Cars, Consumers, and the Environment.* New Haven: Yale University Press. 347 pp.

McDonough, William and Michael Braungart (2002). *Cradle to Cradle: Remaking the Way We Make Things.* New York: North Point Press. 193 pp.

Meadows, Donella H. (2008). *Thinking in Systems: A Primer.* In collab. with Diana Wright. White River Junction, VT: Chelsea Green. 218 pp.

Michaels, David (2008). *Doubt Is Their Product: How Industry's Assault on Science Threatens Your Health.* Oxford; New York: Oxford University Press. 372 pp.

Michelson, Evan S. (2013). ""The Train Has Left the Station": The Project on Emerging Nanotechnologies and the Shaping of Nanotechnology Policy in the United States". In: *Review of Policy Research* 30.5, pp. 464–487. DOI: 10.1111/ropr.12034.

Mihranyan, Albert, Natalia Ferraz, and Maria Strømme (2012). "Current Status and Future Prospects of Nanotechnology in Cosmetics". In: *Progress in Materials Science* 57.5, pp. 875–910. DOI: 10.1016/j.pmatsci.2011.10.001.

Minatec (2016). *Minatec Micro and Nanotechnology Innovation Campus.* URL: https://www.minatec.org/en/minatec-campus/minatec-micro-and-nanotechnology-innovation-campus/.

Montenegro de Wit, Maywa and Alastair Iles (2015). "Getting Past Scientized Scrutiny". In: *Earth Island Journal.* URL: https://www.earthisland.org/journal/index.php/articles/entry/getting_past_scientized_scrutiny/.

Muldoon, Paul and Ramani Nadarajah (1999). "A Sober Second Look". In: *Voluntary Initiatives and the New Politics of Corporate Greening.* Ed. by Robert B. Gibson. Peterborough, ON: Broadview Press.

Mulvaney, Dustin (2019). *Solar Power: Innovation, Sustainability, and Environmental Justice.* Oakland, California: University of California Press.

Murphy, Michelle (2017). "Alterlife and Decolonial Chemical Relations". In: *Cultural Anthropology* 32.4, pp. 494–503. DOI: 10.14506/ca32.4.02.

Murray-Rust, Peter et al. (2011). "The Semantic Architecture of the World-Wide Molecular Matrix (WWMM)". In: *Journal of Cheminformatics* 3.1, p. 42. DOI: 10.1186/1758-2946-3-42.

National Renewable Energy Laboratory (2020). *Energy Information and Data.* URL: https://openei.org/wiki/Main_Page.

National Research Council (US) (2014). *A Framework to Guide Selection of Chemical Alternatives*. Washington, DC: The National Academies Press. 264 pp. URL: https://www.nap.edu/catalog/18872/a-framework-to-guide-selection-of-chemical-alternatives.

Nielsen, Michael A. (2012). *Reinventing Discovery: The New Era of Networked Science*. Princeton, NJ: Princeton University Press.

Nieusma, Dean (2004). "Alternative Design Scholarship: Working toward Appropriate Design". In: *Design Issues* 20.3, pp. 13–24. DOI: 10.1162/0747936041423280.

— (2011). "Materializing Nano Equity: Lessons from Design". In: *Nanotechnology and the Challenges of Equity, Equality and Development*. Ed. by Susan E. Cozzens and Jameson Wetmore. Dordrecht: Springer Netherlands, pp. 209–230. DOI: 10.1007/978-90-481-9615-9_13.

Noble, Safiya Umoja (2018). *Algorithms of Oppression: How Search Engines Reinforce Racism*. New York: New York University Press. 229 pp.

Nowotny, Helga (2003). "Democratising Expertise and Socially Robust Knowledge". In: *Science and Public Policy* 30.3, pp. 151–156. DOI: 10.3152/147154303781780461.

Nowotny, Helga, Peter Scott, and Michael Gibbons (2001). *Re-Thinking Science: Knowledge and the Public in an Age of Uncertainty*. Cambridge, UK: Polity.

O'Brien, Mary (2000). *Making Better Environmental Decisions: An Alternative to Risk Assessment*. Cambridge, Mass.: MIT Press. 286 pp.

O'Neill, Kate (2019). *Waste*. Cambridge, UK; Medford, MA, USA: Polity Press. 232 pp.

O'Rourke, Dara (2005). "Market Movements - Nongovernmental Organization Strategies to Influence Global Production and Consumption". In: *Journal of Industrial Ecology* 9.1-2, pp. 115–128. DOI: 10.1162/1088198054084608.

— (2012). *Shopping for Good*. Boston Review. Cambridge, Mass.: MIT Press. 103 pp.

O'Rourke, Dara and Niklas Lollo (2015). "Transforming Consumption: From Decoupling, to Behavior Change, to System Changes for Sustainable Consumption". In: *Annual Review of Environment and Resources* 40.1, pp. 233–59. DOI: 10.1146/annurev-environ-102014-021224.

OEHHA (2015). *About Proposition 65*. URL: https://oehha.ca.gov/proposition-65/about-proposition-65.

OGN (2006). *Resistance to Nanotechnology in France - Week One*. URL: http://www.earthfirst.org.uk/actionreports/node/1381.

Ostrom, Elinor (1990). *Governing the Commons: The Evolution of Institutions for Collective Action*. The Political Economy of Institutions and Decisions. Cambridge; New York: Cambridge University Press. 280 pp.

Ottinger, Gwen (2013). *Refining Expertise: How Responsible Engineers Subvert Environmental Justice Challenges*. New York: New York University Press. 223 pp.

Ottinger, Gwen and Benjamin R Cohen, eds. (2011). *Technoscience and Environmental Justice: Expert Cultures in a Grassroots Movement*. Cambridge, Mass.: MIT Press.

Oudshoorn, Nelly and Trevor Pinch, eds. (2003). *How Users Matter: The Co-Construction of Users and Technologies*. Inside Technology. Cambridge, Mass.: MIT Press. 340 pp.

Owens, Susan (2012). "Experts and the Environment – The UK Royal Commission on Environmental Pollution 1970-2011". In: *Journal of Environmental Law* 24.1, pp. 1–22. DOI: 10.1093/jel/eqr031.

Pacurari, Maricica et al. (2016). "A Review on the Respiratory System Toxicity of Carbon Nanoparticles". In: *International Journal of Environmental Research and Public Health* 13.3. DOI: 10.3390/ijerph13030325.

Palmer, Sylvia (2016). *GreenScreen, SciVera Hit Back at ACC on Hazard Assessment Tools.* URL: https://chemicalwatch.com/47353/greenscreen-scivera-hit-back-at-acc-on-hazard-assessment-tools.

Panko, J.M. et al. (2017). "A Comparative Evaluation of Five Hazard Screening Tools". In: *Integrated Environmental Assessment and Management* 13.1, pp. 139–154. DOI: 10.1002/ieam.1757.

Perkins+Will (2019). *Precautionary List.* URL: https://transparency.perkinswill.com/lists/precautionary-list.

Petersen, Alan and Diana Bowman (2012). "Engaging Whom and for What Ends? Australian Stakeholders' Constructions of Public Engagement in Relation to Nanotechnologies". In: *Ethics in Science and Environmental Politics* 12.2, pp. 67–79. DOI: 10.3354/esep00124.

Philbrick, Mark and Javiera Barandiaran (2009). "The National Citizens' Technology Forum: Lessons for the Future". In: *Science and Public Policy* 36.5, pp. 335–347. DOI: 10.3152/030234209X442052.

Polanyi, Karl (1944). *The Great Transformation: The Political and Economic Origins of Our Time.* New York and Toronto: Farrar & Rinehart.

President's Cancer Panel (2010). *Reducing Environmental Cancer Risk: What We Can Do Now.* 2008-2009 Annual Report. Washington, DC: National Cancer Institute (US). URL: https://deainfo.nci.nih.gov/advisory/pcp/annualreports/pcp08-09rpt/pcp_report_08-09_508.pdf.

Pretty, Jules N. (1995). "Participatory Learning for Sustainable Agriculture". In: *World Development* 23.8, pp. 1247–1263. DOI: 10.1016/0305-750X(95)00046-F.

Princen, Thomas (2002). "Distancing: Consumption and the Severing of Feedback". In: *Confronting Consumption.* Ed. by Thomas Princen, Michael Maniates, and Ken Conca. Cambridge, Mass.: MIT Press, pp. 103–131.

Project on Emerging Nanotechnologies (2019). *Products.* URL: https://www.nanotechproject.org/cpi/products/.

Ramsden, Jeremy (2011). *Nanotechnology: An Introduction.* Micro and Nano Technologies Series. Oxford; Waltham, MA: William Andrew/Elsevier. 272 pp.

REEEP (2020). *Open Data and Knowledge Management.* URL: https://www.reeep.org/data-and-knowledge-management.

Rey-Mazón, Pablo et al. (2018). "Public Lab: Community-Based Approaches to Urban and Environmental Health and Justice". In: *Science and Engineering Ethics* 24.3, pp. 971–997. DOI: 10.1007/s11948-018-0059-8.

Rinkevich, Joseph (2018). *Using Quantitative Chemical Screening to Select Safer Chemicals — Scivera*. URL: https://www.scivera.com/using-quantitative-chemical-screening-to-select-safer-chemicals/.

Rittel, Horst W. J. and Melvin M. Webber (1973). "Dilemmas in a General Theory of Planning". In: *Policy Sciences* 4.2, pp. 155–169. DOI: 10.1007/BF01405730.

Royal Society and Royal Academy of Engineering (2004). *Nanoscience and Nanotechnologies: Opportunities and Uncertainties*. London: Royal Society: Royal Academy of Engineering.

Safe Cosmetics Action Network (n.d.). *Campaign for Safe Cosmetics*. URL: http://www.safecosmetics.org/.

Sanoff, Henry (2008). "Multiple Views of Participatory Design". In: *Archnet-Ijar International Journal of Architectural Research* 2.1, pp. 57–69.

Sarewitz, Daniel (2004). "How Science Makes Environmental Controversies Worse". In: *Environmental Science & Policy* 7.5, pp. 385–403. DOI: 10.1016/j.envsci.2004.06.001.

Satterfield, Terre, Joe Conti, et al. (2013). "Understanding Shifting Perceptions of Nanotechnologies and Their Implications for Policy Dialogues about Emerging Technologies". In: *Science and Public Policy* 40.2, pp. 247–260. DOI: 10.1093/scipol/scs084.

Satterfield, Terre, Milind Kandlikar, et al. (2009). "Anticipating the Perceived Risk of Nanotechnologies". In: *Nature Nanotechnology* 4.11, pp. 752–758. DOI: 10.1038/nnano.2009.265.

Savadori, Lucia et al. (2004). "Expert and Public Perception of Risk from Biotechnology". In: *Risk Analysis* 24.5, pp. 1289–1299. DOI: 10.1111/j.0272-4332.2004.00526.x.

Schattman, Rachel et al. (2014). "Vermont Agricultural Resilience in a Changing Climate: A Transdisciplinary and Participatory Action Research (PAR) Process". In: *Agroecology, Ecosystems, and Sustainability*. Ed. by Noureddine Benkeblia. Boca Raton: CRC Press, pp. 325–346.

Schlosberg, David (2004). "Reconceiving Environmental Justice: Global Movements and Political Theories". In: *Environmental Politics* 13.3, pp. 517–540. DOI: 10.1080/0964401042000229025.

— (2019). *Sustainable Materialism: Environmental Movements and the Politics of Everyday Life*. New Product Edition. New York: Oxford University Press.

Schomberg, René von and Sarah R. Davies, eds. (2010). *Understanding Public Debate on Nanotechnologies: Options for Framing Public Policy*. Luxembourg: Publications Office of the European Union.

Schot, Johan and Arie Rip (1997). "The Past and Future of Constructive Technology Assessment". In: *Technological Forecasting and Social Change* 54.2-3, pp. 251–268. DOI: 10.1016/S0040-1625(96)00180-1.

Schuler, Douglas and Aki Namioka, eds. (1993). *Participatory Design: Principles and Practices*. Hillsdale, NJ: L. Erlbaum Associates. 319 pp.

Schwarz, Stephanie and Richard A. Denison (2018a). *EPA Practices Are Hindering Transparency and Public Confidence in TSCA's New Chemicals Program*. URL: http://blogs.edf.org/health/2018/04/23/epa-practices-are-hindering-transparency-and-public-confidence-in-tscas-new-chemicals-program/.

Schwarz, Stephanie and Richard A. Denison (2018b). *No Justification: Substantiations for Rampant New Chemical CBI Claims Are Deficient or Lacking Altogether.* URL: http://blogs.edf.org/health/2018/02/16/no-justification-substantiations-for-rampant-new-chemical-cbi-claims-are-deficient-or-lacking-altogether/.

Schwarzman, Megan R. and Heather L. Buckley (2019). "Not Just an Academic Exercise: Systems Thinking Applied to Designing Safer Alternatives". In: *Journal of Chemical Education*. DOI: 10.1021/acs.jchemed.9b00345.

Schwarzman, Megan R. and Michael P. Wilson (2009). "New Science for Chemicals Policy". In: *Science* 326.5956, pp. 1065–1066. DOI: 10.1126/science.1177537.

Schweik, Charles M. and Robert C. English (2012). *Internet Success: A Study of Open-Source Software Commons*. Cambridge, Mass.: MIT Press. 351 pp.

Sclove, Richard (1995). *Democracy and Technology.* The Conduct of Science Series. New York: Guilford Press. 338 pp.

— (2010). *Reinventing Technology Assessment: A 21st Century Model.* Washington, DC: Woodrow Wilson International Center for Scholars. URL: http://www.wilsoncenter.org/sites/default/files/ReinventingTechnologyAssessment1.pdf.

Scruggs, Caroline E. (2013). "Reducing Hazardous Chemicals in Consumer Products: Proactive Company Strategies". In: *Journal of Cleaner Production* 44, pp. 105–114. DOI: 10.1016/j.jclepro.2012.12.005.

Scruggs, Caroline E. and Leonard Ortolano (2011). "Creating Safer Consumer Products: The Information Challenges Companies Face". In: *Environmental Science & Policy* 14.6, pp. 605–614. DOI: 10.1016/j.envsci.2011.05.010.

Scruggs, Caroline E., Leonard Ortolano, et al. (2014). "The Role of Chemical Policy in Improving Supply Chain Knowledge and Product Safety". In: *Journal of Environmental Studies and Sciences* 4.2, pp. 132–141. DOI: 10.1007/s13412-013-0158-4.

Selin, Henrik and Noelle Eckley Selin (2008). "Indigenous Peoples in International Environmental Cooperation: Arctic Management of Hazardous Substances". In: *Review of European Community & International Environmental Law* 17.1, pp. 72–83. DOI: 10.1111/j.1467-9388.2008.00589.x.

Shamasunder, Bhavna and Rachel Morello-Frosch (2015). "Scientific Contestations over "Toxic Trespass": Health and Regulatory Implications of Chemical Biomonitoring". In: *Journal of Environmental Studies and Sciences*. DOI: 10.1007/s13412-015-0233-0.

Shelby, Ryan, Yael Perez, and Alice Agogino (2012). "Partnering with the Pinoleville Pomo Nation: Co-Design Methodology Case Study for Creating Sustainable, Culturally Inspired Renewable Energy Systems and Infrastructure". In: *Sustainability* 4.5, pp. 794–818. DOI: 10.3390/su4050794.

Simonsen, Jesper and Toni Robertson, eds. (2013). *Routledge International Handbook of Participatory Design.* New York: Routledge. 294 pp.

Smith, Ted, David Allan Sonnenfeld, and David N Pellow (2006). *Challenging the Chip: Labor Rights and Environmental Justice in the Global Electronics Industry.* Philadelphia: Temple University Press.

Solomon, Gina M., Anh Hoang, and Peggy Reynolds (2019). "The California Safer Consumer Products Program: Evaluating a Novel Chemical Policy Strategy". In: *NEW SOLUTIONS: A Journal of Environmental and Occupational Health Policy* 29.2, pp. 224–241. DOI: 10.1177/1048291119850105.

State of California (2012). *Safer Consumer Products (California Code of Regulations, Title 22, Div 4.5, Ch. 55).*

Steinemann, Anne C., Ian C. MacGregor, et al. (2011). "Fragranced Consumer Products: Chemicals Emitted, Ingredients Unlisted". In: *Environmental Impact Assessment Review* 31.3, pp. 328–333. DOI: 10.1016/j.eiar.2010.08.002.

Steinemann, Anne C., Pawel Wargocki, and Behzad Rismanchi (2017). "Ten Questions Concerning Green Buildings and Indoor Air Quality". In: *Building and Environment* 112, pp. 351–358. DOI: 10.1016/j.buildenv.2016.11.010.

Stiglitz, Joseph E. (1999). "Knowledge as a Global Public Good". In: *Global Public Goods: International Cooperation in the 21st Century.* Ed. by Inge Kaul, Isabelle Grunberg, and Marc A. Stern. New York: Oxford University Press, pp. 308–325.

Stilgoe, Jack, Simon J. Lock, and James Wilsdon (2014). "Why Should We Promote Public Engagement with Science?" In: *Public Understanding of Science* 23.1, pp. 4–15. DOI: 10.1177/0963662513518154.

Stone, Alex and Damon Delistraty (2010). "Sources of Toxicity and Exposure Information for Identifying Chemicals of High Concern to Children". In: *Environmental Impact Assessment Review* 30.6, pp. 380–387. DOI: 10.1016/j.eiar.2009.11.002.

Strandbakken, Pål, Gerd Scholl, and Eivind Stø, eds. (2013). *Consumers and Nanotechnology: Deliberative Processes and Methodologies.* CRC Press. DOI: 10.1201/b14601.

Szasz, Andrew (2007). *Shopping Our Way to Safety: How We Changed from Protecting the Environment to Protecting Ourselves.* Minneapolis: University of Minnesota Press. 323 pp.

Thorpe, Beverly (2017). *Determining Chemical Hazard in a World of Incomplete Information: GreenScreen's New Benchmark Review Process.* URL: https://www.cleanproduction.org/resources/entry/gs-benchmark-review-process.

Tickner, Joel A. et al. (2015). "Advancing Safer Alternatives through Functional Substitution". In: *Environmental Science & Technology* 49.2, pp. 742–749. DOI: 10.1021/es503328m.

Tilly, Charles (1978). *From Mobilization to Revolution.* Reading, MA: Addison-Wesley. 349 pp.

Toxics Use Reduction Institute (2006). *Five Chemicals Alternatives Assessment Study.* Lowell, MA: University of Massachusetts Lowell. URL: https://www.turi.org/TURI_Publications/TURI_Methods_Policy_Reports/Five_Chemicals_Alternatives_Assessment_Study._2006.

ToxServices LLC (2019). *ToxFMD Screened Chemistry.* URL: https://www.screenedchemistry.com/.

United Nations (2019). *Globally Harmonized System of Classification and Labelling of Chemicals (GHS).* 8th Edition. Geneva. URL: http://www.unece.org/index.php?id=51896&L=0.

United Nations Environment Programme (2006). *Strategic Approach to International Chemicals Management: SAICM Texts and Resolutions of the International Conference on Chemicals Management*. Geneva: United Nations. URL: http://www.saicm.org/Portals/12/documents/saicmtexts/SAICM-publication-EN.pdf.

— (2013). *Global Chemicals Outlook: Towards Sound Management of Chemicals*. Nairobi: United Nations.

— (2019). *Global Chemicals Outlook II: From Legacies to Innovative Solutions: Implementing the 2030 Agenda for Sustainable Development*. Nairobi: United Nations. URL: https://wedocs.unep.org/bitstream/handle/20.500.11822/28113/GCOII.pdf?sequence=1&isAllowed=y.

United States Congress (1986). *Emergency Planning and Community Right-to-Know Act*.

— (2003). *21st Century Nanotechnology Research and Development Act*. URL: https://www.whitehouse.gov/files/documents/ostp/Issues/Nano%20Act%202003.pdf.

US Environmental Protection Agency (2012). *Safer Choice Master Criteria for Safer Chemical Ingredients*. URL: https://www.epa.gov/saferchoice/safer-choice-master-criteria-safer-chemical-ingredients.

US Environmental Protection Agency and ICF Consulting (2004). *The U.S. Solvent Cleaning Industry and the Transition to Non Ozone Depleting Substances*. Washington, DC: US Environmental Protection Agency, Office of Air and Radiation, p. 73. URL: https://www.epa.gov/sites/production/files/2014-11/documents/epasolventmarketreport.pdf.

US Green Building Council (2019). *Building Product Disclosure and Optimization - Material Ingredients*. URL: http://www.usgbc.org/node/12022829.

Van Broekhuizen, Pieter and Lucas Reijnders (2011). "Building Blocks for a Precautionary Approach to the Use of Nanomaterials: Positions Taken by Trade Unions and Environmental NGOs in the European Nanotechnologies Debate". In: *Risk Analysis* 31.10, pp. 1646–1657. DOI: 10.1111/j.1539-6924.2011.01615.x.

Van Giesen, Roxanne I., Arnout R.H. Fischer, and Hans C.M. van Trijp (2018). "Changes in the Influence of Affect and Cognition over Time on Consumer Attitude Formation toward Nanotechnology: A Longitudinal Survey Study". In: *Public Understanding of Science* 27.2, pp. 168–184. DOI: 10.1177/0963662516661292.

Van Oudheusden, Michiel (2011). "Questioning 'Participation': A Critical Appraisal of Its Conceptualization in a Flemish Participatory Technology Assessment". In: *Science and Engineering Ethics* 17.4, pp. 673–690. DOI: 10.1007/s11948-011-9313-z.

Vance, Marina E. et al. (2015). "Nanotechnology in the Real World: Redeveloping the Nanomaterial Consumer Products Inventory". In: *Beilstein Journal of Nanotechnology* 6, pp. 1769–1780. DOI: 10.3762/bjnano.6.181.

Vogel, Sarah A. (2009). "The Politics of Plastics: The Making and Unmaking of Bisphenol A "Safety"". In: *American Journal of Public Health* 99 (Suppl 3), S559–S566. DOI: 10.2105/AJPH.2008.159228.

— (2013). *Is It Safe? BPA and the Struggle to Define the Safety of Chemicals*. Berkeley: University of California Press. 304 pp.

Von Hippel, Eric (2006). *Democratizing Innovation*. Cambridge, Mass.: MIT Press. 204 pp.

Voutchkova, Adelina M., Thomas G. Osimitz, and Paul T. Anastas (2010). “Toward a Comprehensive Molecular Design Framework for Reduced Hazard”. In: *Chemical Reviews* 110.10, pp. 5845–5882. DOI: 10.1021/cr9003105.

Wang, Zhanyun et al. (2020). “Toward a Global Understanding of Chemical Pollution: A First Comprehensive Analysis of National and Regional Chemical Inventories”. In: *Environmental Science & Technology* 54.5, pp. 2575–2584. DOI: 10.1021/acs.est.9b06379.

Wapner, Paul (2002). “Horizontal Politics: Transnational Environmental Activism and Global Cultural Change”. In: *Global Environmental Politics* 2.2, pp. 37–62. DOI: 10.1162/15263800260047826.

Washington State Department of Ecology (2008). *Alternatives to Deca-BDE in Televisions and Computers and Residential Upholstered Furniture.* 09-07-041, p. 118. URL: https://fortress.wa.gov/ecy/publications/documents/0907041.pdf.

Watt-Cloutier, Sheila (2015). *The Right to Be Cold: One Woman's Story of Protecting Her Culture, the Arctic and the Whole Planet.* Toronto: Allen Lane.

Weber, Edward P. (2003). *Bringing Society Back in: Grassroots Ecosystem Management, Accountability, and Sustainable Communities.* American and Comparative Environmental Policy. Cambridge, Mass.: MIT Press. 317 pp.

Weeks, Katie (2013). “Taking a Stance on Transparency”. In: *Architect Magazine.* URL: https://www.architectmagazine.com/technology/products/taking-a-stance-on-transparency_o.

Weininger, David (1988). “SMILES, a Chemical Language and Information System. 1. Introduction to Methodology and Encoding Rules”. In: *Journal of Chemical Information and Modeling* 28.1, pp. 31–36. DOI: 10.1021/ci00057a005.

Westra, Laura (2008). *Environmental Justice and the Rights of Unborn and Future Generations: Law, Environmental Harm and the Right to Health.* London: Earthscan. 326 pp.

White, Ashley and Christopher Pyke, eds. (2016). *Better Building Materials: Understanding Human Health and Environmental Attributes.* US Green Building Council.

Whittaker, Margaret H. and Lauren G. Heine (2013). “Chemicals Alternatives Assessment (CAA): Tools for Selecting Less Hazardous Chemicals”. In: *Chemical Alternatives Assessments.* Ed. by R. M. Harrison and R. E. Hester. Issues in Environmental Science and Technology 36. Cambridge: Royal Society of Chemistry, pp. 1–255. URL: http://doi.org/10.1039/9781849737234-00001.

Wiek, Arnim, Rider W. Foley, and David H. Guston (2012). “Nanotechnology for Sustainability: What Does Nanotechnology Offer to Address Complex Sustainability Problems?” In: *Journal of Nanoparticle Research* 14.9, p. 1093. DOI: 10.1007/s11051-012-1093-0.

Wiek, Arnim, David H. Guston, et al. (2013). “Nanotechnology in the City: Sustainability Challenges and Anticipatory Governance”. In: *Journal of Urban Technology* 20.2, pp. 45–62. DOI: 10.1080/10630732.2012.735415.

Wilsdon, James and Rebecca Willis (2004). *See-through Science: Why Public Engagement Needs to Move Upstream.* London: Demos. 72 pp. URL: http://www.demos.co.uk/files/Seethroughsciencefinal.pdf.

Wilson, Michael P., S. Katharine Hammond, et al. (2007). “Worker Exposure to Volatile Organic Compounds in the Vehicle Repair Industry”. In: *Journal of Occupational and Environmental Hygiene* 4.5, pp. 301–310. DOI: 10.1080/15459620701258021.

Wilson, Michael P. and Megan R. Schwarzman (2009). “Toward a New U.S. Chemicals Policy: Rebuilding the Foundation to Advance New Science, Green Chemistry and Environmental Health”. In: *Environmental Health Perspectives* 117.8, pp. 1202–1209. DOI: 10.1289/ehp.0800404.

Winner, Langdon (1980). “Do Artifacts Have Politics?” In: *Daedalus* 109.1, pp. 121–136. URL: www.jstor.org/stable/20024652.

Wittman, Hannah, Annette Aurélie Desmarais, and Nettie Wiebe, eds. (2010). *Food Sovereignty: Reconnecting Food, Nature & Community.* Halifax: Fernwood. 212 pp.

Woodhouse, Edward J. and Steve Breyman (2005). “Green Chemistry as Social Movement?” In: *Science, Technology, & Human Values* 30.2, pp. 199–222. DOI: 10.1177/0162243904271726.

Woodhouse, Edward J. and Jason W. Patton (2004). “Design by Society: Science and Technology Studies and the Social Shaping of Design”. In: *Design Issues* 20.3, pp. 1–12. DOI: 10.1162/0747936041423262.

ZDHC Foundation (2020). *Roadmap To Zero.* URL: https://www.roadmaptozero.com/.

Zhang, Yi et al. (2014). “Perturbation of Physiological Systems by Nanoparticles”. In: *Chemical Society Reviews* 43.10, pp. 3762–3809. DOI: 10.1039/c3cs60338e.

Zimmer, Anthony T. and HakSoo Ha (2017). “People, Planet and Profit: Unintended Consequences of Legacy Building Materials”. In: *Journal of Environmental Management* 204, pp. 472–485. DOI: 10.1016/j.jenvman.2017.09.026.

Zimmerman, Julie B. and Paul T. Anastas (2015). “Toward Substitution with No Regrets”. In: *Science* 347.6227, pp. 1198–1199. DOI: 10.1126/science.aaa0812.

Zuo, Jian et al. (2017). “Green Building Evaluation from a Life-Cycle Perspective in Australia: A Critical Review”. In: *Renewable and Sustainable Energy Reviews* 70, pp. 358–368. DOI: 10.1016/j.rser.2016.11.251.

Appendix A

Research Interview Guide

These are questions for scientific, technical, or leadership staff in firms, government agencies, academic institutions, and non-profit organizations.[1] Most questions refer to a knowledge resource, community, project, organization, commons, etc. of interest to me, which this guide refers to in shorthand as the "work" or "community".

Opening questions

1. Could you please tell me a little about your background?
    1.1 Could you please describe your institutional affiliation and the type of work that you do with your organization?
    1.2 How did you get involved in [the work/community]?

Characteristics of the knowledge commons

2. How did [the work/community] originate?
3. What are the goals or objectives of [the work/community]?
    3.1 What problem is [the work/community] aiming to solve?
    3.2 Have the goals changed over time?
4. Who would you say are the people or organizations who are most strongly pushing for these goals?
5. How was/is [the work/community] supported or funded?
6. What kinds of knowledge does this [work/community] make available?

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[1] This interview guide is part of CPHS Protocol Number 2016-02-8368.

   6.1 Is this knowledge normally freely available to people, or is it normally protected somehow?

Participation and community characteristics

7. Could you tell me about who participates in [the work/community]?
   7.1 Who was/is involved in it?
   7.2 How did they [participants] get involved?
   7.3 Why were/weren't [. . .] involved?
8. Is anybody allowed to participate?
   8.1 Are there issues or problems with controlling who participates?
   8.2 What if [a problematic stakeholder] wanted to participate?
9. How is [the work/community] managed? By whom?
   9.1 Are there leaders in [the community]?
   9.2 What kind of authority or responsibility do they have?
   9.3 Where does this authority come from?

Rules-in-use

10. Could you tell me about the kinds of roles that participants can have in [the community], for example as users or contributors or managers?
    10.1 Are there distinctly defined roles?
    10.2 What are the differences in terms of what people can and cannot do?
11. Are there any rules or codes of conduct for [the community]? Are they formalized in some way?
12. Considering what participants actually do, what kinds of behavior are considered good for [the community]?
    12.1 What is it that encourages participants to [behave in this way]?
13. What kinds of behavior would be considered bad?
    13.1 What is it that prevents participants from [doing that]?
14. Are there attempts to control or withhold data?
    14.1 If that happens, how do you deal with it?

Validation of knowledge

15. What determines the quality and reliability of the information?

16. How do you decide if data are useful or reliable?

    16.1 In other words, what are the major issues or questions of quality or reliability?

17. Are there ever concerns about the information being correct, valid, or authoritative?

    17.1 How are these concerns addressed?

18. Are there ever conflicts over the information, or about any of the issues we've been discussing?

    18.1 For example, do people ever disagree about the correct interpretation of data, or about whether some data belongs in [the work]?
    18.2 Can you give an example?
    18.3 Where do these conflicts come from? "Inside" or "outside" [the community]?
    18.4 Have any of these conflicts been resolved? If so, how and by whom?

Incentives and values in the knowledge commons

19. Who are the [the producers/contributors of knowledge] accountable to?

20. Are there people or organizations who rely on [the work/community] as a resource? For what purposes?

21. What makes this [work/community] valuable?

    21.1 Who values or benefits from [the work/community]?

Concluding questions

22. Who (else) should I talk to about [this or another work/community]?