Universitat Autònoma de Barcelona

Supercritical Sustainability
A Relational Theory of Social-Ecological Systems with Lessons from a Disenfranchised European Primary Sector

Ansel Renner

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by

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ABSTRACT

From biodiversity loss to soil degradation to pollution of water bodies, our life support systems are in decline. Spaceship Earth is in trouble. We are trouble. Sustainability science has emerged in response, offering to model our way to safety. The spirit of modeling efforts in the sustainability science is, however, dominated by notions of prediction and optimization. While prediction and optimization have proven extremely successful in other domains, leading to the creation of rockets and smartphones and so forth, they fail to grasp the essential intangibilities of social-ecological systems. They have effectively colonized the future, supporting a regime of techno-scientific promises and comforting ex-post motives.

This dissertation explores an alternative approach to sustainability science, one based on anticipation studies and the idea of social-ecological systems as complex adaptive systems. A thorough revision of the conceptual basis of modeling for sustainability is made, based on insights from societal metabolism and relational biology. That revision is then used to inform the characterization of social-economic systems as metabolic-repair systems, meaning organisms. New light is thereby shed on global megatrends of globalization and urbanization, through which societies are losing control over their identities. Insights on modeling provided by societal metabolism and relational biology are then crossed with insights from philosophy of mind and philosophy of language to re-conceptualize the architecture of social-ecological knowledge spaces, within which models exist. An emphasis is made on the role of justification, explanation and normative narratives in creating knowledge space bounds and breaking impredicativities.

Having established a robust conceptual basis, two case studies are presented. The first, a quantitative storytelling on the quick deployment of alternative sources of electrical energy to decarbonize the economy, highlights several shortcomings of current governance efforts. It is asserted, for example, that the hasty way energy storage is considered in contemporary energy transition discussions is leading society towards a grave situation of structural-functional mismatch. The second case study, a quantitative storytelling on agricultural re-internalization, highlights a set of security concerns associated with the extreme levels of agricultural externalization found in modern social-economic systems.

Neither of the quantitative storytellings presented in this dissertation make any attempt to predict the future. Their offering is as learning-type storylines, helping society clarify its vision of a desirable future. Indeed, although critical of them, none of the insights in this dissertation are arguments for the elimination of conventional approaches to modeling. This dissertation is merely an effort to break the hegemony of predictivity and optimizability, to complement those ideas with notions of impredicativity. A paradigm of supercritical sustainability is ultimately proposed, being a mode of sustainability where the self-referentiality of complex systems is understood to be a virtuous cycle, not a vicious one. Supercritical sustainability re-opens discussion of the ruptured future, providing insights into the deliberative creation of extensible social-ecological models in support of responsible development pathways.

RESUMEN

Desde la pérdida de la biodiversidad hasta la degradación del suelo y la contaminación de las masas de agua, nuestros sistemas de soporte vital están en declive. La nave espacial Tierra tiene problemas. Nosotros tenemos problemas. La ciencia de la sostenibilidad ha surgido como respuesta, ofreciendo modelos de nuestro camino a la salvación. No obstante, el espíritu de los esfuerzos de modelado en la ciencia de la sostenibilidad está dominado por las nociones de predicción y optimización. Mientras que la predicción y la optimización han demostrado ser extremadamente exitosas en otros campos, llevando a la creación de cohetes y teléfonos inteligentes entre otros, estos planteamientos no logran comprender las intangibilidades más esenciales de los sistemas socio-ecológicos. Estas nociones han colonizado efectivamente el futuro, apoyando un régimen de promesas tecnocientíficas y reconfortantes razones ex-post.

Esta disertación explora un enfoque alternativo de la ciencia de la sostenibilidad. Un enfoque basado en estudios de anticipación y en la idea de que los sistemas socio-ecológicos son sistemas adaptativos complejos. A partir de las teorías del metabolismo social y la biología relacional, se realiza una revisión exhaustiva de la base conceptual de la modelización de la sostenibilidad. Posteriormente, se utiliza esta revisión para fundamentar la caracterización de los sistemas socioeconómicos como sistemas de reparación metabólica, es decir, organismos. De este modo se arroja nueva luz sobre las megatendencias mundiales de la globalización y la urbanización, a través de las cuales las sociedades están perdiendo el control sobre sus identidades. Posteriormente, los enfoques de modelización proporcionadas por el metabolismo social y la biología relacional se discuten con los de la filosofía de la mente y la filosofía del lenguaje para reconceptualizar la arquitectura de los espacios de conocimiento socio-ecológicos, dentro de los cuales encontramos los modelos. Con especial detenimiento es analizado el papel de la justificación, la explicación y los relatos normativos en la creación de los límites del espacio de conocimiento y en la ruptura de las impredicatividades.

Habiendo establecido una sólida base conceptual, se presentan dos estudios de caso. El primero, una narración cuantitativa sobre el rápido despliegue de fuentes alternativas de energía eléctrica para descarbonizar la economía, pone de relieve varias deficiencias en los actuales esfuerzos de gobernanza. Se afirma, por ejemplo, que la forma precipitada en que se considera el almacenamiento de energía en los debates contemporáneos sobre la transición energética está llevando a la sociedad a una grave situación de desajuste estructural-funcional. El segundo, una narración cuantitativa sobre la reinternalización de la agricultura, pone de relieve un conjunto de preocupaciones en materia de seguridad relacionadas con los niveles extremos de externalización de la agricultura observados en los sistemas socioeconómicos modernos.

Ninguna de las narraciones cuantitativas presentadas en esta disertación hace ningún intento de predecir el futuro. Se ofrecen como historias de aprendizaje, ayudando a la sociedad a clarificar su visión de un futuro deseable. De hecho, aunque son críticas, ninguna de las tesis de esta disertación presentan argumentos para eliminar los enfoques convencionales de la modelización. Esta disertación no es más que un esfuerzo por romper la hegemonía de la predictividad y la optimizabilidad, para complementar esas ideas con nociones de impredictibilidad. En última instancia, se propone un paradigma de sostenibilidad supercrítica, que es un modo de sostenibilidad en el que la auto-referencialidad de los sistemas complejos se entiende como un ciclo virtuoso, no vicioso. La sostenibilidad supercrítica reabre el debate sobre el futuro roto, aportando ideas sobre la creación deliberada de modelos socio-ecológicos extensibles que apoyen vías de desarrollo responsables.

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1 INTRODUCTION

1.1 OPENING REMARKS

1.1.1 *Motivation*

On the south face of Vignemale Massif (3298 m / 10820 ft) lies the rapidly disappearing Ossoue Glacier, the second largest glacier in the Pyrenees. Ossoue has lost roughly 59% of its area in the past 100 years and will disappear sometime around the middle of this century (René, 2011). When I mention to someone that I research issues of sustainability and the environment, it's images like this that come to mind. Receding glaciers, rising sea levels, stranded polar bears. Climate change. This dissertation isn't about that any of that. Not directly at least.

On the other side of Vignemale Massif, in the long shadows of its north face, is *Refuge des Oulettes de Gaube*. During the summer, a shepherd tends a flock of sheep in the alpine pasture by the refuge. The sheep enjoy laying in the nearby snowfields to cool off during the heat of day and, at peace with their surroundings, provide the hardworking shepherd with a reliable supply of milk. That milk supply gets made into cheeses such as *Tomme des Pyrénées*, a cheese with over 900 years of tradition behind it, now sold internationally. Two of those sheep are featured on the cover.

Unfortunately, small-scale farmers like Vignemale's hardworking shepherd are becoming a thing of the past. J. Wojciechowski, the current Commissioner for Agriculture of the European Commission, paints the trend most eloquently:

> [D]uring one decade, from 2005 to 2015, we lost four million farms in the European Union. The number of farms was almost 15 million, and after a decade there were fewer than 11 million farms. If we lose four million per decade, it is 400 000 per year. More than 30 000 per month. More than 1 000 per day. Our debate is scheduled to last three hours, which means that during this debate more than 100 European farmers will probably lose their farm and their job. For many of them it will be a tragic, shocking situation because it is not so easy to be a farmer today and then tomorrow to do something different—to be a taxi driver, for example. In many cases, this is a dramatic situation for European farmers.
>
> (AGRI, 2019)

Wojciechowski goes on to mention an ongoing "problem of suicide" among farmers in France.

In fact, the issue is considerably more worrisome than Wojciechowski's statement lets on. The progressive disenfranchisement of farmers has been ongoing across the world for many decades. In Europe, it occurs despite the pouring of tens of billions of euros a year into the support of domestic agriculture.

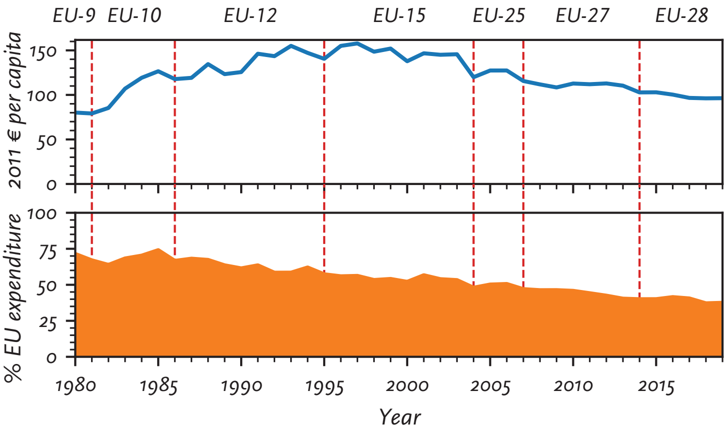

Figure 1 Evolution of expenditure on the Europe Union's Common Agricultural Policy (CAP), 1980–2019. Data sources: (Eurostat, 2019; DG AGRI, 2020).

🟦
🟧 *CAP expenditure*

The finality of this trend is a fully commodified industrial complex perhaps better labeled "agribusiness". It is a new type of organ within Europe's metabolic pattern, one that has very little in common with the agriculture sector of a hundred years ago. As agriculture slowly fades into the afterthoughts of urban life, the influence of it on Europe's cultural identity is seen to lessen.

What insight does science for policy offer? Are we to be concerned by this radical trend? Are we to be concerned by agriculture's ongoing transformation? Apparently, not so. The knowledge space of science for policy is still dominated over by conventional economics, which proposes about the agricultural trend the narrative, "No cause for alarm." Consider the following, infamous statement of W. Nordhaus, winner of the 2018 Nobel Memorial Prize in Economic Sciences, speaking on the intersection of agriculture and climate change.

> Agriculture, the part of the economy that is sensitive to climate change, accounts for just 3% of national output. That means there is no way to get a very large effect on the U.S. economy. It is hard to say it is the nation's number one problem.
>
> (reported by Roberts, 1991, p. 1206)

How can the rhetoric of Wojciechowski, a policymaker, and Nordhaus, an academic, be so diametrically opposed? Wojciechowski seems to imply that we should do more to support farmers, Nordhaus seems to indicate that farmers are irrelevant. How can sustainability researchers possibly hope to deliver lasting insight on the science-policy interface in the face of such clear lack of consensus?

The matter is further complicated by the realization that the agricultural trend and corresponding lack of expert consensus is not an isolated incident. Similar realities can be observed across all the primary sectors. Consider the energy sector. Although spending on the energy sector is much smaller than spending on the agriculture sector, in some ways, the energy sector trends are even more alarming. For starters, the act of primary extraction of energy sources (coal, crude oil, natural gas) has been mostly eliminated within Europe, concentrated into the hands of a global elite. Who now extracts, from primary energy sources, a significant portion of the energy they consume? Who now has a personal relation with the actors charged with primary extraction?

V. Smil (2010, p. 89) estimates that two-thirds of the useful power capacity in society a century and a half ago was endosomatic, meaning in the form of domesticated animals and people. Only one-third was inanimate, predominantly being water wheels, water turbines and windmills. In modern times, domesticated animals and people represent an infinitesimal proportion of total useful power capacity, significantly less than one-hundredth. The modern economic agent is merely a decision-maker, exerting trigger-action over machines. N.B. There is no relation between the minimal energy expended by the pulling of a trigger and the potentially massive amount of energy released by that pulling.

Nota bene / Note well

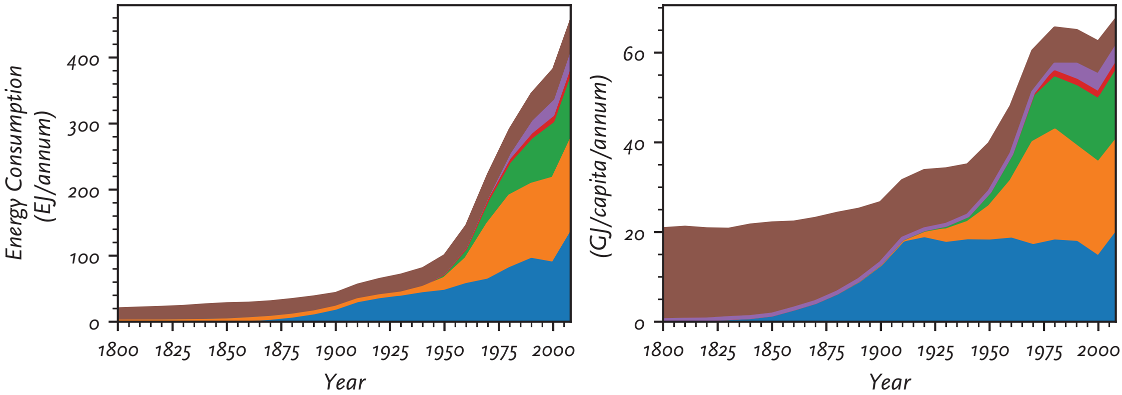

Figure 2 The dramatic rise in global energy consumption, extensive and intensive 1800–2008. Consumption data source: (Smil, 2010, p. 155). Population data source: (Gapminder, 2019).

🟦 *Coal*
🟧 *Crude Oil*
🟩 *Natural Gas*
🟥 *Hydro Electricity*
🟪 *Nuclear Electricity*
🟫 *Biofuels*

The trend towards heavy reliance on inanimate power capacity is yet more accentuated in high-income economies, such as the European Union or the United States (Giampietro, Mayumi and Sorman, 2012). High-income economies account for half of all commercial energy consumption, despite representing only 20% of the global population (Smil, 2010, p. 150).

If these are the trends in the energy sector, intensification, externalization, alienation, what is the vision for the future? In the energy sector, the dominant futures narratives, both political and scientific, provoke the belief that we will willingly transition to "renewables" in "just a few years, decades at most." It is further supposed that our economies will become "fair and prosperous" by that transition (EC, 2019, p. 2). The European Union, the posterchild of renewables promises, exemplifies the notion. The European Green Deal aims towards a 2050 where there are "no net emissions of greenhouse gases […] and where economic growth is decoupled from resource use" (*ibid.*, p. 2), recognizing that the "production and use of energy […] account[s] for more than 75% of the EU's greenhouse gas emissions" (*ibid.*, p. 6).

These rosy visions of the future stand in contrast to our collective memories of past energy transitions. When fossil fuels overtook biomass as the leading form of energy in the economy sometime around the turn of the twentieth century, human society "only" consumed about 40 EJ per annum. As Figure 2 shows, society now consumes well over 10x that. The scale of the modern transition task is an order of magnitude greater than that of the previous transition but we claim to be able to achieve it, self-motivated, no less, within a much narrower time frame. The narratives that dominate the energy sector discourse assert that, in achieving this Herculean task, we will *increase* our economic competitiveness, equitability and standard of living.

At some point of development, the maintenance of Earth's biological system will demand an amount of free energy equivalent to the Sun's generous donation. At this point, sustained further development will be impossible. If the exponential growth of human society pushes it past its allowance in Earth's biological system by overdrawing energy generously stored by fossilized biota, what F. Soddy (1933, p. 102) fittingly referred to as the "original capitalists", it will be at the cost of society's ecological foundations. How close are we to those ultimate limits? Elliot (1973, p. 6) refers to the scale of man-made death as "the central moral as well as material fact of our time." Is it possible that we have already reached hard limits? What would that mean for the impending renewables transition? What mechanism of reflection is in place?

Like agriculture, the energy sector is being guided by economic narratives. But as M. Slesser (1978, p. 6) points out in *Energy in the Economy*, the "price system does have one disadvantage. It is possible to conduct one's entire affairs without regard to the physical world." No matter how many "panels of experts" are convened, economists cannot even agree on the future direction of the change in price. And yet, price is perhaps the single most central focus of energy research and policy. It is being used to guide rosy visions of the renewables transition, such as that set by the European Green Deal. Has it been consciously decided that "Christmas list governance" is the preferable way into the unknown, or is something more ominous afoot?

M. Giampietro (2018) refers to the modern ignorance of physical reality the *delirium of the urban elite*. Where does food come from? The supermarket. Where does energy come from? The gas station. Where does money come from? The automated teller machine. The modern, hyper-urban world we live in epitomizes the utopian narrative, again from economics, that the "world can, in effect, get along without natural resources, […] production can be freed of dependence on exhaustible resources altogether" (Solow, 1974, p. 11). And the proportion of urban elite is monotonically increasing.

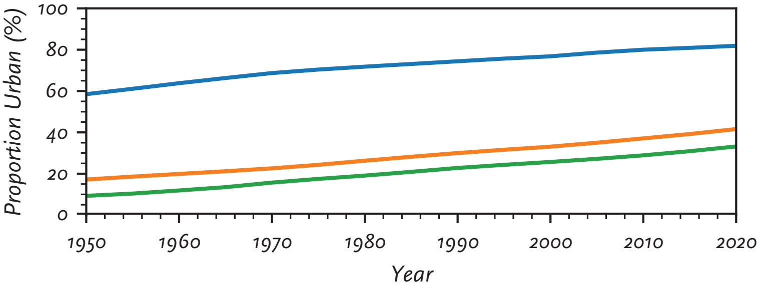

Figure 3 Proportion of urban humans worldwide. Data source: (UN, 2018).

The conventional defense of the delirium of the urban elite is of course that, in our highly urbanized world, an unprecedented number of people live, in material terms, like royalty. While true, that argumentative line categorically neglects the more complicated, worrying aspects of the modern condition. Modern social-ecological systems are losing their metabolic identities and they're giving very little hesitative reflection on the feasibility, viability and desirability of the dramatically new ones that are being created. Urban life comes hand-in-hand with the paradigm of service sector economy, the end of which is to "entertain and distract a population which—though it is busier than ever before—secretly suspects that it is useless" (Gray, 2003, p. 160). Is this hedonic reality not cause for concern?

If we can agree that there is indeed some cause for concern, a dose of epistemological therapy seems due. It is argued in this dissertation that the ability of science to explain changes in metabolic identity is impaired and in severe need of improvement. It is argued that society's mechanisms of cybernetic control are, overall, weakening, and that science's poor track record of anticipating societal changes leaves us ill prepared for the challenges ahead. This dissertation contributes to the betterment of that situation. Some years ago, the unorthodox economist N. Georgescu-Roegen (1976, pp. xxi–xxii) left us with the following question:

> The fact that econometric models of the most refined and complex kind have generally failed to fit future data—which means that they failed to be predictive—finds a ready, yet self-defeating, excuse: history has changed the parameters. If history is so cunning, why persist in predicting it?

His statement proves just as relevant today as it did then. In sustainability science, the use of optimizable, predicative modeling is widespread. Regularly, it takes the form of partial or general equilibrium models, even though, since L. von Bertalanffy (1968) and E. Schrödinger (1944), it has been abundantly clear that most systems of interest are interesting precisely because they are not in equilibrium. Other times it takes the form of "Frankenstein models", the false pretense of integrated assessment, constructs that are a lethal mix of efforts concerned with essentially non-equivalent external referents observable only in non-reducible descriptive domains.

The impact of colonizing the future in this manner, the economics of techno-scientific promises (Joly, 2010) based on "because motives" (ex-post) (Poli, 2017, p. 30), has been immense. It has made the practice of exploration and deliberation over possible futures off-limits to civil society, given a false sense of security and has contributed to the creation of our contemporary sustainability debacle. There is no question that the challenges we face are of an unprecedented magnitude, but we must resist that that reality discourages frank discourse on the future and how to use it. As Gray (2003, p. 124) put it, "Tyrannies begin as festivals of the depressed". A central motivation of this dissertation is to advance sustainability science towards something that empowers, not distracts. A humble approach is taken, grounded in the idea that social-ecological systems are inherently and unavoidably impredicative. That view is seen to be both liberating and encouraging. A novel set of methods capable of exploring sustainability issues as impredicative issues in a robust manner is presented. These methods enable anticipation into the discontinuous future, openly acknowledging the existence of incalculable uncertainty. The discussion is thereby opened up to a new class of "in-order-to motives" (ex-ante) (Poli, 2017, p. 30). Foundationally, this dissertation proposes a paradigm of *supercritical sustainability*.

2	4		3
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4	3	2	1
1			4

A subcritical Sudoku.

2			
			2
1			4

A supercritical Sudoku.

The Sudoku analogy of Giampietro and Bukkens (2015) helps to convey the idea. Standard Sudokus are subcritical, meaning the mutual information provided perfectly defines the location of all numbers involved. They are puzzles with only one correct answer, a solution that we can be sure is obtainable. Like a dynamical model, which can be fast-forwarded and rewound at will, the information space of a subcritical Sudoku is "dead". A *supercritical* Sudoku is a completely different beast. There are many possible ways in which numbers can be arranged in its grid, with no one way better than the other. Where a subcritical Sudoku is a puzzle, a supercritical Sudoku is a game. There are multiple correct answers, no one of which is better than another.

The paradigm of supercritical sustainability is exactly analog. The idea of supercritical sustainability is that it is unavoidable that sustainability scientists deal with contingency and impredicativity in their research. Rather than solve subcritical puzzles, sustainability scientists should empower the playing of supercritical games. They themselves are active participants in those games, helping to define the rules, which, we must keep in mind, can always be adjusted or cheated on.

If I succeed at my goal, this dissertation will be a bit like the adventure of the Square in Abbott's (2006) *Flatland*. If a two-dimensional thinker (a Square) is exposed to a one-dimensional thinker (a point on a line), he thinks himself quite clever. If instead the two-dimensional thinker is exposed to a three-dimensional thinker, he is greatly humbled and perhaps upset. His mind is expanded. Sustainability science is special in that there exists a massive number of relevant dimensions and scales of analysis. A sustainability science based on composite indicators or conventional economics, in particular one-dimensional comparisons of price, is blind to this reality. This dissertation contributes to the reform of that state of affairs and to the expansion of the notion of what should be considered sound sustainability science.

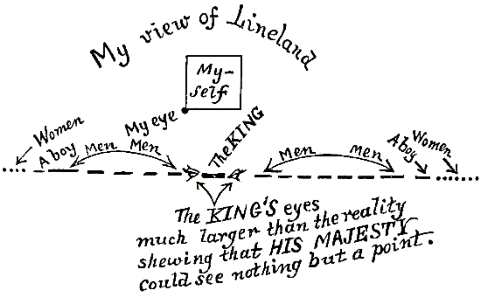

Figure 4 Illustration from Abbott's (2006, p. 69) *Flatland: A Romance of Many Dimensions*. "Myself" exists in Flatland (a two-dimensional world) and "The King" exists in Lineland (a one-dimensional world). Try as he might, "The King" cannot come to understand Flatland, no matter how "Myself" tries to project himself. *Flatland* was first published in 1884, a polemic on the social hierarchy of Victorian culture. But "Victorian culture" can easily be replaced with "Kuhnian normal science." As scientists and natural philosophers, we should always try to expand our minds by seeking out higher-dimensional perspectives.

Hence, this dissertation is a heterodox one. It stands on its own but draws heavily from the legacy left by the Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) accounting framework. MuSIASEM was first proposed by M. Giampietro and K. Mayumi (2000) in order to deal with the epistemological challenges of quantitative analysis of complex adaptive systems. In inheriting its legacy, this dissertation draws from an impressively wide breadth of fields, including hierarchy theory, non-equilibrium thermodynamics, cybernetics, theoretical ecology, biophysical economics, post-normal science, semiotics, biosemiotics, relational biology and participatory integrated assessment. With that said, if the reader has not yet been scared off, let us begin.

1.1.2 *Objectives*

First, in very general terms, how does sustainability science hold up to philosophy, the tribunal of science? If we compare contemporary modeling efforts to their theoretical foundations, how well are we doing? Can any shortcomings be identified? If so, how can modeling efforts be systematically improved? In a similar vein, if we agree that predicative methods of modeling are failing at providing robust insights, how can a sustainability science based on impredicativity be built? What are the implications of admitting to the existence of impredicativities? How can a sustainability science based on impredicativity be used on the science-policy interface? How can methods of anticipation inform the way we handle impredicativities in sustainability science?

Next, consider that problems in "normal science", identified by the practitioners themselves and always solvable, are "comfortable problems". What assurance do we have that the correct problems are being identified? There must also exist "uncomfortable problems", ones without a certain solution. Surely some of those must also be important to address. How can sustainability science learn to accommodate such problems? How must sustainability science change in order to accommodate them?

How then can the conceptual insights resulting from the answering of these questions inform practice? How can we characterize the changing metabolic patterns of social-economic systems? In terms of the energy sector, do we have the tools we need to model change under a renewables transition? Accounting for energy in the economy is like accounting for money in the sense that energy is an abstraction that defies absolutes. What do we refer to by "money"? Do we include currency in circulation? In vaults? Demand deposits? Savings deposits? Analogously, what do we refer to by "energy"? What are the different classes to consider? What if nobody can even assess those classes? When renewables power capacity including wind turbines and solar panels is injected into the electrical grid, does the set of energy classes to be considered change? How does it change? How does change in the set of relevant energy classes affect the way we model?

In terms of the agriculture sector, are we sure that agribusiness is a desirable, long-term strategy? If not, what type of information should be used to deliberate about a desirable level of openness through trade? How can we go about characterizing what is at stake? Is it reasonable to view agriculture as economically irrelevant? How can agricultural models based on price be complemented with others based on a buffet of incommensurable, biophysical dimensions? How can we assess the robustness of resource security, often complicated by globalization?

Above all, how can consensus narratives on sustainability be created? What is the rightful role of sustainability science in that dialogue? How can methods of sustainability science support the development of responsible development pathways?

1.2 OUTLINE

1.2.1 *Overview*

This dissertation contains six chapters. The middle four chapters present the main content, roughly organized in two parts. Chapters 2 and 3 are primarily conceptual. They contribute an epistemological breakdown on sustainability science and offer insight into how to go about creating more expressive and responsible models and knowledge spaces. Chapters 4 and 5 are applied contributions. They work with the foundation set by Chapters 2 and 3 and present studies of the "disenfranchised" energy and agriculture sectors. Chapter 5 concludes. A brief afterword then gives context to the course of study behind this dissertation, providing due mention to the associated projects, grants, dissemination events and publications. Appendices A and B follow, being a set of programming considerations and a set of data wrangling notes and calculation techniques for Chapters 4 and 5.

Finally, an observation is due in relation to a standard problem associated with interdisciplinary and transdisciplinary works. When comparing the thickness of literature review on each and every concept used in the text of conventional disciplinary dissertations with the coverage given in this dissertation, the reader may perceive there to be a lack of proper effort in literature review. On the contrary, if modern institutions of academia stress the need to be more transdisciplinary, it is obvious that, as consequence of this effort, it becomes difficult to explain the history, the different interpretations and the minutiae of details of each one of the theoretical concepts presented in a dissertation (they are many!). This dissertation is immensely transdisciplinary. Effort has been made such that every section of every chapter presents value-added far beyond regurgitation of the discourse. If the reader comes away from this dissertation with newfound faith that we, sustainability scientists, do have convincing alternatives to the "normal science" approach and to the predicative modeling hegemony, then the dissertation will have succeeded.

1.2.2 *Social-Economic Systems as Organisms*

In Chapter 2, *Social-Economic Systems as Organisms*, the concept of social-ecological modeling is first reviewed. The ideas of relational biology, especially those of R. Rosen, inform the discussion throughout. The relational approach to modeling and the reductionist approach to modeling are discussed and the difference between models and simulations is explained. A framework of causality is presented and used to explore the signature causal structures of machines, complexity and life. Those ideas are then used to explore the metabolic nature of social-economic systems. A general understanding relating the various constituent components of social-economic systems in a relational network is presented and used to assert that social-economic systems are metabolic-repair (M,R) systems of the type explored in relational biology, meaning "societal metabolism" is not merely a metaphor. It is argued that, through urbanization and globalization, social-economic systems are losing certain functional entailment relations and their ability to control replication. It is further argued that modern social-economic systems are losing control over their identity. Insights from Chapter 2 may be especially useful for modelers in search of epistemological therapy, or decision-makers wishing to make responsible decisions concerning the control of system identity change.

1.2.3 *Social-Ecological Knowledge Spaces*

In Chapter 3, *Social-Ecological Knowledge Spaces*, we take a step back from the modeling endeavor and look at the construction of knowledge spaces, which bound models. The role of narratives in breaking chicken-egg paradoxes (impredicativities) is explained and three narrative archetypes are presented, justification, explanation and normative. The idea of supercriticality is presented, giving context to the title of this dissertation. The role of normal scientists as "puzzle-solvers" is criticized and the idea of post-normal scientists as "game-players" is put forth, in a non-derogatory manner. The creation of two different types of classification is discussed along with the essential role classifications play in describing knowledge spaces. Cartesian products of classifications are then used to construct multidimensional classifications, being the structured "backbone" of knowledge spaces. Wittgenstein's idea of grammar is engaged with in its ability to check the appropriateness of the characterization of a knowledge space. Various endnotes conclude the chapter, touching on the shortcomings of input-output analysis, exploring transferable insights from sensitivity analysis and shedding new light on the classic analogy of science as cartography. N.B. Appendix A provides some general programming considerations for the creation and use of multidimensional classifications.

1.2.4 *Quantitative Storytelling on a Renewable Energy Transition*

In Chapter 4, *Quantitative Storytelling on a Renewable Energy Transition*, various insights from Chapters 2 and 3 are synthesized into a standardized approach called *quantitative storytelling*. Rather than using complicated models which try to predict and control the future evolution of complex adaptive systems, quantitative storytelling is proposed to check, first of all, the plausibility of proposed policies. As a case study, the plausibility of the sociotechnical imaginary of "a radical decarbonization of the European economy based on a quick deployment of alternative sources of electrical energy generation" is explored. Starting things off, the essentials of accounting for electrical energy are reviewed. Three types of watt-hours associated with three types of power capacity are differentiated. A conceptual discussion on storage technologies and the role of alternatives in the grid is then made. In conjunction with a large dataset of approximately ten million data points covering roughly ten years, these insights are used to frame a calculation of the extent of the anticipated worst annual failure event in the Spanish and German electrical grids, hypothetically powered purely by wind and solar, across various consumer guarantee and confidence levels. Related to the worst annual failure event, the maximal instantaneous power gap and integrated energy gap, both critical aspects of contingency planning, are calculated. These numerical results are then discussed from a structural-functional perspective. Serious concerns about the claims endorsed by European Union policies are raised, intended as a warning that a political strategy based on the mobilization of expectations about results that are not reachable in the promised time horizon may lead to the choice of unwise and unfair policies.

1.2.5 *Quantitative Storytelling on an Agricultural Internalization*

In Chapter 5, *Quantitative Storytelling on an Agricultural Internalization*, a second exercise in quantitative storytelling is presented, being an anticipation of pressure increases associated with a near-complete re-internalization of agricultural production in the European Union. The exercise explores how domestic environmental pressures such as pesticide residue, fertilizer leakage and waterbody overdraft would change if European agricultural production were to be re-localized, and how those increases might stress local habitats, soils and freshwater reserves. More in general, the idea that feasibility, viability and desirability are functions of the choice of system boundary, spatial and temporal, is explored. Specific results to the exercise might prove relevant in the event of an end of the era of cheap food imports, or when considering the plausibility of economic circularization efforts (as suggested by the European Green Deal). Rather than produce quantitative results determined by a given set of supposedly uncontested pre-analytical assumptions, the approach is seen to accommodate several possible results driven by contradictory yet equally legitimate insights. According to the results, which build on current trade profiles and assume business as usual change in agricultural technical coefficients, a near-complete re-internalization of agricultural production by each European Union member state is not environmentally feasible. Additionally, in relation to social viability, the required changes in social practices would include a significant increase in the share of agricultural workers in the economy and important dietary adjustments.

1.2.6 *Conclusion*

Chapter 6 concludes by summarizing the contributions of the dissertation, exploring some limitations and making suggestions for future work. Suggestions focus on the possibility of further axiomatic development, which could go a long way in enhancing the design of a new class of "technologies of humility" (Jasanoff, 2003).

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2 SOCIAL-ECONOMIC SYSTEMS AS ORGANISMS[1]

2.1 SUSTAINABILITY SCIENCE

2.1.1 *Questions*

Sustainability science is about forward-looking explanations. It is about the creation of models, in a very liberal sense, in order to answer questions of “How?”. It is often hoped that insights from models for sustainability will incite collective action and that they will be transferable across geopolitical boundaries. In more general terms, it is arguable that models are the primary offering of the scientific endeavor. But what is a model, anyway? As we will see in this chapter and the next, the fundamental questions of what a model is made of and how to go about modeling are, perhaps surprisingly, unresolved.

2.1.2 *Modeling Relation*

Following relational biologist R. Rosen, modeling is the art of bringing entailment structures into congruence. In its canonical form, it is an attempt to represent a natural phenomenon in a formalism. By bringing the entailment structure of a natural phenomenon into congruence with that of a formalism, it is hoped that some important aspect of the natural phenomenon will be explained.

Figure 5 presents the canonical modeling relation, adapted from Rosen (2005). Entailment structure in the natural world (Arrow 1) is referred to as *causal* and entailment structure in the world of formalism (Arrow 3) is referred to as *inferential*. Structures of causal entailment are themselves referred to as *natural systems* and structures of inferential entailment are referred to as *formal systems*. It is a non-trivial observation that formal systems exist on the basis of suggestion. They are *notional constructs defined against external referents*. The reverse cannot be said. External referents are not defined in reference to formalisms. The notional elements of a formal system, in order for that system to maintain its relevance as surrogate of a natural system, must be continuously reworked, fine-tuned and adapted to the continuously updated, revised and expanded set of observational data. Inter-system Arrows 2 and 4, encoding and decoding, respectively, represent this labor. They are, in a sense, the establishment or revision of a *modeling dictionary*.

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[1] Some parts of Sections 2.3 and 2.4 of this chapter are from Renner *et al*. (2020).

Renner, A., Louie, A. H., & Giampietro, M. (2020). Cyborgization of Modern Social-Economic Systems: Accounting for Changes in Metabolic Identity. In Dan Braha (Ed.), Unifying Themes in Complex Systems X. Cham, Switzerland: Springer.

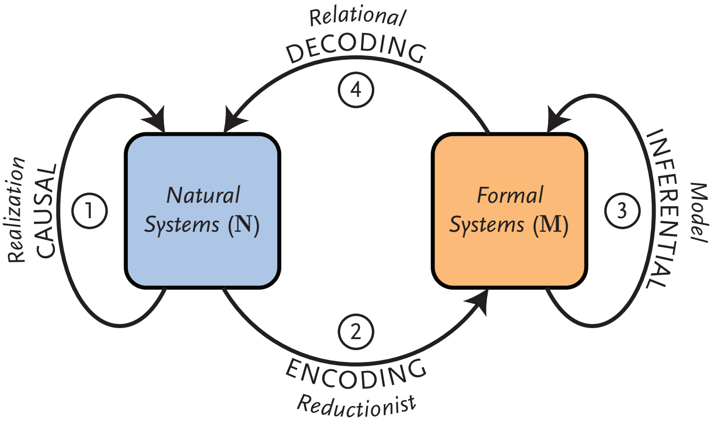


Figure 5 Rosen's modeling relation in its canonical form, generalized with inspiration from Louie (2017).

2.1.3 *Two Acts of Coding*

Arrows 2 and 4 in Figure 5 associate with two distinct approaches to/aspects of science. Arrow 2 (encoding) can be associated with the reductionist approach and Arrow 4 (decoding) can be associated with, what N. Rashevsky and Rosen referred to as, the "relational" approach. The two approaches, reductionist and relational, are operational inverses of each other. Where the former takes matter and seeks models and the latter takes models (more generally: organization) and seeks realizations. Rosen (2005, p. 119) summarizes the reductionist approach with the mantra

> throw away the organization and keep the underlying matter

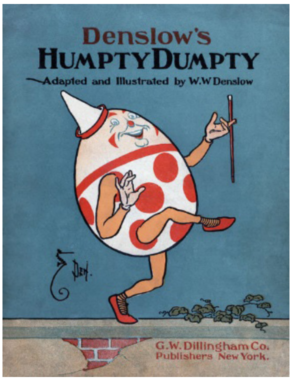
and the relational approach in the mantra

> throw away the matter and keep the underlying organization.

For example, the venerable reductionist would begin their analysis by killing their system of interest, or otherwise destroying its organizational unity so as to dissect it. Their analysis would then progress through increasingly precise characterizations of the system's constituents, say from organs to tissues to cells and so forth. Ultimately, the question would arise as to whether or not it is possible for them to reconstruct the original organizational unity from their precise characterization of its fragments. The reductionist is taught to murmur in response that "structure implies function" (Louie, 2009, p. xx), and to make the assertion that their precise characterization does of course generate a reliable description of the original system of interest.

N.B. The reductionist makes their assertion based on habit alone, and they maintain their assertion no matter what type of system is being addressed. In the case that a living system is being addressed, this assertion is a very peculiar one in that it stands in the face of all our experience up until this point—

experience that indicates that something irretrievable is, in fact, lost when an organism is destroyed or otherwise invitiated. Consider the case where a set of frogs is presented to a biology student for dissection. Assume, for argumentative purposes, that the student has never seen or even heard of a frog before. Would it be reasonable to assume that the student, upon killing and then thoroughly and meticulously dissecting the frogs, might possibly bring the frogs back to life? Would it be reasonable to assume that the student could learn, through that destructive process, about how the original set of living frogs functionally interact? On the subject of the assembly of analytic fragments, make no further consideration than the tale of Humpty Dumpty (Louie, 2009, pp. 191–200).



Humpty Dumpty before his great fall, from the eponymous 1904 book by W.W. Denslow. Not matter how the king's horses and men tried, they couldn't put Humpty back together again. The fact that they tried leads us to believe that the king's horses and men are reductionists.

The reductionist approach to science has been enormously successful and there is nothing inherently wrong with it, but our experiences do clearly indicate the need to complement procedures of encoding with procedures of *decoding*. Remarkably, relatively little attention has been given to the broad-level development of methods of decoding. Although decoding is an essential aspect of the modeling relation, it is unsung. In this work, to that end, inspiration is taken from the established approach of relational biology. It is applied here to social-economic and social-ecological systems. I give the stage to Rashevsky, who is generally identified as the father of relational biology[2], to weigh in on the dialectic between encoding and decoding.

> While the quantitative aspects of biology are very important, there are a number of qualitative, or as we called them, relational aspects that are at least just as important, if not even more important. […] Quantitatively no two biological systems are completely identical.
>
> (Rashevsky, 1968, p. 404)

Note that Rashevsky loosely associates here the reductionist approach with quantitative aspects and the relational approach with qualitative aspects—we will have a lot more to say about that in Chapter 3. Where the murmur of the reductionist approach is "structure implies function", the murmur of relational approach is "function dictates structure" (Louie, 2009, p. xx). The approach of the relational scientist is to start with an organizational unity in the world of formalism, constructed of inferential entailment, and explore how that organizational unity is *realized* by natural phenomena. For example, the relational biologist might start with a notional model of a frog, contrasted to those of other types of species, and explore which of the organisms in the natural world (structures of causal entailment) serve as realizations of their model (a structure of inferential entailment). That act would allow the relational biologist to hypothetically *explain* certain unobserved aspects of the frogs that fit their model. Although "[q]uantitatively no two biological systems are completely identical" (Rashevsky, 1968, p. 404), the relational biologist's formalism allows them *transferrable insight*.

One would be forgiven for wondering at this point what is meant by the term "organization" in the mantras of the two approaches. Indeed, organization is a

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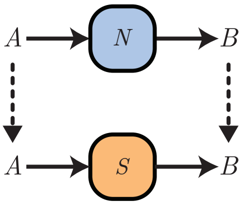
[2] Rashevsky himself wrote that J.H. Woodger (1937) was the "real father of relational biology" (Rashevsky, 1968, p. 405). Woodger, however, took the nucleus of the idea in a dramatically different direction, and a loyal student of Woodger (1937) would not necessarily appreciate Rosen's (2005) later *Life Itself*.

slippery term—even the "What Is Organization?" passage of von Bertalanffy's (1968) seminal *General System Theory* doesn't give much to work with. For now, we will stick with the vague notion that *system theory is the study of organization*, and wait until Section 2.3.2 to develop a more workable understanding.

2.1.4 *Models and Simulations*

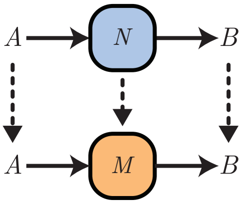
Up until this point, we have discussed structures of inferential entailment as models. As with the relational biologist analyzing frogs, models offer the possibility of explaining both observed and unobserved aspects of natural phenomena. They give the relational biologist transferrable insight. It must be stressed, however, that while all models are inferential systems, not all inferential systems are models. In the field of relational biology, there exists a useful distinction between *models* and *simulations*. Insufficient attention is given to that important distinction.



A simulation, A and B are entailed by the encoding procedure, S is not.

A simulation is an encoding of *the set of inputs and the set of outputs* of some system together with a structure of inferential entailment capable of transforming the set of inputs to the set of outputs. A model, on the other hand, encodes not only inputs and outputs but also the *inferential structure of transformation* itself. Where a simulation makes a *claim of correlation*, perhaps purely coincidental, a model makes a *claim of causation*. In relation to Figure 5, we can state that for an inferential system to *simulate* a natural system, the composition of Arrow 4 following Arrow 1 following Arrow 2 must be equal to Arrow 3[3]. In other words, in the case of simulation, the encoding relation entails the domain and codomain of the structure of inferential entailment, but not the structure of inferential entailment itself.

If, however, the encoding relation also entails the structure of inferential entailment itself, the formal system is referred to as a *model*. There is said to be a *modeling relation* between the two systems—a congruence between the two structures of entailment.



A model, A, B and M are entailed by the encoding procedure.

It deserves to be stressed that the requirements necessary for a formal system to be a model are far more demanding than the requirements that must be sufficed for the formal system to be a simulation. It is much easier to develop a simulation than it is to develop a model. Whereas simulation is descriptive, modeling is explanatory. In the case that a formal system simulates a natural system, there may or may not exist any meaningful correspondence between the inferential and causal entailment structures of those two systems. Simulation does not generate transferable insights; it may likely be entirely coincidental and we cannot learn anything substantial about the system it attempts to represent. Georgescu-Roegen's (1971) commentary on the typical inappropriateness of econometric "models" (read: simulations) is a prime example. Developing an understanding of inputs and outputs is no doubt important, but what about the external referents of those flows? What about the metabolic processors consuming inputs and producing outputs? Generally,

[3] $3 = 4 \circ 1 \circ 2$

these “metabolic processors” are not considered in econometrics, to the demise of the ability of econometric assessments to explain phenomena in a changing world. We don’t yet have the language to make a full discussion on the subject, but we will work to develop that language over the course of this chapter and we will return to the subject of input-output modeling in Section 3.3.4.

2.1.5 *Tri-System Modeling Relation*

Some light can be shed on the matter of models, simulations and transferrable insights by considering Figure 6. In Figure 6, the leftmost pane (Pane 1) illustrates a situation referred to by Rosen (2005) as *analogy*. In the case of the existence of an analogy between natural systems, we make the claim that it is possible to learn something about a natural system (N_1) by looking at another natural system (N_2). The two natural systems (N_1 and N_2) are said to share a common model (M). When the pharmaceutical industry tests new medical treatments on animal test subjects, for example, they typically do that under the premise that the animal test subjects are analogs of *Homo sapiens*. Note that, in contrast, the sharing of a common simulation between two natural systems (N_1 and N_2) does not tell us anything beyond the trivial fact that the relation between the given sets of observed inputs and outputs of the two natural systems is representable using a common inferential structure.

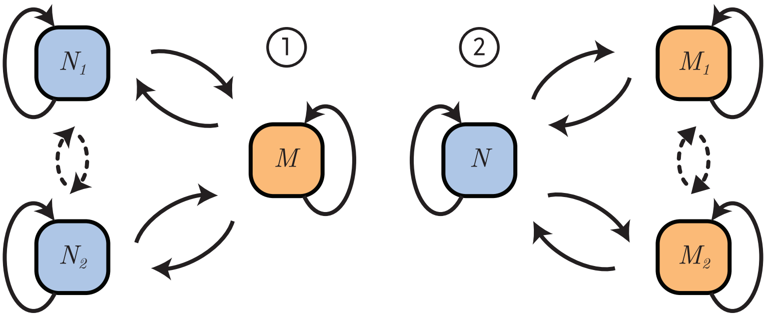


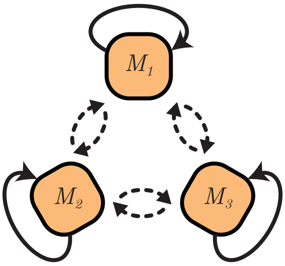
Figure 6 Two types of system relation, based on Rosen (2005, pp. 62–63).

The rightmost pane of Figure 6 (Pane 2) then illustrates the common situation in science where two distinct formal systems are proposed as models for a given natural system. In such a situation, we should ask ourselves whether or not it is possible to reduce the two models (M_1 and M_2) to a single largest model without losing relevant information. For example, *Homo sapiens* have been modeled variously as *Homo economicus* and as *Homo reciprocans*. Whereas the former is perfectly rational and optimality seeking within a framework of selfishness, the latter is cooperation seeking within a framework of reciprocity. Can *Homo economicus* or *Homo reciprocans* be disproven? Can the two be reduced into a single largest model without losing relevant insight? Generally, normal science claims that the reduction of any two models of the same natural system is possible. The respective advocates of the two competing models (M_1 and M_2) are typically instigated to debate each other until a “superior” model emerges. As we will later see in Section 2.3, it is entirely impossible to reduce the set of models of a *complex system* into a single largest model. We will also see that most systems of interest are complex. Those two facts will motivate us to move from a paradigm of normal science to a paradigm of post-normal science.

2.1.6 *Non-Canonical Modeling Relations*

Our final commentary on the modeling relation concerns its non-canonical forms. So far, we have been discussing modeling relations between natural systems and formal systems. That is indeed the most relevant type of modeling relation for science. But we do not need to limit ourselves to it—much of contemporary science makes no attempt to engage with biophysical reality. That is to say, much of contemporary science is concerned with theorizing about the theories of other theoreticians, or, the formal study of other formal structures.

Philosophizing on abstract ideas existing only in the formal world, rather than philosophizing on perceptions of external referents existing in the natural world, is a perilous activity. One of L. Wittgenstein's main criticisms of philosophy as he knew it was the use of invariant, syntactical rules to judge an assertion as sensical or nonsensical. As we will see in Section 2.3, such activities are a mainstay of not only philosophy but of normal science in general. With the aim of improving the state of affairs, Wittgenstein's criticism of philosophy is inspiration for us to critique the use of normal scientific methods to validate or invalidate formalisms. Formalisms do not depend solely on syntax! We will have a lot more to say about this idea when discussing post-normal science and Wittgenstein's concept of grammar in Chapter 3.



[4] A round-table discussion of models—philosophizing on abstract ideas from within the world of formalism.

2.2 FRAMEWORK OF CAUSALITY

2.2.1 *Aristotelean Causality*

In Section 2.1, we related the reductionist approach to acts of encoding in the modeling relation and contrasted it to the relational approach, related to acts of decoding. Concerning the modeling relation's canonical form, we understood a simulation as an encoding of the set of inputs and the set of outputs of some natural system of interest together with some unencoded inferential structure capable of transforming the set of inputs to the set of outputs. In the case of simulation, the relation between the inferential structure serving to transform inputs into outputs and the causal structure it means to represent is only superficial. The idea of simulation against modeling is like a grand extension of the hypothesis of *ceteris paribus*—the analyst makes the assumption that the relations they seek to represent will remain fixed in space and time, thereby justifying their disregard for the underlying causal relations and their many compounding factors. In contrast to simulation, we understood modeling as encoding not only inputs and outputs but also the inferential structure of transformation itself. Where a simulation makes a claim of *correlation*, a model makes a claim of *causation*. The profound implication of this seemingly basic observation is that scientific modelers must accept, explicitly or implicitly, a *causal framework* as the basis of their endeavors. The metalanguage of that framework must be, in some sense, comprehensive. It must allow for the generation of complete descriptions of any given natural phenomenon.

In response to that need, relational biology proposes the framework of Aristotelean causality, which details four fundamental ways of providing an explanation of that which is responsible for some object ("To what is the object indebted?"). Each of the four causes of Aristotle may be considered as an irreducible explanatory resource, essential to answer an inquiry of "Why?".

- *Material cause* is the material or "matter" out of which something is constituted.
- *Formal cause* is the form or "shape" into which the material enters, or the "account of what it is to be".
- *Efficient cause* is the primary agent or source of change realizing or initiating something which is done.
- *Final cause* is the sake for which something is done. It addresses: To what end?

These four causes are our explanatory building blocks, from which we can derive many things. Typical examples of using the four causes to explain include "Why a table?" (wood, design, carpenter, dining) and "Why a statue?" (bronze or marble, figure, sculptor, decoration), but we need not limit ourselves to such mundane phenomena.

To what is a city indebted? Why a city? The concrete and steel that constitute the city's roads and buildings can be identified as material cause. The "layout" or "configuration" of the city can be identified as formal cause. The construction workers which erected the roads and buildings can be identified as efficient cause. Lastly, the desire to live closer to other humans can be identified as a final cause of the city.

Three last notes on the identification of causes serve to close our initial discussion of them. First, note that the final cause of our city could easily also have been identified as something else, for example the desire to shelter oneself from the unpredictable nature of the non-constructed environment. The ease in which it is contested, or the ease in which multiple final causes can be identified, differentiates final cause from the other three. Second, note the existence of a need to eliminate accidental coincidence between causes. The persons who act as construction workers while building the city are not *only* construction workers. In their "off-time" they are athletes, party-goers, photographers and so forth. For this reason, it is sometimes phrased that the *art of construction* within the relevant persons is the efficient cause, not the person itself. Third, note that, for each type of cause, multiple different causes of cascading relevance can typically be identified. There exist, for example, efficient causes that are more proximate agents of change than others. The individuals investing money in the city to be built catalyze its construction. In a sense they are an efficient cause of the city. The observing analyst will ultimately have to decide which efficient cause is the more proximal in accordance with the purpose of their study.

2.2.2 *Finality and Teleology*

Final cause is, in fact, a significant source of frustration in the scientific discourse. We would be remiss if we didn't defend our use of it—final cause is passionately disallowed by scientists who endorse the machine metaphor (scientists that murmur "structure implies function" and wish a dissected frog back to life). Aristotle himself admitted that final cause was not applicable in certain cases, such as when explaining the movement of celestial bodies. In *Metaphysics*, Aristotle uses the case of a lunar eclipse to elaborate the point. Although lunar eclipses lack matter per se, the Moon itself can be identified as a material substrate of the phenomenon. The efficient cause of a lunar eclipse is then the Earth, which blocks the Sun's light. The formal cause is the full "account" of the event—the "privation of light [...] by the passage of the earth between moon and sun" (Aristotle, 1998, p. 1044b). The final cause is as well not applicable, the Earth does not seem to block the Sun's light with a particular end in mind.

In the case of celestial events, it may be perfectly valid to omit consideration of final cause, and astrophysicists who disallow final cause within their domain do appear justified in doing so. The same allowance cannot be made when considering living systems, however, including social-economic systems. It will take the rest of this chapter to justify that claim, and the rest of this dissertation for the assertion to result convincing. Meanwhile, note that Aristotelean causality was originally conceived with living systems in mind, not with the movement of celestial bodies in mind. Aristotle is traditionally recognized as the father of biology, and his framework of causality is more aligned with metabiology than metaphysics. In contrast, consideration of the movement of celestial bodies is what inspired Newton's mechanics, which accompanied Descartes' philosophy as a fundamental impetus of reductionism and normal science as we know it.

Final cause is unusual in that it requires that the object of interest entails something else in the present. Building on that observation, Rosen (2005, p. 48) adds that final cause is further unusual in that it has a "peculiar reflexive character". What he means is that final cause *entails the entailment of the object of interest itself*. Neither of these two aspects are shared by material, formal or efficient causes—three explanatory resources that only just *entail the object of study*. One important consequence is that final cause cannot be assessed within the same temporal framing as material, formal and efficient cause. Final cause is in a league of its own.

For example, in our previous example of a city, the final cause “living closer to other humans” entails the existence of humans wanting to live like sardines in a can. Barring the unlikely state of affairs that the city in question is abandoned, the identified final cause entails the actual existence of humans living in the city in a tightly packed formation. All the other phenomena that we mentioned—the concrete, the steel, the layout, the construction workers—served only to entail the dense agglomeration of buildings and streets. The concrete, the steel and the layout themselves entail aspects *intrinsic* to the city. On the other hand, the construction workers are *extrinsic* to the city, but they are only ever implied in the past and they serve only to entail the physical presence of the city itself. For all we know, the construction workers may no longer exist. Although the final cause “living closer to other humans” is, similar to efficient cause, extrinsic to the city, it entails, unlike the construction workers, something else in the present. It entails the entailment of the city itself.

Hence, it should be self-evident that it would be unreasonable to assess the concrete, the steel, the city layout and the construction workers within the same temporal framing as the humans wanting to live there. The identification of final cause(s) for the object of study itself *dictates the description of the other three causes*. It is precisely for this reason that we will spend time in Chapter 3 discussing the use of narratives in science.

Lastly, although final cause and teleology are frequently considered to be synonymous, an important clarification can be made. Final cause is teleological to the extent that it references an end, but it is not psychologized in the sense there is no notion of intention when a final cause is formally mapped in a model. In contrast to formal mappings of final cause, teleology often implies the existence of intentionality. Plato’s concept of teleology contrasts with, and is often misconstrued with, Aristotle’s concept of final cause. Where Plato’s concept supports the idea that the “magnificent order of the world requires the work of the demiurge” (Walsh, 2008, p. 118), Aristotle’s makes no such assertion. A rejection of Plato’s concept of teleology is not grounds for the rejection of Aristotle’s concept of teleology! For our purposes, whether final cause is a self-standing explanatory factor (ontologic) or a heuristic (epistemic) is beside the point. Even the necrophiliac[5] reductionist approach does not, on a theoretical basis, disallow the practical use of formal mappings of final cause. And without final cause there cannot be identity (Giampietro and Renner, 2020).

It is inevitable that some readers—defendants of the *machine metaphor*—will still feel apprehensive at the inclusion of final cause in our causal framework. On the other hand, it is also true that this dissertation could be spend the rest of its pages justifying why final cause is a valid inclusion. Therefore, no more direct philosophical discussion on the matter will be made. In the subsequent chapters, it will be illustrated that final cause can be seen to play an essential practical role in scientific explanations. Although often used in an implicit manner, it would in fact be difficult to imagine the explanation of a sustainability predicament

[5] “Necrophilia in the characterological sense can be described as *the passionate attraction to all that is dead, decayed, putrid, sickly; it is the passion to transform that which is alive into something unalive; to destroy for the sake of destruction; the exclusive interest in all that is purely mechanical. It is the passion ‘to tear apart living structures’*” (Fromm, 1973, p. 332).

that didn't include a consideration of final cause. There do exist situations where final cause is not a necessary component of a valid response to "Why?", but those situations are the exception rather than the rule.

2.2.3 *Machines*

When we say the *machine metaphor*, we refer to the legacy inspired by R. Descartes' comparison of the human body to a clock. What the machine metaphor does is allow its adherents to justify the elimination of final cause. For context, Descartes (1985, p. 315) writes:

> I will now [...] give such a full account of the entire bodily machine that we will have no more reason to think that it is our soul which produces in it the movements which we know by experience are not controlled by our will than we have reason to think that there is a soul in a clock which makes it tell the time.

In the nearly four centuries since Descartes, the machine metaphor, together with Descartes' mind-body dualism, has been heavily criticized. A. Koestler's (1967) seminal *The Ghost in the Machine* is one popular example, the title coming from G. Ryle's (1949) polemic *The Concept of Mind*. To crudely summarize the view shared by Ryle and Koestler: "[m]en are not machines, not even ghost-ridden machines" (Ryle, 1949, p. 67). More expressly and cynically, Ryle (1949, p. 301, emphasis added) writes at the close of *The Concept of Mind*:

> The Newtonian system is no longer the sole paradigm of natural science. Man need not be degraded to a machine by being denied to be a ghost in a machine. He might, after all, be a sort of animal, namely, a higher mammal. *There has yet to be ventured the hazardous leap to the hypothesis that perhaps he is a man.*

Despite the convincing body of philosophical and scientific work highlighting the inadequacy of the machine metaphor, it has become common to merely acknowledge the metaphor's inadequacy and then proceed with methods that are, effectively, Cartesian. It seems to be an extremely useful but ultimately unfortunate extrapolation that, since everything in the natural world is *constrained* by mechanistic laws of physics, natural systems must be purely mechanistic systems. As we have stated once already, machines are the exception rather than the rule, and most systems of interest are not machines. Ryle (1949, p. 68) summarizes the view expressly: "[a]valanches and games of billiards are subject to mechanical laws; but they are not at all like the workings of machines".

In practical terms, what the machine metaphor does is assert that every natural process is an *effective process*—a process evaluable by a (pure syntax) mathematical machine. Effective processes are formalizable by a finite computational procedure, called a *decision procedure*. The related *decision problem* refers to the issues surrounding the discovery of that decision procedure (Louie, 2020). Figure 7 depicts this relation. N.B. The machine metaphor asserts that natural systems themselves are effective processes. We do not necessarily support that view in Figure 7, where the effective process of interest (Pane 1) is itself presented as a formal system.

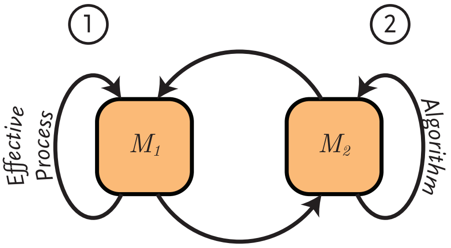


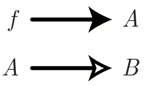
Figure 7 Resolving a decision problem in a world of machines, adapted from Louie (2020).

What the machine metaphor does is assert that every natural process is representable algorithmically. In practice, the belief is tied up with notions of optimality and the possibility of running decision procedures to optimize algorithms used to predict and control natural processes. As we will see, the machine metaphor applied to social-economic systems is not only precisely that—a metaphor, a piece of figurative language—but also a dangerous fetish. The treating of social-economic processes as optimizable, effective processes is a contributor to what Renner, Louie and Giampietro (2020) have called *the cyborgization of modern social-economic systems*. We proceed to elaborate in the following.

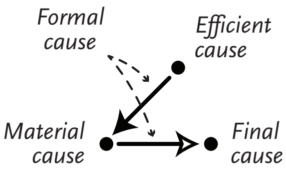
2.3 IMPREDICATIVE NATURE OF LIFE

2.3.1 *Modes of Composition*

A rejection of the machine metaphor is by no means a rejection of the formal representation of natural systems. Consider now that we wish to formally represent a social-ecological transformation, and consider the axiom in relational biology: "*[e]very process is a mapping*" (Louie, 2009, p. 98)[6]. Using arrow notation, we can write $f:A\to B$, meaning some processor f inducting or constraining the flow of input A to output B. We can also generate a graph-theoretic *relational diagram* for the transformation. Using the convention set in relational biology, we can formally represent the social-ecological transformation as a solid-headed arrow followed by a hollow-headed arrow, where the solid-headed arrow begins with processor f and terminates with input A and the hollow-headed arrow begins with input A and terminates with output B.



Where, you might ask, are the four causes we spent so much time discussing? Processor f is our efficient cause, input A is our material cause and output B is our final cause. The ordered pair of arrows itself is our formal cause . Although we won't use relational diagrams outside of this section (Section 2.3), they are extremely powerful conceptual devices and help here to visualize two key modes of process composition. In the previous example of



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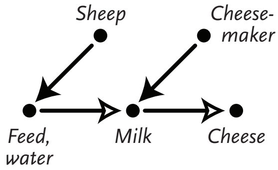
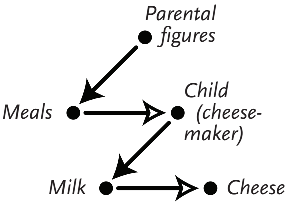
[6] A "transformation" is a "map" or "mapping" in the metamathematical language of category theory.

"Why a city?", the construction workers (f) induced concrete and steel (A) into the form of a city, made up of buildings and streets and such, yielding a city intended for humans desiring to live close together in a manner protected from the unpredictable nature of the non-built environment (B).

The next step in learning to formally represent a natural system is to consider connections between transformations—the composition of transformations, where a first transformation entails a cause in a second transformation. The two most important connections for our purposes are *sequential composition* and *hierarchical composition*; for a more thorough discussion on relational diagrams and modes of composition, readers are referred to Louie (2009, pp. 105–130).



Sequential composition, when the final cause of a first transformation entails the material cause of a second transformation.



Hierarchical composition, when the final cause of a first transformation entails the efficient cause of a second transformation.

- *Sequential composition* refers to a connection between transformations where the final cause of a first transformation entails the material cause of a second transformation. An example of sequential composition in a social-economic system is an agriculture sector process (transformation one) with the end to produce agricultural commodities, which are then entailed to a service sector process (transformation two) that takes those generic products and generates culinary delights.
- *Hierarchical composition* refers to a connection between transformations where the final cause of a first transformation entails the efficient cause of a second transformation. An example of hierarchical composition in a social-economic system is a household sector process (transformation one) with the end to reproduce human beings, which are then entailed to a service sector process (transformation two) that employs those human beings in the generation of culinary delights.

Hierarchical composition is one of the most important concepts in understanding the nature of life and complexity. It gives rise to essential intangibilities and is the key that allows us to differentiate between simple systems and *complex systems* (including living systems, such as social-economic systems).

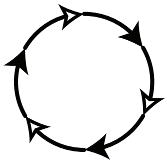
2.3.2 *Complexity and Organisms*

W. Weaver's *Science and Complexity* (1948) is often credited with establishing the term *complexity* in the scientific debate. Although the number of researchers involved directly in the formal study of complex systems has grown astronomically over the past 70+ years, the definition of the term complexity has not, across the field of complex systems analysis, become any clearer since Weaver's article. The providing of a precise definition is typically openly avoided—complexity as a certain *je ne sais pas* phenomenon, "You'll know it when you see it!". Various schools of thought exist in the field of complex systems analysis, with little shared between them besides the understandings that *simplicity* and *complexity* are antonyms, that complexity and *complicatedness* are somehow perceptually different and that life is the quintessential example of a complex system.

G. West's (2017) *Scale*, a recent emblematic work from the school of complexity focused on power scaling laws, openly avoids giving a detailed definition of what it is to be a complex system. Instead, a heuristic is provided: in complexity, the whole is greater than and often dramatically different to the "*simple linear* sum of its parts" (West, 2017, p. 21, emphasis added). S. Wolfram's (2002) *A New Kind of Science*, an emblematic work of the school of complexity focused on cellular automata, instead indirectly asserts its view: "very simple programs can produce great complexity" (Wolfram, 2002, p. 4) and "essentially all common forms of perception and analysis correspond to rather simple programs" (Wolfram, 2002, p. 558).

Many additional understandings of complexity exist, I have merely chosen the aforementioned two due to them being both well-known authors/works in the field of complexity studies and divergent from the definition I will ultimately endorse. Other than to point out the *compatibility* of the two aforementioned definitions with complex systems as effective processes (Section 2.2.3), I will not weigh in on whether the two definitions provided are satisfactory. I will instead directly present a divergent understanding based on the framework we have been discussing, one that is grounded in the concept of *impredicativity*.

First, to be impredicative (formerly "non-predicative") is to be self-referential (Russell, 1906; Feferman, 2005). Second, note that self-referentiality is a property of the set of causal relations between system components. Third, following Rosen (2005), complex systems are those that contain self-referential loops of efficient causation. Louie clarifies: "[w]hen two or more compositions involved in [a] cycle are hierarchical, one has a closed path of efficient causation. In other words, a closed path of efficient causation is an entailment cycle that contains two or more efficient causes" (Louie, 2009, p. 147).

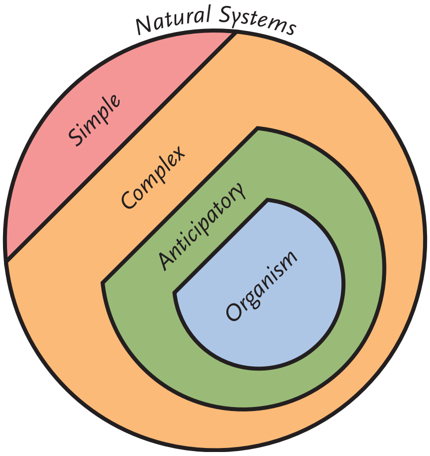


A hierarchical cycle, emblematic of an organism and generator of impredicativity. The example contains three processes/efficient causes.

Consider the quintessential example of complexity—a living system. The organs of the human body are involved in a complicated structure of causal entailment where each organ serves to *reproduce* one or more of the other organs. Each organ is an efficient cause and the final cause of its actions is to produce, reproduce and otherwise enable the functioning of the other organs in the body. That authoritative relation is what we have understood as *hierarchical composition*. Furthermore, since all the organs in the human body are reproduced internally, there exists a *closure to efficient causation*. That closure is an impredicative loop—the set of organs is self-referential. N.B. We are describing here living systems as the quintessential example of complexity. *Complex systems* in general do not necessarily exhibit *closure* to efficient causation, they must merely *contain* self-referential loops of efficient causation. All living systems ("organisms") are complex systems, but not all complex systems are living systems. The degree to which the efficient causes of a system of interest are caught up in hierarchical composition can actually be understood as a *metric* of the complexity of that system.

Figure 8 provides a summary of the different relevant classes of systems, as understood by relational biology. The set of simple systems and the set of complex systems are disjoint. All anticipatory systems are also complex systems and all living systems are also anticipatory systems. We won't get caught up with the formal, causal characteristics of anticipatory systems, but we will use the concept of anticipation extensively in Chapters 4 and 5, so it is helpful to begin placing it on the map.

Figure 8 The taxonomy of systems in relational biology, see Louie (2009, pp. 284–288).



N.B. Closure to efficient causation does not, in any way, imply that organisms are *isolated* systems. A central topic of E. Schrödinger's (1944) seminal book *What is Life?* is that living systems feed on (identity dependent) negative entropy. But flows of negative entropy such as food and water are material entailments, not functional entailments. In our metalanguage, they are a sequential composition of processes. After processing flows of negative entropy, organisms output positive entropy to their surroundings. In this situation, the organism is merely acting as, to use I. Prigogine's term, a dissipative structure (Prigogine and Stengers, 1984). Neither the input nor the output aspect of dissipation is hierarchical composition.

Finally, in Section 2.1.3 it was promised that a more precise concept of organization would be provided at this point. The term organism derives from the term organization, and now that we have a more exacting definition of what organisms are, it is fitting to provide a better definition of organization. I defer to Rosen (2005, p. 126): "organization is that attribute of a natural system which codes into the form of an abstract block diagram". Abstract block diagrams are relational descriptions constructed by composing mappings, like the sequential and hierarchical compositions illustrated previously in the page margin. Although we won't visualize abstract block diagrams again in this work, we will discuss them in spirit many more times.

2.4 SOCIETAL METABOLISM

2.4.1 *What is Metabolism? What is Societal Metabolism?*

For something to be termed *metabolic*, it needs to be living. Now that we have an understanding of what life is, we can begin to assess whether social-economic systems are *living* (and therefore metabolic). We will spend the rest of this chapter using the tools that we have presented in the previous sections to illustrate that social-economic systems are indeed living, and hence that the term *societal metabolism* is not merely figurative language.

As originally noted in the field of physical biology, such as the work of Lotka (1925), metabolic processes may be meaningfully divided into an endosomatic class and an exosomatic class. *Endosomatic metabolism* refers to processes taking place *within* a given organism insofar that an organism uses fluxes of negative entropy available in the environment to sustain a process of exergy degradation[7] and stabilize their metabolic pattern while reproducing, maintaining and adapting their structural and functional elements. An *exosomatic process* refers to a situation in which the processes of exergy degradation used to stabilize a metabolic pattern take place *outside* a given organism. This essential distinction between types of metabolic process also applies in the domain of social-economic systems, where the body (*soma*) being referred to is the human body (Georgescu-Roegen, 1971). In that context, for example, it is advantageous to differentiate between an endosomatic population (such as the population of humans) and an exosomatic population (such as the population of supporting machines) (Mayumi, 2020). Post-Industrial Revolution, the exosomatic population has been seen to dramatically increase in both absolute and relative terms (Giampietro, 2004). This is a change in metabolic identity that cannot be ignored—we will come back to it in Sections 2.4.3 and 2.4.4 in an exploration of its grave implications.

In his discussion of the biophysical nature of the economy, Georgescu-Roegen (1971) made a further critical distinction in his flow-fund model. In a metabolic pattern, flow elements are those which do not maintain their identity over the course of an analysis. Food or exosomatic energy inputs that are consumed during the course of an analysis certainly do not maintain their identity—they are examples of flow elements. Fund elements are those that do maintain their identity over the course of an analysis. Over the timespan of a week, an organism typically maintains its identity, assuming it consumes an acceptable flow of food and exosomatic energy inputs—it is an example of a fund element. The same could be said for the organs of the organisms. Stocks are not the same as fund elements. If a deposit or withdrawal is made to or from a stock, the stock does not maintain its identity.

So, flows, funds, and stocks can be used as descriptive categories when describing endosomatic and exosomatic metabolic processes and populations.

[7] Use of available energy forms that can be converted into useful work according to the characteristics of the user and the environment within which the conversion takes place (Gaudreau, Fraser and Murphy, 2009).

This is a good first step in understanding social-economic systems as metabolic systems. We will now proceed with applying the methods of relational biology to social-economic analysis. Ironically, applying the methods of relational biology to the study of social-economic systems is, in some ways, easier than applying them to the study of individual biological organisms. For starters, people typically don't resent the assertion that humans act purposefully. Humans also tend to make the purposes of their actions explicit, therefore easier to characterize. It may actually be the case that Schrödinger's (1944) celebrated conceptualization of organisms as systems feeding on negative entropy was ultimately, in some sense, inspired by social-economic insights. Georgescu-Roegen writes that "purists maintain that thermodynamics is not a legitimate chapter of physics" (1971, p. 276) and "of all physical concepts only those of thermodynamics have their roots in economic value" (1971, p. 277). N.B. Negative entropy is a concept coming from non-equilibrium thermodynamics. At any rate, our new conceptualization of social-economic systems using Aristotelean causality and relational theory complements both Georgescu-Roegen and Schrödinger.

2.4.2 *Relational Characterization of a Societal Node*

In social-economic systems, Aristotelean causality can be intuitively applied at a low-level scale in the description of social practices. Bundles of social practices can, in turn, be used as building-block descriptions of societal sectors—the nodes of a relational description of a social-economic system. At a very basic level, social practices describe the convergence and linkage between meanings, competences, and materials, as expressed by a group of agents (Shove, Pantzar and Watson, 2012). Meanings are characterizable as final causes, competences as formal causes, materials as material causes, and expressing agents as efficient causes. Figure 9 and the discussion that follows illustrate a consideration of these explanatory resources in relation to a generic conceptualization of an agriculture sector—an entity that emerges from a bundling of the expression of social practices related to agriculture.

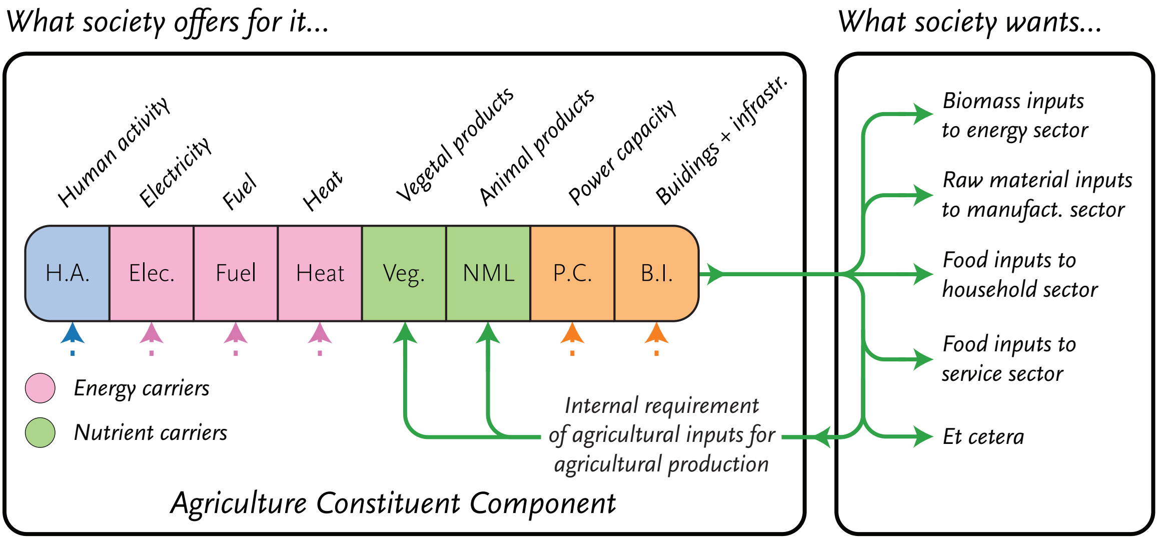


Figure 9 Biophysical demand placed by a social-economic system on its constituent component “agriculture”.

H.A.	*Human activity*
Elec.	*Electricity*
Veg.	*Vegetal products*
NML	*Animal products*
P.C.	*Power capacity*
B.I.	*Buildings & infrastruct.*

The right-hand side of Figure 9 explores the final causes of agriculture—the set of behaviors expected from it. In this sense, the right-hand side details the array of end-uses (a “hologram”) of agriculture and considers the agriculture sector as a social-economic component. The left-hand side of Figure 9 explores the various material, formal, and efficient causes of agriculture. In this sense, the left-hand side of Figure 9 refers to the agriculture sector as a social-economic constituent. Used in contrast to component, the term constituent refers to a structural definition. In material terms, the agriculture sector is made up of various vegetal and animal organisms and products, machinery, buildings, infrastructure, and so forth, in which human activity is used to control the processes of exergy transformation. Its formal cause is the configuration of such material considerations, including, for example, the relative breakdown and arrangement of materials. Lastly, an account of human activity controlling the power capacity provided by machines is a consideration of the efficient cause of social practices of agriculture—the proximate agents behind the realization of the agriculture sector (see Patching, 1990).

Keeping in mind the basic metabolic terms presented in Section 2.4.1, the ratio comparison between the use of an exosomatic population of funds (such as machines, buildings, and infrastructure) and the use of an endosomatic population of funds (humans) can provide a characterization of the degree of capitalization of an agriculture sector. A similar comparison between flows can provide further contextual information such as the degree of reliance on external inputs—expected relations that must be guaranteed.

2.4.3 *Society as a Relational Network*

We now wield the tools needed to represent social-economic systems as metabolic networks in which constituent components stabilize each other in an impredicative (self-referential) set of relations. Such a representation allows for the generation of characteristics such as the relative size of constituent components, their expected metabolic rates, and, more in general, a definition of societal identity.

Societal sectors, such as the agriculture constituent component depicted in Figure 9, are distinguishable elements of social-economic systems that generate an emergent property. Each sector has a meaningful and relevant identity regarding an identity-dependent coupling of positive and negative forms of entropy. Each of the sectors of a social-economic system can also be said to have a final cause. Historically, a dialectical exchange of functional entailment (a mapping where the final cause of one process becomes the efficient cause of another, also referable to as hierarchical composition) was made between the various sectors of social-economic systems. In the modern world, a world prevailed over by biophysically affluent urbanities, the mapping of functional entailment has become predominantly unidirectional between some sectors.

The social-economic system presented in Figure 10 is a model view into an archetypical modern social-economic system. It is divided between dissipative sectors (sectors involved in the metabolism of biophysical flows and use of exosomatic devices, without producing either of them) on the top and hypercyclic sectors (sectors which output more biophysical flows and/or exosomatic devices than they use for their own metabolism and repair) on the bottom. N.B. The distinction between dissipative and hypercyclic processes was proposed by Ulanowicz (1986) in his analogous study of the organization of ecological metabolic networks. If the purpose of social-economic systems is understood to purely be the reproduction of the endosomatic population at a desirable level of metabolic dissipation, then the set of dissipative sectors can also be understood as anabolic and the set of hypercyclic sectors as catabolic.

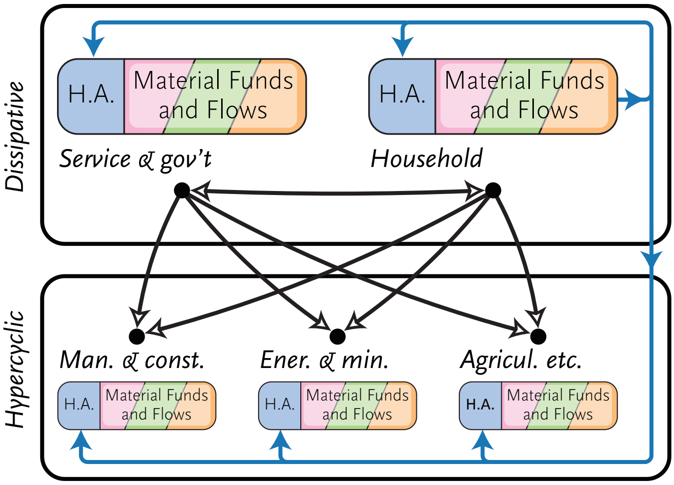


Figure 10 Functional entailment between the components of a social-economic system (hollow-headed black arrows) and its vector of control (solid-headed blue arrows) with sector details: 1) household, 2) service and government, 3) manufacturing and construction, 4) energy and mining and 5) agriculture, forestry and fishing.

H.A. *Human activity*

In modern societies, the final causes of dissipative sectors map to the efficient causes of each other and to the various hypercyclic sectors of the economy.

The dissipative sectors provide a system of control for the hypercyclic sectors. The final cause of the hypercyclic sectors, on the other hand, is more and more to provide exosomatic flows of biophysical material to dissipative sectors—no questions asked. This role of the hypercyclic sectors was not always the case—this role was not the case in pre-industrial agrarian societies, for example (Giampietro, 2004).

1) In the *service and government sector*, an effective interface between production and final consumption is made. The preservation, notional reproduction, and adaptation of institutions occurs. Trust, one prerequisite for proper market operations, is generated. Regulations are made. Education, security, and law enforcement are enacted.
2) In the *household sector*, humans as individual or family-level agents are reproduced and maintained. Social practices and normative values are shaped. Market preferences are shaped and voting and political participation occurs.

Together, the two dissipative sectors identified in Figure 10 provide a reflexive analysis of a social-economic system's identity, feelings, emergent concerns, and interactions with the external world (due to the presence of humans). Contingent analysis, required to establish societal priorities in an impredicative option space, is made. Likewise, analyses required for the tackling of the unavoidable existence of uncertainty and the unavoidable existence of legitimate but contrasting perspectives are made.

However, functional entailment, shown in Figure 10 as running between the dissipative sectors and from the dissipative sectors to the hypercyclic sectors, can only be defined after matching a definition of "metabolic demand", coming from a specific metabolic pattern of system components, with a definition of "metabolic supply", coming from a specific metabolic pattern of system components. Functional entailment represents a top-down constraint (directly resulting in "downward causation") related to an emergent property (an "identity"). Material entailment (a mapping where the final cause of one process becomes the material cause of another), on the other hand, relates to the need for establishing coherent biophysical relations. In this sense, material entailment represents a bottom-up constraint (indirectly resulting in so-called "upward causation"). Material entailment is about establishing a feasible and viable state-pressure relation with various local admissible environments. In the language of non-equilibrium thermodynamics, it can be represented by the definition of a local coupling of patterns of exergy degradation (state) mapping onto fluxes of negative entropy (pressure) across different levels. Figure 11 presents a different view of our archetypical modern social-economic system. Figure 11, supplementary to Figure 10, highlights relations of material entailment. It should be clear that the set of hypercyclic sectors, in their provisioning of material flows to dissipative sectors, present a biophysical constraint on each other and on the dissipative sectors.

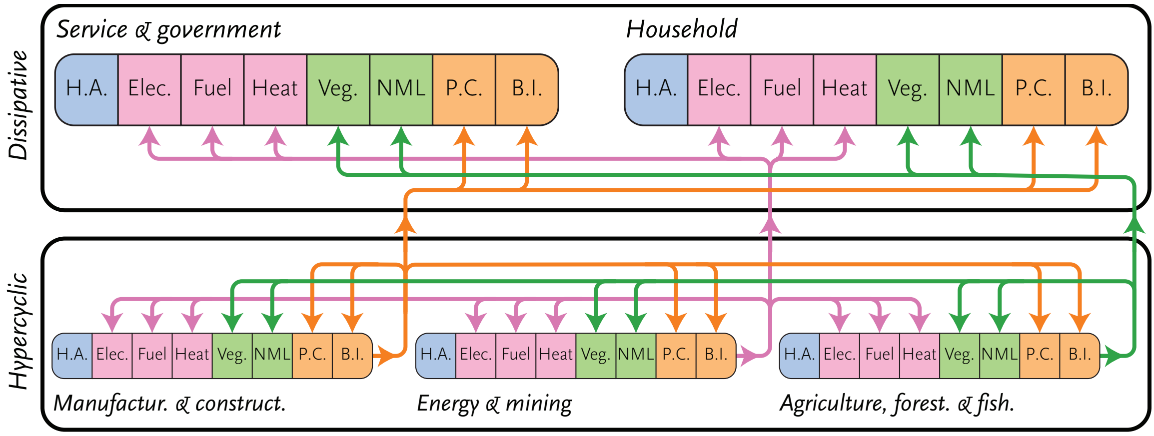


Figure 11 Material entailment between the constituents of a social-economic system.

H.A. *Human activity*
Elec. *Electricity*
Veg. *Vegetal products*
NML *Animal products*
P.C. *Power capacity*
B.I. *Buildings & infrastruct.*

2.4.4 *Society as an (M,R)-System*

There is a theorem in the field of relational biology that states that all living systems are formalizable as *replicative* metabolic-repair (M,R) systems. Let's dig deeper. In terms of the concept of metabolism, we've already established a respectable understanding. Repair, on the other hand, is the reproduction of a catalyst of change. In terms of causal mappings, functional entailment is repair and material entailment is metabolism. Lastly, replication is not "self-replication" in the modern biological sense. Rather, the output of replication in (M,R)-systems is repair (Rosen, 1958, 1959; see Louie, 2009). A similar concept is found in the bioeconomics of Georgescu-Roegen—the economy does not produce goods and services but rather reproduces the fund elements producing and consuming goods and services to guarantee adaptability and a desirable state (Giampietro and Pastore, 1999).

If the functional entailment relations presented in Figure 10 were a complete graph[8]—as could easily be claimed to have been the case in pre-modern society—then we would consider social-economic systems to be in a situation of deadlock. Deadlock, the relational analog of impredicativity (that great hallmark of complexity), is a "situation wherein competing actions are waiting for one another to finish, and thus none ever does" (Louie, 2009, p. 208) (p. 208). Under a state of deadlock, with all mappings of final causality locked up in hierarchical composition, a social-economic system could be said to be *closed to efficient causation*. To apply Georgescu-Roegen's flow-fund concept, the social-economic system could be said to be in a situation where all metabolic funds internally generate each other, given the presence of favorable boundary conditions. In that circumstance, a social-economic system could be referred to as living under the same causal foundation that conventional biological organisms are said to be living. Unlike the machine metaphor, the

[8] Since our mappings are directed, we refer here to a complete directed graph, meaning that every pair of vertices (contextually, societal sectors) is connected by a pair of unique edges (contextually, functional entailments)—one in each direction.

metabolism metaphor isn't figurative language—it reflects reality. In our effort to liberate ourselves from reductionism, we should try and liberate ourselves from this unfortunate linguistic convention.

Our novel application of the approach of relational biology to social-economic and social-ecological systems is, in a sense, an actual return to the roots of relational biology. Rashevsky (1972, p. 61) writes the following—emphasis is due on the last sentence:

> Any human organization, such as a scientific society, a corporation or a military unit, has a structure in an abstract space. […] The relations between the individuals of any social organization are customarily represented by "organization charts." From a topological point of view any organization chart is a *graph*, usually an *oriented graph*. A graph, however, is a topological structure. In fact, this circumstance led us (Rashevsky, 1964) to the idea of representing living organisms also by oriented graphs and resulted in the creation of topological biology, which since then was developed by a number of scientists into general relational biology.

2.4.5 *Externalization and Cyborgization*

In addition to the interactions presented in Figure 10 and Figure 11, social-economic systems interact with their context in at least two essential ways. Firstly, they interact with the local biosphere. Secondly, they interact with other social-economic systems, such as through trade.

The first type of interaction implies a change in consideration from social-economic systems to social-ecological systems. A social-ecological system can be defined as a complex of constituent components that operates within a prescribed boundary and is controlled in an integrated manner by activities expressed both by a given set of social actors and institutions operating in the economy (under human control, in the technosphere) and a given set of ecosystems (outside human control, in the biosphere). This change in consideration from economic to ecological involves a description of an entropically favorable state-pressure relation between a symbiotic technosphere and biosphere.

For the second type of interaction, we will focus on the externalization of economic processes through trade. Through imports, a social-economic system is able to reduce its requirement to secure a reliable internal flow of biophysical material—a flow that would otherwise need to be produced by its own hypercyclic sectors. In this sense, externalization increases the ability of a system to free itself from the need to establish internal relations of material entailment. It reduces the constraints determined by the counterfactual local pressures of downward and upward causation.

However, from a relational perspective, externalization also has a dark side. Externalization may be seen as a major reason why many modern social-economic systems are losing their control over the reproduction, maintenance, and adaptation of their own identity. Through processes of modernization (and changes in considerations of desirability, related to rising expected levels of material standard of living), the ability of dissipative sectors to provide feedback through functional entailment relations with hypercyclic sectors—to "cast their vote"—has been seen to systematically reduce. The primary sector is becoming *disenfranchised*. As a result, social-economic systems are losing their ability to replicate[9] and losing control over their ability to repair. In essence, they are losing control over their identity. The many benefits of modernization may be seen to have come hand-in-hand with a local breaking of the closure to efficient causation of social-economic systems—a process of "cyborgization" of society in which societal identity is being increasingly determined by external factors.

As Swyngedouw (2006) points out, cities are exemplars of this process of cyborgization of society. (Cities also epitomize externalization in social-economic systems.) A cyborg is a hybrid between an organism and at least one artificial component, where an artificial component is a simple system tasked with restoring an organic function. From the relational biology perspective, a human (a type of organism) equipped with and reliant on a pacemaker (a type of artificial component) is already a cyborg, albeit a very basic cyborg. With no great stretch of the imagination, we can similarly conceptualize cities as extensive mechanical cocoons that offer a wide array of inert goods and services as replacements of societal functions. It is undeniable that cities have many desirable characteristics, but it is also undeniable that they are the technocratic havens of social agents operating, as Turkle (2012) phrased it, "alone together". As previously mentioned, the unorthodox economist Georgescu-Roegen was clear in identifying that the final cause of the economy is not "producing goods and services", but rather that of reproducing fund elements associated with the production and consumption of goods and services. That is, the final cause of the economy is simply the reproduction of itself while guaranteeing an "enjoyment of life" to citizens. Considering Georgescu-Roegen's understanding of the economy, it would be advisable for social-economic systems to make a careful assessment of their intrinsic, complex network of functional and material entailments before making the societal decision to off-shore, or replace with artificial components, their societal organs.

What we have done in this chapter is build a *model* (not a simulation) of a social-economic system, motivated by the need for that careful assessment. An organism turned cyborg can no longer decide how it wishes to enjoy life. In Chapters 4 and 5, we will explore case studies of Europe's disenfranchised energy sector and agriculture sector, respectively.

2.4.6 *Endnote on Autopoiesis*

Before closing the chapter, I will make some brief commentary on H. Maturana and F. Varela's concept of autopoiesis. An autopoietic unit is understood to be "a system that is capable of self-sustaining owing to an inner network of reactions that re-generate all the system's components" (Luisi, 2003, p. 51). For

[9] "Replication" not in the molecular biology sense, rather in the relational biology sense described at the head of Section 2.4.4.

comparison, relational biology states that "a material system is an organism if, and only if, it is closed to efficient causation" (Rosen, 2005, p. 244). Superficially, those two ideas seem to have a lot in common. The only goal of my commentary in this endnote is to point out that the autopoiesis concept of life and relational biology's concept of life are not at all the same, despite superficial similarities. In doing so, I defend as novel the line taken by this chapter's characterization of social-economic systems as living systems.

First, we must recognize that function is a fundamental consideration in relational biology's concept of life. As we have been discussing, relational biology's "closure to efficient causation" refers to the idea that "every efficient cause is *functionally* entailed within the system" (Louie, 2009, p. 156, emphasis added). In contrast, and notwithstanding 50 years of lively discourse, it remains unclear if the concept of autopoiesis is intended to rely on a consideration function. The clearest, literal indication is a resounding "No!", but implicitly it is not so clear.

On the one hand, Maturana and Varela make statements such as: "[n]otions of purpose, function or goal are unnecessary and misleading" (1980, p. xix) and "since the relations implied in the notion of function are not constitutive of the organization of an autopoietic system, they cannot be used to explain its operation" (1980, p. 86). Maturana and Varela (1980, p. xiii) write that

> any attempt to characterize living systems with notions of purpose or function was doomed to fail because these notions are intrinsically referential and cannot be operationally used to characterize any system as an autonomous entity. Therefore, notions of purpose, goal, use or function, had to be rejected, but initially I did not know how.

Of course, the relational theory we have been exploring asserts that organisms are unavoidably self-referential, that they use material flows specifically to maintain *functional closure*. As Schrödinger (1944) realized early on, what sets organisms apart is their ability to perform a balancing act between generating positive entropy and consuming *identity dependent* negative entropy in order to *keep closure on a set of functions*. Organisms rely on material flows (a source of negative entropy) produced *outside their boundaries* and that reliance is *identity dependent* (referential).

The stance of autopoiesis becomes less clear when considering further statements such as: "[b]ehavior (function) depends on the anatomical organization (structure) of the living system, hence anatomy and conduct cannot legitimately be separated and the evolution of behavior is the evolution of anatomy and vice versa" (Maturana and Varela, 1980, p. 31). To understand what is intended by this second variety of statement, it is necessary to recall the notion of cognition as it is used in the discourse of autopoiesis. To wit, Maturana and Varela (1980, p. 13) write: "[l]iving systems are cognitive systems, and living as a process is a process of cognition." The notion of cognition in the discourse of autopoiesis is itself a consideration of purpose/function. Maturana and Varela, so to break bread between their assertion that behavior/cognition and autopoiesis come hand-in-hand and their loud rejection that function has anything to do with autopoiesis, assert that cognition *follows* autopoiesis. Maturana and Varela (1980, p. 82, emphasis added) write "autopoiesis [(which exists in the physical space)] is *necessary and sufficient* to characterize the organization of living systems" and Luisi (2003, p. 54, emphasis added) clarifies that Maturana and Varela "apply the notion of cognition only to systems that have first been found to be autopoietic according to the *structural criteria*".

What is this modern Prometheus? Have Dr. Frankenstein's secrets finally been revealed? We're forced to conclude from these statements that the traditional concept of autopoiesis views life as a machine, albeit one with a ghost in it. Such a view is in outright contradiction with relational biology's concept of life, which emphasizes intangibilities. To any that deny that autopoiesis views life as a machine, look no further than Maturana and Varela (1980, p. 76, emphasis added):

> We maintain that *living systems are machines* and by doing this we point at several notions which should be made explicit. First, we imply a non-animistic view which it should be unnecessary to discuss any further. Second, we are emphasizing that a living system is defined by its organization and, hence, that it can be explained as any organization is explained, that is, in terms of relations, not of component properties. Finally, we are pointing out from the start the dynamism apparent in living systems and which the word 'machine' connotes.

Sir S. Beer's statement in the preface to *Autopoiesis: The Organization of the Living* sheds further light on the matter: "[t]he second reason why the concept of autopoiesis excites me so much is that it involves the destruction of teleology" (Maturana and Varela, 1980, p. 67). Considering such statements, Maturana and Varela's as well as Beer's, it is not surprising that autopoiesis is often misconstrued as a theory of artificial intelligence.

Setting aside the differing perspectives on the rightful consideration of function, there are also various terminological tensions between autopoiesis and relational biology, tensions that cannot be ignored. Consider the following historical exposition by Maturana on the "Santiago school":

> [A] formalization could only come after a complete linguistic description, and we immediately began to work on the complete description. Yet we were unhappy with the expression "*circular organization*", and we wanted a word that would by itself convey the central feature of the organization of the living, which is autonomy.
>
> (quoted in Maturana and Varela, 1980, p. xvii, emphasis added)

Relational biology of course *embraces* the term circular organization, placing it at the heart of its main theorem of life and at the basis of its assertion that models of organisms are not Turing computable. The autopoiesis diehard, relational biology sympathizer, might claim in defense that Maturana's discontent was less a rejection of the term circular organization and more a support of a term he considered to be more to the point (autopoiesis). Possibly, but we can't help but then wonder why in the first place an attempt was made to write a computer program for a self-referential entity (a synthetic lifeform), or if proper attention to the circular organization of life had been made, if that programming effort could have been avoided. Whatever the case, Maturana and Varela (1980, p. xviii) put a few more nails in the coffin of possible terminological cross-pollination with relational biology in their statements on causality:

> I submitted to the pressure of my friends and talked about causal relations when speaking about the circular organization of living systems. To do this was both inadequate and misleading. It was inadequate because the notion of causality is a notion that pertains to the domain of descriptions, and as such it is relevant only in the metadomain in which the observer makes his commentaries and cannot be deemed to be operative in the phenomenal domain, the object of the description.

Obviously, our introductory exposition on relational biology's modeling relation is in clear contrast. Causal entailment exists in the natural world and inferential entailment exists in the world of formalism. Causal relations are the *external referents* of inferential relations in models. Setting aside this grave linguistic difference, why the notion of causality being in the domain of descriptions should imply that its use is misleading is not clear. As observers, we cannot ever know the true nature of external referents, only their projections onto our perceptual apparatus (see Chapter 3). If the science endeavor is not about explaining structures of causal entailment in the natural world using structures of inferential entailment in the formal world (in the "domain of descriptions"), what is it about? In such a statement as the above display quote, we can see the origins of the criticism that autopoiesis "flies in the face of […] scientific knowledge", and that it is grounded on a foundation of solipsism (Swenson, 1992, p. 267).

In conclusion, there are major differences between relational biology and autopoiesis. Despite precedents, such as N. Luhmann's (1995) admirable characterization of social systems as autopoietic systems, what we have achieved in this chapter is entirely novel. In the next chapter, I will continue to develop our approach to modeling social-ecological systems by exploring various pragmatic consequences of social-economic systems as (M,R)-systems.

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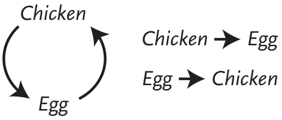
3 SOCIAL-ECOLOGICAL KNOWLEDGE SPACES

3.1 POST-NORMALITY

3.1.1 *Breaking the Chicken-Egg Paradox*

In this chapter, in an effort to segue from conceptual modeling to applied modeling, we will discuss the structure of social-ecological knowledge spaces. Although our discussion will remain mostly abstract, with conceptual examples provided, it will prepare us well for the case studies in Chapters 4 and 5.

We start our discussion with some comments the role of narratives in setting knowledge space boundaries. Consider the chicken-egg paradox, which is a standard example of a hierarchical loop. One of the many final causes of chickens is eggs and one of the many final causes of eggs is chickens. Early Greek philosophers, such as Aristotle, considered the chicken-egg paradox to be an infinite regress. However, not everyone in history shares their view. Christianity, for example, proposes to its adherents that chickens, created by God, came before eggs .



This proposal, chickens before eggs, is a *narrative* that serves the useful purpose of excluding from the Christian community the second way in which the impredicative loop can be made predicative. It thereby creates order and unity of experience, hence social cohesion. Douglas (cited by James, Lincoln and Guillot, 2004, p. 12), in discussion of Durkheim's investigation into the practices of Aboriginal Australians, shares a similar story:

> The [feast day] rite imposes order and harmony. [...] Great rituals create unity in experience. They assert hierarchy and order. In doing so, they affirm the value of the symbolic patterning of the universe. Each level of patterning is validated and enriched by association with the rest.

[10] The Great Chain of Being, from Didacus Valades's *Rhetorica Christiana* (1579).

Narratives are neither right nor wrong, only relevant/useful or irrelevant/misleading. Recall that in Chapter 2 we identified social-economic systems with impredicativities. Whenever we uncover an impredicative loop during the analysis of a social-economic system, there are certain to exist narratives that serve to break that impredicativity—to make ordered sense of things. Destroying the organization of a complex system prior to the analysis of its constituents is equivalent to breaking the chicken-egg paradox.

This realization sheds new light to the pretentious claim of reductionism that after a system of interest has been sufficiently fractionated into its constituents and those constituents sufficiently studied on an individual basis, the original system can be meaningfully reconstructed from its parts. "The sum of the parts is the whole!". Once an analyst assumes as unquestionable a narrative, there is no going back to explore alternatives—*the breaking of an impredicative loop is a* *one-way street*. If we admit to ourselves that impredicative loops existed in the original state of some system of interest—and by definition they always do exist when the system of interest is a social-ecological system—then we must realize that our analytical results are dictated by our own subjective choice of how to destroy the original, impredicative form of organization. They are dictated by our choice, individual and societal, to endorse some specific set of narratives over others.

This backdrop of reductionism and normal science allowed Gray (2003, pp. 27–28) to describe, by the way, the struggle for "scientific truth" as the luxurious disability of a "tormented" person. In normal scientific life, against an illusion of objective inquiry, the "tormented" normal scientist searches for meaning (soothing familiarity) in the distressing unintelligibility of the natural world, in denial of the reality that their actions are influenced by rhetoric and politics. The thrust of the matter is that breaking chicken-egg impredicativities is, to paraphrase Rosen, a *destruction of the organization of the system of interest*. Narratives are necessary epistemological commitments that serve to create manageable hierarchies, order and unity of experience, but in their capacity as breakers of impredicative loops, their destructive nature has implications for the way in which we conduct science.

3.1.2 *Three Types of Narrative*

We discussed in Section 3.1.1 how the breaking of a hierarchical loop requires an epistemological commitment—a system of faith in the broadest sense of the term. In taking that observation to heart, we can identify two potential ways of proceeding. We could either try to avoid breaking loops altogether, accepting that it will then be challenging to explain matters, or we could learn to keep better track of the epistemological commitments being made when a loop is broken.

As sustainability scientists, the choice between these two options is relatively straightforward. The results of a sustainability assessment must be meaningful within a certain sociocultural setting. Hence, they must, to some degree, break bread with the loop-breaking, order-creating narratives that are upheld in that setting. We have little choice but to ultimately accept the second way of proceeding.

In total, no less than three types of narratives must be considered when evaluating the epistemological commitments of sociocultural actions and actors.

1) When a society is confronted with an internal concern, *justification narratives* identify where a lack of action will cause troubles. They respond to the question "Why should we act?". Justification narratives are about prioritization over concerns—moral power.
2) In relation to a given potential trouble, *explanation narratives* identify the factors and mechanisms causing troubles. They respond to the

question "How should we act?". Explanation narratives are about the robustness of knowledge claims—scientific inquiry.

3) In relation to the factors and mechanisms generating trouble, *normative narratives* identify the action to be taken in order to eliminate them. They respond to the question "What should we do?". Normative narratives are about the possibility of implementation—political power.

A first observation about justification, explanation and normative narratives is that they form three disjoint sets. Although basic, this observation forces us to realize that scientific results—related to explanation narratives—never advocate for certain actions over others. To do so would be one of Ryle's (1949) category mistakes, or "type trespasses". It is grave logical error. If I say anthropogenic climate change will force fifty percent of animals into extinction by 2050, I do not in any way imply that society should make any attempt to stop the climate from changing. That is a decision to be made collectively.

A second observation is that justification, explanation and normative narratives, while disjoint, are *entangled*. They influence each other. Although normal science would like to imagine that it can get away with the ideal of *only* considering explanation, that ideal is a falsehood. Consider again Nordhaus' infamous narrative statement from his participation in a National Academy of Sciences panel on greenhouse warming, mentioned previously in Chapter 1.

> Ninety percent of U.S. economic activity has no interaction with the changes Lubchenco is concerned about. Agriculture, the part of the economy that is sensitive to climate change, accounts for just 3% of national output. That means there is no way to get a very large effect on the U.S. economy. It is hard to say it is the nation's number one problem.
>
> (reported by Roberts, 1991, p. 1206)

Against the backdrop of Nordhaus, Solow (1974, p. 11) summarizes and further clarifies the sentiment: "[t]he world can, in effect, get along without natural resources." Here, Nordhaus and Solow endorse the neoclassical narrative that the primary sector is irrelevant to the economy. Faced with an agriculture sector struggling to survive—the reality in all modern, "developed" countries—Nordhaus and Solow propose to answer the justificatory question "Why should we act?" with "Actually, we shouldn't act because the loss of the primary sector (in particular agriculture) isn't a 'relevant concern'." It demands to be stressed that this particular assertion of which concerns are relevant is one of many. In biophysical terms—adopting a non-equivalent narrative to frame the issue—the claim does seem quite absurd. No farms, no food.

Recall that the process of societal cyborgization entails a progressive breaking of impredicative loops. In the case of the narrative of Nordhaus and Solow, the loop breaking that occurs takes the form of an elimination of the functional entailment that once existed from the primary sectors (especially agriculture) to the dissipative sectors (such as service or household). How could the primary sectors possibly exert economic authority if they are viewed as economically irrelevant? The narrative of Nordhaus and Solow is a way of simplifying reality that creates a specific type of order and a specific flavor of unity of experience in modern urban societies, one where farmers are irrelevant.

If we accept the neoclassical narrative, which again, although masquerading as scientific, has much more to do with moral power, the field of possible explanation and normative narratives is pre-constrained. If faced with a struggling economy, it is no longer valid or possible to respond to questions of "How should we act?" or "What should we do?" with narratives that suggest to protect the deteriorating agriculture sector. The rub of the matter is, justification narratives—outside the domain of science—affect explanation and normative narratives. *All three types of narrative are entangled!*

One final line of thought elaborating on the connection between justification narratives and knowledge spaces, in particular the role of justification narratives in defining which concerns are legitimate, will help to fill out the matter. First, at the individual level, there is a generation of concerns from processes of emotion, feeling and affective relation. Individuals can only ever consider a small set of concerns, what has been called a "finite pool of worry" (Linville and Fischer, 1991; Weber, 2006) and what was, at least in part, referred to in H. Simon's (1955) discussion of bounded rationality. Second, at the societal level, there is a political, institutional process that effectively filters and prioritizes the small sets of concerns of individuals. This is a very important point! The act of prioritization of concerns, being the endorsement of a specific set of concerns as representative of the collective, societal understanding, is a *political process*. It is a process that can be understood as a process of knowledge space colonization. Boundaries are placed on the set of legitimate concerns to be considered and actions to be taken. Preference is given to certain problems over others.

Visually, the set of knowledge space boundaries, being concerns identified through narratives, can be interpreted as the creation of a "mosaic". Instead of material tesserae (stones, ceramic), the tesserae of our mosaic are surface territories colonized by narratives, being manifestations of beliefs, preferences, emotions and values. Figure 12 provides an example, still conceptual but concrete enough to give some substance to these abstract ideas. The left pane of Figure 12 is an identification of the primary concerns of two major primary sector policy packages, the European Union's Common Agricultural Policy (CAP) and the Clean Energy for All Europeans (CEAE) package. The right pane is an interpretation of the Special Eurobarometer 468 survey, which assessed the concerns of European society. Despite referring to the same social-economic system, the left and right panes do clearly give different weights and preferences to the various environmental concerns. They are two very different knowledge spaces, giving rise to two different sets of permissible explanation and normative narratives.

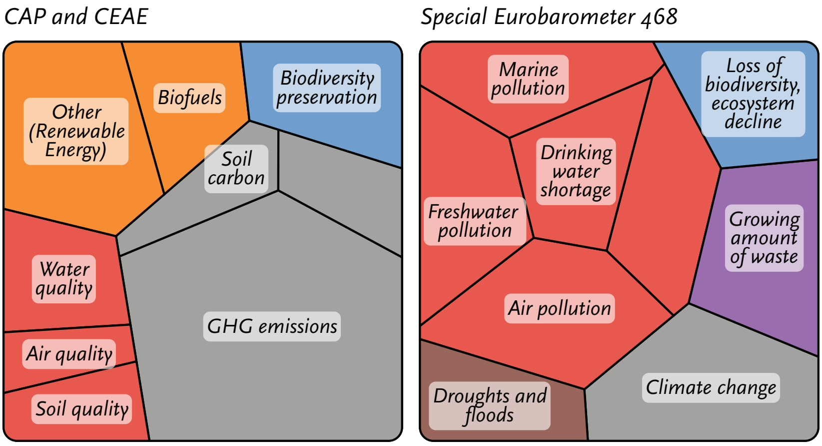


Figure 12 Concerns of the CAP and CEAE versus an interpretation of the concerns identified by Special Eurobarometer 468. Left from: (Giampietro and Renner, 2018). Right inspired by: (EC, 2017).

Legend

- 🟥 *Natural resources*
- 🟧 *Renewable energy*
- 🟦 *Biodiversity*
- ▨ *Climate change*
- 🟫 *Natural disasters*
- 🟪 *Waste*

In conclusion, the act of knowledge space colonization through narrative endorsement can be understood as the delineation of epistemic boundaries. Knowledge space colonization is associated with the creation of meaning and societal or political identity, but it is also associated with the crowding out of certain knowledge. The relative importance given to competing justification narratives in the political processes will be reflected in the priority given to the actions to be implemented (normative choices). Explanation narratives, generated through scientific inquiry, are only minorly responsible for the decisions that are ultimately made.

3.1.3 *Knowledge Space Criticality*

A criticality is a critical point. Something which is *supercritical* is beyond a critical point and something which is *subcritical* is below a critical point. A supercritical nuclear reaction, for example, is self-sustaining. A subcritical nuclear reaction will die out. Similarly and analogous to Giampietro and Bukkens' (2015) concept of a supercritical Sudoku, the term *supercritical sustainability* in the title of this dissertation refers is a self-sustaining conceptualization of sustainability science, one where the discussion is lively and never concludes.

Unbroken impredicative loops, including the chicken-egg paradox, are generators of *supercriticality*. This realization reveals the allure of reductionism in so far as reductionism proposes to start analytical procedures with a breaking of impredicative loops, either physically or with narratives. When operating from within a reductionist *subcritical knowledge space*, an objective solution can be found. The normal science puzzle can be solved. But we must not lose sight of the reality that when a supercritical system is transformed into a subcritical one, "That's all she wrote!". The space can *never again be made supercritical*, or, Humpty Dumpty cannot be put back together again.

As already mentioned in Section 3.1.2, we are obligated by sociocultural setting to work, as sustainability scientists, with subcritical knowledge spaces.

Such knowledge spaces are always contestable—what other impredicativity-breaking narratives coule have been endorsed? Hence, as emphasized in Section 3.1.2, we must always make an effort to take stock of the narratives that bound knowledge spaces.

Given a system of interest, a *Homo economicus* like Nordhaus or Solow would generate one knowledge space, say K_E , and a *Homo reciprocans* would generate a quite different knowledge space, say K_R. The sets of narratives endorsed by those two species of scientist are distinct and result in, first, different perceptions, and second, different representations of the natural world. N.B. The former of the two species of *Homo* believes humans are somehow rational and selfish and the latter believes humans are somehow cooperative and altruistic. As a society, or as a decision-maker, *both knowledge spaces are of interest*. Consideration of multiple knowledge spaces gives a society optionality, which is a source of resilience and a potential for growth (Taleb, 2012). Optionality is in the long-term best interests of a social-ecological systems as complex systems (Lewin, 1936; Kauffman, 1993).

Different knowledge space representations, which result from different social perspectives and institutional contexts, each have their own preferential uses. Some of those uses may be obvious, others may be less obvious. The role of the sustainability scientist is to act as a *Homo supercriticalis*—to start with humility and gather multiple perspectives leading to multiple representations. Of course, we are not saying with this that anything goes. Representations of the natural world can also be just wrong, plain and simple. Figure 13, for example, is a representation of a natural system that is, for all intents and purposes, invalid. Hence, after a knowledge space has been generated, it's every aspect must be *audited for sense* (Sections 3.3.2 and 3.3.3) before any models are built within it. This action of auditing is an act aligned with the concept of philosophers as the tribunal of science, *eliminators of intellectual myth*, and so scientists as natural philosophers.

> Every source of truth […] may also be a source of *intellectual mythology*, against which it is typically powerless. One great and barely recognized source of such mythology in our age is science itself. The unmasking of scientific mythology (which is to be distinguished from scientific error) is one of the tasks of philosophy. […] Its aim is neither to engage in nor to abjure science, but to […] restrain scientists and philosophers who have been beguiled by their myth-making from metaphysical nonsense.
>
> (Hacker, 1996, p. 123)

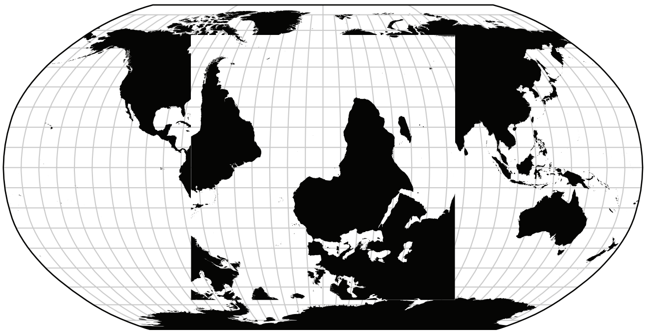


Figure 13 Example of an invalid representation of Earth, an invalid knowledge space.

3.1.4 *Puzzle-solving and Game-playing*

In *The Structure of Scientific Revolutions*, T. Kuhn, philosopher of science, famously described scientists engaged in "normal science" as *puzzle-solvers*. Kuhn (2012, p. 33) writes that "[t]he man who succeeds [in bringing a normal research problem to a conclusion] proves himself an expert puzzle-solver, and the challenge of the puzzle is an important part of what usually drives him on." Kuhn (*ibid*., p. 33) adds a word of warning about scientists as puzzle-solvers in that "[i]t is no criterion of goodness in a puzzle that its outcome be intrinsically interesting or important".

As we have been discussing, aside from the lack of a criterion of goodness, puzzle-solving in complexity is problematic in that the "resolving" of a complex problem implies the breaking of an impredicative loop—a simplifying destruction of the original organizational unity. While it is not possible to tame complexity, it is possible to put a harness on complexity. Normal science is about the solving of puzzles determined by the choice of just a single narrative for framing the analysis. In acknowledging the implications of complexity, the use of science for governance is about *staying on the horns of the dilemma*.

Observation of the failure of normal science to find adequate solutions in situations of complexity ultimately led S. Funtowicz and J. Ravetz to introduce *post-normal science*. Funtowicz and Ravetz (1990, p. 1) write that their "guiding principle [therein] is that high quality does not require the elimination of uncertainty, but rather its effective management". Post-normal science therefore shifts the focus from *knowing-that* to *knowing-how*, from *quantity* to *quality*: "whenever there is an urgent issue for resolution, it is quality rather than quantity that presents the problem" (Funtowicz and Ravetz, 1990, p. 14).

If normal scientists are puzzle-solvers, what then are post-normal scientists? What is their *modus operandi*? In Chapter 2, we warned against the use of pure syntax to judge an assertion as sensical or nonsensical—useful or not useful for guiding action. The idea that pure syntax can be used in that way is bound to the subcritical landscapes of commonplace reductionism. What post-normal science does is reimagine the role of scientists. Scientists accepting to take a post-normal stance become active participants in supercritical landscapes, they are *Homo supercriticalis* cartographers embedded in an extended peer community[11]. In the new, organic world of post-normal science, scientists are *game-players*.

To be clear, no belittlement is intended by that labeling. Science-games are serious games. The term *game* is being used here in a sense parallel to that of Wittgenstein (2009, p. 15): "[t]he word 'language-*game*' is used […] to emphasize the fact that the *speaking* of language is part of an activity, or of a form of life." Like Wittgenstein's language-games, *science-games* are an active, living counterpart to science-puzzles. When working on something so complex and dynamic as the sustainability of social-ecological systems, it is surely more desirable to play science-games than solve science-puzzles. Even if we take for granted that the set of observations used to motivate the existence of a knowledge space are reasonable reflections of ontological reality in the past, there is no guarantee that they are relevant or sufficient appraisals of the present or future. Systems experiencing issues of sustainability are *becoming systems*—the set of observations, gathered in the past, is an unavoidably incomplete knowledge claim. When a system experiences a sustainability crisis, the system, by definition, is being required to reinvent itself. The "game" must be patched by game-players, it must be tested for usefulness and its content and ruleset must be allowed to coevolve with societal concerns.

Recall the use of the term *art*, rather than, say, *science*, in our Chapter 2 definition of modeling (modeling as "art of bringing entailment structures into congruence"). Against the idea of sustainability scientists as post-normal scientists and post-normal scientists as game-players, that seems a fitting choice. Modeling is artistic in that involves the unavoidable use of heuristics and intuition. It relies heavily on the tacit knowledge of the extended peer community, in general but especially in the face of impredicative loops. Our "contentious" Chapter 2 endorsement of final cause also seems a fitting choice from our adopted post-normal stance. J.L. Russell (1962, p. 351. emphasis added) sheds light on the matter, one has only to consider *scientists as natural philosophers*: "[t]he difference in approach to philosophy between Descartes and Aristotle can be summarized without too much over-simplification by saying that for Descartes the philosopher is a spectator of the physical world; *for Aristotle he is a participant*."

Ultimately, post-normal scientists as game-players, rather than normal scientists as puzzle-solvers, forces us to rethink the entire humanist foundation of normal science. It requires us to rethink the idea that scientists, by their own volition, drive progress and the development of human society. Humanism is deeply ingrained in modern science, however, and one would not expect puzzle-solvers to yield the field to game-players without a fight. I give the last

[11] A community "consisting of all those with a stake in the dialogue on the issue," not limited to credentialed "experts" (Funtowicz and Ravetz, 1993, p. 739)..

word on the subject to political philosopher and harsh critic of humanism J. Gray (2003, pp. 18–19, emphasis added):

> Scientific fundamentalists claim that science is the disinterested pursuit of truth. But representing science in this way is to disregard the human needs science serves. Among us, science serves two needs: for *hope and censorship*. Today, *only science supports the myth of progress*. If people cling to the hope of progress, it is not so much from genuine belief as from fear of what may come if they give it up.

3.2 CLASSIFICATIONS

3.2.1 *Equivalence Classes*

Having accepted justification, explanation and normative narratives as knowledge space boundaries, this section changes gears and continues the discussion with a deconstruction of *equivalence classes*, which serve as the monads or "building blocks" of knowledge spaces. We will both clarify the nature of the concerns addressed by equivalence classes and cover the essentials of the semiotic process through which stable classes are created.

What is an equivalence class? To answer that question, it is easiest to describe how an equivalence class comes into being. An equivalence class is the result of a successful fitting of an *equivalence relation* over a collection of *non-arbitrary observations*. *Equivalence* relation hence *equivalence* class, hereafter simply "class". For example, a modeler interested in the construction of cities might observe various crews of construction workers and, over time, find that there tends to be individuals engaged in the task of building up structures made of bricks and individuals that seem to walk around telling everyone what it is that they should do. Despite the fact that every phenomenon and *every piece of information is unique*, the modeler makes the authoritative decision that the individuals they observed nicely fit into two distinct sets, each of which is reasonably *homogenous in relation to the goals of their analysis*. The modeler therefore declares the existence of an equivalence relation over each set, a declaration which generates the stable classes "bricklayers" and "foremen".

In acts of scientific modeling, classes either *directly or indirectly address one or more of the four causes*. A class that *directly* addresses one of the four causes might, for example, address an efficient cause, such as one of the various types of construction workers needed to build a city (foremen, bricklayers), or it might detail a material cause, such as a one of the various types of materials needed to build a city (concrete, steel). A class that *indirectly* addresses the four causes might detail a contextual modifier, such as location in space (Boston, Wonderland) or location in time (2020 A.D., 14:01 UTC), or it might detail an abstract modifier such as a qualitative (new, impure) or normative (good, bad) consideration. Spatial-temporal context and qualitative and normative considerations are all useful pieces of information when used to enrich classes addressing one or more of the four causes—they increase the explicitness of models and the transferability of model insights.

The process of class creation is not only universal to modeling but indeed to everything we do as cognitive beings. But that does not mean we can assume that everyone is born with a sophisticated idea of how it works. In the field of semiotics—the study of signs and how they are used and interpreted—C.S. Peirce's *type-token distinction* has been at the center of a vibrant century-long discourse attempting to understand the process of class creation. (*Classes* are *types* and the concrete particulars driving the definition of classes are *tokens* or *instances*.) What is critical to appreciate when considering the insights of semiotics on the process of class creation in relation to the characterization of social-ecological knowledge spaces is the organic nature of the relation between classes (function) and instances (structure). None of the classes that we use to structure knowledge spaces and construct models are uncontestably identifiable, even to an individual observer, and they are constantly evolving.

There may be construction workers that at times lay bricks and at times give orders. Such workers are at once bricklayers, not-bricklayers, foremen and not-foremen. Biophysical economist N. Georgescu-Roegen referred to such fuzzy entities as *dialectical concepts*—concepts where the concept and its opposite "overlap over a countourless penumbra of varying breadth" (Georgescu-Roegen, 1971, p. 14). As Georgescu-Roegen's discussion goes, no improvement in our ability to sense reality could possibly force it unequivocably into a discretely distinct entity, what he terms an arithmomorphic concept, the root of which is *arithmetic*. Simply increasing the number of classes is also not a reliable method of resolving a dialectical fuzziness as that same logic would apply until a class exists for each instance.

Quantification in science has claimed to open the door to precision and objectivity, but we must not lose sight of the fact that it is ultimately *the mind that measures*, not the ruler. It is the mind that subjectively reduces a dialectical concept to an arithmomorphic one. Hence, throwing time and resources at more precise and pervasive sensor technologies ("smart cities", smart everything) is not necessarily an effective way of generating more reliable classes. Wittgenstein (2009, p. 135) writes:

> "Put a ruler against this object; it does not say that the object is so-and-so long. Rather, it is in itself — I am tempted to say — dead, and achieves nothing of what a thought can achieve." — It is as if we had imagined that the essential thing about a living human being was the outward form. Then we made a lump of wood into that form and were abashed to see the lifeless block, lacking any similarity to a living creature.

To stress the point, which is not obscure or without purpose, I turn to a classic example from the field of cognitive science. Unlike English, the Russian language makes an *obligatory distinction* between lighter blues and darker blues. As a result, Russian speakers perform simple perceptual tasks related to blue stimuli differently than English speakers (Winawer *et al.*, 2007). A speaker-of-Russian's perception of a panel of various shades of blue is different from that of a speaker-of-English! But the effects of nurture on categorical perception are pervasive—they go far beyond the rather mundane case of blue stimuli. They impact all observations we make. It may be that one group of modelers does not even perceive the existence of a *difference* between bricklayers and foremen, and that another group of modelers does not perceive the *similarity* between bricklayers and foremen, so to say. Despite the best intentions of modelers, culture does strongly influence the generation of the building blocks used to construct knowledge spaces and, ultimately, scientific models.

Although our discussion is still highly abstract, it's implications for modeling in practice are widespread. The set of classes used in a modeling endeavor needs to be constantly questioned, and it needs to be approached with humility. N.B. Perception does not depend on the consciousness, a reality that Gray (2003, p. 59) termed the *poverty of consciousness*. The set of classes used in the description of a knowledge space needs to be constantly revised—we need to track the births and deaths of relevant classes. Implications are felt particularly strongly when a model is being used to address a sustainability concern. When a system is experiencing a sustainability crisis, *the system is being forced to reinvent itself*. That reinvention implies the need for the system to generate a recharacterization of reality along the dialectic between classes and instances. The discussion of numerical benchmarks for pre-defined equivalence classes—where modern normal science prefers to invest its time—is, per se, of secondary importance. Rashevsky (1968, p. 404), who, it should kept in mind, himself came to biology from physics and mathematics, writes:

> in spite of their importance, the quantitative, or as we called them, the metric aspects of biology may be subordinate in their importance to the qualitative or relational aspects.

In so far as we are advocating for a heterodox approach to science, one should begin to appreciate why we belabor the philosophical discussion. In the coming sections, we will have a lot more to say in terms of practical implications.

3.2.2 *From Classes to Classifications*

A *classification* is a collection of interrelated *classes*. We previously asserted that classes can address *one or more* of the four causes, either directly or indirectly. We only provided examples of classes that addressed just one cause or one modifier, however. We did that on purpose. When modeling, concerns should remain as modular as possible. We should be able to add and subtract concerns from our model, extend, filter or revise them or cross them in different ways. This is especially important when addressing an issue of sustainability. In a similar vein, Floridi, a philosopher of information, criticizes structures that do not keep phenomenological concerns disjoint ("functionally heterogeneous structures”), stating that “their ontological commitment is embedded and hence concealed” (Floridi, 2008, p. 321).

As a rule of thumb, each classification should gather classes that are homogenous in terms of the concern that they address. We would typically prefer to use a first classification of efficient cause and a second classification of final cause rather than a singular classification mixing efficient and final cause. A practical revision of our initial definition of classification is therefore: a classification is a collection of interrelated classes that, within reason, *all fall under the same category of concern*.

Why “concern”? Since the start of this chapter we’ve been claiming that classes and therefore classifications address *concerns*. Up until this point, we’ve taken that assertion for granted. Could we have substituted the term for something similar? What about issue, interest or problem? In short, no, we cannot substitute those words. The term concern was very carefully selected.

In cognitive psychology, decision-making is generally explained as being related to needs or problems, not concerns. However, the concepts of needs and problems preselect specific subsets of decisions. The concepts of needs and problems are also inappropriately assertive that the decision to be made cannot be gone without. A look at the distinction between demand and requirement in economics helps illustrate the essential distinction between concerns and needs or problems. In economics, a requirement does not imply a demand. A demand only exists when a requirement coincides with willingness to pay. According to Freudian psychic structure, the identification of a true requirement is an instinctual process occurring in the id. A demand, on the other hand, is the result of an internal negotiation between requirement and so-called *perfection-seeking* in a cultural setting. Demands therefore result from a process of mediation. They evolve in the ego.

In a similar sense, concerns have instinctual origins. A newborn baby expresses concerns, but only its caregivers have the capacity to decide whether those concerns are valid problems. Once mediated by social-ecological setting, concerns may or may not evolve into problems. It is notable to point out that the first step (at times implicit) in just about any method aimed at improving decision-making processes is to define concerns. Scientific modelers are the same as decision-makers in this regard. A classification built on the basis of needs or problems is like taking a classification built on the basis of concerns and putting blinders on it.

As with the term concern, we chose the phrasing *knowledge space* very carefully. *Knowledge* about a system of interest is information together with a theoretical or practical understanding of that system. Scientists build models on knowledge, be it explicit knowledge or Polyani’s (1962) tacit knowledge. An information space, even if accurate, doesn’t necessarily imply any practical understanding of the system of interest. Lastly, a *space* is defined in mathematics as a set with some added structure. The concept of *dimension* differs between spaces. As we will see in Section 3.3.1, each classification being considered by a modeler is a knowledge space dimension hence concerns are dimensions. Later, in Chapters 4 and 5, we will talk about *option spaces*, which are forward-looking knowledge spaces.

3.2.3 *Hierarchical or Taxonomical*

Now that we know classifications are collections of classes and now that we have an idea of how classes come into being, I will discuss the nature of the relations between classes in classifications. Often, classifications assert a notion of scale. Indeed, all the classifications explored in this work are levelized. But not all levelized classifications are made the same. In this section, I will highlight the essential difference between the inter-class relations in *taxonomies* (taxonomic classifications) and those in *hierarchies* (hierarchic classifications). I will contrast that understanding with the modern, degenerate understanding.

Consider the classification presented in Figure 14, which is understood to address a concern of efficient cause in our running motif (building a city). The labeled points in Figure 14 are classes, as discussed in Section 3.2.1, and the unidirectional arrows between the labeled points are the inter-class relations. What is the nature of the inter-class relations in Figure 14? Their nature is one of authority, or domination. Bricklayers, carpenters and electricians do not combine or group into each other to form a construction foreman. Rather, a foreman is understood to manage and command the former three.

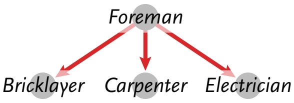


Figure 14 A hierarchical classification detailing efficient causes.

Figure 14 is what we would call a *hierarchy* of efficient cause, rudimentary in that it has just two levels. The term hierarchy has linguistic roots in the Greek word *hierarkhēs*, which is *hieros*, meaning sacred, and *arkhēs*, meaning ruler, put together (Stevenson, 2010). Although theological in origin, the term broadened during the Enlightenment period, coming to include profane concerns (military, administrative, social). Even as the term extended into the profane, though, it maintained its characteristic relation of authority between classes defined across levels. For example, in referring to hierarchies of human settlements, ranging from hamlets to cities, French cartographer R. de Hesseln (1771) was one of the early adopters of the broadening of the term. But in Hesseln's hierarchy of human settlements, the relation between settlements across levels was one of authority and subordination—the larger the settlement, the more nobility it conferred. More recent usage of the term risks flushing the baby with the bathwater.

Contrast Figure 14 with the classification of building materials presented in Figure 15, which we understand as being concerned with material cause. What is the nature of the inter-class relations? Our response depends on *how* *the classification is being used by the modeler*, but generally the kind of relation represented in Figure 15 is understood to indicate a simple grouping. It would be analogous to what Georgescu-Roegen (1963, 1971, pp. 107–110) referred to in his discussion of the external addition of economic processes—processes which, despite being grouped together, continue to run in parallel. In contrast to Figure 14, there is *no relation of authority between classes* in Figure 15. It is not that there is a material entity "steel" that dominates a material entity "stainless"! Figure 15 is what we would call a *taxonomy*.

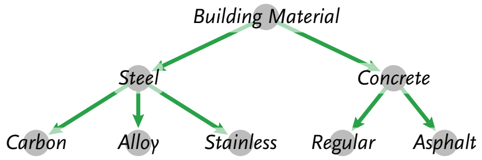


Figure 15 A taxonomical classification of building materials, representing for us a material cause.

A second example of a taxonomy is the description of economic sectors presented by Figure 16. What phenomenological concern does Figure 16 refer to? One of the four causes? Or is it a modifier? Again, it depends on how the classification is used by the modeler. As a classification of end-uses specifying which sector(s) the materials in Figure 15 are used in, it could represent a final cause. As a description of which sector a construction worker is employed in, it could work as a modifier of a classification of efficient cause. Either way, we generally would not understand the inter-class relation in Figure 16 to be one of authority.

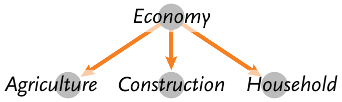


Figure 16 A taxonomical classification of economic sectors (economic in an institutional sense), representing for us a final cause.

A third and final example is the elaboration of geopolitical boundaries presented by Figure 17. What is the concern of such a classification? Figure 17 might provide spatial context, in which case it is a modifier taxonomy providing geographical context. Figure 17 might also be a representation of the political chain of authority between Spain and Barcelona, in which case it is a modifier hierarchy providing geopolitical context. The epistemological claim differs between the two, but either way Figure 17 could give us context for a final cause, such as one of the classes presented by Figure 16, or a material cause, such as one of the classes presented by Figure 15. The type of information provided is not one of the four causes, but it is certainly useful when creating an insightful, reproducible model.

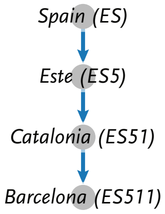


Figure 17 A spatial context modifier detailing levels of political boundary from country-level down to city-level; parenthetical details note the corresponding NUTS classification identifier.

It should be duly noted that some authors have proposed terminology to distinguish "hierarchies" exhibiting the types of relations historically presented by taxonomies. E. Mayr (1982) distinguishes between constitutive hierarchies and aggregational hierarchies as well as inclusive hierarchies and exclusive hierarchies. M. Grene (1987) distinguishes between control hierarchies and taxonomic hierarchies, also known as hierarchies of embedment or classification hierarchies, respectively. Many other propositions could be added to the list, those of Salthe (2002) and so forth.

From our perspective, indeed from an etymological perspective, terms such as “aggregational hierarchy”, “taxonomic hierarchy” and “classification hierarchy” are at best confusing and at worst oxymoronic. A broadening of the definition of hierarchy is not necessarily a bad thing, but severe issues in our ability to understand and model complex systems arise when we do not enforce an obligate distinction between taxonomic inclusion and hierarchical composition. Recall that in Section 2.3.1 we identified hierarchical composition as a mapping where the final cause of one process becomes the efficient cause of a second process. This is just one possible understanding proposed by relational biology, but note that it is indeed true to the term’s origins—hierarchical composition is a relation of authority, one process over the other. As we saw in Sections 3.1.1 and 3.1.2, the epistemological commitments embedded in hierarchies are necessary when modeling social-ecological systems in so far as they create meaning and order. It is essential for modelers to be clear in their representation of those claims.

3.3 MULTIDIMENSIONAL CLASSIFICATIONS

3.3.1 *Cartesian Products*

In the previous section, each of the classifications that was presented addressed just one single concern, be it an efficient cause, a material cause, a spatial context modifier, or what have you. In Chapter 2, we mentioned that *all four of Aristotle’s causes* must be declared if one hopes to generate a complete explanation. As modelers, in the act of, for example, generating databases, we typically aim to keep our concerns like this—disjoint. The classifications we use thereby remain modular, and our use of them agile (they can easily be added or removed, for example). How then should we go about bringing multiple classifications into play?

Classifications are formally representable as directed graphs (“digraphs”). For some digraph , we have the definition $G = (V, E)$, where V is a set of vertices (nodes) and E is a set of ordered pairs of vertices—the directional “edges” or links between vertices. Assume an accountant is using the classifications previously presented in Figure 16 and Figure 17 to describe a system. We will refer to those classifications as G and H, respectively. We can talk of a phenomenological *space* that is somehow generated by both classifications under consideration. Mathematically speaking, to combine G with H, we use a graph product. As any introductory textbook on discrete mathematics will detail, there are many kinds of graph product, each with different properties and end-results. For our purposes, the Cartesian graph product[12] will serve the purpose of intuitively combining G and H, written

[12] Historically, $G \times H$ was used in reference to the Cartesian product of graphs. In modern times, $G \times H$ typically refers to the tensor product of graphs. Following our criticism of reductionism, related to the legacy of Descartes, the term “Cartesian” in Cartesian product can be seen as an unfortunate (but benign) coincidence.

$$G\square H \qquad (1).$$

Consider the graph presented by Figure 18, which is a laid out[13] visualization of the result of Eq. (1). Figure 18 is a *multidimensional classification*—it contains two reasonably disjoint dimensions, one concerned with economic sectors as final cause and one concerned with a geopolitical modifier. It is the skeleton of a *knowledge space* resulting from the use of G and H in an analysis.

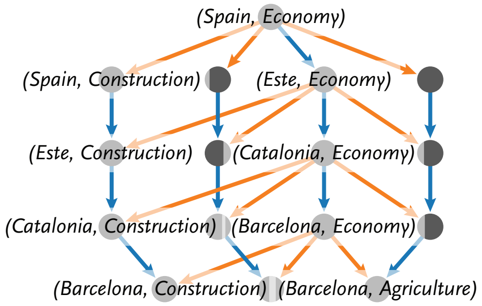


Figure 18 A two-dimensional classification detailing, for us, a final cause and a geographical modifier.

Consider also Figure 19, which presents the Cartesian product of Figure 15 and Figure 17. Figure 19 is a consideration of material cause together with a spatial context modifier.

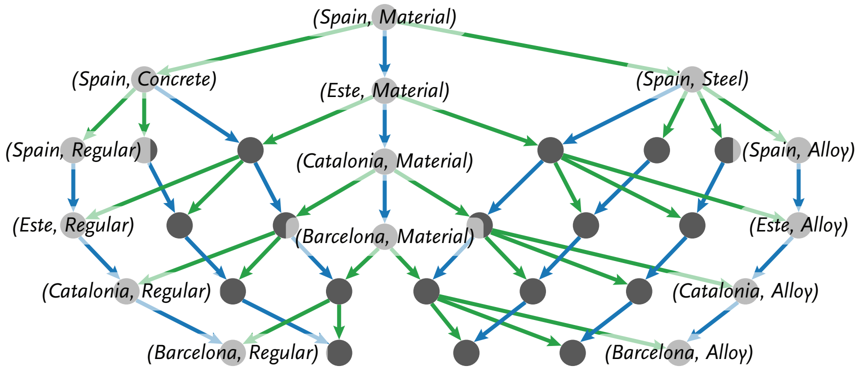


Figure 19 A two-dimensional classification detailing, for us, a material cause and a spatial context modifier.

Naturally, there's nothing limiting us to the combination of just two classifications. We can and should continue our line of thought and combine at once all the relevant classifications used in our analysis. Figure 20 presents the Cartesian product of the classifications presented in Figure 15, Figure 16 and Figure 17, meaning it is a consideration of material cause, final cause and spatial context modifier. One can see where we're headed with this.

[13] All figures of multidimensional classifications in this section use the layout algorithm of Sugiyama et al. (1981). As an alternative, I can recommend the fast multiple multi-level method (FM^3) algorithm of Hachul and Jünger (2005), which may better convey the multidimensional nature of the graph but lowers readability (it tends to stack and therefore obscure nodes).

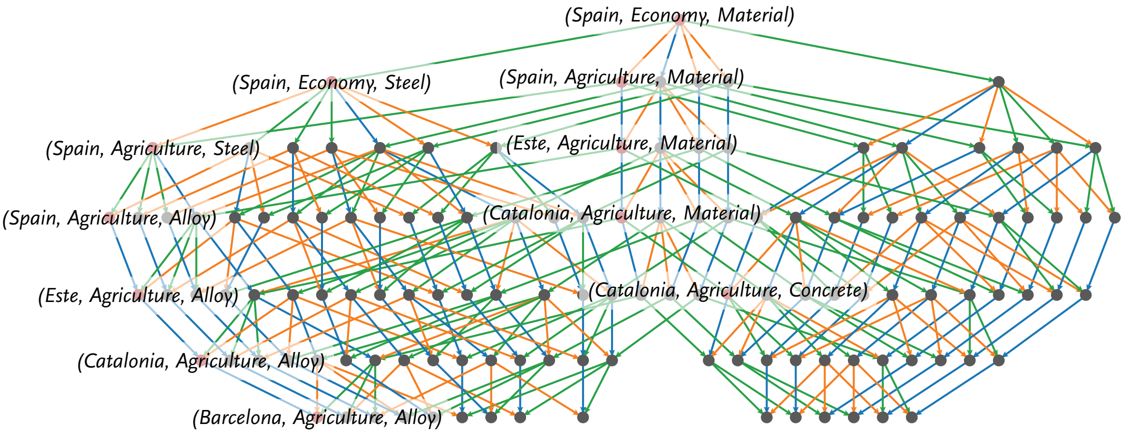


Figure 20 A three-dimensional classification detailing, for us, a material and a final cause with a spatial context modifier.

In the discourse, there are breadcrumbs hinting at the value of creating and using multidimensional knowledge spaces in this way. Unfortunately, the breadcrumbs remain…breadcrumbs. The cooperative application of classifications along the lines of our discussion is a largely unexplored topic that complements well Chapter 2's discussion of how conceptually to go about modeling social-economic systems.

In *The Ghost in the Machine*, Koestler (1967, p. 88) claims that "memory is 'dissectible' into hierarchies [sic] with different criteria of relevance". He immediately moves on after that assertion, however, leaving the breadcrumb undeveloped in operational terms and qualifying it as "frankly, speculative" (Koestler, 1967, p. 88). In a similar vein, Hardesty defines Hutchinson's concept of an ecological niche (1957, 1965) as "a euclidean [sic] hyperspace whose *dimensions* are defined as environmental variables[14] and whose *size* is a function of the number of values that the environmental variables may assume for which an organism has *positive fitness*" (Hardesty, 1975, p. 71). Like Koestler, Hardesty leaves the breadcrumb largely unexplored in practical terms. Both Koestler and Hardesty's musings are compatible with what we have been doing in this section. Their dismissal may have been duly justified in the realms of cognitive science and theoretical ecology—not so when modeling social-ecological systems.

The thrust of this section is that the Cartesian product of classifications is a capable way of structuring a knowledge space. It is an approach that maintains concern dimensions in an intuitively modular fashion, and we will show its remarkable practical worth in Chapter 5 when interpolating and exploring the option space of agriculture in the European Union. Of course, there are practical limitations to combining a large number of classes. Figure 20 was already starting to become complicated to visualize, and it reflected still a very basic knowledge space. We should be careful to not let that practical concern limit our imaginations, however. Combinatorial explosion cannot be entirely

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[14] In a properly formatted database, each classification is its own column—what is in statistical terms a *variable*. More on the subject in Appendix A.

avoided, but it can be worked around if we're clever with the programming. Appendix A elaborates some practical ways of navigating the issue, organizing databases and working with them in a non-resource-intensive manner.

3.3.2 *Checking for Completeness*

Now that we have constructed a skeleton for our knowledge space, are we done? Can we proceed to elaborate social-ecological models within its bounds? Not quite. The final step in the construction of a social-ecological knowledge space is to *audit the multidimensional structure* that emerges from the Cartesian product of classifications. Firstly, the scientist must check the structure for completeness. Does it lack classes that it should have?

In Chapter 2, we mentioned that, when considering social-ecological phenomena, all four causes must be declared in a complete explanation. So, does the knowledge space being considered allow for the robust consideration of all four causes? If not, how can the expressive power of the underlying multidimensional structure be improved or expanded? There are two levels to checking the completeness of the multidimensional structure of a knowledge space:

1) Are all four of the causes explicitly considered?
2) For each of the four sets of causes considered, are the primary causes included?

The three-dimensional structure presented by Figure 20 includes, for our purposes, dimensions of material cause, final cause and geographical context. What of efficient cause and formal cause? The knowledge space represented by Figure 20 fails the first check—it has no hope of supporting a robust social-ecological model.

We could attempt to fix that shortcoming by taking the Cartesian product of Figure 20 and the classification of construction workers presented in Figure 14. That would add to our knowledge space an ability to express efficient cause (albeit rudimentarily). We would then only miss a dimension of formal cause. Or do we?

Formal cause can be tricky to audit as there are many non-standard ways in which formal cause can be considered in a model. We need to tread carefully here. Aristotle noted that the explanation of formal and final cause is often one and the same—inseparable. In our consideration of "Why a city?" in Chapter 2, we identified one of the final causes as the human desire to live like sardines in a can. That particular final cause does tell us a little about the layout of the city being constructed, for example, the infrastructure must be laid out so as to enable humans to live in close proximity, but it doesn't allow for detailed information on the distribution of offices and apartments, the gridwork of roadways, possibly bike paths and so forth. It doesn't articulate formal cause to a significant extent.

If we wanted to get serious about improving our explanatory power, we could continue with our approach of adding new classifications, this time adding one or more concerned with formal cause. Figure 21, for example, details different *forms* that steel can take. It could be used to specify formal cause against the classification of building materials presented by Figure 15.

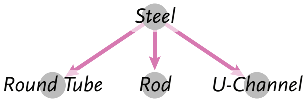


Figure 21 A taxonomical classification detailing different forms steel can take.

One alternative way that consideration of formal cause could be realized is to extend a knowledge space with a spatial or geographic information system. For example, we could generate a cartographic layout of the city being constructed, showing us exactly how it is that humans prefer and intend to live like sardines in a can. This would be one intuitive way of getting at formal cause. Geographic information systems are themselves built on classifications and extending a knowledge space with a geographic account means crossing the multidimensional structure of the knowledge space with the underlying classifications of the geographic account. As would have been the case if we had proceeded to find a Cartesian product in the prior manner, all class combinations are expressible.

By the end of the day, we must somehow have included all four causes as dimensions in our knowledge space. Otherwise, it is not possible that models derived from our knowledge space will consider all four causes, hence derived models will not be able to generate robust explanations of reality. Although it is not necessarily the case that all four causes are included in the same way, we should be able to explain or otherwise justify any abnormalities.

What about the second task of the auditor? Are the *primary* causes included? It may seem *prima facie* that a cause is being considered due to the inclusion of a certain classification in the structure of a knowledge space, when, in reality, that classification's ability to speak towards the natural transformation of interest is merely *secondary*. If we were to consider the tools of construction used by the workers in the construction of the city, that's certainly a useful consideration, but tools are likely best understood as a less proximate consideration of efficient cause than the workers. That statement stands true at least from a perspective of societal metabolism. Tools don't have agency, they themselves must be motivated by an agent—a agent that should be given consideration in the knowledge space. N.B. Different philosophers take different approaches to expressing "efficient cause". In the canonical example of explaining a marble sculpture, some philosophers will identify the sculptor as the efficient cause and some will identify the "art of sculpting", drawing attention to the fact that the sculptor agent also identifies with other, coincident, "accidental causes". B. Russell (2005, p. 161) writes that "efficient cause is the contact of the chisel with the marble”, being yet another take on expressing efficient cause—a much more specific, microscale one.

3.3.3 *Detecting “Infelicity”*

In addition to verifying the *completeness* of a knowledge space, and possibly expanding it, scientists in the act of auditing must verify whether any knowledge space aspects should be removed. Does the multidimensional structure include classes that it shouldn’t?

Thanks to our efforts to maintain modularity, the removal of entire, irrelevant concern dimensions is trivial. What is less trivial is the removal of individual, nonsensical classes emerging from the initial act of space creation. There is no guarantee that all “multidimensional” classes (speaking now of classes in the multidimensional structure, classes made of classes) are sensical. For example, the meaningfulness of the class in Figure 19 referring to agriculture in Barcelona seems questionable. Barring a transition to a new urban agriculture utopia, we should strongly consider removing that class from the knowledge space, it may be misleading. But how can we defend our choice, eliminate or maintain?

The general grounds for class elimination are that the class in question is *ungrammatical*. Still, “grammar” is not an easy concept to understand. In the words of Wittgenstein (2009, p. 123), “grammar tells what kind of object anything is”. Hence, grammar expresses essence. Wittgenstein (1980, p. 60) clarifies that “[g]rammar describes the use of the words in a language” and the “use of a word in the language is its meaning”. Hence, grammatical rules are normative conventions. They are purely descriptive, not explanatory. N.B. For our discussion, the term “word” can be replaced with *class* and the term “language” with *knowledge space*.

In *Philosophical Investigations*, Wittgenstein (2009, pp. 146–147) presents a proper example:

> When I say that the orders “Bring me sugar!” and “Bring me milk!” have a sense, but not the combination “Milk me sugar”, this does not mean that the utterance of this combination of words has no effect. […] When a sentence is called senseless, it is not, as it were, its sense that is senseless. Rather, a combination of words is being excluded from the language, withdrawn from circulation.

Wittgenstein’s “Milk me sugar” *does* provoke an effect, but yet, in “everyday” speech, it is judged nonsensical. In “everyday” speech, “Milk me sugar” is *ungrammatical*. Similarly, it is not that agriculture in Barcelona has no effect, it is simply that the combination of *agriculture* and *Barcelona* is somehow inappropriate, or *infelicitous*, within the “everyday” system of grammatical rules. Who gets to decide those rules?

On the one hand, the scientist building the knowledge space has the final word in deciding the rules. But just as language comes to the speaker from the embedding society (past and present), a knowledge space comes to the scientist from the extended peer community. Its vehicle is narratives. If we run an exercise in anticipation and choose to endorse the narrative that technological innovation will soon result in an urban agricultural utopia, perhaps the class is appropriate. If we instead take a more skeptical stance on the growth of urban agriculture, the class may better be considered inappropriate. The final determination depends on *which narrative is endorsed*.

This is, actually, a very important and not at all obvious realization. It affects nothing less than *how we go about conducting science*. Scientific mythologies are born from the examination of ideas abstracted from their original contexts. They are not uncommon. S. Jasanoff's (2015) discussion of sociotechnical imaginaries provides good evidence of their ubiquity. Scientific mythologies emerge when we compare two notions with similar syntax but dissimilar semantics. The point of reviewing Wittgenstein on grammar is to smash the idea that the rules of the game could ever possibly be pure syntax. The extended peer community needs to check scientific grammars in accordance with their guiding set of narratives, to verify each point of a knowledge space.

To be clear, syntactically, agriculture in Barcelona makes sense. It is the combination of an economic sector and a geopolitical entity, and certainly geopolitical entities have economic sectors. It is on semantical grounds that we question its sense. Ryle (1945, p. 206, cited by Tanney, 2015), a contemporary of Wittgenstein who engaged with many of the same topics, writes: "a given word will, in different sorts of context, express ideas of an indefinite range of differing logical types […] [a]nd what is true of single words is also true of complex expressions and of grammatical constructions." It is not only up to the scientist to decide the context of a social-ecological model used in sustainability science, rather it is the task of the extended peer community.

The ultimate question for a social-ecological system expecting to manage a sustainability crisis is to discover what the grammar of *sustainability* is for them. The grammar is, of course, supercritical. It does not resolve into uncontestable visions of "sustainability". In fact, from an entropic perspective, social-ecological systems are not sustainable and can *never* hope to do. As Taleb (2012) further, eloquently points out in *Antifragile*, social-ecological systems also do not even *want* to be subcritical, they *gain from disorder*. The specific selection of justification, explanation and normative narratives define the grammar of sustainability for a given social-ecological system, a reality which then dictates the structure of the knowledge spaces used for models created to support sustainability assessments.

3.3.4 *Endnote on Input-Output Analysis*

Before moving on to case studies in Chapters 4 and 5, it is useful to provide a brief "real world" example drawing attention to the fact that, while what we have discussed in Section 3.3 can seem abstract and hopelessly philosophical at times, it is indeed a powerful and informative way of approaching the construction of a social-ecological model.

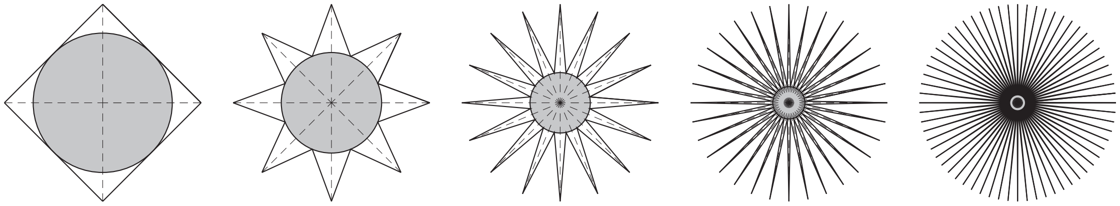
Whether or not they realize it, proponents of input-output analysis à la Leontief use impoverished knowledge spaces similar to that represented by the multidimensional structure presented in Figure 20 (which detailed materials, economic sectors and geopolitical context). Hence, although approaches based on input-output analysis, such as material and energy flow analysis, can provide useful descriptions of certain aspects of natural systems, but they cannot hope to serve as models. Analysts and policymakers can often be found to have fallen into the trap of overextending knowledge claims generated by the use of such approaches, overlooking the fact that the underlying explanatory basis is impoverished.

Georgescu-Roegen's war on conventional economics, epitomized by *The Entropy Law and the Economic Process* (Georgescu-Roegen, 1971), is brought to mind. One essential way in which Georgescu-Roegen critiqued input-output analysis was his assertion that such an approach lacks consideration of funds—system elements that maintain their identity throughout the course of analysis despite the existence of input and/or output flow(s) to and from them, mentioned previously in Section 2.4.1. As a refresher, two examples of a fund resource are a sustainably managed dairy cow and a sustainably managed aquifer—despite the feed inputs, milk output (dairy cow) and water output (aquifer), both resources typically maintain their identity over the course of, say, a year. As Georgescu-Roegen's critique went, funds like dairy cows and aquifers provide external referents against which intensive values can be calculated. They provide something against which to scale and give an idea of what is possible. Without them, we're liable to generate wild extrapolations outside the realm of possibility, such as taking seriously the demand to increase milk production far beyond what is biophysically possible given the standing herd of milk cows, which cannot be produced in a factory overnight. In addition to giving an idea of what is possible, funds provide a grasp on how system state will change depending on the pressures exerted on it. If 20–30 liters of milk per day are expected from a dairy cow, the cow will be culled at 3–6 years of age, but if 3–5 liters/day are expected, the cow will easily live to 20 years. Slesser (1978, p. 41) got at a somewhat similar notion to Georgescu-Roegen in his statement, instigated by frustration over the handling of energy in the economy by economists, that "any production function which omitted a key element of the process could lead to faulty conclusions, especially if applied to some new situation."

But funds are, after all, a certain type of efficient cause, one with the added quality of maintaining its identity throughout the analysis. A knowledge space audit can safeguard analysts and policymakers from overextending knowledge claims—a quick check of an input-output knowledge space will reveal that no efficient cause is considered, hardly an encouraging sign!

3.3.5 *Endnote on Sensitivity Analysis*

It is instructive to explore how a classic lesson from numerical sensitivity analysis can help inform the exploration of the multidimensional structures of knowledge spaces presented in Section 3.3.1. Consider Figure 22, which illustrates various n-cubes with inscribed n-balls, projected into two-dimensions. Here n represents the number of dimensions, before projection. The inscribed n-balls are shown in grey.



2-dimensions *4-dimensions* *8-dimensions* *16-dimensions* *32-dimensions*

Figure 22 Various n-cubes with inscribed n-balls, projected down to two dimensions.

N.B. We're visualizing here an idealized case where the dimensions of the knowledge space are orthogonal. We previously advocated that concern dimensions are modular, not necessarily independent. Movement along one concern dimension in a knowledge space does not need to be mutually exclusive to movement along any number of other concern dimensions[15]. The example is nevertheless useful.

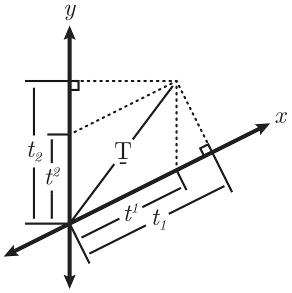
As the discussion in sensitivity analysis goes, the inscribed n-balls represent the proportion of numerical model results explored by "one factor at a time sensitivity analysis". As the number of factors (variables) in a model grows, the proportion of numerical model results explored by "one factor at a time sensitivity analysis" asymptotes to zero. As the number of dimensions increases in Figure 22, the majority of the volume of the hyperspace shifts outside of the grey area. Formulaically, the volume percent taken up by the inscribed n-ball can be found as

$$f(n) = \frac{\pi^{n/2}}{n2^{n-1}\Gamma(n/2)} \tag{2}$$

where Γ is the gamma function. As the number of dimensions increases, a relatively smaller fraction of the n-cube volume is captured by the n-ball. With two dimensions, 78.5% of the volume is explored by "one factor at a time sensitivity analysis". With ten dimensions, just 0.2% of the volume is explored! Leaving so much volume unexplored means that we cannot say much about the output values of the model—we leave most of their potential numerical range unexplored. (See Saltelli *et al.* (2010) for an involved discussion from within the field the sensitivity analysis.)

Rather than representing numerical model results, the dimensions of the various n-dimensional shapes presented in Figure 22 can be meaningfully interpreted as distinct concern dimensions of knowledge spaces, such as in the

1	100%
2	78.5%
3	52.4%
4	30.8%
5	16.4%



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[15] Orthogonal and parallel projections in a skew coordinate system.

multidimensional classification we visualized in Section 3.3.1, material, final and so forth. This interpretation indicates an appropriate way of conceptualizing how it is that we should go about navigating knowledge spaces—never one dimension at a time.

3.3.6 *Endnote on the Cartographic Analogy*

The analogy between cartography and the actions of scientists is not, as a subject, new. One recalls in Chapter 1 the discussion of Abbott's *Flatland* and Ryle's thoughtful characterization of scientists as cartographers. S. Toulmin (1953, p. 105), himself greatly inspired by Wittgenstein, writes in *The Philosophy of Science*:

> the analogy between physical theories and maps extends for quite a long way and can be used to illuminate some dark and dusty corners in the philosophy of science. […] [A]fter an overdose of arguments in which physics is treated on the pattern of natural history, it can act as a healthy purge.

But the cartographic analogy extends quite a bit further than Abbott, Ryle, Toulmin and other like-minded philosophers have cared to explore. It is a particularly fertile ground for discussion in light of what has been said in Sections 3.2 and 3.3, and for creating an argument for post-normal science and methodological pluralism. Past renditions of scientists as cartographers have focused on the act of the scientist as the generator of a scale-representation of reality on a piece of paper, epitomized by A. Korzybski's (1994, p. 58) famous line:

> [a] map *is not* the territory it represents, but, if correct, it has a similar structure to the territory, which accounts for its usefulness.

But it emerges that the scientist's dynamic role as a *projector* is also critical. Exploring this new take on the cartographic analogy should help visual thinkers, myself included, conceptualize the role of scientists as post-normal game-players. B. Mandelbrot's (1967) famous question, "How long is the coast of Britain?", the answer to which *depends on the descriptive domain of the observer*, gets more towards the general idea. Mandelbrot showed us how tricky a concept dimensionality is, eloquently teaching the world about the fractionality of dimensions.

It is useful to start by briefly refreshing on map projections. Imagine peeling an orange and then trying to flatten the orange peel. There are multiple ways of going about flattening, none of which is "optimal". When a cartographer projects a three-dimensional representation of Earth onto a two-dimensional plane, the same statement applies. The cartographer has the option of preserving area, form, distance, direction or shortest route—it is not possible to preserve all five simultaneously.

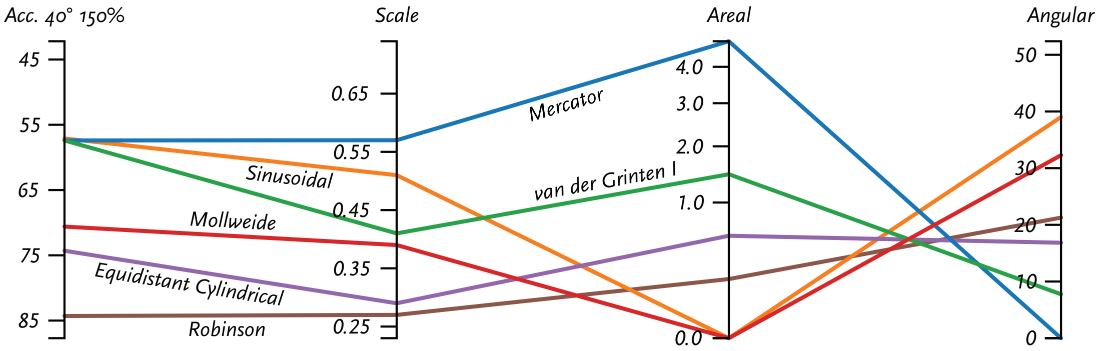

Figure 23 Comparison of a few popular map projections detailing four metrics of distortion. Lower is better. Inspired by the work of Bostock (2019).

Figure 23 presents some of the most important metrics of distortion for a few popular map projections—the acceptance index (Jenny, Patterson and Hurni, 2010) and scale, areal and angular distortion. For each metric, the lower the value, the lower the distortion. What Figure 23 visually demonstrates is the unavoidable existence of trade-offs when projecting maps. The choice to accept certain types of distortion over others implies the preselection of a specific purpose for the map to be generated. Figure 24 complements Figure 23 by visualizing four popular projections—Mercator, sinusoidal, "Mecca" (or Craig retroazimuthal) and Littrow.

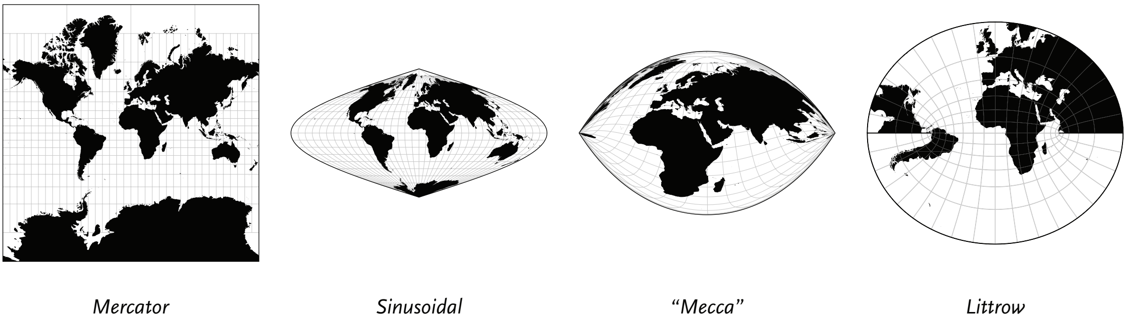

Figure 24 Comparison of four different map projections.

The *Mercator projection*, a type of conformal projection, does a perfect job at locally preserving angle but an overall terrible job at preserving area and scale. Google Maps uses a version of the Mercator projection. The *sinusoidal projection*, a type of equal-area projection, does an overall terrible job at preserving angle and a poor job at preserving scale but a perfect job at preserving area. A sinusoidal projection is a good choice for thematic cartography, such as the mapping of populations or biomes. The "*Mecca projection*" preserves directions to any one point, and therefore could be of help to Muslims looking to find the qibla (direction to the Kaaba in Mecca). Finally, the *Littrow projection*, although off-putting in that it clips shapes along its centerline, is the only conformal retroazimuthal map projection. It is the only projection that preserves angle measurements locally and directions (azimuths) radiating out from either one or two points, and hence it has its own set of distinct advantages.

Again, no single projection is optimal. Each projection has its advantages, its disadvantages and its domains of appropriate applicability. The point to stress is that the identification of one projection over another follows the identification of a purpose. It remains only to then realize that scientists working with multidimensional knowledge spaces also "project" those spaces. N.B. We already had to project the multidimensional classifications presented in Section 3.3.1 in order to get them onto the pages of this dissertation. Consider how absurd it would be to present a complicated, high-dimensional knowledge space to decision-makers. The rudimentary examples visualized in Section 3.3.1 were already getting cluttered. If the scientist *combines* dimensions, therefore reducing the overall number, they can present a more manageable construct. Such an action might occur when the scientist creates a composite index, for example. Just like map projections, however, there is an infinite number of ways in which a knowledge space can be "projected" into a lower dimension. All of those projections are political and follow the predetermination of a purpose.

Continuing where 3.1.2 left off, we could visually re-interpret the narrative bounds of knowledge spaces to illustrate the point. Figure 25 presents orthographic (left) and cylindrical (right) projections of the narrative mosaic of a three-dimensional knowledge space. Although both projections are faithful manipulations of the same three-dimensional object, they are not, in any way, shape, or form, interchangeable. Recall that the tesserae of the mosaic are territories colonized by different narratives—different projections preference one decision over another. Comparing left with right, it should be clear that different projection choices subjectively emphasize certain knowledge space aspects over others.

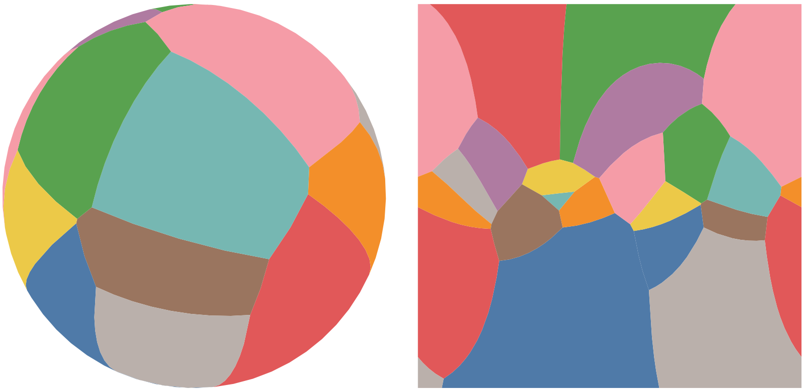

Figure 25 Comparison of orthographic (left) and cylindrical (right) projections of a visually interpreted three-dimensional knowledge space.

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4 QUANTITATIVE STORYTELLING ON A RENEWABLE ENERGY TRANSITION[16]

4.1 INTRODUCTION

4.1.1 *Introduction to the Issue*

In Chapters 2 and 3, we discussed modeling for sustainability science. We also proposed a new approach. In this chapter and the next, two case studies inspired by that approach will be provided, here to the European energy sector and in Chapter 5 to the European agriculture sector. We will be working out practical ramifications of our new approach along the way and exploring ways in which both the energy sector and the agriculture sector have become subjugated to the dissipative sectors—disenfranchised, unable to "vote" on the set of narratives used to guide society along the elusive path to a "sustainable future".

One of the flagship initiatives of the European Commission is to transform the European Union into a resource efficient, low-carbon economy (EC, 2018). The primary justification narrative ("Why?") of that initiative is the perceived need to combat climate change. The Commission also asserts the explanation narratives ("How?") that, within a few decades, economic growth and energy use must be decoupled while economic competitiveness must increase and energy security must be realized. Unprecedented societal determination and commitment would be needed to realize such a heroic vision. Entire sectors of the economy would need to reinvent themselves inside a very short period of time. A reflection on the Commission's choice of normative narratives ("What?") reveals, however, that their ambitious energy policy package is based almost entirely on *structural* and *technological* change. The understanding of "sectoral reinvention" is incomplete (EC, 2010a, 2010b; EU, 2012).

Adding to the concern over the Commission's framing of the knowledge space is the expectation that the European Union's energy transition will be achieved by a series of technological innovations driven by the *invisible hand of the market*. The expensive transition experiment done in Germany, the *Energiewende*, illustrates. According to the German Federal Court of Auditors, the *Energiewende* has thus far been *characterized by inefficiency* (Bundesrechnungshof, 2016, p. 19). The Court states that the German Ministry of Economics and Energy has "so far not taken *any* steps to ensure that inefficient programmes which at the same time contribute little to energy transition are phased out" (*ibid.*, 2016, p. 40, emphasis added). At the same time, significant economic investments in alternative energy sources—nearly €200 bn—has led Germany to the highest electricity prices in Europe (EC, 2019) *without significantly reducing emissions levels* (Scholz *et al.*, 2014). This

[16] Some parts of this chapter are from Renner and Giampietro (2020).

Renner, A., & Giampietro, M. (2020). Socio-technical discourses of European electricity decarbonization: Contesting narrative credibility and legitimacy with quantitative story-telling. *Energy Research & Social Science, 59*. https://doi.org/10.1016/j.erss.2019.101279 experience, including societal hesitance to question the decisions of the *Energiewende* policies, flags the existence of a systemic problem with the quality of the scientific evidence used to inform the process of policymaking when dealing with complex issues.

Simultaneous consideration must be given to non-equivalent dimensions and scales of analysis and legitimate but divergent expressions of concerns when addressing complex issues. When faced with impredicativity, the very definition of what should be considered rational and what should be considered fact will *always* be contested (Lyotard, 1979; Latour, 1993). Using the Cartesian dream of prediction and control to guide an energy transition is hence problematic in that it invites a massive generation of expectations translating into a political activity with the goal of mobilizing resources in order to *colonize the future* of the society. S. Jasanoff (2015, p. 4) refers to this act as the establishment of *sociotechnical imaginaries*, which she defines as

> collectively held, institutionally stabilized, and publicly performed visions of desirable futures, animated by shared understandings of forms of social life and social order attainable through, and supportive of, advances in science and technology.

Established imaginaries are influential insofar as they create and manage future expectations (Felt and Wynne, 2007). Expectations, through their creation of "dynamism and momentum" (Brown and Michael, 2003, p. 3), play an essential role in "guiding technological innovation and sustainability transitions" (Lazarevic and Valve, 2017). It must be realized that an aggressive mobilization of expectations during an energy transition translates into an ideological endorsement—a certain, unquestioned way of breaking social-ecological impredicativities. Once that ideology is established, it need no longer be reflected upon (Konrad, 2006) and any myths that exist in conjunction with it are not allowed space for critical and hesitative reflection (Buclet and Lazarevic, 2014; Lazarevic and Valve, 2017).

In the case of the *Energiewende*, a massive set of expectations has been created. The conflict of those lofty expectations with widespread failures has led to substantial disillusionment and to the concern of Kay Scheller, the president of the German Federal Court of Auditors, that "voters could soon lose all faith in the government because of [the *Energiewende*'s] massive failure" (Dohmen *et al.*, 2019). If we can agree that renewable energy transitions are indeed urgent things, societal disillusionment truly is an unfortunate reality.

4.1.2 *Quantitative Storytelling*

In post-normal science for governance, the quality of analytical outcomes depends on clarifying the choices that have shaped the content of the evidence base and the modes of analysis considered as salient and credible. Before refining the minutiae of existing dynamical models—solving puzzles—it is important to explore counterfactuals to hegemonic hero-type storylines and to question whether existing science-policy consensuses are ignoring crucial issues by taking too narrow a view of the challenges to be faced—playing games. Janda and Toupizi (2015) suggest that learning-type storylines can gainfully problematize hero-type storylines such as those of the *Energiewende* and the Commission. The intent of problematizing with learning-type storylines is not to undermine, the intent is to balance and develop the standing discussion. Learning-type storylines provide a positive discursive feedback and lead valuably to the co-creation of increasingly robust transition imaginaries (Jasanoff, 2015; Roberts, 2017). Surely a more informed discussion about the problems and potential troubles of standing hero-type storylines will benefit society and improve policy framings.

In the *Moving Towards Adaptive Governance in Complexity* project[17], we have developed a new approach to the assessment of storylines called *quantitative storytelling* (Saltelli and Giampietro, 2017). The approach begins by taking stock of the narratives used to shape the storyline of interest—the set of justification, explanation and normative narratives. It then uses quantifications to test the validity of the narratives across the following three dimensions, typically through an anticipatory exercise.

1) Feasibility, meaning compatibility with biophysical constraints.
2) Viability, meaning compatibility with economic and technical constraints.
3) Desirability, meaning compatibility with institutions, normative values and aspirations of the actors in the society.

The aim of quantitative storytelling is simply to check the *quality* of the elected storyline. No solutions to the problem ("Whose problem?") are proposed and no improvements ("For whom?") are suggested. Quantifications should not be used in complexity to predict future states of a system or to identify an ostensibly optimal course of action, but they should be used to check the robustness of storylines. In this chapter, we use quantitative storytelling to falsify the storyline that "in two or three decades, it will be possible to scale-up the supply of intermittent sources of electricity (wind- and solar-based) to obtain a significant decarbonization of European economies". In Section 4.2, we start by developing a rudimentary knowledge space.

4.2 ENERGY QUANTITY AND QUALITY

4.2.1 *Accounting for Electrical Energy*

An energy sector transition is a very complicated ordeal. It requires a rewiring of sector couplings and a re-arrangement of social practices, associated with the patterns of consumption in both paid and non-paid work sectors. It also requires a change in existing technologies, a revolution in economic business models and a re-thinking of institutional regulation. In short, an energy sector under transition is being forced to "go for something completely different".

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[17] The afterword provides more information on the *Moving Towards Adaptive Governance in Complexity* project.

Analytical approaches that work well at predicting the continuous future fall apart when used to anticipate this ruptured future. We must pay close attention to the fundamentals of energy accounting.

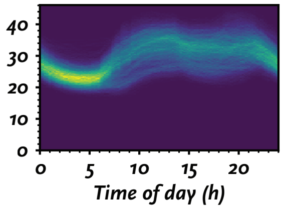
Different forms of energy present different challenges. Electrical energy happens to be convenient, versatile, reliable and precise. Technologies that convert electrical energy to other useful forms of energy (mechanical, chemical, thermal) are also highly efficient. All these characteristics are extremely desirable for society. However, electrical energy does have a fundamental drawback in that it is a flow resource. As previously discussed in Sections 2.4.1 and 3.3.4, flow resources are not directly useful unless they are either put to immediate use or stored. In contrast to electrical energy, chemical energy (fossil fuels, biofuels) and nuclear energy (fissile material) can typically be treated as stocks—they allow a consumer to generate a flow of energy whenever the consumer desires. The chemical energy in the tank of a car, for example, can be used whenever the owner of the car fancies a drive.

Electrical energy's special aspect as a flow implies the need for modelers to consider a high-resolution spatial-temporal coupling between power capacity creating supply and power capacity creating demand[18]. Crude oil consumption measured in gigajoules per year may be an insightful indicator when the system of interest is a country-level social-ecological system, but electrical energy measured in gigawatt-hours per year has serious drawbacks. When looking to anticipate issues of desirability, viability and feasibility, it would be vastly more relevant to assess kilowatt-hours of electrical energy at a localized resolution.

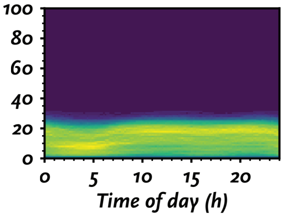
We can use these insights to propose a *classification of quality* of any given watt-hours in relation to regulatory and policy aspects (recall Section 3.1.4 on science as the *assurance of quality*, not truth). Our "engineering perspective" stands in contrast to business-as-usual economic methods such as the popular "levelized cost of electricity" metric, based on the assumptions that "electricity output is perfectly interchangeable and homogeneous" (Mezősi, Szabó and Szabó, 2018), and the idea that the invisible hand will shoulder the burden of managing issues of substitutability, hence we need not worry ourselves. In the words of H.T. Odum, a "gallon of gasoline will power a car the same distance no matter what its price" (Brown, Hall and Wackernagel, 2000, p. 707). Three classes of watt-hours are relevant for our storyline, as follows.

1) Peak-load, the supply of which is reliable and easy to regulate.
2) Base-load[19], the supply of which is reliable but somewhat difficult to regulate.
3) Intermittent[20], the supply of which is *not* reliable and *cannot* be regulated, only curtailed.

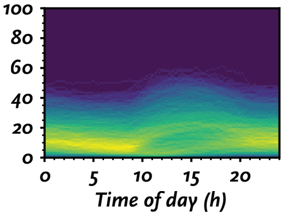
These three classes of watt-hours are presented in order of descending quality and it should be noted that there does exist a correlation between quality and price—the higher the quality, the higher the price. Peak-load watt-hours generally cost more to produce than base-load watt-hours and base-load watt-



[18] The 24h-fingerprint of total electrical energy production (GW), Spain 2007–2019. Production and consumption are closely matched.



[19] The 24h-fingerprint of electrical energy production from coal primary energy sources as % of daily max, Spain 2007–2019.



[20] The 24h-fingerprint of electrical energy production from intermittent (wind and solar) primary energy sources as % of daily max, Spain 2007–2019.

hours generally cost more to produce than intermittent watt-hours. The fact that intermittent watt-hours produced by wind turbines and solar photovoltaic panels are cheaper in terms of fixed and operating costs than base-load or peak-load watt-hours produced by coal thermoelectric plants or open-cycle gas turbines is not by itself a particularly relevant piece of information for the design of an electrical grid. All three classes of watt-hour have their uses. Despite the fact that journalists, policymakers and a fair share of researchers and accountants don't give a second thought to summing all watt-hours together, *not all watt-hours are the same*.

Table 1 Characterization of performance factors for three different types of power capacity. Usage rates based on (Strauss and Reeh, 1979), capacity factors calculated as annual-national averages using the datasets presented in Section 4.3.2.

Type	*Power capacity*	*Gross usage*	*Capacity factor*	*Grid demand*	*Utilization factor*	*Energy-to-power ratio*
Baseloaders	1 MW	6000+ h/yr	0.7+	approx. 100%	0.7+	6+ GWh/MW
Peakable	1 MW	1000–4000 h/yr	0.1–0.5	approx. 100%	0.1–0.5	1–4 GWh/MW
Intermittents	1 MW	400–3000 h/yr	0.05–0.3	0–00%	0–0.3	0–3 GWh/MW

Table 1 complements our classification of watt-hours with the presentation of key technical coefficients for the three classes of power capacity associated with the three classes of watt-hours. *Capacity factor* scales *gross usage* based on an 8760-hour year. *Grid demand*, in particular relevant for intermittents, can be used to proxy-calculate curtailment. *Utilization factor* is calculated by crossing *capacity factor* with *grid demand*.

4.2.2 *Utility-scale Storage of Electrical Energy*

Due to electrical energy being a flow resource, supplied electrical energy that is not immediately used must be either stored or "wasted". Unfortunately, utility-scale storage is highly problematic. Modern society seems to have one of Koestler's (1967, pp. 84–94) "memories for forgetting" when it comes to energy storage, which, for most of human history, was a major concern.

WWII-era mountains of firewood in Hakaniemi Market (Helsinki), delivery trucks in foreground. Source: (Kyytinen, 1941–1944).

Electrical energy can actually be stored without conversion in capacitors. However, using capacitors as a means of utility-scale energy storage in electrical grids is not feasible neither currently nor in the foreseeable future. Supercapacitors self-discharge completely in just three to four days, a self-discharge rate two orders of magnitude higher than that of, for example, lithium-ion (Li-ion) batteries. The energy density of supercapacitors is furthermore relatively low, at least an order of magnitude less than that of Li-ion batteries (Chen *et al.*, 2009; Ibrahim, Beguenane and Merabet, 2012).

Firewood in Kallio (Helsinki), 1943. Little girl for scale. Source: (Väinö, 1943).

To overcome the practical difficulties of using supercapacitors, electrical energy must be converted into another form of energy in order to be effectively stored. Electrical energy can be stored by utility companies in forms such as mechanical energy (flywheels), gravitational energy (pumped hydro), thermal energy or chemical energy (flow, lead-acid, Li-ion, sodium, zinc batteries). By far the most prevalent utility-scale energy storage technology to date is pumped hydro, covering roughly 96% of storage capacity globally. In the developed world, however, relatively limited expansion potential exists—most of the low-hanging fruit pumped hydro locations have already been developed. Other energy storage technologies are also rapidly becoming cost competitive. In particular, the battery family of storage technology has been gaining momentum in energy outlooks and high-level policy (IRENA, 2017). For example, Lazard's annual *Levelized Cost of Storage Analysis* goes so far as to entirely omit from their consideration mechanical, gravitational and thermal energy storage technologies. This omission is a decision based on their identification of "limited current or future commercial deployment expectations [for those technologies]" (Lazard, 2018, p. 45). Bloomberg's *New Energy Outlook* similarly focuses on batteries for storage, although not exclusively like Lazard (BNEF, 2018). Bloomberg New Energy Finance forecasts that an eye-watering 1291 GW of new battery capacity will be added by 2050, primarily but not exclusively Li-ion. 30% of that capacity is assumed to be added in Europe, where a 77% portion is expected to go to utility-scale batteries (*ibid.*).

According to such forecasts, one of the major inroads of battery technology in the electrical grid is through a surge of uptake in electric vehicles. While this prediction may become a reality one day, we should treat with great humbleness the immense difficulties that will need to be overcome. Electric vehicles were first introduced in 1828, some *50 years before the first internal combustion engine vehicle*. They met with success in the late-1890s and early-1900s, outselling all other types of car in the United States, but were later eclipsed by the internal combustion engine vehicle and made virtually obsolete by 1935 (Chan, 2013). Energy consumption rates and direct exhaust emissions in electric vehicles have been reasonably lowered by technological innovation, at least partly due to the exceptional energy and power density as well as charge acceptance rate and cycle allowance (lifespan) characteristics of Li-ion batteries, but convenience of use, related to user-friendly infrastructure, is *still seriously lacking* (*ibid.*).

H. Morris and P. Salom Electrobat taxis in Manhattan (New York City), 1898. Source: (Van der Weyde, 1919).

4.2.3 *Alternative Sources in the Modern Electrical Grid*

Now that we've established a baseline understanding of electrical energy, including its beneficial and problematic aspects as well as its storage potential, we can discuss the role of alternatives in the modern electrical grid. The following symbolic equations, Eq. (1) and Eq. (2), are a rudimentary comparison between, respectively, a conventional fossil fuel-based electrical grid and an electrical grid with a relatively large quantity of its electrical energy generated from intermittents power capacity. The two equations are a macro-characterization critical to the understanding of the issue of scaling-up alternatives in the electrical grid. N.B. In practice, intermittents power capacity is power capacity converting solar and wind primary energy sources into electrical energy. Key technologies, fueling the contemporary renewables energy transition, include solar photovoltaic panels and wind turbines.

$$PC \times GU = GE_{el} \tag{1}$$

$$PC \times GU \times GD = TE_{el} + WE_{el} \tag{2}$$

The variables found in Eq. (1) and Eq. (2) are defined as follows.

- PC stands for *power capacity*, generally nameplate, for example measured in megawatts.
- GU stands for *gross usage*, meaning the total time of use over given a period, for example measured in hours/year.
- GE_{el} stands for *gross electrical energy*, meaning gross generated, for example measured in gigawatt-hours/year. GE_{el} is equivalent to $TE_{el} + WE_{el}$.
- GD stands for *grid demand*, meaning the demand, placed by the grid, on physically identifiable power capacity represented as a percentage of generated electrical energy.
- TE_{el} stands for *transmitted electrical energy*.
- WE_{el} stands for *wasted electrical energy*.

In relation to Table 1, Eq. (1) would be an extensive representation of *utilization factor* in the case of 100% *grid demand*. Eq. (2) would be an extensive representation of *utilization factor* in the case *grid demand* is less than 100%.

The predicament of an electrical grid with high intermittents penetration is that intermittents power capacity is constrained by both GU and GD when not given grid priority. In this situation, curtailment typically occurs when curtailment is economical. As a result, GU is lower than it would be if determined only by natural constraints and WE_{el} increases—observed utilization factors decrease in relation to corresponding capacity factors. On the other hand, when intermittents power capacity is given grid priority, only GU constrains the equation. In that circumstance, however, intermittents power capacity will have either forced the curtailment of base-load power capacity, leading to an increase in losses at the system level similar to the previous case, created an additional requirement for peak-load power capacity capable of compensating low-quality supply of electrical energy from intermittents with high-quality supply of electrical energy, or created a situation of unfulfilled demand, meaning major power outages.

Mitigating the unwelcome effects resulting from the injection of large quantities of a low-quality supply of electrical energy in the electrical grid—the effect of intermittents integration—is an exceptionally delicate task for electrical grid operators. In general, increasing the temporal ability for a base-load system subcomponent to dispatch (increasing its ability to ramp power output) causes that subcomponent to suffer in terms of thermodynamic efficiency, capital investment and operational investment. The solution of peak-load power capacity, the classic example of which is open-cycle gas turbines, is both relatively expensive in financial terms and relatively inefficient in thermodynamic terms. In Section 4.2, we will contribute to the understanding of those difficulties with a storytelling that explores a major scaling-up of intermittents power capacity. We will estimate the GD and explore the option space around WE_{el} and GU .

4.2.4 *Structure and Function in the Electrical Grid*

Section 4.2 can be roughly summarized in the assertion that the large-scale accommodation of alternatives in a centralized electrical grid implies the need for any or all of:

1) A considerable non-intermittent operating reserve.
2) A considerable energy storage ability.
3) A considerable change in the social practices creating the demand for electrical energy.

Such are the selection of strategies available to decision-makers to accommodate failure events—when the wind doesn't blow and the sun doesn't shine.

The first strategy can be understood as somewhat ironic in the sense that electrical grids transitioning towards a "fossil free future" are not actually decoupling if they are simply maintaining their conventional power plants as operating reserve. The second strategy, storage, is not yet a central policy measure, but it has gained significant traction in recent years (IRENA, 2017). The third strategy stands out in that it includes, unlike the first and second options, an important aspect of *functional change*. It implies a questioning of the patterns of electrical energy consumption, a questioning of the final cause of electrical energy in society. To what end is electrical energy used? Which social practices does it support? As might be expected by our structuralist-reductionist upbringings (Chapter 2), the third option typically takes a backstage position in contemporary energy transition efforts (Shove, 2010, 2015), which are primarily concerned with technological promises and optimizable dynamical models of the electrical grid's structural composition. A new approach capable of coordinating both structural and functional aspects is required in order to consider all three strategies.

By shifting the analytical focus from the simple recombination of structural elements to real, phenomenological change, the adoption of the relational framework presented in Chapters 2 and 3 provides us with the expressive power we require. It allows us to entertain the third strategy. In a relational framework, structural elements are considered as realizations of a system's functional relations. Rather than assume that "a sufficiently elaborate characterization of [a system's] structural detail will automatically lead to a functional understanding of [that system's] behaviors" (Rosen, 2012, p. 4), in a relational framework, there exists a dialectic between structural elements and final cause. No level of description of the intrinsic properties of structures used to generate peak-load watt-hours (open-cycle gas turbines, hydropower) and structures used to consume peak-load electrical energy (certain consumer appliances) is sufficient to create a robust understanding of the inherently functional, social demand for peak-load electrical energy in the first place. Similarly, no understanding of the functional, social demand for peak-load electrical energy suffices to create a robust understanding of the instantiating structures. Both descriptions are needed.

N.B. The list of strategies presented in this section is not exhaustive. As intermittent generation penetrates the electrical grid, system administrators have further structural options. From a non-centralized perspective, one could rely on imports from pan-European interconnectors, which serve to increase the range of effective spatial smoothing. Substantial capacity mechanisms in recent years (Newbery and Grubb, 2014; Hawker, Bell and Gill, 2017) contrast rosy visions of a highly cooperative European super-grid, however, not to mention even spatial smoothing within a country's borders will prove difficult. Kies *et al.* (2016) estimate that, in Germany, even with a considerable expansion of high voltage transmission lines, curtailment in a 100% renewables scenario may be forced into the realm of 60–80%. Kies *et al.* (2016) estimate that utilization factors for wind farms in Northern Germany, where a majority of the wind power capacity is currently located in Germany, would be on the order of 2%. This future is drastically different from the present reality, where curtailment is negligible and serious issues of intermittents integration are only just beginning to surface. In Section 4.3, we focus only on a centralized perspective.

4.3 ANTICIPATION OF STRUCTURAL-FUNCTIONAL MISMATCH

4.3.1 *Goal of the Analysis*

Let us now put ourselves in the shoes of a grid planner looking to integrate intermittent sources of electrical energy into the existing German and Spanish grids and see how grid problems such as those experienced in the *Energiewende* could have been better anticipated. Let us generate a quantitative storytelling to explore the sociotechnical imaginary that "in two or three decades, it will be possible to scale-up the supply of intermittent sources of electricity (wind- and solar-based) to obtain a significant decarbonization".

But this imaginary is a radical departure from the current system state? Yes, but it does contribute meaningfully to current policies. In the global context, and in both absolute and relative terms, both Germany and Spain are leaders in the use of intermittent primary renewable energy sources. In Spain, the most recent legal proposals make plans for 100% of the nation's electrical energy to be sourced from renewable primary energy sources by 2050 (Congreso de los Diputados, 2018). Similarly, Germany's Renewable Energy Sources Act states that renewable primary energy sources should fulfill "at least 80% of gross electricity consumption" by 2050 (BMWi, 2015, p. 4). In order to fulfill their part of the Paris Agreement, however, Quaschning (2016) finds that Germany will likely need to go 100% renewables in the electrical grid by just 2040.

OK, but this imaginary, based on intermittent sources, does not fully reflect "renewables"? Yes, hydro and biomass currently account for 10–12% of the net electrical energy generation in Germany and Spain (Eurostat, 2018c). But, as previously noted in Section 4.2, both hydro and biomass have markedly limited expansion potential (EURELECTRIC, 2010; Quaschning, 2016). The margin of error introduced by their omission from our imaginary is furthermore insubstantial in comparison with other analysis uncertainties. For example, electric vehicle uptake is widely predicted to force a major increase in electrical grid demand over both the medium- and long-terms. Due to extreme uncertainties surrounding the exact degree of electric vehicle uptake (Robinson, 2018), anticipations of grid demand in the medium- and long-term in the United Kingdom fluctuated no less than 100% between 2017 and 2018 (National Grid, 2017, 2018). And such a massive variation in forecast is not even cause alarm—anticipations of the future of our electrical grids are marked by high uncertainty. No less of a man than M. Slesser (1978, p. 3) fitting describes energy in *Energy in the Economy* as the most uncertain of primary economic inputs. The point of exploring our transition imaginary is not to precisely predict the future, but rather to open and close frontiers.

4.3.2 *Datasets*

Table 2 summarizes the electrical energy production datasets used in our case study. The data is characterized by a high degree of completeness in the sense very few data points were missing or contestably outliers[21]. Although the data reflects electrical grid demand, it provides insight into total feasible renewable electrical energy generation remarkably well. To date, for Germany and Spain and in large part because of legal priority granted to it, a negligible amount of electrical energy from renewable energy sources has been curtailed (within the range of 0–2%) (Bird *et al.*, 2016; Kies, Schyska and von Bremen, 2016).

Table 2 Summary of datasets used in the case study. Intermittents level reflects the percentage of electrical energy generated by wind and solar primary energy sources in the respective country (annual average). Spain refers to Peninsular Spain only. Sources as follows. Spain: (Red Eléctrica de España, 2018b). Germany: (50Hertz, 2018; Amprion, 2018; Tennet, 2018; TransnetBW, 2018).

				Intermittents level	
Region	*Start date*	*Length*	*Resolution*	*End*	*Start*
Spain	1/1/2007	144 mo	10 min	20.1%	9.4%
Germany	1/1/2011	96 mo	60 min	30.0%	13.3%

Figure 26 accompanies Table 2 in describing the changes in the power capacity used to generate electrical energy in Germany and Spain. Power capacity breakdowns are provided at both the start point (1/1/2011 or 1/1/2007) and the end point (1/1/2019) for each generation dataset.

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[21] The data for Spain includes 630k observations of 14 variables. The data for Germany includes 70k observations of 14 variables. A detailed account of data fidelity is located in Appendix B.

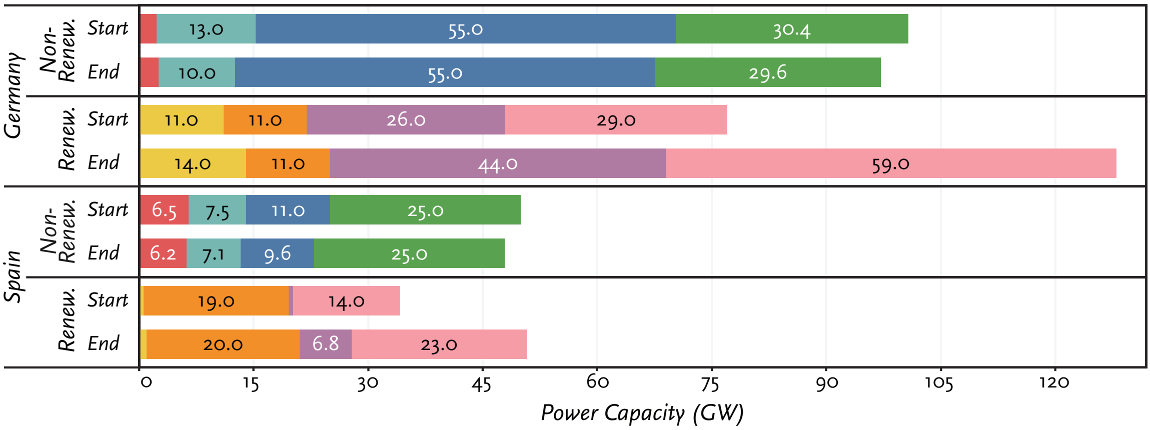

Figure 26 Structural reading of the electrical grid power capacity composition. Table 2 details the points in time associated with the start and end points. Sources as follows. Spain: (ENTSO-E, 2018; Red Eléctrica de España, 2018b, 2018a). Germany: (50Hertz, 2018; Amprion, 2018; BMWi, 2018; Tennet, 2018; Transnet-BW, 2018).

Perhaps the most striking aspect of Figure 26 is the fact that, while renewables power capacity increased significantly over the time period analyzed (due to an injection of intermittent primary energy sources), non-renewables power capacity hardly budged. Spain observed a 17% increase in total system power capacity over 12 years and Germany observed a 27% increase in 8 years, 14.5 GW and 47.5 GW, respectively. This increase was the result of respective 11% and 17% increases in intermittently sourced electrical energy generation. While prodigious amounts of wind and solar power capacity were added in both countries, conventional fossil-fuel and nuclear power capacity only marginally decreased *notwithstanding of a negligible change in demand*. This remarkable long-term trend is highlighted by Figure 27.

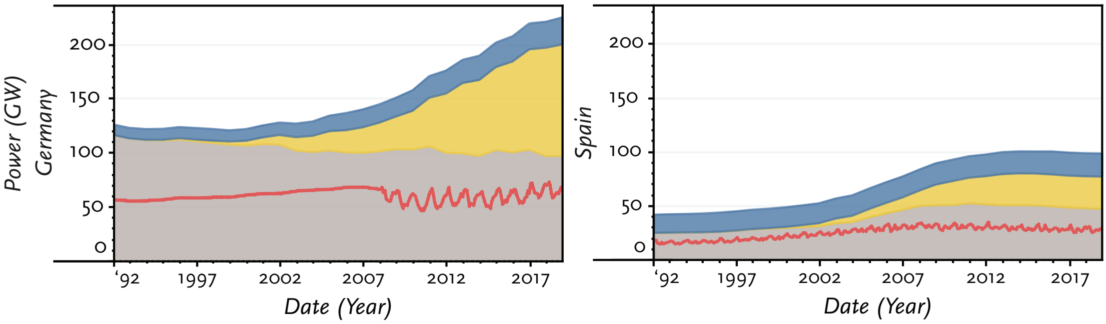

Figure 27 Electrical energy generation and growth in power capacities over time during the German and Spanish renewable energy transitions. The generation data overlay is presented at a monthly resolution for Spain and yearly until 2008 for Germany, monthly thereafter. Sources as follow. Spain: (Red Eléctrica de España, 2017, 2018a). Germany: (ENTSO-E, 2018; Eurostat, 2018c, 2018b).

🟥 *Generation* 🟦 *Other Renew.*
▨ *Conventional* 🟨 *Intermittent*

As discussed in Section 4.2.3, the idea behind retaining conventional power capacity during a renewables transition is to provide backup in the case of a failure event, assuming demand doesn't grow. It must be stressed that that techno-fix strategy, applied in Germany and Spain (Figure 26 and Figure 27), represents just one of the three strategies decision-makers have available to them in a centralized grid.

4.3.3 *Imaginary*

Now to open the option space and explore the limits of our sociotechnical imaginary. Table 3 provides an ensemble of anticipations characterizing the challenges that would need to be overcome by decision-makers in our vision of a future electrical grid where intermittent renewable primary energy sources are used to generate electrical energy at a scale equal to 100% of the present-year electrical grid demand. It details the extent of the anticipated worst annual production failure event across two dimensions, consumer guarantee and confidence level, and proves an effective way of provoking a discussion over differences in structural and functionals strategies of handling the Achilles' heel of wind and solar power capacity. Two descriptive domains critical for contingency planning are provided in Table 3, the maximal instantaneous power gap and the energy gap. Table 3 is a rudimentary *option space* capable of informing a diverse set of decision-makers each with different but equally relevant considerations and concerns. Each point of data in Table 3 is an "option", the basis of a unique transition pathway characterized by different assumptions about the rightful place of electrical energy in society. N.B. The selection of a certain confidence level and guarantee over another has a key *functional* component to it—it defines the functional role electrical energy can be expected to play in society. Note also that functional assumptions limit the set of structural possibilities.

Variable / Country		Guarantee	Confidence Level 50%	Confidence Level 75%	Confidence Level 99%
Power Gap	Spain	95%	31 GW (73%)	34 GW (78%)	39 GW (91%)
		90%	32 GW (74%)	34 GW (78%)	38 GW (88%)
		75%	31 GW (71%)	33 GW (75%)	37 GW (86%)
		50%	29 GW (67%)	31 GW (73%)	38 GW (87%)
	Germany	95%	65 GW (81%)	71 GW (88%)	84 GW (100%)
		90%	65 GW (81%)	70 GW (87%)	84 GW (100%)
		75%	63 GW (79%)	69 GW (86%)	84 GW (100%)
		50%	60 GW (74%)	67 GW (83%)	83 GW (100%)
Energy Gap	Spain	95%	4.2 TWh	4.7 TWh	5.8 TWh
		90%	3.7 TWh	4.2 TWh	5.4 TWh
		75%	2.8 TWh	3.2 TWh	4.3 TWh
		50%	1.5 TWh	1.8 TWh	2.5 TWh
	Germany	95%	14 TWh	17 TWh	22 TWh
		90%	13 TWh	15 TWh	21 TWh
		75%	10 TWh	12 TWh	17 TWh
		50%	6.6 TWh	7.3 TWh	9.1 TWh

Table 3 Statistical description of annual "worst events" in two imagined electrical grids where 100% of the electrical energy is generated from intermittent sources (annual average, combined wind and solar). Table 3 helps inform expert decisions, it is an option space. *Power gap* is characterized as both an absolute level (GW) and a relative level (% of the total electrical energy demanded but unfulfilled). The presented power values are comparable, within reason, to the estimates of Steinke *et al* (2013). *Energy gap* refers to a singular, continuous period where less than the guaranteed level of total electrical energy was fulfilled by intermittent energy sources. The presented energy values are comparable, within reason, to the estimates of Kuhn (2012).

Table 3 shows that we would expect annual failure events in our imaginary to be of a power magnitude equal to that of the *entire electrical grid*. We can conclude that *a majority of conventional power capacity* would need to be retained if the first strategy—retainment of conventional power capacity—is maintained as the way forward. Although our anticipation is a rather rudimentary one, it does already shed serious doubt on the role of the first strategy. What is also interesting in Table 3 is the scale of difference in energy gaps between confidence levels and guarantees. The difference between a guarantee of 50% and one of 95%, maintaining constant the confidence level, is roughly 2.5x. The difference between a guarantee of 50% at a confidence level of 50% and a guarantee of 95% at a confidence level of 99% is roughly 4x. We can conclude from these substantial discrepancies that the deliberation over the functional role of electrical energy in society, "Is electrical energy a 'civil right'? When you flick a switch, how sure should you be that the light turns on?", implies massive differences in terms of what infrastructure is required.

What sort of infrastructure are we speaking of? Let us now explore the idea of using utility-scale Li-ion batteries as backup storage, which is the modern hype, as defended in Sections 4.2.2 and 4.3.1. Table 4 builds on Table 3's generation gaps, adding estimates of the monetary costs and greenhouse gas externalities associated with the use of Li-ion batteries as utility-scale electrical grid storage. Working as a peak-load provider, the unsubsidized, levelized cost of Li-ion batteries is currently estimated to be between $285–$581/MWh

(Lazard, 2017). The greenhouse gas emissions resulting from the manufacture of just the Li-ion batteries, other required infrastructures not included, is estimated to be between 33 t–172 t CO_2-eq/MWh (Hao *et al.*, 2017).

Table 4 Interpreted infrastructural implications of Table 3, assuming that electrical energy discrepancies (unfulfilled guarantees) are fulfilled by Li-ion batteries. Monetary figures refer to the unsubsidized levelized cost of storage from Lazard (2017), which includes capital, operation and maintenance, charging, taxes and extended warranty costs. Monetary figures are in USD. Greenhouse gas figures refer only to the manufacturing of the battery, using range estimates from a review of the literature (Hao *et al.*, 2017).

Variable	*/ Country*	*Guarantee*	*Confidence Level* 50%	75%	99%
Energy Gap ($[USD])	*Spain*	95%	\$1.2bn–\$2.4bn	\$1.3bn–\$2.7bn	\$1.7bn–\$3.4bn
		90%	\$1.1bn–\$2.2bn	\$1.2bn–\$2.4bn	\$1.5bn–\$3.1bn
		75%	\$0.79bn–\$1.6bn	\$0.92bn–\$1.9bn	\$1.2bn–\$2.5bn
		50%	\$0.44bn–\$0.89bn	\$0.52bn–\$1.1bn	\$0.71bn–\$1.5bn
	Germany	95%	\$4.1bn–\$8.3bn	\$4.7bn–\$9.6bn	\$6.4bn–\$13bn
		90%	\$3.7bn–\$7.5bn	\$4.4bn–\$8.9bn	\$6.0bn–\$12bn
		75%	\$3.0bn–\$6.1bn	\$3.5bn–\$7.2bn	\$4.9bn–\$10bn
		50%	\$1.9bn–\$3.8bn	\$2.1bn–\$4.2bn	\$2.6bn–\$5.3bn
Energy Gap (CO2-eq)	*Spain*	95%	0.14 Gt–0.72 Gt	0.15 Gt–0.80 Gt	0.19 Gt–1.0 Gt
		90%	0.12 Gt–0.64 Gt	0.14 Gt–0.72 Gt	0.18 Gt–0.92 Gt
		75%	0.091 Gt–0.47 Gt	0.11 Gt–0.55 Gt	0.14 Gt–0.74 Gt
		50%	0.050 Gt–0.26 Gt	0.060 Gt–0.31 Gt	0.082 Gt–0.43 Gt
	Germany	95%	0.47 Gt–2.4 Gt	0.55 Gt–2.9 Gt	0.74 Gt–3.9 Gt
		90%	0.43 Gt–2.2 Gt	0.50 Gt–2.6 Gt	0.69 Gt–3.6 Gt
		75%	0.34 Gt–1.8 Gt	0.41 Gt–2.1 Gt	0.56 Gt–2.9 Gt
		50%	0.22 Gt–1.1 Gt	0.24 Gt–1.3 Gt	0.30 Gt–1.6 Gt

Table 3 stated that if a Germany highly concerned with national security aimed to guarantee 95% of their annual average 100% intermittents electrical energy generation at a 99% confidence level, they should expect to prepare contingency storage capable of providing 22 TWh and an 84 GW peak output. Table 4 characterizes the structural costs of that storage, assuming the use of utility-scale Li-ion batteries, to be in the range \$6.4 bn–\$13 bn. In terms of greenhouse gas emissions, the structural costs of storage related to just the manufacture of the Li-ion batteries is expected to be in the range 0.74 Gt–3.9 Gt CO_2-eq. These are simple, back-of-the-envelop calculations, but they serve well enough to generate a rough idea of the implications of our storyline.

For context, Eurostat (2018a) reports the 2016 emissions for Germany and Spain as 0.9 Gt and 0.3 Gt CO_2-eq., respectively, for all sectors including indirect emissions[22]. Hence, the figures presented in Table 4 are on the order of the entirety of annual greenhouse gas emissions for each country. While the financial costs are substantial, they are rather minor in comparison to the cost of replacing existing conventional power capacity with renewable alternatives, assuming current price points (Quitzow *et al.*, 2016). Using the United Nation's (UN, 2017) population estimates, while planning for the expected annual worst event in the most extreme scenario, assuming a 99% confidence interval and 95% guarantee, the anticipated levelized costs of Li-ion battery storage

[22] Not including land-use, land-use change and forestry (LULUCFs).

backup supply are on the order of \$37–\$73 per capita for Spain and \$77–\$157 per capita for Germany. Annual greenhouse gas emissions from Li-ion battery manufacturing are on the order of 4 t–21 t CO_2-eq per capita for Spain and 9 t–47 t CO_2-eq per capita for Germany. The emissions figures are between 0.5x–3x of the 2015 per capita greenhouse gas emissions (Kyoto basket) for both Spain and Germany (Eurostat, 2016).

So far, the imaginary doesn't seem so bad. A conventional economist might even choose to stop here, comforted by the approximation. Note, however, that we haven't considered material cause yet. More concerning than the financial and emissions figures is the magnitude of lithium that would be required—the primary material cause of Li-ion batteries. At the 99% confidence level and 95% guarantee, for Spain and Germany, respectively, we would expect to consume some 7% and 13.5% of the world's proven lithium reserves, which is 4x and 15x the current annual production volume of lithium or 12x and 43x the current annual production volume of lithium used in the production of batteries (USGS, 2015; Hao *et al.*, 2017; Martin *et al.*, 2017; Narins, 2017). If we were to further extend our rudimentary model to take into account additional storage capacity required to avoid damaging depths of discharge, additional additive factors such as imperfect round-trip efficiency, self-discharge rates, climate control of the storage facilities and compensation for transmission losses, subtractive factors such as time-of-use tariffs (-15%–25%) and other possible grid flexibility measures, our estimates would only increase further (Yang *et al.*, 2018).

4.4 DISCUSSION

4.4.1 *Science-Policy Interface*

Modern society demands a flow of electrical energy at a remarkably high confidence level. An ideological assumption has been made that, rather than change our practices of consumption, the supply of electrical energy derived from renewable primary energy sources should increase. Although the average generation from intermittents for both Germany and Spain was in the range 20–30% in 2018, there have already been moments in both countries where nearly all electrical energy consumed was derived from renewable primary energy sources—moments where the combination of weather patterns and energy demand was remarkably favorable. In a sense, the continued policy mandate to increase renewables power capacity is tied to unquestioned assumptions of social practices and inflexible functional demand.

What we have tried to do in Section 4.3 is explore a learning-type storyline to re-open the discussion of the electrical grid future. Ultimately, is the presented option space cause for policy concern? Yes. According to our back-of-the-envelope calculations, the finances and emissions seem bearable, but the sheer quantity of lithium required is certainly not environmentally feasible. Considering also that the effective lifespan of a Li-ion battery is on the order of 5–10 years (Lazard, 2016; Cembalest, 2017), one can conclude that, insult to injury, utility scale Li-ion battery storage is not currently a large-scale feasible option for developed nations. This is a concerning point given the hero-type storyline of massive Li-ion inroads, endorsed by major supranational energy outlooks and policies.

You might say, "But what about the success story of so-and-so-country?" There will always exist special circumstances that allow some blocs to pursue rosy transition pathways. Denmark has received widespread critical acclaim in recent years in response to its renewable energy transition successes. However, while Denmark itself has no significant hydropower potential, it sits on the doorstep of a cooperative Norway and a cooperative Sweden, which together have nearly 70% of Europe's hydropower (maximum storage capacity) (Graabak *et al.*, 2017). Every year there are multiple weeks where Denmark imports on average *60–80% of the electrical energy it consumes* (Nord Pool AS, 2018). The Denmark model is not easily reproducible. Setting aside the poster children for a moment, we are forced to conclude that the pathway to "100% renewables" is more problematic than current hero-type storylines let on. Major functional hurdles are almost certain to emerge in the near future.

Why not complement physical-technical and economic models in decision-making processes aiming to incite a "renewables" energy transition? Normal approaches have generally failed to accept as a relevant consideration functional hurdles (Lutzenhiser, 1993, 2014; Guy, 2006). Better still would be to move away from a discussion based on "matters of fact" and towards a discussion on "matters of concern" (Chapters 2 and 3). An analysis of a matter of concern is necessarily based on multiple, non-equivalent and non-reducible quality checks. One major issue with sociotechnical imaginaries is that they are often shaped more by narratives and endorsed storylines than biophysical reality (Asayama and Ishii, 2017; Kuchler, 2017). Surely those narratives and storylines based more on myth than reality should pass through a reflexive gauntlet? A quality check needs to be in place (Giampietro and Funtowicz, 2020). For starters, analysts must be equipped to assess how much electrical energy can be produced by the different relevant classes of electrical energy (base-load, peak-load, intermittents) when matching demand across space and time. This analysis of biophysical congruence is entirely *independent from the price* of a watt-hour.

After being cross-checked for biophysical feasibility, the analysis of a matter of concern should also check for desirability and viability. Desirability checks require establishing a bridge between a technical analysis and the implications of proposed changes on the patterns of consumption in the society. How will the proposed changes affect the expression of the current mix of social practices? How will they affect the quality of life in terms of material standard of living and social activities? Technical information will remain useless if technical analyses of feasibility are not coupled with analyses of policy relevance, meaning the implications of choices in terms of desirability for society. Similarly, an economic viability check implies that those solutions that have been identified as feasible and desirable by experts and the extended peer community are verified in relation to their reasonable chances of economic success. It is only in using a series of quality checks, such as that proposed by quantitative storytelling, that we can generate policies that are both effective and robust.

In this chapter, in order to reach a better framing of a sustainability issue, we attempted to show the importance of considering an option space that includes more than one lens at a time—not a "optimized" forecast. We used the discussion on alternative sources of electrical energy as a case study and learning-type story. We focused primarily on one lens, biophysical feasibility. This choice does not imply that the other lenses are less important—we stopped after our feasibility check merely because serious issues with the storyline had already emerged. The message of quantitative storytelling is that we need to start with humility and learn how to integrate the great diversity of available knowledge claims relevant to the understanding of wicked problems. To achieve this result, we should avoid as much as possible the hegemonization of narratives and hero-type storytellings (Funtowicz and Ravetz, 1993; Janda and Topouzi, 2015). A diversity of framings of a given issue is essential in order to reduce the unavoidable generation of Lakoff's *hypocognition* (2010), associated with any representation of a problem or solution. The possibility of more informed, responsible and equitable choices emerges.

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5 QUANTITATIVE STORYTELLING ON AN AGRICULTURAL INTERNALIZATION[23]

5.1 INTRODUCTION

5.1.1 *Introduction to the Issue*

Although agriculture in the European Union (EU) contributes minorly to economic factors such as gross domestic product and employment, the environmental pressures it exerts are, by all measures, major. In the EU, half of local non-CO_2 greenhouse gas emissions are produced by agriculture (EC, 2018), one-third of water abstraction is for agricultural use and nearly one-half of land under economic use is agricultural land (Parris, 2001). Since the EU imports substantial quantities of agricultural products (Eurostat, 2019a), considerable externalized environmental pressures—pressures exerted on foreign lands—are also implied. Unfortunately, relatively few studies consider extraterritorial effects of agricultural externalization as associated with the interregional flow of ecosystem services (Tancoigne *et al.*, 2014; Koellner *et al.*, 2018).

In this chapter, a quantitative storytelling on the extraterritorial effects of agricultural externalization is made. A broad-scale perspective is taken to assess how dependent the good standing of the environment of each EU member state is on ecosystem services located outside of respective national boundaries. In modern times, the openness of the EU agriculture sector is essential to protect the local biodiversity and integrity of EU ecosystems. However, this dependency entails that some ecosystem services, delivered in foreign social-ecological systems, benefit European consumers differently from the way they benefit the people of the social-ecological system in which their production takes place. This disparity opens a new framing of the issue of trade. How threatened are the environments of EU member states by reliance on volatile food imports ("environmental security")? Can we anticipate impending troubles concerning this dependence? How much is the good standing of the environment of importing countries helped by the virtual embodiment of ecosystem services in agricultural imports?

These questions, questions of resource security confounded by value pluralism, are tricky to assess using the methods of, for example, conventional economics. The general approach to modeling and knowledge space construction outlined in this dissertation is instead adopted to explore the implications of biophysical limits to economic growth and the suitability of existing governance structures to put reigns on the complexity inherent to associated issues of sustainability. Building on previous work, which presented a diagnostic assessment of the agricultural account presented in this study

[23] Some parts of this chapter are from Renner *et al.* (2020).

Renner, A., Cadillo-Benalcazar, J. J., Benini, L., & Giampietro, M. (2020). Environmental pressure of the European agricultural system: Anticipating the biophysical consequences of internalization. *Ecosystem Services*, 46. https://doi.org/10.1016/j.ecoser.2020.101195

(Cadillo-Benalcazar, Renner and Giampietro, 2020), this chapter presents a long-term anticipation of one possible agricultural future for each of the twenty-seven member states of the EU plus the United Kingdom and Norway. This chapter explores a learning-type storyline, framed at the national level, investigating how dependent EU agriculture sectors are on externalization and how patterns of production and consumption amongst EU agriculture sectors affect the biosphere.

First, for each country, a biophysical assessment of how much of the total throughput of agricultural products is domestically produced and how much is imported is made. Following the identification of the various flows belonging to these two categories, information relevant to questions such as the following is generated. What if the projected 60% increase in the global food demand by 2050 (Alexandratos and Bruinsma, 2012) brings an end to the era of cheap food imports? What if growing perceptions of the existence of planetary boundaries result in geopolitical turmoil and force European states to rely more on local resources to guarantee their national food security? What would happen if current EU policy initiatives, such as those related to economic circularity, the Farm to Fork Strategy (EC, 2020) and the European Green Deal (EC, 2019c), inspire a major effort to re-internalize agricultural production? Even if the modern, high-external input model of agriculture is maintained (massive use of technical inputs on monocultures), are there enough agricultural resources for a full internalization? The main objective of this chapter's learning-type storyline is, therefore, to question conventional delineations of system boundary and improve our understanding of possible biophysical and social limitations to agricultural transformations by exploring what would happen to the remaining natural habitats, soil and aquifers of each EU member state if each member state were forced to locally produce all or nearly all the food that it currently imports.

As in Chapter 4, the quantitative storytelling presented in this chapter is implausible if considered as an actual prediction or simulation of *the future*. The results merely aim to provide a robust exploration of *a possible future* together with a systematic assessment of possible constraints and concerns associated with current forward-looking policy decisions. Using the wording of Beckert (2013) to frame the dialogue, the presented quantitative storytelling aims simply to present an imaginary of a "future [situation] that provide[s] orientation in decision making despite the incalculability of outcomes" (Beckert, 2013, p. 325; cited by Poli, 2017).

5.2 ACCOUNTING FOR AGRICULTURE

5.2.1 *Computational Methods*

Metabolic patterns of agriculture sectors differ immensely between social-economic systems. Physical, environmental and climatic factors provide a heavy set of initial constraints on what is agroecologically possible. Sociocultural context then provides a second set of constraints through its definition of what a desirable or acceptable "societal diet" is. As a result of this situation, computational methods for agricultural accounting must be designed in such a way as to accommodate extremely complicated knowledge spaces covering a diversity of technical coefficients. Figure 28, showing blue water (irrigation) usage by vegetal crop type for the Netherlands, Spain and France, provides a rough, initial idea of just how different agricultural systems can be. Cross-coefficient comparisons within the same geographic region, for example blue water usage versus land usage or nitrogenous fertilizer application in France, often show a similar level of diversity.

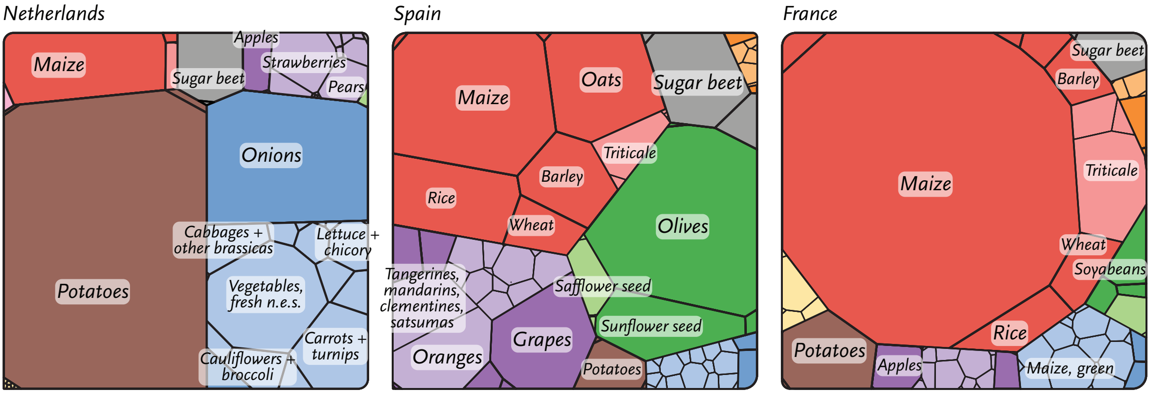


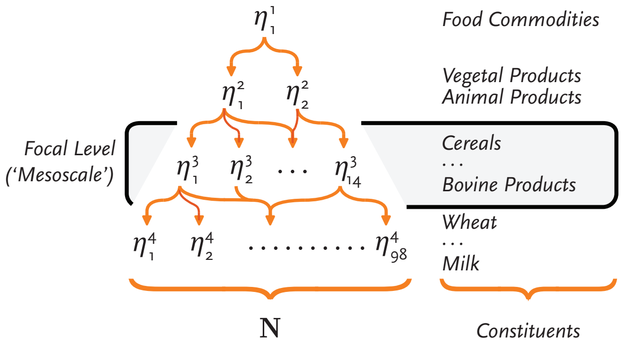
Figure 28 Blue water use by vegetal crop type for three Western European countries (extensive value). Voronoi treemaps are a compelling alternative to the spaghetti diagrams common in network analysis, particularly useful for the rapid communication of large, multi-scale datasets. Reference year: 2012. Data sources: (Mekonnen and Hoekstra, 2011; FAO, 2017). Tessellation algorithm: (Nocaj and Brandes, 2012).

■ □ *Cereals*
■ □ *Roots and tubers*
■ □ *Fruits*
■ □ *Vegetables*
■ □ *Sugar crops*
■ □ *Oil-bearing crops*
■ □ *Nuts*
■ □ *Pulses*
■ □ *Spices/Stimulants*

With that prologue in mind, this section provides an overview of the computational methods used to generate the numerical results presented in Section 5.3. We will be brief with it, presenting a small number of symbolic blueprints to cover the overall idea of the approach. Readers eager to learn more about the issues involved with the vectorization of networks of metabolic processors are encouraged to continue their reading with Chapters 2 and 3 of Heijungs and Suh's (2002) *The Computational Structure of Life Cycle Assessment*. Many of the issues discussed there are relevant also for us, for example, issues of matrix inversion when handling processes with multiple outputs.

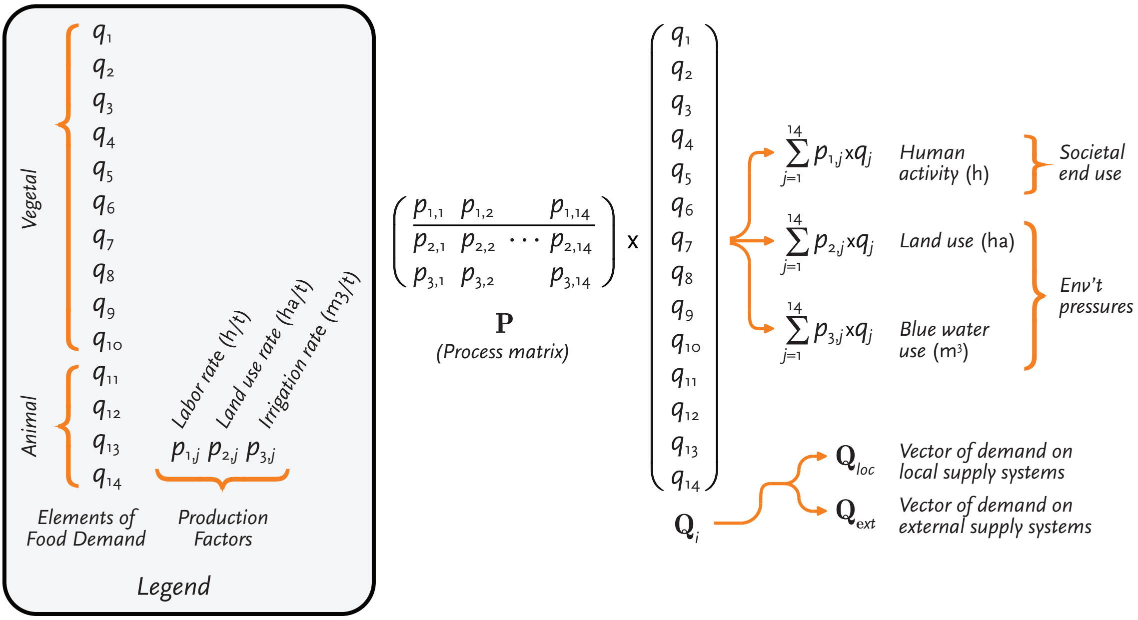
A crucial first step to understanding agroecosystems is to assume a multi-scale perspective (Simon, 1962; Allen and Starr, 1988). Figure 28 already provided one example of how a multi-scale perspective can be effectively used to communicate an agricultural production factor. As we will see throughout this chapter, there are a wide range of benefits. Figure 29 provides a summary of the multi-scale structuring of food items used in this chapter. The classification used is an excerpt from the FAOSTAT Commodity List with some added top-level aggregation.

Figure 29 Structure of the taxonomy of food items (N) used in the account. The fourteen elements of the third level correspond to the 14 elements of the two demand vectors (Q_i) referenced in Figure 30. Upper indices represent taxonomic level and lower indices distinguish elements within that respective level.



In this chapter's diagnostic analysis, demand vectors and technical coefficients for agricultural production factors are collected at the "microscale" level of N, meaning for each of ninety-eight different commodities (N^4). Microscale data is then translated to the "mesoscale", meaning demand vectors are summed and weighted averages of technical coefficients are calculated, reducing the original ninety-eight classes to the fourteen mesoscale commodities (N^3). Anticipated rates of change for both production factors and demand refer to the mesoscale level. The presentation of the agricultural imaginary in Section 5.3 also makes use of the mesoscale.

Figure 30 Graphical summary of the computational structure used. Technical coefficients for human activity, land use and blue water use ($p_{i,1}, p_{i,2}, \dots, p_{i,14}$) are calculated for each of twenty-nine European countries then scaled by both local (Q_{loc}) and external (Q_{ext}) demand for fourteen food commodity flows.



Following Figure 29, Figure 30 then presents the computational structure used for scaling technical coeffcients. Starting on the left, the fourteen elements of food demand ($q_1, q_2, \dots, q_{14}$) represent societal demand for key food groups. A main goal of our quantitative storytelling is to explore changes in externalization, hence, food demand is defined separately between that which is locally produced and that which is imported. System internal demand is summarized in vector Q_{loc} and system external demand is summarized in vector Q_{ext}. Moving rightward from demand to the process matrix P, production factors ($p_{i,1}, p_{i,2}, \ldots, p_{i,14}$) represent technical coefficients defined uniquely for each country in the analysis, each of the fourteen elements of food demand and for production factors of human activity, land use and blue water use. Each column of P can be interpreted as the structural characteristics of a metabolic processor. The knowledge space defined by these considerations allows for the exploration of three important agroecosystem dimensions, acknowledging that several additional, relevant dimensions, such as nitrogen, phosphorous and potassium-fertilizer, energy carriers, commodity prices and pesticides, present further constraints to the option space. N.B. Using Georgescu-Roegen's scheme, human activity and land use are fund variables and blue water use is a flow variable. Human activity may be further classified in the domain of societal end uses and both land use and blue water use may be further classified in the domain of environmental pressures.

5.2.2 *Semantic Interpolation*

Section 5.2.1's discussion entails the existence of over 8000 technical coefficients in our agricultural account.

$$98 \text{ commodities} \times 29 \text{ countries} \times 3 \text{ factors} = 8526 \text{ coefficients}$$

Many additional, intermediate variables exist as well. For example, when a country imports a live animal, that animal must be passed through a series of coefficients in order to generate a complete picture of the agricultural consequences of its internalization. First, the live animal is passed through live weight and carcass weight coefficients. The result of that calculation is then passed through a feed profile. Finally, processed feed class estimates generated by the feed profile, such as *Soybean cake*, are passed through a series of conversion coefficients themselves—a material flow account coefficient then a fresh matter coefficient. In this way, the analyst is able to determine the production factors needed to raise the imported live animal in terms of primary product equivalent. The livestock production technical coefficients are scaled by the carcass weight equivalent of the imported animal and the vegetal production technical coefficients are scaled by the expected feed profile, represented in terms of primary product equivalent. The accounting is clearly rather involved, though, we could easily get distracted from the message of our learning-type storyline. Further details are located in Appendix B.

When working with so many different coefficients, it is inevitable that some will be "not available". They will need to be imputed. In Chapter 3, it was promised that our philosophical discussion of knowledge space exploration would be put to use in this chapter. Let's fulfill that promise. Consider the case where some technical coefficient for *Malta* is unavailable. Say, *Human activity* for *Oranges* production is missing. An intuitive way of imputing the missing value would be to assume the average value of the bounding agroeconomic region. Figure 31 shows the idea.

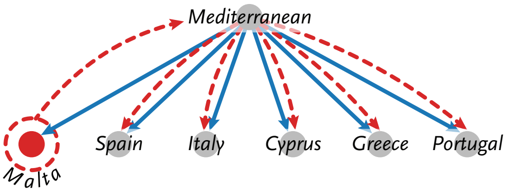


Figure 31 A geopolitical classification (spatial modifier), one of the eight agroeconomic regions in the classification of Olesen and Bindi (2002).

Is this a reasonable assumption? We must be careful, but it seems reasonable enough to get a rough idea of the situation in *Malta*. Figure 31 is a slice of a classification of agroeconomic regions, designed specifically with homogeneity of production factors in mind. *Orange* production techniques in *Malta* are probably not so different from *Orange* production techniques in *Cyprus*.

Even if no imputation is needed to complete the diagnostic analysis, meaning that none of the points of data we require are "not available", a method of interpolation like that shown in Figure 31 will surely be needed when we explore our imaginary. In *Luxembourg*, for example, *Oranges* are imported but there is no significant local production precedent with which to estimate local production factors. In order to estimate what would be needed to produce some sort of equivalent product, we need once again to explore the knowledge space. We need to look for semantically similar classes. Would it be reasonable to traverse a map of agroeconomic regions, like in Figure 31? Probably not. The agroeconomic neighbors of *Luxembourg*—*Germany*, *Belgium*, and so forth—also do not cultivate significant quantities of *Oranges*. Hence, when searching for technical coefficients for *Oranges* in *Luxembourg*, we would likely need to expand our consideration to all Europe states. But using coefficients ultimately taken from the south of Europe doesn't quite make sense, the agroeconomic context of *Spain* is completely different from that of *Luxembourg*.

In our search for semantically similar classes in our knowledge space, we could instead try traversing the classification of food commodities. Consider Figure 32, which is a small slice of the food commodity classification indicated in Figure 29 (N), inspired by the FAOSTAT Commodity List.

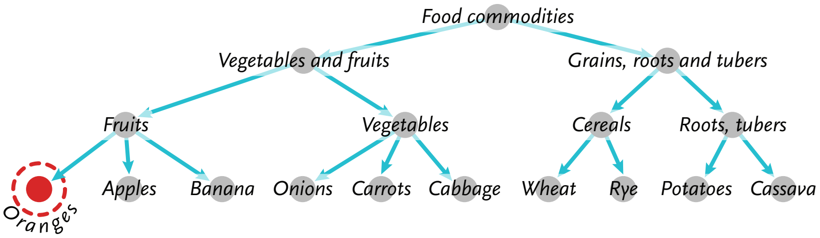


Figure 32 A point of missing data in a food commodity classification (material cause).

We can look to the "siblings" of the *Oranges* class for reliable technical coefficients. In graph theoretic terms, a generic term for what we are doing is retrieving is the *1-step neighborhood ego graph* of *Oranges* (minus the "ego" itself, meaning the *Oranges* class itself).

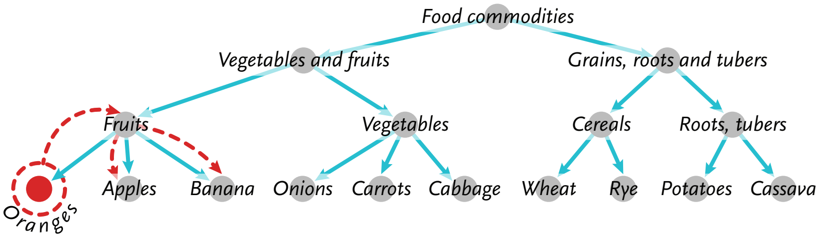


Figure 33 Semantic interpolation with a 1-step neighborhood ego graph for the *Oranges* class.

Is this a reasonable semantic interpolation? Maybe. *Luxembourg* will be missing coefficients for *Banana* as well, but it will likely have them for *Apples*. *Apples* and *Oranges* are canonically different, agroeconomically different as well, but they serve somewhat similar dietary roles. If the *Luxembourg* we're imagining in our learning-type storyline is required to internalize production, we might reasonably imagine that it is *Apples* that will be substituted for the *Oranges* that can no longer be imported. If the intention of our analysis is to get simply in the ballpark, the technical coefficients seem reasonably transferable. Of course, we could continue with this line of thinking if we still didn't manage to collect a technical coefficient for *Oranges*, extending our ego graph one step further.

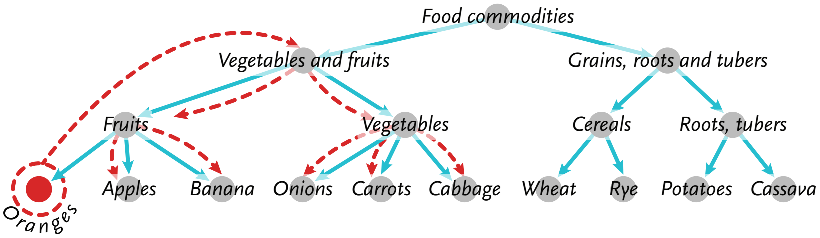


Figure 34 Semantic interpolation with a 2-step neighborhood ego graph for the *Oranges* class.

Figure 34 is the logical extension, highlighting how, as modelers, we must constantly check the semantics of our interpolation as we explore increasingly deep in our knowledge space. It seems doubtful that the technical coefficients of the class *Cabbage* are transferable to the class *Oranges*—doubtful also that they are at all substitutible in a dietary sense.

But this is the general idea of interpolation. We traverse the multidimensional structure of our knowledge space (such as visualized in Chapter 3). And this is exactly what we do as analysts, often unbeknownst. Depending on the semantics of the task at hand, for example, which production attribute we're looking for, we might choose to explore along a geopolitical axis or a food commodity axis, or some other one. The emphasis of our discussion is returned to its rightful place—the original structure of the underlying knowledge space. How casual considerations or causal modifiers are considered and represented between classifications completely determines the results of a semantic imputation or interpolation. As sustainability scientists, in particular because we are future oriented, we must be extremely careful when we choose to accept a classification into our knowledge space, or when we design one in conjunction with the extended peer community. We must also be constantly willing to modify the structure of our knowledge space, updating it to changing external referents and, potentially, changing purposes of our model.

Aside from the explorations presented in Figures 31 through 34, we might also choose to explore along multiple classifications simultaneously. We might search past one level in our geopolitical classification first, then one level in our food commodity classification, then back to the geopolitical one, and so forth. To handle the case that the semantic difference between levels in one classification is much large than in another classification, we can also add a distance function to our semantic interpolator. For example, we could program our semantic interpolator to increase the ego graph radius *once* along the geopolitical dimension, then *twice* along the food commodity dimension, then repeat until a useful quantity of technical coefficients is collected ("tick, tock, tock" and repeat). To avoid gathering an singleton outlier, we might set the interpolator to run until the set of classes with values is greater than a certain quantity, say $n \geq 2$, hence the imputed or interpolated results can be informed by an uncertainty range (low and high value estimates). This is exactly what is done in the generation of results in this chapter, except the multidimensional structure of the knowledge being traversed has 10s of 1000s of classes in it—exact figure depending on in which production step is being calculated.

It should be clear then that the crux of the matter is in the original definition and layout of the classifications used to structure the knowledge space. All of the numbers we generate are mere side-products of those majestic things. Hence, it is a pity that the essential role of classifications isn't treated with more care, that the birth and death of classes isn't tracked more closely and that classifications aren't so very constantly questioned and reworked according to the needs of analyses. N.B. Appendix A contains methods in Python overviewing the process outlined in this section.

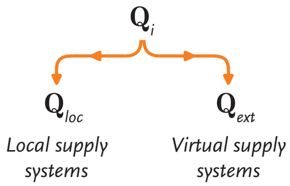
5.3 ANTICIPATION OF ENVIRONMENTAL INSECURITY

5.3.1 *Goal of the Analysis*

Since the launching of the Common Agricultural Policy (CAP) in 1962, the European community has experienced rapid economic linearization and a massive reduction, in relative terms of human activity, of its primary productive sectors. Over that same period, since the CAP's inception, the demands being placed on the shrunken and shrinking agricultural primary productive sector have increasingly diversified. For example, the CAP has increasingly given reference to the local and global environmental sustainability agenda. This new emphasis may be seen to compound the numerous pre-existing tensions and conflicting aims existing in the policy, leading to new governance difficulties and a reduction in legitimacy. Externalization of agricultural production can be understood as an avoidance of such tensions.

There exists, on the one hand, the narrative in the CAP that efficient farms are more effective at delivering food security, protecting the environment and providing rural employment. As they realize economies of scale, it is large farms, however, that are more efficient in the conventional economic sense. Hence, this first narrative sets itself against narratives and explicit goals to uphold small farms and protect their defining role in the European identity. The average farm size for the EU-27 plus the United Kingdom is less than twenty hectares. For comparison, the average farm size in the United States is roughly 180 hectares (9x larger) and for Canada over 300 hectares (15–16x larger). The narrative that technological innovation and uptake should be supported in the agriculture sector is, in many ways, in contrast with the protection of the European agricultural identity. Support of technological innovation and uptake in the agriculture sector has historically been a primary method of *reducing* (in quantity) farmers, *consolidating* farm holdings and reducing the rural population in general. This contentious process, W. Cochrane's so-called "agricultural treadmill", is also known as "scale enlargement", and its steps have been well documented. See, for example, Cochrane (1958, 1993) for the introduction of the principle and a history of its effective application in the United States.

Reliance on imports spells trouble in light of longstanding concerns on food security and increasing foreign demand for resources currently being imported, in particular related to tensions in international trade governance (EPRS, 2018) and associated global megatrends of an increasingly multipolar world, intensified global competition for resources and growing pressures on ecosystems. Considering that preface, this chapter's quantitative storytelling sets to explore an imaginary of a 90% re-internalization of food commodity imports in the long-term (2050). This target translates into an equal 90% internalization for each of the fourteen focal level food commodities demanded in



each of the twenty-nine European countries assessed, meaning that local supply systems are imagined to be forced to supply 90% of that is currently imported from virtual supply systems.

While dramatic, this internalization target proves valuable for learning about potential constraints related to increasing concerns over food security in the long-term—concerns largely driven by rapidly rising food demand in developing countries, cf. an estimated 60% increase in global food demand by 2050 (Alexandratos and Bruinsma, 2012). The internalization target also stands in place of the lack of explicit targets for agricultural trade loop-closing in the EU circular economy policies (EC, 2019b, 2019a)—an absence representing a significant shortcoming identified in the literature (Jurgilevich *et al.*, 2016; Giampietro and Funtowicz, 2020). Lastly, the assumed target is set so as to assess the agriculture sectors of the twenty-nine countries assessed against their safe operating space limits. In this sense, the target aims to explore the possibility of downscaling the global safe operating space concept—a concept with currency from the planetary boundary framework (Rockström *et al.*, 2009; Steffen *et al.*, 2015)—to the national scale, where policy efforts have more traction (Häyhä *et al.*, 2016; Hossain *et al.*, 2017).

Finally, it must be pointed out that the goal of this chapter's imaginary is highly relevant for contemporary policy discussions. The European Commission has indicated that sustainability "from farm to fork" (EC, 2020) is one of the key policy foundations for a sustainable future in Europe in which a modernized CAP is likely to play a crucial role (EC, 2019d). In a similar albeit broader vein, the Commission has presented the European Green Deal, which calls for deeply transformative change in food and agriculture, specifically endorsing digital technology and precision agriculture techniques as crucial enablers (EC, 2019c).

5.3.2 *Data and Assumptions*

The following briefly summarizes the exogenous parameters used to populate the computational model introduced in Section 5.2.1, giving substance to our imaginary. For vegetal products, technical coefficients are had for

1) crop yield (tonne/hectare)
2) blue water use (m^3/hectare)
3) human activity (hour/hectare)

and for animal products, production factors include

1) crop yield, including both meat yield (tonne/head) and milk yield (liter/head)
2) blue water use, including water for drinking and service water (m^3/head).

Quantitative data for these five classes are collated from a wide variety of sources, the primary one being the United Nation's Food and Agriculture Organization (FAO). For supplementary information on the microscale biophysical diagnostic readers are directed to Appendix B.

In addition to the technical coefficient data, three separate population projections from Eurostat (2019b) are used in the generation of results:

1) low-fertility
2) baseline
3) low-mortality

where, in Section 5.3.3, results refer to the baseline population prediction.

Estimates of future food demand profiles are based on a Holt's linear trend forecasting algorithm (additive trend, double exponential smoothing), harmonized with the estimates of Alexandratos and Bruinsma (2012), EC (2017), Farm Europe (2015) and OECD and FAO (2017). A major implication of the adopted approach to modeling food demand is that food export is assumed to remain relatively constant even though decreasing imports are explored. In political terms, this assumption is questionable, for example, trade conflicts would likely erupt. Nevertheless, the exploration of system constraints assuming current economic expectations is a valuable starting storyline. In the event this chapter's anticipation results in biophysical implausibilities, a societal discussion can be opened concerning which aspects could or should be changed.

Lastly, agricultural yield estimates are calculated using constant average annual growth rates (AAGRs) for each of the mesoscale food commodities, based on the established literature (Alexandratos and Bruinsma, 2012; EC, 2017; OECD and FAO, 2017). In all cases of production factor interpolation (described in Section 5.2.2), high- and low-bound projections in Appendix B are informed with a 50% confidence interval (normal distribution) for the calculation of production factor mean values.

5.3.3 *Imaginary*

At last, to explore what insights our sociotechnical imaginary might bring. The geopolitical classification of Olesen and Bindi (2002) is used to present the results, which, based on environmental and socio-economic factors, divides Europe into eight major agricultural regions. The previous Figure 31 was an excerpt from that classification. The *North eastern*, *South eastern* and *Eastern* regions are characterized by a relatively less industrialized form of agriculture and the *Nordic*, *British Isles*, *Western* and *Alpine* regions a relatively more industrialized form. In the *Mediterranean* region, a mix of low- and high-agricultural industrialization is found.

Figure 35 provides an overview of the results for the EU-27 plus the United Kingdom and Norway. N.B. The Netherlands and Malta are excluded from the land use and blue water use characterizations in Figure 35 on the basis that they are extreme outliers. The anticipated land use in the Netherlands in the long-term is close to 1000%, resulting from the fact that the Netherlands has a very large agribusiness sector and a very small crop area. Despite having 75x less arable land, the export of agricultural products in the Netherlands is roughly equal to that of Argentina and Canada summed (measured in monetary terms and including re-export) (FAO, 2017). In the case of Malta, the anticipated use of blue water in the long-term is roughly 215% of its internal renewable water resources. This figure is understandable in light of the fact that Malta is in the lower 4% of countries globally in terms of renewable water resources per capita (FAO, 2016).

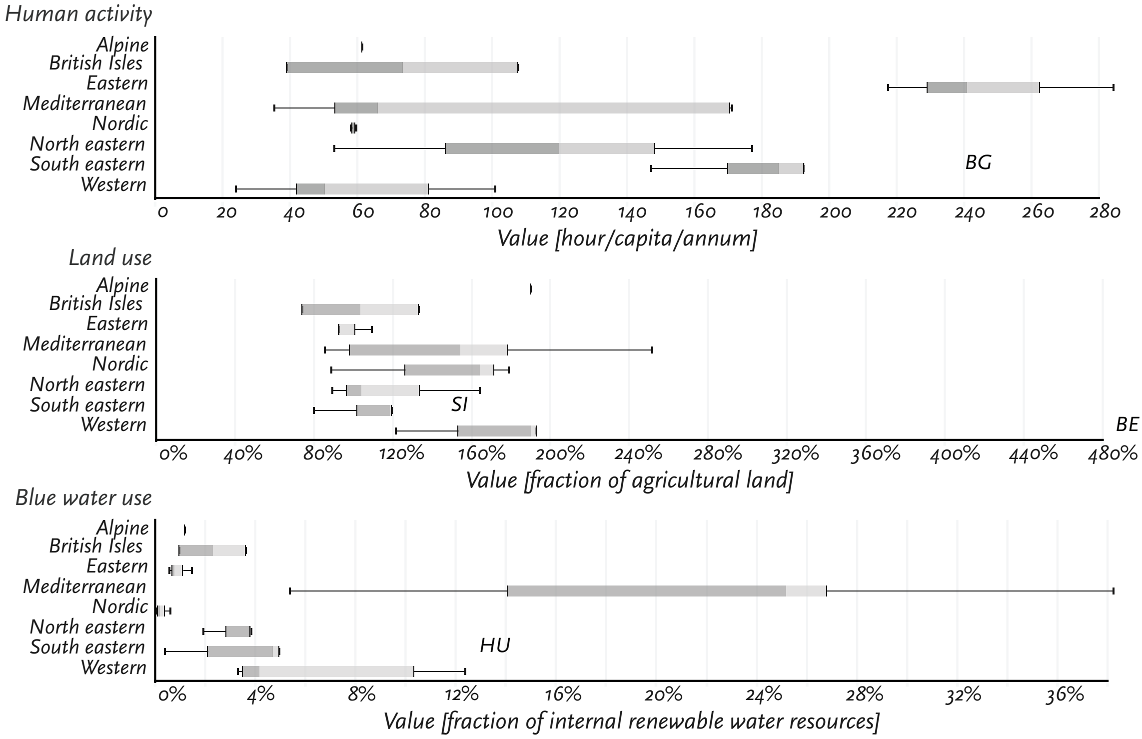


Figure 35 Overview of the anticipation of three production factors in the long-term (2050) following a 90% agricultural internalization for the EU member states plus the United Kingdom and Norway. For land use and blue water use, both Malta and the Netherlands are excluded from the figure for readability purposes and on the basis that they are extreme outliers. Prevailing outliers (more than 1.5 the interquartile range) are labeled with their ISO-2 country acronym.

Figure 35 does seem to show some concerning trends. According to our anticipation, most countries seem to be requiring more than 100% of their agricultural land. Not nearly a clear possibility! The human activity values have also risen considerably, and the renewable water resources are under a concerning load in the Mediterranean countries. Let's disaggregate further. In the following, one representative country is selected for each of the eight major agricultural regions and food commodities by source and use-type are presented at the mesoscale level using two distinct color scales. Source categories, shown on the leftmost subplots, include local production, direct trade and indirect trade. N.B. In the case of indirect trade, processed products are represented in terms of primary commodity equivalent.

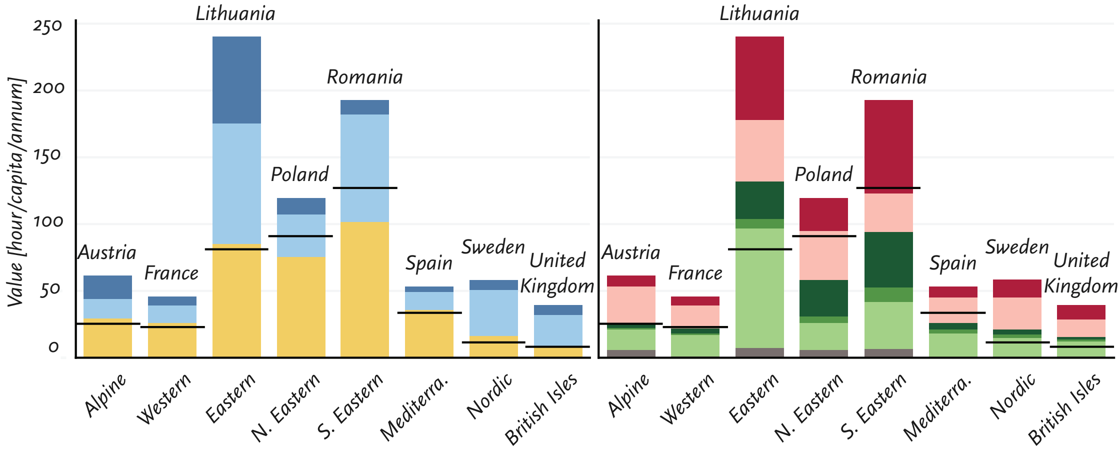


Figure 36 Anticipated human activity in the long-term (2050). Reference lines show 2012 baseline estimates. Long-term anticipations reflect a 90% re-internalization of imports, where the “Trade” legend items refer to commodities that were previously received from trade but whose production has been internalized.

Production category

- 🟦 *Direct trade*
- 🟦 *Indirect trade*
- 🟨 *Local production*

Crop category

- 🟥 *Animal (feed)*
- 🟥 *Animal (products)*
- 🟩 *Vegetal (grains, roots, tubers)*
- 🟩 *Vegetal (oilcrops)*
- 🟩 *Vegetal (vegatables, fruits)*
- ⬛ *Vegetal (vegetal n.e.s.)*

Figure 36 addresses the implications of the change in bio-economic pressure resulting from the anticipation of an increase in human activity in agriculture. In countries with very large import quantities, particularly animal products, extra significant changes are observed. For example, this proves to be the case for Sweden (among the Nordic countries) and the United Kingdom (among the British Isles). As touched upon in Chapters 1 and 2, the history of EU agriculture over the past century could be summarized as the elimination of the need for significant labor in the agriculture sector. This process, effectively one of cyborgization and disenfranchisement, is a result of increasing use of external inputs, such as fertilizers and fossil fuels, a glut of farm machinery power capacity (Giampietro, 1997; Arizpe-Ramos, Giampietro and Ramos-Martin, 2011) and a massive process of externalization. From the perspective of social desirability, we anticipate that affluent countries that have come to take a trend of increasingly high external input agriculture for granted would need to come to terms with substantial relative readjustments in the state of their societal metabolic profiles. Whereas Lithuania, Poland and Romania exhibit relatively low levels of agricultural industrialization and relatively high demand for human activity, Austria, France, Sweden and the United Kingdom represent relatively high levels of agricultural industrialization and relatively low demand for human activity. Spain remains in the middle of those groupings.

In general, far less human activity is required per unit of agricultural product in countries focused on highly industrialized, market-oriented agriculture than in countries with low levels of agricultural industrialization. Indeed, in the long-term and from an absolute perspective, human activity in the agriculture sector in countries performing highly industrialized agriculture remains low. That said, countries performing highly industrialized agriculture would be required to come to terms with a still significant relative increase of human activity in the agriculture sector. In Sweden and the United Kingdom, for example, a roughly 5x increase in human activity per capita is observed. This increase results mostly from the major internalization of animal production and represents a substantial bio-economic pressure. Even so, total levels of human activity likely represent a less-concerning pressure variable than the two other production factors assessed.

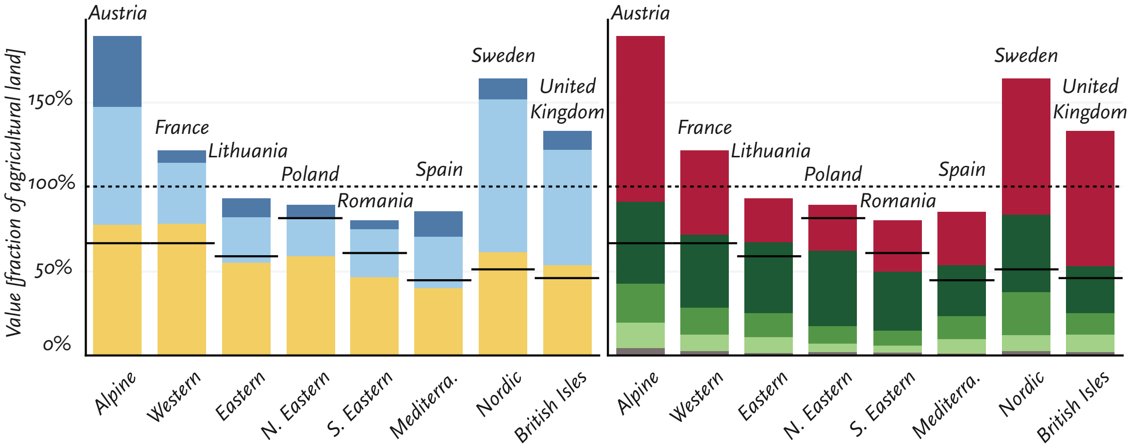


Figure 37 Anticipated agricultural land use in the long-term (2050). Reference lines show 2012 baseline estimates. Percentage values are conservative estimates, due to varying differences in the definition of agricultural land. Long-term anticipations reflect a 90% re-internalization of imports, where the "Trade" legend items refer to commodities that were previously received from trade but whose production has been internalized.

Production category

- 🟦 *Direct trade*
- 🟦 *Indirect trade*
- 🟨 *Local production*

Crop category

- 🟥 *Animal (feed)*
- 🟩 *Vegetal (grains, roots, tubers)*
- 🟩 *Vegetal (oilcrops)*
- 🟩 *Vegetal (vegatables, fruits)*
- ⬛ *Vegetal (vegetal n.e.s.)*

Figure 37 presents an anticipation of the requirement for agricultural-use land as a fraction of total agricultural land. Calculated values are compared against FAO baseline estimates of agricultural land—a class that includes arable land, permanent crops and permanent meadow and pasture. Land that is not used for production purposes but is eligible for subsidy payments is included in the FAO agricultural land estimate. Permanent meadow and pasture include such categories as land crossed during transhumance (seasonal movement of livestock), agroforestry land used for grazing and land out of production for extended periods of time (more than 5 years) but maintained in good agricultural condition. These marginal categories are generally either not considered or underestimated in our imaginary, which is based on standard yield values. For this reason, it must be repeated, the calculated land-use estimates in this work are conservative.

It should also be noted that the suitability of "marginal land" for agricultural production—land considered as inappropriate for agriculture due to its low or non-existent levels of profitability—is highly dependent on agricultural paradigm, agricultural technology and product prices. Intensive, highly industrialized agriculture generally requires high-quality land and the industrialization of agriculture and associated land marginalization is seen as the leading driver of strong trends of farmland abandonment in Europe since the 1950s (Buttrick, 1917; Li and Li, 2017). Agricultural land such as the iconic terracing on the steep slopes of Machu Picchu would certainly not be considered suitable for agricultural use in the modern, highly industrialized sense. Still, that land functioned perfectly well for the Inca in centuries past. Notwithstanding, an increased use of marginal land for agricultural activities may or may not be desirable in environmental terms as buffer zones prove essential for the management of effects on downstream ecosystems.

In general, expansive, low population density countries such as Sweden (among the Nordic countries) are unlikely to be faced with serious internalization issues regarding land use. On the other hand, highly urbanized countries such as France (among the Western countries) and the United Kingdom (among the British Isles) would be faced with an insurmountable task when attempting to internalize. According to FAO estimates, France is roughly 45% agricultural land and the United Kingdom is roughly 75% agricultural land (FAO, 2017). Assuming a 90% internalization rate in the long-term, we anticipate the need for roughly 65% of France's *total land* and roughly 95% of the United Kingdom's *total land*, both impossible changes in system state. Translated, these figures represent roughly 120% of total agricultural land for France and roughly 130% of total agricultural land for the United Kingdom. Austria, the singular Alpine country, would likely also be faced with acute difficulties in internalization concerning land requirements on account of relatively high levels of import and a relatively low percentage of agricultural land (32%, by FAO standards) (FAO, 2017).

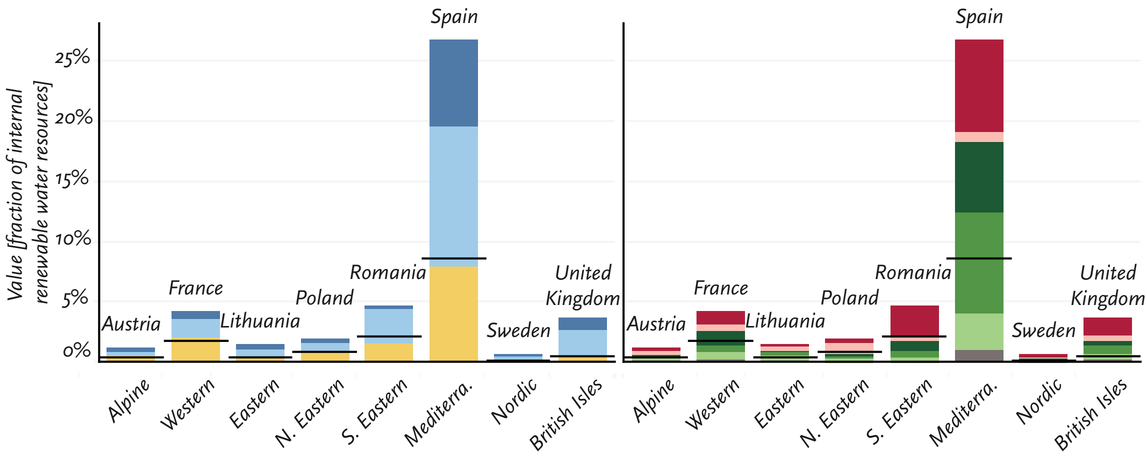


Figure 38 Anticipated blue water use in the long-term (2050). Reference lines show 2012 baseline estimates. Long-term anticipations reflect a 90% re-internalization of imports, where "Trade" legend items refer to commodities that were previously received from trade but whose production has been internalized.

Indicated on the left side of Figure 38, most of the anticipated increase in blue water use derives from the internalization of direct and indirect vegetal trade. Blue water use in feed production is low in relation to the actual mass of feed consumed because a majority of feed crops are not irrigated. For example, roughage, pasture and silage are typically non-irrigated. Nordic countries such as Sweden (illustrated) or Norway (not illustrated) are unlikely to be presented with serious issues on account of them having ample freshwater resources and relatively low irrigation rates. In other regions, such as the Mediterranean and the British Isles, serious issues arise. In the Mediterranean, the mixture of an arid climate and high levels of irrigation have already led to critical freshwater over-exploitation in several agrarian provinces. For example, this is the case for numerous agrarian provinces in Spain and Portugal (EEA, 2018). Spain's current water exploitation index of roughly 30% already translates into acute impacts at the regional scale (Eurostat, 2018). Assuming a 90% re-internalization in the long-term, we would anticipate Spain to require a blue water abstraction rate roughly 350% higher than its baseline value. Although our national-level data is not geographically resolute enough to calculate watershed impacts, it is anticipated that virtually the entire country would be in an acute water crisis on account of such a strong pressure signal. In other countries with substantially lower blue water usage, significant adjustments in ecosystem interactions would still be required, largely as a result of the internalization of processed animal feed components. For example, this is the case for the United Kingdom and Romania.

5.4 DISCUSSION

5.4.1 *Science-Policy Interface*

In this chapter, a learning-type storyline explored one possible characterization of the ecosystem impacts following a 90% re-internalization of food and feed imports by each of the twenty-seven member states of the EU plus the United Kingdom and Norway. On average, across the countries explored, it was anticipated that 2–3x more land for agricultural use would be required. Blue water exploitation was anticipated to be as much as 8–9x higher than the status quo in Northern European states. What types of environmental impact would these changes imply? Concerning social-economic factors, countries across the board would likely require roughly 2–3x more human activity in agriculture. Social desirability concerns would confront with, and need to be checked against, social norms and social practice expectations of the modern service sector economic paradigm, where the role of farmers in European society has become, in a sense, to feed cities (Renner, Louie and Giampietro, 2020).

Anticipated environmental pressures further indicated that current and foreseeable technological development rates would not alone be sufficient to match the challenges provided by re-internalization. On top of business as usual expected improvements, land use and water efficiency would need to improve on average 3–4x, entailing that environmental pressures would be incompatible with existing biophysical constraints. The assessment of biophysical constraints in this chapter was not comprehensive, it lacked consideration of factors such as nitrogen, phosphorous and potassium fertilizers, energy carriers such as various liquid fuels and electricity and plant protection products such as pesticides and insecticides. Nonetheless, the magnitude of the incompatibility of the two environmental pressures explored in Section 5.3.3 raises concerns across the environment dimension.

In light of the trends explored in Section 5.3.1 and results presented in Section 5.3.3, it would be advisable for countries to carefully consider pathways for at least a partial re-internalization of their agriculture sector. The EU should also consider a more careful integration of the agriculture sectors of member states. The elaboration of a sound transformation pathway is not possible without an accounting approach that is rooted in multi-scale, biophysical analysis. The analysis presented in this chapter is one example of such an approach. Given the many non-trivial, impredicative causal relations among the complex components of social-ecological systems, quantifications can easily lead to problematic oversimplifications. In conventional, "sophisticated" approaches involving economic modeling of trade in agricultural commodities, such as the CAPRI model (Britz and Witzke, 2014), economic and environmental variables including biophysical constraints are often dealt with at a single scale and dimension at a time. Such models thus appear more suitable for short-term assessments rather than long-term transformations and societal reconfigurations, as the assumptions underpinning model equations are very likely to fall apart under anticipations which entail radical changes in existing patterns. Similarly, dynamical modeling simulations can only meaningfully reflect small oscillations in the proximity of current conditions, and therefore cannot represent and be used to explore possible long-term reconfigurations of national food systems or agriculture sectors. This aspect implies that standalone econometric analyses based on forecasts of aggregate production and consumption are fully insufficient for producing robust indicators, contrary to what is presented in this work.

Instead, the biophysical lens proposed and applied to this chapter's prospective assessment can provide a complementary approach relevant for agroecosystem accounting. Prospective assessments must allow for the identification of which system elements and which biophysical vectors contribute most to specific pressures (for example, in the column charts presented in Section 5.3.3), thereby allowing decision-makers and stakeholders to identify critical points associated with a specific mix of concern and anticipation. All these indicators are informative and relevant, though they speak differently to different stakeholders and inform different aspects of decision processes as dependent on stakeholder interest (Saltelli and Giampietro, 2017). Evaluating whether policies have had or are likely to have significant impacts (positive and/or negative ones) or have reached prefixed objectives necessitates a sound, multi-dimensional knowledge base and robust biophysical accounting methodology. In the context of studies of ecosystem services and disservices, different stakeholders and cultural groups have different, equally legitimate preferences (van Zanten *et al.*, 2016) and the use of methods capable of integrating value pluralism proves essential (Jacobs *et al.*, 2016).

The strongest assets of this approach are its authentic consideration of system change[24] and its internal biophysical consistency—an aspect well suited for assessing trade-offs, burden-shifting and inherent limits associated with alternative configurations of the system under investigation. When used as

[24] System dynamics were considered through the substitution of classes (associated with metabolic processors). In this way, despite using simple, linear transfer functions and in contrast to conventional dynamical modeling, authentic system change was explored.

an anticipatory impact assessment tool, this approach is able to show whether transformation scenarios and pathways aimed at minimizing impacts on natural capital are within the realm of feasibility, could lead to viable socio-economic reconfigurations and could open-up debate concerning the overall desirability of the proposed changes across different sustainability goals. Even just an indicator tracking the level of openness of various resources and commodities would prove highly relevant for tracking EU loop-closing efforts in agriculture and the food system at large. Without such an indicator, a perverse incentive for European countries to further open their agriculture sector (relying on foreign imports and markets) may be created.

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6 CONCLUSION

6.1 CONCLUDING REMARKS

6.1.1 *Contributions*

This dissertation is a contribution to the formalization of a new accounting framework emerging at the junction of the fields of relational biology and societal metabolism. It builds on the legacy of the *Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism* approach. The insights provided support the deliberative creation of extensible social-ecological models that consider, in an intuitive and scalable manner, both *intrinsic causality* (an explanation of biophysical material and formal causality, related to being) and *extrinsic causality* (an explanation of efficient and final causality, related to becoming and including human activities and normative values). Notably, perhaps uniquely, the proposed accounting framework is able to coherently encode impredicative loop analyses (Giampietro and Ramos-Martin, 2005; Giampietro, Mayumi and Ramos-Martin, 2009). It therefore allows for the establishing of congruence across scales of

1) the representation of the dynamic behavior expressed by the observed system (input/output ratios),
2) expected changes in what is generating the behavior (processes determining input/output ratios),
3) what is needed to stabilize the interactions determining the behavior (interface of the observed and its surroundings) and, at the meta-level but still crucial for the discussion,
4) changes in the observer-observed complex, related to changes in the usefulness and relevance of the analysis.

While it is true that the very idea of impredicative loop analysis conflicts with the zeitgeist of modern modeling efforts, complementing predicative approaches with impredicative ones should be understood as a liberation, not an admission of defeat. The self-referentiality of complex systems is understood in this dissertation to be a virtuous cycle, not a vicious one.

Building on that premise, the theoretical contributions of this dissertation are various. In Chapter 1, a discussion of the modes of composition of social-ecological processes provided new insight into the idea that "societal metabolism" is reality, not a metaphor. In particular, a characterization of the relations of hierarchical composition and sequential composition between hypercyclic sectors and dissipative sectors of social-economic systems was used to assert that social-economic systems are metabolic-repair (M,R) systems of the type proposed in relational biology. Phrased equivalently, a characterization of the relations of functional entailment and material entailment between the agriculture, energy/mining, building/manufacturing, service and household sectors was used to assert that social-economic systems are organisms. This defense of the idea of societal metabolism represents a bold returning of relational biology to its roots[25]. It also allowed for several contributions to be made.

For example, it allowed for the idea that social-economic systems are losing their relations of functional entailment. In Chapter 1, the idea of loss of functional entailment was presented and associated with two new concepts: *societal cyborgization* and *primary sector disenfranchisement*. These ideas are powerful in that they shed light on the mechanism of dominance of the service sector in the modern economy and on the dark side of processes of globalization and externalization. Despite the identification of a dark side, it should be kept in mind that no value-judgements were offered. These ideas serve simply to enhance the ability of social-economic systems to reflect on it the identities they wish to create. A defense of the consideration of finality in social-ecological modeling was also contributed, where consideration of finality is understood to be a necessary precursor to insights on societal cyborgization and primary sector disenfranchisement. Notably, the inclusion of finality in the characterization of social-economic systems as metabolic-repair stands in contrast to the idea of autopoiesis, which is more mainstream but based on a purely structural foundation. The contributions of Chapter 1 therefore imply the need for an adjustment in the way we pursue sustainability science, namely the need to better integrate into our models considerations of functional relations.

Working to integrate functional considerations, a contribution on the role of narratives in sustainability science was made in Chapter 2. The justification, explanation and normative narrative trio is not new in this dissertation, but it is still young and has yet to be given significant attention. First, the use of Voronoi tessellations ("mosaics") to visualize knowledge spaces is new. Such a technique offers a powerful way of communicating knowledge spaces, including how they change over time. For example, Voronoi tessellations of knowledge spaces could prove extremely useful in deliberations with the extended peer community. Second, a new dynamic within the narrative trio is contributed in Chapter 2's discussion on the role of justification narratives in breaking impredicative loops (chicken-egg paradoxes). The idea of justification narratives as breakers of impredicative loops provides compelling insight into the rightful place of contemporary predicative/optimizable modeling efforts. It also provides insight into how an understanding of complex systems as impredicative, coupled with an understanding of the narrative bounds of the knowledge space in which models are created, can still result in actionable research.

Insights into how scientists can consider the extended peer community then led to two assertions, first that post-normal scientists act as *game-players* (versus Kuhnian normal scientists as puzzle-solvers) and second that scientists fulfill an essential role of projecting reality into formalizations (revisiting the

[25] See Rashevsky's (1966) *A Sociological Approach to Biology*, which discusses how sociology inspired the creation of relational biology.

idea of scientists as cartographers). The idea of game-playing, inspired by Wittgenstein's "language-games", is a theoretical contribution that helps inform the role of sustainability scientists together with the extent of their domain of research. It is a contribution that helps orient sustainability scientists, supporting the idea that they must always make an effort to remain on the "horns of the dilemma". In this sense, sustainability scientists must always be questioning the relevance of scientific problems (instincts mediated by perfection-seeking in a cultural context) and assessing the intersection of scientific problems with societal concerns (which are purely instinctual).

Chapter 2 made considerable effort to bridge its theoretical contributions with the practical aspects of social-ecological modeling. A new way of structuring knowledge spaces was contributed, based on hierarchical and taxonomic classifications of fourfold causality and their modifiers. This proposed approach is an exploration of how a sustainability scientist, acting on the "horns of the dilemma", can both organize and audit modeling efforts. Wittgenstein's ideas on grammar were used to clarify what exactly the act of knowledge space auditing entails. Although the discussion of grammar is not new to societal metabolism, the take of Wittgenstein's conceptualization to improve the multidimensional structures of knowledge spaces is. Its practical value was illustrated in Chapter 2's critique of the input-output analysis approach. Lastly, the idea of using Cartesian products to create multidimensional classifications, the "skeletons" or "backbones" of knowledge spaces, is, to the best of the knowledge of the author, new to social-ecological modeling. As indicated in Chapter 5 (the agricultural case study), its value is substantial not only conceptually, for example for visual thinkers, but also as an approach to semantic interpolation of empirical data (Appendix A).

Ultimately, all the various theoretical contributions of this dissertation are intended as an offering made with civil society in mind. They have the potential to help us overcome our ongoing failure to engage with sustainability issues and they advance society one step further towards informed deliberation over responsible development pathways.

Commonalities across the energy and agriculture case studies contribute a rudimentary vision of how that informed deliberation might proceed. The analysis contributed by the energy sector case points at an excessive reliance on economic narratives as one of the possible causes leading to the underestimation of the structural and functional hurdles to be faced when implementing renewable energy transition policies. It was asserted that civic discussions about a future, completely distinct energy system should be complemented with other types of narratives. It was suggested to move away from a "Yes, we can!" mode of discussion in which the solution is to set a business models with the goal of achieving a certain set of normalized expectations. It is also suggested to move away from a mode of discussion which assumes that "no matter the problem" human ingenuity and the invisible hands of the market will be capable of solving it. Instead, as the contribution goes, it may be advantageous to start exploring a mode of discussion based on, "Houston, we've had a problem!".

The approach used in Chapter 4 and Chapter 5, quantitative storytelling, does not claim to provide uncontested "facts" to the process of deliberation over sustainability policies. Chapter 4 was elaborated as part of the *Moving Towards Adaptive Governance in Complexity* project[26] and, as a matter of fact, we were constantly confronted in that project by strong believers of a quick decarbonization through a massive and rapid deployment of intermittent electricity sources—supporters of the "economics of techno-scientific promises" (Joly, 2010). This disagreement is perfectly legitimate. Any analysis of the possible evolution of a complex adaptive system can always be contested by challenging specific technical assumptions. However, critiques of this nature should not be used to avoid the discussion of the proposed concerns. A discussion about the plausibility of policies should not be focused on "what may happen" but rather on reaching an agreement on "what cannot happen". Numerous learning-type stories should be included to balance hero-type stories (Janda and Topouzi, 2015). Those convinced that technological innovation represents a panacea in the modern sustainable energy crisis often avoid discussing concerns about the plausibility of policies currently proposed. The usefulness of the quantitative storytelling approach does not depend on whether the analysis presented should be considered as a fact. Rather, its usefulness depends on whether the concerns raised provide a sobering reminder about the risks of bad planning. Quantitative storytelling is about learning how to handle *uncomfortable knowledge* that is disturbing our visions and aspirations for the future. As Rayner (2012) reveals, the systemic refusal to handle uncomfortable knowledge is the main mechanism of the social construction of ignorance in science and environmental policy discourses.

The term "energy transition" is nearly always used in reference to a change in the structural composition of primary energy supply (Smil, 2010, p. vii). Unfortunately, over the past century, our economies have become so intertwined with oil and gas that substituting fossil fuels will take an Olympic effort. This does not entail that a transition away from fossil energy cannot be done. We, as a society, will have to do it either willing or not. However, it is essential to acknowledge that when dealing with a complex pattern of production and consumption (the metabolic pattern of social-ecological systems) it is unthinkable to imagine a transition based on the maintenance of the same pattern of consumption (required for the stabilization of existing institutions and social practices) coupled to the introduction of a new pattern of production (Giampietro, Mayumi and Sorman, 2012). That is, in order to be capable of using alternative sources of electrical energy we must change the existing institutions and social practices. Society as a whole must move to a different integrated pattern of production and consumption. This is not an easy task and above all this is not a task that can be achieved by structural change

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[26] See the afterword for more details.

alone. Any change in the existing pattern of production and consumption of energy will require adjustments in both the existing power structure and existing social relations. Regarding this point, the natural inertia of social systems may explain why, globally, fossil fuel subsidies still outpace renewables subsidies 4:1 (REN21, 2017). The massive replacement of fossil fuel as an energy carrier in modern economy is a task so complex that it will require an exercise of extreme humility by those attempting to analyze it. This transition cannot be predicted and controlled by simple technocratic planning nor left to the invisible hands of the market in accordance with ideology. In a situation where the characterization of the future is highly uncertain and highly contested, it is not advisable to operate under command and control or put blind faith in the market forces. Otherwise, we risk propelling ourselves headlong and blindfold into a situation of structural-functional mismatch.

In the agriculture sector case, a set of novel methods was applied in anticipatory fashion to explore an imagined agricultural future for twenty-nine European countries in the long-term. The methods used were selected based on their ability to coordinate the biophysical accounting of agriculture sectors understood as social-ecological systems, viewed through the lens of complexity. Specifically, the near-complete re-internalization of agricultural production was explored (90% in the long-term). The results presented in Chapter 5 show that if, in pursuit of resilience or national security agendas, a significant re-internalization of food supply inside the respective borders of the twenty-nine countries explored is considered to be a long-term goal or necessity, major social, economic and environmental challenges would be need to be overcome. For example, significantly more employment and land-use in the agriculture sector would be required and changes in agricultural paradigm away from market-oriented agriculture would need to be explored.

Although an extreme level of agricultural re-internalization in the European Union may currently seem an unrealistic future, its plausibility cannot be ruled out *a priori*. As the foresight approach to exploring the future asserts, exploration of the repercussions of “improbable” scenarios allows to stretch-out thinking and supports the identification of “blind spots”, which can be of relevance for current policies. Coupling anticipation science with biophysical accounting methodology, as developed in this dissertation, contributes unique insights for policymakers by exposing and exploring implausibilities—questioning the possibility of “living well within the limits of the planet” (EC, 2013) without a fundamental reconfiguration of production and consumption patterns if not society at large. These insights are clearly relevant for the policy debate occurring in the European Union on policies and strategies such as the Common Agricultural Policy, the Farm to Fork Strategy (EC, 2020) and the European Green Deal (EC, 2019). These insights are also highly transferrable to a variety of other geopolitical contexts, such as to the United States of America as it mulls over the idea of a Green New Deal.

As levels of agricultural openness have risen over the years, interregional assessments of the nature's contributions to people have increased in importance. Notwithstanding, many studies continue to neglect them. Chapter 5 contributed an integrated approach to assessing cross-boundary flows, thereby providing a new perspective on the complex issues involved. Examples of complex issues include aspects such as resource security and value pluralism, both of which would have been tricky to explore using methods of conventional economics. As with the energy sector case, the uncontested endorsement of economic storytelling was seen to be a formidable filter against societal reflection on uncomfortable knowledge about the agricultural sustainability predicament (Giampietro, 2019). The approach demonstrated demands a major shift in thinking away from reductionist sustainability.

None of the insights in this dissertation are arguments for the elimination of methods of conventional economics or reductionism. Rather, the idea that methods of contemporary science should be expanded to include methods based on the premise of unavoidable impredicativity is presented and defended. This dissertation is a concerted effort to merely break the *hegemony* of predictivity and optimizability. At its core, it develops a paradigm of *supercritical sustainability*, being a mode of sustainability where the generation of knowledge is admitted to be contingent on the specific arrangement of information within impredicative relations. Supercritical sustainability is an argument to shift away from puzzle-solving in a world of artifice, being the orthodox strategy of subcritical sustainability, to game-playing in a world of organic change. This dissertation will have succeeded if the reader has newfound appreciation, or enthusiasm, for impredicative modeling for sustainability. At the very least, it is hoped that the reader believes to have been exposed to sound, original thinking.

6.1.2 *Limitations*

A major limitation to the general approach presented in this dissertation, or rather a serious obstacle to be confronted, is the fact that modern institutions of scientific modeling are ideologically possessed by the ideas of predictivity and optimality. It will be a challenge to convince the "old guard" of the worth of approaches to modeling grounded in impredicativity. Predictivity and optimality are tied to an important cultural legacy extending back at least to the Age of Enlightenment. They are to thank for an impressive array of technological innovations (rockets, smartphones). Questioning predictivity and optimality can feel like a questioning of the worth of those innovations. This feeling is clearly the result of illogical thinking—a proposal to complement predicative modeling efforts with impredicative modeling efforts is not a denial of the historical successes of predicative modeling. Notwithstanding, the feeling that the impressive array of technological successes is being attacked does exist and it does create a very difficult situation for those who propose to embrace impredicativity.

Complementary to the difficulty of admitting to impredicativity, there is difficulty in getting political processes to admit to the existence of uncomfortable knowledge. In modern society, we often feel entitled to know the "optimal way" forward, as if it's a civil right. The "optimal way" forward is understood as comforting, whereas uncertainty and the "frightening" unknown are "bad" and in need of domestication or prophylaxis. Career decision-makers, acting under the assumption of "politics as a vocation" (Weber, 1919), are generally hesitant to admit to unknowability and incalculability—a safe strategy of "evidence-based policy" is normally preferred. What would be needed to question this state of affairs is more reflexivity at the societal level. If civil society learns to admit to and reflect on uncomfortable knowledge at a deeper level, perhaps uncomfortable knowledge will find inroads into the political sphere?

The approach elaborated in this dissertation also proposes substantial engagement with the extended peer community. That's perhaps not an easy task. Certainty, it's much more soothing for a researcher to remain in their proverbial Ivory Tower behind a stack of books or a computer screen. Still, development of responsible development pathways will require that we think outside the box, across sociocultural divides. It will require that science learns to better work with the extended peer community. The empirical work presented in this dissertation, for example, would have benefited from a more thorough engagement with the extended peer community. This is a shortcoming of Chapters 4 and 5. While stakeholder engagement in the *Moving Towards Adaptive Governance Project* did inform the storytelling explored in Chapters 4 and 5, policy document analysis was heavily relied on to identify narratives and more extensive stakeholder exchanges might have led to a more nuanced identification of the underlying justification, explanation and normative narratives.

In general terms, this dissertation's empirical work was, in many ways, crude. On the one hand, the results of the back-of-the-envelope calculations presented in Chapters 4 and 5 were perfectly good enough to draw insightful conclusions. They highlighted several inadequacies in mainstream visions of energy and agriculture sector futures. On the other hand, more precise and certain quantitative characterizations would be desirable if Chapters 4 and 5 are to be meaningfully used by decision-makers. Such characterizations can be difficult to generate. Biophysical accounting is often found to be considerably more difficult than econometric accounting in that good sets of biophysical data are difficult to come by. Human activity data is particularly sparse, always but especially for non-paid activities.

6.1.3 *Recommendations for Future Research*

The easiest way of recommending future research is to call for more case studies. That strategy may be particularly appropriate in the present context since the approach presented in this dissertation is both novel and heterodox, drawing itself on a breadth of esoteric fields. There is a general lack of biophysical accounting, a lack of attention to the relational approach (over the reductionist approach), an overlooking of the idea of societal metabolism (social systems as organisms), and so forth. More case studies engaging with any or all those ideas would increase the apartness of their worth.

Indeed, the elaboration of additional quantitative assessments, for example of the patterns of metabolic change of the primary industrial sectors and the security implications of externalization, is urgently needed by governance efforts. In terms of energy analysis, future research could deepen the discussion over how to best define a relation between power capacity and gross supply (utilization factor, power load, or, the characterization based on production factors per type). Depending on the level of centralization of an electrical grid, present or future, research could explore how much energy must be stored in order to integrate a given quantity of intermittents in the grid in order to balance demand and supply. Storage loss profiles and the spatial/temporal distribution of dispatched, stored energy could be explored. Better consideration of the degradation rates of storage infrastructure and embodied inputs in the manufacturing and installation of storage infrastructure could also be made.

In terms of agricultural analysis, more work is needed in terms of the biophysical characterization of agricultural processes in general. The biophysical limits of agricultural option spaces could be better defined, allowing societies to make agile decisions in an increasingly uncertain world. It would be particularly helpful to shine more light into the black box that is processing (post-harvest). The potential impacts of alternative food system paradigms could also be explored, for example food system paradigms other than the current one based on maximization of convenience. N.B. A lot of this empirical work, both for the agriculture sector and energy sector, is synthetic in nature. Science has done very well at accumulating a wealth of knowledge, "facts", but much work is still needed in transforming that wealth of knowledge into actionable wisdom.

A slightly less trivial recommendation for future research would be to investigate how to better integrate the extended peer community into processes of deliberative modeling and societal anticipation. The only way to inform ourselves over the possibility, probability, uncertainty and preferability of anticipated futures (Amara, 1991) is through better engagement with the extended peer community—drawing on society's immense base of tacit knowledge (Polanyi, 1962). Empirical stocktaking of the justification, explanation and normative narratives used by extended peer communities would shed new light on goal-oriented (rather than stimulus-driven) (Poli, 2017, p. 24) development pathways.

Additionally, a lot of exciting work remains on the conceptual side. The language of relational biology is category theory, a theory which provides a bird's eye view of mathematics. While category theory was jokingly referred to at its inception as "general abstract nonsense" (Mac Lane, 1997, p. 5983), category theory has come to incite revolutions in a variety of fields ranging from computer science to cognitive science and beyond. While it is sure that the full integration of category theoretic concepts into the approach discussed in this dissertation will further strain the patience of readers, it is also sure that category theory has a lot to offer. For example, category theory has proven extremely valuable in its ability to inform computational patterns, most notable in pure functional programming languages, such as Haskell, but importantly also in others, such as Python. These insights, delivered through the conduit of 60+ years of work in the field of relational biology, could help with the design and implementation of intuitive, scalable technologies grounded in the paradigm of supercritical sustainability. These technologies could serve as a new class of what S. Jasanoff (2003, p. 227) calls "technologies of humility":

> These are methods, or better yet institutionalized habits of thought, that try to come to grips with the ragged fringes of human understanding – the unknown, the uncertain, the ambiguous, and the uncontrollable. Acknowledging the limits of prediction and control, technologies of humility confront 'head-on' the normative implications of our lack of perfect foresight.

At a very profound level, these technologies, perhaps together with additional insights from biosemiotics, could contribute to the answering of longstanding questions surrounding when artificial intelligence will cross the barrier of meaning.

So, the axiomatic basis of relational biology should be engaged with further, used to create an axiomatic basis for relational sociology. This work could help with the creation of a more effective vocabulary of human-machine interfacing. If the timeless nature of L. Wilkinson's (2005) *The Grammar of Graphics* is any testament, such work has immense potential. It could improve methods of knowledge visualization and help with the delivery of data insights into the feasibility, viability and desirability of sustainability concerns. It could then improve the ability of non-technical users/extended peer communities to discuss uncomfortable knowledge and to hold better-informed deliberations over development pathways. Axiomatic development with category theory could furthermore improve the reproducibility and comparability of analyses.

Lastly, it must kept in mind that all these recommendations for future research are ultimately motivated by, like this dissertation, the urgent need to empower sustainability science with new approaches capable of supporting the elaboration of responsible development pathways.

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Supercritical Sustainability

AFTERWORD

Any reader who made it to this point will, I believe, agree that this dissertation is not a very orthodox one. What is meant by that is, the knowledge engaged with is not “mainstream”. Determination was required to uncover the theories herein. This afterword details several key personal events that motivated and shaped this dissertation. It is equal parts personal anecdote, acknowledgment and résumé, existing in response to official content requirements.

DEGREES

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Institute of Environmental Science and Technology
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Departments of Geography, Environment and Mathematics (Minor in Mathematics)
McGill University

DOCTORAL GRANT

University Professor Formation Grant 2016–2021
Formación de Profesorado Universitario (FPU15/03376)
Ministry of Education, Culture and Sport, Spain

In addition to my doctoral grant, for which I am eternally grateful, I had the good pleasure for working with the *Moving Towards Adaptive Governance in Complexity: Informing Nexus Security* (MAGIC) project over the entire course of my time as a doctoral student. MAGIC, for which Mario was the principal investigator, was the culmination of nearly two decades of development of the *Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism* (MuSIASEM) framework. Granted by the European Commission, the premise of MAGIC was to use MuSIASEM to critically appraise the policies of…the European Commission. Is that not refreshing? Involvement with the MAGIC project granted me dozens of new colleagues covering a wide range of expertise, located across Europe. It allowed me to learn from the unquestioned authorities on relational biology and post-normal science, among many others. It also opened the door for me to interactions with policymakers, the pinnacle of which was a close collaboration with the Integrated Assessment and Knowledge Development unit of the European Environment Agency. Exploring the science-policy interface is an essential litmus test for sustainability scientists. This dissertation is greatly better off for it.

SELECTED CONFERENCES

As presenter

2020	Global Food Security	*Montpellier, France*
2020	International Conference on Complex Systems	*Nashua, U.S.A.*
2020	Dresden Nexus Conference	*Dresden, Germany*
2019	EU Conference on Modelling for Policy Support	*Brussels, Belgium*
2019	Open University of Catalonia Young Researcher's Symposium	*Barcelona, Spain*
2018	Sustainable Energy and Environment Sensing	*Cambridge, U.K.*
2017	European Geoscience Union General Assembly	*Vienna, Austria*

As co-author

2020	World Sustainability Forum	*Geneva, Switzerland*
2019	The EU Biodiversity Strategy [...] (ALTER-Net & EKLIPSE)	*Ghent, Belgium*
2019	European Association of Agricultural Economists Seminar	*Brussels, Belgium*
2018	International Conference 'Water Science for Impact'	*Wageningen, Netherlands*
2018	Energy Modelling Platform for Europe (EMP-E)	*Berlin, Germany*
2018	European Parliament Post-Growth Conference	*Brussels, Belgium*
2017	International Congress on Modelling and Simulation	*Hobart, Australia*

As attendee

2019	EU DataViz	*Luxembourg, Luxembourg*

UNIVERSITY TEACHING

As per the regulations of my doctoral grant, I taught these past few years at the undergraduate level at the Autonomous University of Barcelona. This obligation was meaningful insofar as learning how to communicate in a classroom setting is an incredibly important skill for a young researcher involved with heterodox theories.

Complementary to my teaching in Barcelona, I had the good pleasure of co-teaching and co-designing a master's course titled *Socio-Ecological Impact Assessment* at the Namibia University of Science and Technology, part of their program on *Sustainability Energy Systems*. Just as it is important for sustainability scientists to teach and to bridge the science-policy chasm, it is essential for them cross sociocultural divides. The challenges facing the Northern American, Western European and sub-Saharan contexts are all extremely different!

July–November 2019 Socio-Ecological Impact Assessment
Master of Sustainable Energy Systems
Department of Electrical and Computer Engineering
Namibia University of Science and Technology
Windhoek, Namibia

Various Courses — April–May 2020
Department of English and German Philology — February–June 2019
Faculty of Philosophy and Language — February–May 2018
Autonomous University of Barcelona
Barcelona, Spain

SUMMER SCHOOL TEACHING

Summer schools provided me, as an educator, with a creative allowance far beyond would could naturally be expected in a university setting. I benefited greatly from teaching at and helping organize the following schools. Episodes marked with an asterisk (*) indicate events hosted or co-hosted by the LIPHE4 association together with the Autonomous University of Barcelona's Institute of Environmental Science and Technology. LIPHE4 summer schools are week-long sagas that bring together diverse student bodies, from politicians to statisticians, biologists, environmentalists, geographers, engineers, activists and more, junior through senior.

*Complex Sustainability Challenges: The nexus between water, energy and food — 8–12 July 2019
Bellaterra, Spain

*Can Cities Be Sustainable? Novel Tools to Explore Urban Metabolism — 2–6 July 2018
Co-host: ENVIROSPACE Lab, University of Geneva
Geneva, Switzerland

Energy Metabolism — 5–7 July 2017
Borgofuturo Social Camp
Ripe San Ginesio, Italy

*A Critical Appraisal of Current Narratives of Sustainability through Quantitative Storytelling — 26–30 July 2017
Co-host: Department of Biology, University of Naples Federico II
Naples, Italy

*The Nexus between Food, Energy, Water and Land-use: Quantitative Storytelling with MuSIASEM — 11–15 July 2016
Bellaterra, Spain

SELECTED PUBLICATIONS

The following is a list of selected publications made during the past years as a doctoral student. Three are in conference proceedings, six are in indexed journals. This dissertation contains parts of Renner and Giampietro (2020), Renner *et al.* (2020) and Renner, Louie and Giampietro (2020).

Cabello, V., Renner, A., & Giampietro, M. (2019). Relational analysis of the resource nexus in arid land crop production. *Advances in Water Resources, 130(January)*, 258–269. https://doi.org/10.1016/j.advwatres.2019.06.014

Cadillo-Benalcazar, J. J., Renner, A., & Giampietro, M. (2020). A multiscale integrated analysis of the factors characterizing the sustainability of food systems in Europe. *Journal of Environmental Management, 271(July)*. https://doi.org/10.1016/j.jenvman.2020.110944

Chifari, R., Renner, A., Lo Piano, S., Ripa, M., Bukkens, S. G. F., & Giampietro, M. (2017). Development of a municipal solid waste management decision support tool for Naples, Italy. *Journal of Cleaner Production, 161*, 1032–1043. https://doi.org/10.1016/j.jclepro.2017.06.074

Giampietro, M., & Renner, A. (2020). The Generation of Meaning and Preservation of Identity in Complex Adaptive Systems: The LIPHE4 Criteria. In D. Braha (Ed.), *Unifying Themes in Complex Systems X*. Cham, Switzerland: Springer.

Giampietro, M., Renner, A., Cadillo-Benalcazar, J. J. (2020). An accounting framework recognizing the complexity of the nexus. In Brouwer, F. (Ed.), *Handbook on the Water-Energy-Food Nexus*. Cheltenham: Edward Elgar.

Renner, A., Cadillo-Benalcazar, J. J., Benini, L., & Giampietro, M. (2020). Environmental pressure of the European agricultural system: Anticipating the biophysical consequences of internalization. *Ecosystem Services, 46*. https://doi.org/10.1016/j.ecoser.2020.101195

Renner, A., Louie, A. H., & Giampietro, M. (2020). Cyborgization of Modern Social-Economic Systems: Accounting for Changes in Metabolic Identity. In Dan Braha (Ed.), *Unifying Themes in Complex Systems X*. Cham, Switzerland: Springer.

Renner, A., & Giampietro, M. (2018). The Regulation of Alternatives in the Electric Grid: Nice Try Guys, But Let's Move On. In *International Conference on Sustainable Energy and Environment Sensing (SEES)* (pp. 1–16). Cambridge, UK. ISBN: 978-1-912532-01-8.

Renner, A., & Giampietro, M. (2020). Socio-technical discourses of European electricity decarbonization: Contesting narrative credibility and legitimacy with quantitative story-telling. *Energy Research & Social Science, 59*. https://doi.org/10.1016/j.erss.2019.101279

CLOSING REMARKS

The projects, collaborations, conferences, symposiums, policy advisories and teaching episodes realized during the past few years, taken all together, were both extremely challenging and extremely rewarding. Knowledge can, perhaps, be learned from books. Wisdom, being knowledge plus how to use it, cannot, however, be learned from books. The extra-curricular journey that shaped this dissertation provided a modicum of wisdom, I think, without which the theories knit together here could never have been knitted together. That journey has shown me that, when dealing with post-normal situations, it is unwise to wait expectantly for a highly particular vision of the future to arrive. The future will come knocking, that much is sure, but the version that arrives is sure to differ in important ways from the one naturally expected.

A classic World War II story from K. Arrow (1992, p. 47), which may as well be an excerpt from J. Heller's *Catch-22*, provokes reflection on our overarching topic of discussion and provides a fitting way to close.

> The statisticians among us subjected these [weather] forecasts to verification and they differed in no way from chance. The forecasters themselves were convinced and requested that the forecasts be discontinued. The reply

> read approximately like this: "The commanding general is well aware that the forecasts are no good. However, he needs them for planning purposes."

Who is to blame for a sustainability scientist caught in the act of producing predicative models with outputs differing in no way from chance: the scientist or the society that demands such models for planning purposes, well aware of their infidelity?

REFERENCES

Arrow, K. J. (1992) 'Eminent Economists: Their Life Philosophies', in Szenberg, M. (ed.) *'I Know a Hawk from a Handsaw'*. Cambridge: Cambridge University Press, pp. 42–50.

A EXPLORING KNOWLEDGE SPACES IN *PYTHON*

A.1 VISUALLY INTUITIVE WAY

A.1.1 *Construct the Classifications*

This first way of exploring knowledge spaces is intuitive against the context of the mental model of multidimensional structures presented in Chapter 3. A useful conceptual discussion is provoked, but, as we will see, this first way is a fairly sloppy way of handling things as far as computational resource management goes.

First, let's recreate the figures presented in Chapter 3 as networkx directed graph objects ("multi-scale classifications"). A graph populator function is hacked together for the purpose and the graphs are created.

In [1]

```python
import networkx as nx
```

In [2]

```python
def populate_graph(nodes):
    """
    Helper function for this appendix that takes a
    dictionary of nodes and turns it into a graph.

    Args:
        nodes: Dictionary of graph nodes to be added,
               formatted as {parent: [children]}
    Returns:
        Populated networkx DiGraph
    """
    g = nx.DiGraph()
    for parent, children in nodes.items():
        for child in children:
            g.add_edge(parent, child)
    return g
```

In [3]

```python
nodes_fig_15 = {'Building Material': ['Steel', 'Concrete'],
                'Steel': ['Carbon', 'Alloy', 'Stainless'],
                'Concrete': ['Regular', 'Asphalt']}
g_fig_15 = populate_graph(nodes_fig_15)
```

In [4]

```python
nodes_fig_16 = {'Economy': ['Agricul.', 'Construction',
                'Househo.']}
g_fig_16 = populate_graph(nodes_fig_16)
```

In [5]

```
nodes_fig_17 = {'Spain': ['Este'],
                'Este': ['Catalonia'],
                'Catalonia': ['Barcelona']}
g_fig_17 = populate_graph(nodes_fig_17)
```

A.1.2 *Visualize the Classifications*

Next, let's visualize the graphs we just created, so as to make things a little bit less abstract. We'll also lay them out using the *dot* algorithm, which works well with "family tree"-like data.

In [6]

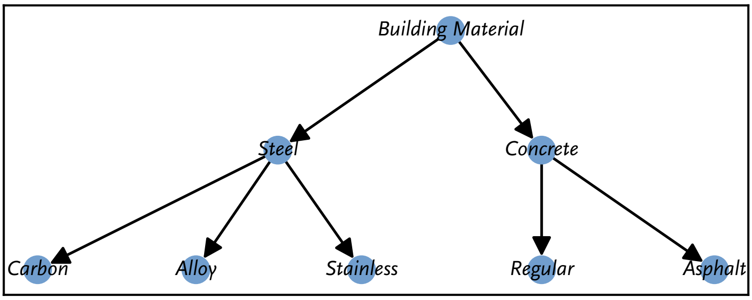
```
from networkx.drawing.nx_agraph import graphviz_layout
import matplotlib.pyplot as plt
```

In [7]

```
kwargs = {'node_size': 100, 'font_size': 8, 'arrowsize': 15,
          'node_color': '#719ECE'}
```

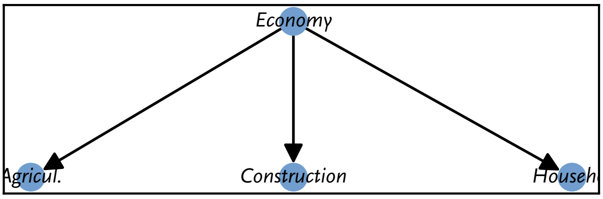
In [8]

```
positions = nx.nx_pydot.graphviz_layout(g_fig_15, prog='dot')
plt.figure(figsize=(5,2))
nx.draw_networkx(g_fig_15, positions, **kwargs)
```



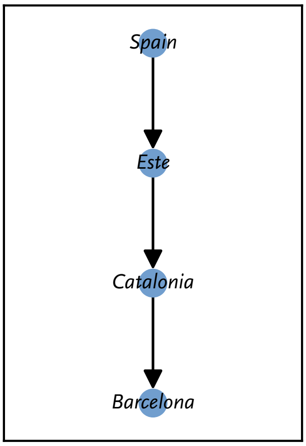
In [9]

```
positions = nx.nx_pydot.graphviz_layout(g_fig_16, prog='dot')
plt.figure(figsize=(4,1.3))
nx.draw_networkx(g_fig_16, positions, **kwargs)
```



In [10]

```
positions = nx.nx_pydot.graphviz_layout(g_fig_17, prog='dot')
plt.figure(figsize=(2,3))
nx.draw_networkx(g_fig_17, positions, **kwargs)
```



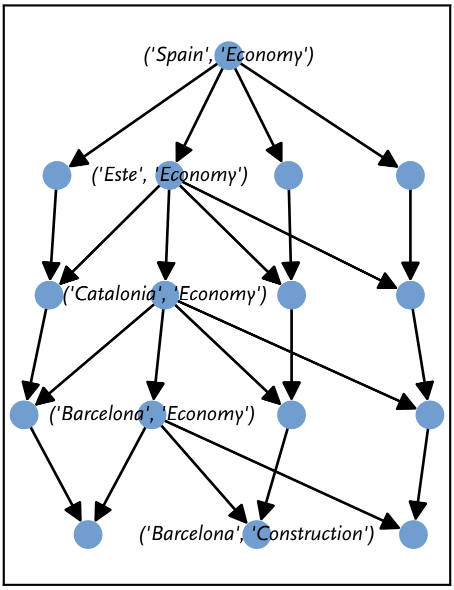
A.1.3 *Create the Multidimensional Structure*

Just like in Chapter 3, we can then proceed to turn our simple classifications into "multidimensional structures", the "backbones" of knowledge spaces. The following is Figure 18 from Chapter 3, being the Cartesian product of the geographical classification (Figure 17) and the economic sector classification (Figure 16).

In [11]
```
g_fig_18 = nx.cartesian_product(g_fig_17, g_fig_16)
```

In [12]
```
# Let's just set to label a few of the nodes, the graphs are
becoming cluttered
nodes = [('Spain', 'Economy'), ('Este', 'Economy'),
         ('Catalonia', 'Economy'),
         ('Barcelona', 'Economy'), ('Barcelona',
          'Construction')]
labels_fig_18 = {node: node for node in nodes}
```

In [13]
```
positions = nx.nx_pydot.graphviz_layout(g_fig_18, prog='dot')
plt.figure(figsize=(3,4))
nx.draw_networkx_labels(g_fig_18, positions, labels_fig_18, font\
                        _size=8)
nx.draw_networkx(g_fig_18, positions, with_labels=False,
                 **kwargs)
```



In a similar manner, the following recreates Figure 19 from Chapter 3, being the Cartesian product of the geographical classification (Figure 17) and the building material classification (Figure 15).

In [14]

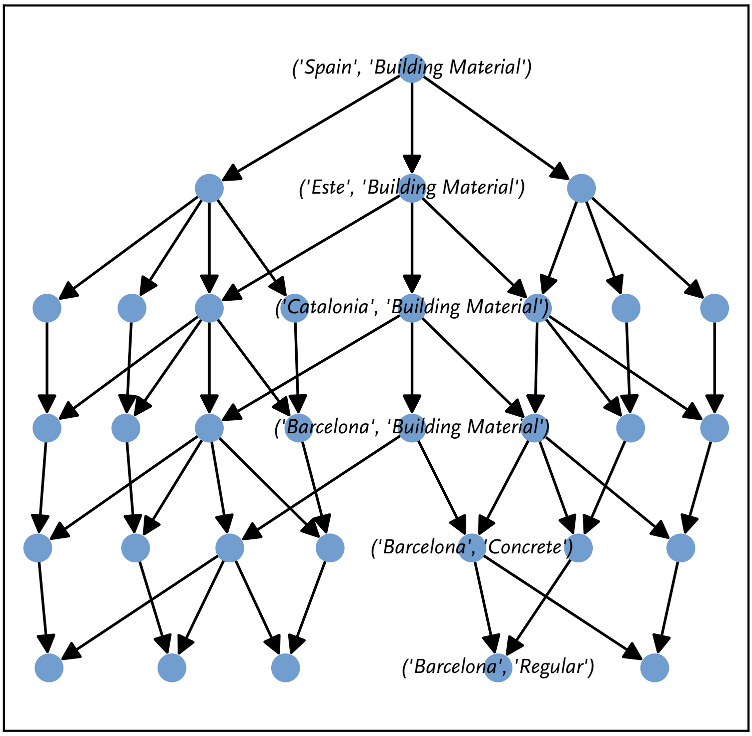
```
g_fig_19 = nx.cartesian_product(g_fig_17, g_fig_15)
```

In [15]

```
nodes = [('Spain', 'Building Material'), ('Este',
             'Building Material'), ('Catalonia',
             'Building Material'),
            ('Barcelona', 'Building Material'), ('Barcelona',
             'Concrete'), ('Barcelona', 'Regular')]
labels_fig_19 = {node: node for node in nodes}
```

In [16]

```
positions = nx.nx_pydot.graphviz_layout(g_fig_19, prog='dot')
plt.figure(figsize=(5,5))
nx.draw_networkx_labels(g_fig_19, positions, labels_fig_19, font\
                        _size=8)
nx.draw_networkx(g_fig_19, positions, with_labels=False,
                 **kwargs)
```



We could proceed by recreating the "three-dimensional" classification from Chapter 3. If we wanted to improve our visualizations here, we could also add an attribute to the graph edges referencing the original classification from before the Cartesian product. That way we could color the graph edges differently, like in Chapter 3, and we would know what dimension is being traversed as we navigate around the structure (Does the edge being traversed mark a change in building material? A change in economic sector?). Also, we could have explored other types of graph product, but the Cartesian product is almost certainly the most intuitive.

A.1.4 *Exploration*

Let's now proceed to "explore" the structures we just created. When fed a specific node in a specific classification, the following functions serve to gather other nodes defined at the same scale, filtered to a certain level of dissociation. For example, first the *coterie_graph()* function would collect siblings (radius = 1), then first cousins (radius = 2), then second cousins (radius = 3), and so forth. N.B. The presented functions are conceptual. If we were to deploy this code, there are a number of things we could do to speed things up. For example, graph reversal is a costly operation. We wouldn't want to be doing it every time we ran a semantic interpolation, which is something we might be doing a lot of in a big database. We would prefer to pass a pre-reversed graph to the *coterie_graph()* function.

In [17]

```
def invert_map(m):
    """
    Helper function taking a dictionary with non-unique
        values and reversing the mapping.

    Args:
        m: Dictionary
    Returns:
        The dictionary, with keys and values inverted
    """
    i_m = {}
    for k, v in m.items():
        i_m.setdefault(v, []).append(k)
    return i_m

def coterie_graph(g, s, r, weight='length'):
    """
    Finds a group of nodes-the "coterie"-for a semantic
        interpolation.
    With r = 1, sibling nodes are returned, r = 2, first
        cousin nodes, and so forth.
    N.B. The source node is included in the return list.

    Args:
        g: A networkx DiGraph
        s: Source node in g
        r: Radius, being how far out to search (maximum
           dissociation)
        weight: Optional edge-weighting parameter for
           traversal distance calculation
    Returns:
        A list of "coterie" nodes
    """
    # Get predecessors of the source node
    dij_preds = nx.single_source_dijkstra_path_length(g.\
                   reverse(), source=s, weight=weight)
    i_dij_preds = invert_map(dij_preds)
    # Set a ceiling on the radius, for safety
    r_c = r if r < max(i_dij_preds.keys()) else max(i_dij_preds.\
                                                      keys())

    # Get the return group, plus the predecessor neighborhood
    # (for later removal)
```

```
  coterie, i_dij_preds_sibs = (set(), set())
    for pred in i_dij_preds[r_c]:
        coterie.update(nx.ego_graph(g, pred, r_c).nodes())
        i_dij_preds_sibs.update(nx.ego_graph(g, pred, r_c - 1).\
                                   nodes())

    # Remove the predecessor neighborhood, saving the source
    # node if the radius is zero
    if r > 0:
        for pred in i_dij_preds_sibs:
            coterie.remove(pred)

    return list(coterie)
```

The following then illustrates the worth of the *coterie_graph()* function. In the classification of building material (material cause in the city construction motif), the following takes the *Stainless* class and finds the set of sibling nodes.

In [18]

```
coterie_graph(g_fig_15, 'Stainless', r=1)
```

Out[18]

```
['Carbon', 'Stainless', 'Alloy']
```

This action, this "semantic interpolation", might have been done because we were missing a technical coefficient for *Stainless*. Assuming that's the case, we would then have to ask ourselves, do the semantics of this interpolation make sense? The production factors of *Alloy* steel and *Carbon* steel might be similar enough to *Stainless* steel, but ultimately that decision (whether or not the semantics of the classes are close enough) will depend on the model being created within the knowledge space being explored, including on the purpose of the model. If we decide that yes, the set of classes that were gathered by our function are similar enough for our purposes, then we could proceed with collecting any values associated with those classes and applying a reduction function over the set of collected values (mean, median, and so forth) to get an approximate picture of *Stainless*.

What if, with these three nodes the *coterie_graph()* function gathered, there still isn't the information we need? We could of course expand the radius one step further.

In [19]

```
coterie_graph(g_fig_15, 'Stainless', r=2)
```

Out[19]

```
['Carbon', 'Stainless', 'Asphalt', 'Regular', 'Alloy']
```

We would then have to ask outselves whether or not the this interpolation still makes sense. In this case, it seems unlikely. The difference in production factors between concrete and steel are very different.

If we were to explore a full multidimensional classification instead of this simple "monodimensional" one of building material, like if we were to explore one of the structures we created in the previous section, we might now choose to switch to begin semantic interpolation along a different dimension. For example, we might go from (*Stainless*, *Barcelona*) to (*Stainless*, *Catalonia*), then in *Este*, then in *Spain*—looking for useful values as we go.

A.2 MUCH BETTER WAY

A.2.1 *Working with* `DataFrames`

The first way of exploring knowledge spaces was OK. It works well enough, but as our database grows bigger it will likely hold us back. All these graph searches are slow! In this section, we will explore a second way of exploring knowledge spaces. This second way makes a lot of sense computationally. It's *much* faster, uses *much* less memory, and so forth. It's vectorized and better in most ways.

In [20]

```
import networkx as nx
import pandas as pd
import numpy as np
```

Let's also consider a slightly more complicated classification while we're at it. The following reads in an Excel worksheet with the food commodity classification shown in Chapter 5.2.2, which, again, is a slice out of the FAOSTAT Commodity List with some minor adjustments.

In [21]

```
df_classification = pd.read_excel('appendix-a-v1.xlsx')
df_classification
```

Out[21]

	UUID	LABEL	PREDECESSOR	LEVEL
0	FDCM	Food commodities	NaN	0
1	VGFT	Vegetables and fruits	FDCM	1
2	GRTU	Grains, roots and tubers	FDCM	1
3	0007	Vegetables	VGFT	2
4	0008	Fruits	VGFT	2
5	0000	Onions	0007	3
6	0426	Carrots	0007	3
7	0358	Cabbage	0007	3
8	0515	Apples	0008	3
9	0490	Oranges	0008	3
10	0486	Banana	0008	3
11	0001	Cereals	GRTU	2
12	0002	Roots, tubers	GRTU	2
13	0015	Wheat	0001	3
14	0071	Rye	0001	3
15	0116	Potatoes	0002	3
16	0125	Cassava	0002	3

Let's then transform it into a networkx graph, like the ones we used in the previous section, and also visualize it.

In [22]

```
from networkx.drawing.nx_agraph import graphviz_layout
import matplotlib.pyplot as plt
```

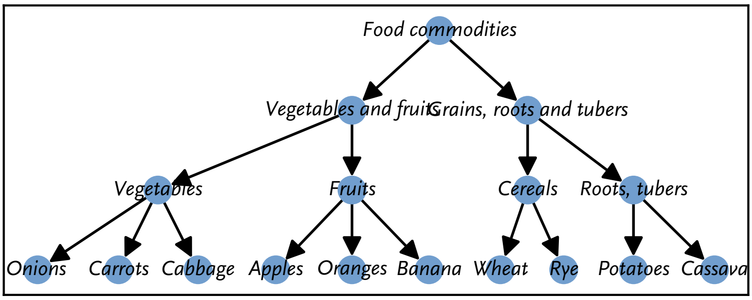
In [23]

```
kwargs = {'node_size': 100, 'font_size': 8, 'arrowsize': 15,
          'node_color': '#719ECE'}
```

In [24]

```
g = nx.from_pandas_edgelist(df_classification,
  source='PREDECESSOR', target='UUID', create_using=nx.DiGraph())
g.remove_node(np.nan)
g = nx.relabel_nodes(g, dict(zip(df_classification['UUID'],
                     df_classification['LABEL'])))

pos = nx.nx_pydot.graphviz_layout(g, prog='dot')
plt.figure(figsize=(5,2))
nx.draw_networkx(g, pos, **kwargs)
```



What we will do next is create a `MultiIndex` out of that new classification. A standard dataframe has one index, which is essentially a special sort of column that allows for efficient searching. An index might be a sequence of numbers (0, 1, 2, 3, ...), one for each row, but it might also be something else, like a timestamp. A `MultiIndex` is essentially multiple indices simultaneously, where the various index levels are nested across scales.

In [25]

```
def create_multiindex_structure(g):
    """
    Get ancestors for each leaf node.

    Args:
        g: A networkx digraph
    Returns:
        A 2D array for turning into a Pandas MultiIndex
    """
    leaves = [n for n in g.nodes() if g.out_degree(n) == 0]

    g_r = g.reverse()
    structure = []
    for leaf in leaves:
        row = list(nx.dfs_tree(g_r, source=leaf))
        row.reverse()
        structure.append(row)
    return structure
```

In [26]

```
structure = create_multiindex_structure(g)
multiindex = pd.MultiIndex.from_arrays(list(map(list,
                                       zip(*structure))))
df = pd.DataFrame(index=multiindex)
df.index.names = ['Level 0', 'Level 1', 'Level 2', 'Level\
                                                  3']
```

We just created a Pandas dataframe with a MultiIndex. Let's go ahead and add some dummy data to make the `DataFrame` more intuitive, then let's visualize it.

```python
df['Value'] = np.random.randint(0, 100, size=10)
df['Unit'] = 'kg'
df
```

In [27]

Out[27]

				Value	Unit
Level 0	Level 1	Level 2	Level 3		
Food commodities	Vegetables and fruits	Vegetables	Onions	18	kg
			Carrots	62	kg
			Cabbage	50	kg
		Fruits	Apples	16	kg
			Oranges	17	kg
			Banana	80	kg
	Grains, roots and tubers	Cereals	Wheat	0	kg
			Rye	13	kg
		Roots, tubers	Potatoes	16	kg
			Cassava	61	kg

Perhaps without realizing, we've just paved the basis of an efficient semantic interpolation machine. One of the major advantages of giving a `DataFrame` a MultiIndex when representing multi-scale data is that it can be intuitively (and efficiently) sliced. The following is an example of drilling down to all data related to *Fruits* using the MultiIndex Slicer method `xs`. If we were looking to interpolate some technical coefficient for *Oranges*, this would collect the sibling nodes, similar to before. This time, we have all the values on hand, no need for a second step to retrieve them like before. N.B. Lexigraphically sorting the `DataFrame` before slicing it can pay dividends in performance, but it isn't strictly necessary. We could talk about advanced slicing and querying of `DataFrames` for a while, but let's keep our eye on the prize.

```python
df.xs('Fruits', level='Level 2', drop_level=False)
```

In [28]

Out[28]

				Value	Unit
Level 0	Level 1	Level 2	Level 3		
Food commodities	Vegetables and fruits	Fruits	Apples	16	kg
			Oranges	17	kg
			Banana	80	kg

Let's then see an example of using this approach to run a step-wise interpolation procedure for *Oranges*. N.B. In the following function, if we were concerned with optimizing things, we likely wouldn't want to be reversing the graph within the function.

First, we'll retrieve all the ancestors of *Oranges* between distances of 1 and 3.

In [29]:

```python
def get_ancestors(g, r, s, e):
    """
    Gets the ancestors of a node.

    Args:
        g: A networkx DiGraph
        r: The node for which ancestors should be found
        s: Inner distance (search "start")
        e: Outer distance (search "end" or "cutoff")
    Returns:
        A list of ancestors between distances s and e
    """
    g_r = g.reverse()
    dijkstra_ce_g = nx.single_source_dijkstra_path_length(g_r,\
                           source=r, weight='length', cutoff=e)

    neighborhood = {k: v for k, v in dijkstra_ce_g.items() \
                    if v in list(range(s,e+1))}
    # This is essentially a topological sorting ("toposort").
    # Our nodes are already sorted, so this isn't actually
    #     necessary here, but it often is.
    # Best for us to play things safe.
    neighborhood_topo_sorted = {k: v for k, v in \
                sorted(neighborhood.items(), key=lambda i: i[1])}

    return list(neighborhood.keys())
```

In [30]:

```python
ancestors = get_ancestors(g, 'Oranges', 1, 3)
ancestors
```

Out[30]:

```
['Fruits', 'Vegetables and fruits', 'Food commodities']
```

We can now use that list of ancestors to slice our dataframe (the one we made the MultiIndex for), collecting all of the values for a semantic interpolation.

In [31]:

```python
ancestors.reverse()
df.xs(ancestors)
```

	Value	**Unit**
Level 3		
Apples	16	kg
Oranges	17	kg
Banana	80	kg

We could also use our list of ancestors to run through a sequence of node searches. In the following, we interpolate three times (distances of 1, 2 and 3)! We would of course need to be very careful as we went along, checking whether the semantics of the classes being collected are semantically similar enough for the purposes at hand. If we're talking about technical coefficients for agricultural production, mixing *Oranges* and *Cabbage* probably doesn't make sense, but it might for some other criteria. The structure of the classification we use as the backbone of our knowledge space is heavily dependent on the purpose of the analysis, and needs to be constantly revised by the modeler and extended peer community.

In [32]

```
n1 = df.xs(ancestors[:1])['Value'].mean()
n2 = df.xs(ancestors[:2])['Value'].mean()
n3 = df.xs(ancestors[:3])['Value'].mean()
print('Level-N1 Interpolation: %.3f, Level-N2 Interpolation:
%.3f, Level-N3 Interpolation: %.3f.' % (n1, n2, n3))
```

```
Level-N1 Interpolation: 33.300, Level-N2 Interpolation: 40.500,
Level-N3 Interpolation: 37.667.
```

An "N" prefix was added to the levels in the previous cell's print statement ("Level-N1") to indicate the "N" classification, referring to the one of food commodities. If we aren't content with our semantic interpolation here, we might then reindex the DataFrame with a geospatial classification (prefix "S", or whatever) and then repeat the same interpolation procedure with the "S" classification. In this way, multidimensional classifications used to structure knowledge spaces can effectively be explored.

It should be evident that this second approach to knowledge space exploration is programmatically much simpler. It is dramatically more scalable and, at scale, hugely more computational efficient. We could get additional speed gains if we skipped the finding of the ancestors each time (with the *get_ancestors()* function) and just work through the various MultiIndex indices one by one from a certain source node in need of interpolation. An effort was made in this appendix to error on side of more didactic, less efficient.

A.3 NOTES

A.3.1 *Graphing Library*

A substantial performance gain could be realized by switching graph libraries, for example, from networkx to iGraph. Whereas the backend of networkx is written in Python, the backend of iGraph is written in C. iGraph is much more computationally efficient, albeit a bit less friendly to use for most users.

A.3.2 *Structured Arrays*

An intuitive alternative to using a MultiIndex Pandas `DataFrame` would be to use a NumPy structured array. Whereas the use of structured arrays implies less overhead, the Pandas solution makes an extensive suite of invaluable data wrangling methods available. Furthermore, the difference in overhead between the two really only makes a big difference at small database sizes. Pandas uses NumPy internally, so dataframe elements take up the same amount of memory as structured array elements. Python objects in general require a substantial amount of memory to initialize but increment only slightly as their contents grow. For example, a string with one ASCII character is 50 bytes whereas a string with two ASCII characters is 51 bytes. Structured arrays have a further downside in that they don't accomodate variable-size datatypes.

A.3.3 *Tidy Databases*

The reader may also be wondering, when do I leave Microsoft Excel behind and invest in a ticket to the promised land of programming? For an extensive semantic interpolation procedure of the type explored in this appendix, it's most likely worth setting up an analysis programmatically. But, at a small scale or with other purposes in mind, it often isn't worth the overhead to move from Excel. Excel gets a lot of criticism for being "unable to handle" large, multidimensional databases. While Excel certainly has its limitations, many of these criticisms result from poor database design and a lack of Excel know-how. The classifications we used to create multidimensional structures of knowledge spaces in Chapter 3, which either refer directly to one of the four causes or modify one of the four causes, are, statistically speaking, variables. In a tidy database structure, variables are columns and each row of data is an observation (Wickham, 2014). It is not always straightforward to distinguish between what is better suited as a classification, what is better suited as an class within a classification and what is better suited as a measurement domain, but keeping this general heuristic on tidy database structure in mind can go a long way in easing the more painful aspects of a large quantitative analysis. Generally speaking, observations are better suited for grouping and comparison whereas variables and, to a subordinate degree, elements/classes are better suited for functionally relating. Insightful systems analysis relies on the ability to achieve both these tasks in accordance with the purpose of the analysis. Before deciding whether or not it is worth investing in moving from Excel to a research procedure based on a language like Python or R, it is advisable to first ensure that the database(s) being worked with are in a tidy format. That alone can eliminate many a frustration. It is surprising how few databases in sustainability science, from large statistical bodies and small research facilities alike, are tidy formatted!

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B DATA WRANGLING FOR CHAPTERS 4 AND 5

B.1 CHAPTER 4

B.1.1 *Figure 26*

Data is directly from sources listed in caption except for Germany in 2018 where final power capacities are forecasted using ENTSOE-E growth rates applied to 2015 Eurostat values. The following aggregations were made:

1) *Spain*: “Oil/Gas” represents “fuel”, “gas” and “combined cycle” categories. “Hydro” includes “Hydro: Mixed Conventional”, “Hydro” and “Other Hydro”. “Solar” includes “Solar: Photovoltaic” and “Solar: Thermal”.
2) *Germany*: “Coal” includes “Hard Coal (Anthracite)” and “Brown Coal (Lignite)”. “Wind” includes “Wind: Onshore” and “Wind: Offshore”.

B.1.2 *Figure 27*

“Intermittent Renewables” includes all forms of wind and solar power capacity. “Other Renewables” includes all other renewables (hydro, biofuel, waste, geothermal, etc.). “Conventional” includes all non-renewable energy sources (oil, gas, coal, nuclear, etc.). Generation data is net production measured at the power plant (for example, before distribution losses). For Germany, generation data is at a yearly resolution until 2008, thereafter it is at a monthly resolution, due to data availability constraints. For Spain, generation data is at a monthly resolution for the complete timeframe.

B.1.3 *Table 3 and Table 4*

For several reasons, portions of the Spain and Germany electricity production datasets were interpolated. Overall, interpolated values represent a minor portion of the datasets. The results are not significantly impacted. 5.3% of the timestamps in the Spain dataset contain interpolated data points and 0.2% of the values in the Germany dataset are interpolated. Figure 39 and Figure 42 show the frequency of the interpolated values in time. A piecewise cubic hermite interpolating polynomial (PCHIP) was selected for interpolation due to its preservation of monotonicity—it is not prone to exaggerating oscillations as, for example, a standard cubic spline interpolation might. The following provides statistics for the relative breakdown of missing or discarded values.

1) Fixing instances where not all accounting categories are reported (incomplete data). Spain: 3.6% (22713; minor concentration bias between

3h and 4h); Germany: 0.2% (155).

2) Fixing an unlikely autocorrelation between at least one of the individuated generation time series (set of windows ranging from 1 to 6 timestamps; allowance of 10% maximum delta between windows excepting in comparisons between windows where at least one of the windows averages less than 10 MW). For example, for Spain on 11 November 2007 between 12h20 and 12h40 hydroelectric generation trembles nearly 1500% and all other sources of generation are zeroed—this is unrealistic, the data is incorrect. Spain: 1.3% (8478); Germany: 0.0% (0).
3) High standard error between reported total demand and calculated total demand (sum of individuated generation sources). Errors more than 1±0.25 discarded. N.B. The vast majority lie within 1±0.01. Spain: 0.3% (2151); Germany: 0.0% (0).

In the case that multiple, distinct values were reported for the same time period, the first reported value was kept. This issue only presented itself with the Spain dataset.

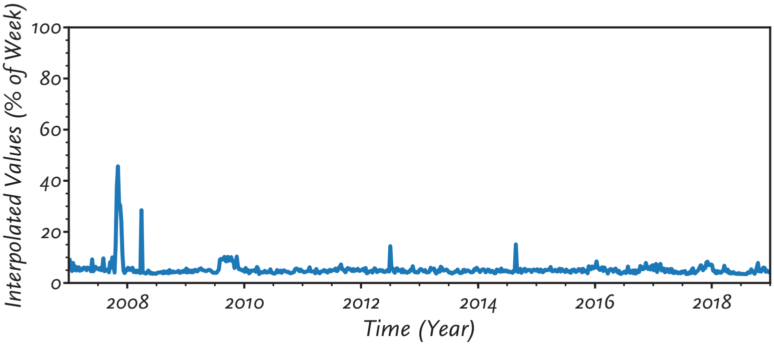


Figure 39 Temporal location of interpolated values for *Spain*, representing 5.3% of the total.

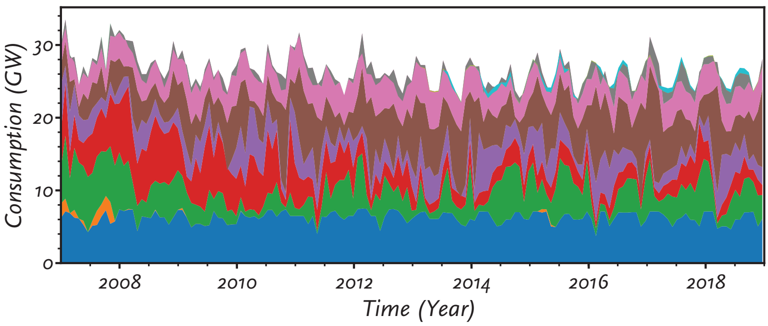


Figure 40 Full breakdown of electricity consumption for *Spain* 2007–2018 inclusive.

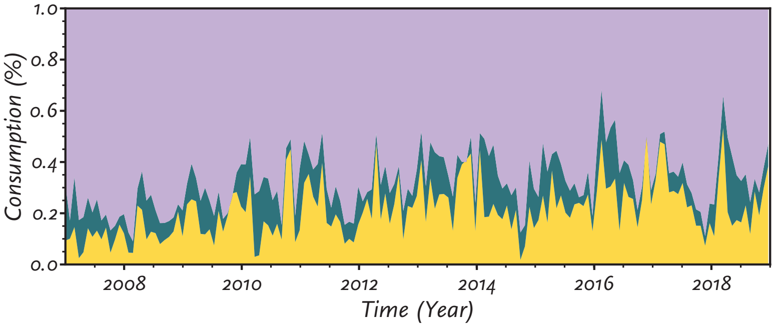


Figure 41 Relative generation mix between three functional classes for *Spain*.

Figure 42 Temporal location of interpolated values for *Germany*, representing 0.2% of the total.

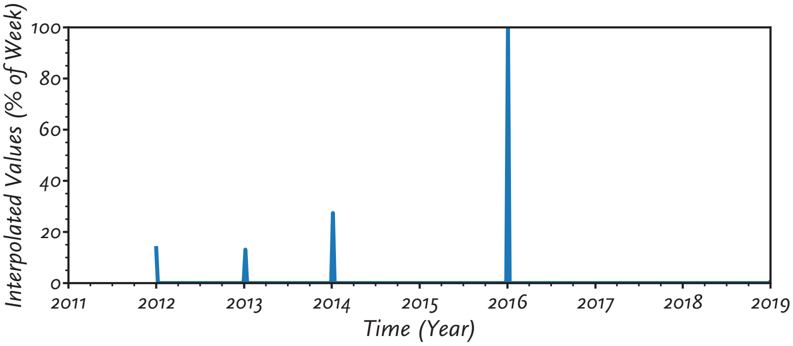


Figure 43 Full breakdown of electricity consumption for *Germany* 2011–2018 inclusive.

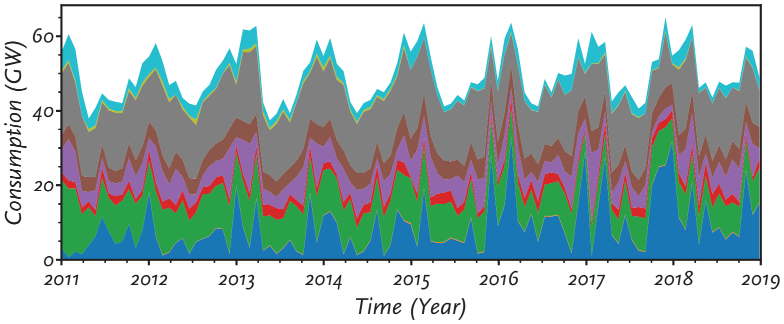
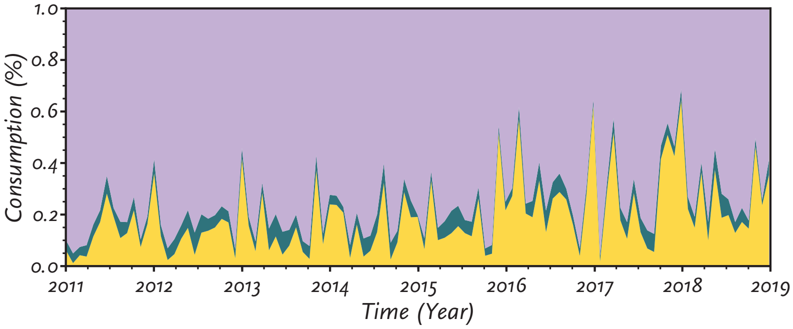


Figure 44 Relative generation mix between three functional classes for Germany.



The following pseudocode details the general statistical procedure used to calculate the confidence levels and guarantees in Table 3 and Table 4.

```
1) Calculate the percentage of the total generation sourced from intermittents (wind or solar) for each timestamp (row).
2) Find the one-year window centered rolling mean for each data point.
3) For each row, calculate the guaranteed percentage for each of the guarantee levels (0.5, 0.75, 0.9 and 0.95) by multiplying the total mean generation by each of the guarantee levels.
```

4) Calculate the discrepancy between the intermittents generation and the guaranteed percentage by multiplying the total production (power) by the intermittents generation percentage less the guaranteed percentage.
5) Locate all time intervals of the discrepancy values with an average under the guaranteed percentage (using a rolling sum method).
6) Calculate, in hours, the length of all located time intervals.
7) Find the maximum subarray (the contiguous subarray of the time series with the largest sum) of the hourly discrepancies from Step #6. Calculate the additive inverse of the sum of that subarray, which represents the energy gap of the "most significant" failure event. Report this value in the table.
8) For each year, calculate the mean, max, min, standard deviation ("n -1" method, meaning sample not population) and standard error of the located time interval lengths.
9) Report the 50% confidence level in the table.
10) Calculate and report the 75% and 99% confidence levels using 1-tailed normal z-scores of 0.68 and 2.33, respectively.

It should be noted that the standard error and standard deviation methods were run over low population sizes (the number of complete years in the dataset). For Spain $n=12$, for Germany $n=8$. Readers concerned with the relatively low n values are reminded that the nature of this quantitative storytelling is to illustrate the approach and highlight plausible concerns related to a learning-type storyline, not to precisely predict the future.

B.2 CHAPTER 5

B.2.1 *Technical Coefficients*

This section and the following summarize the exogenous parameters used to populate the computational model introduced in Section 5.2.1. For vegetal products, production factors include:

1) crop yield (tonne/hectare)
2) blue water use (m^3/hectare)
3) human activity (hour/hectare).

For animal products, production factors include:

1) crop yield, incl. both meat yield (tonne/head) and milk yield (liter/head)
2) blue water use, incl. water for drinking and service water (m^3/head)

Changes in technical coefficients in the long-term are proxied by changes in yield (see Section 2.1.4). Feed consumption (tonne/head) minus the import of processed feed is scaled by the demand for animal products and accounted for directly as vegetal matter for animal production. Indirect land uses, blue water uses and human activity embedded in imported/processed feed are included with and scaled by the calculation of vegetal product flows. Disaggregation by use type of the processed vegetal imports proved impossible. Lastly, in the case of animal products, direct (non-feed) land use is considered negligible. Irrigation of grazing lands is also considered negligible. The derivation of the underlying microscale technical coefficients used in the calculation of mesoscale aggregates is based on primary data sources (Chatterton, Hess, & Williams, 2010; FAO, 2014c, 2014d, 2014b, 2014a, 2016, 2017b, 2017a, 2018; FAO *et al.*, 2002; Huyghe *et al.*, 2014; Mekonnen & Hoekstra, 2011; Portmann, 2011; USDA, 2014). For supplementary information on the microscale biophysical diagnostic readers are directed to Cadillo-Benalcazar, Renner and Giampietro (2020).

B.2.2 *Population Estimates*

Three separate population projections are used to consider the long-term in a well-rounded manner. The population projections used are the

1) baseline
2) low-fertility
3) low-mortality

scenarios from Eurostat (2019). In Section 5.3, displayed results refer to the baseline population prediction. A sensitivity analysis including the high- and low-bound population estimates is found in Section B.3.1. In the long-term, discrepancies between population predictions have the least effect on the numerical model's output uncertainty.

B.2.3 *Food Demand Estimates*

The characterization of baseline food demand estimates is based on 2012 data from the FAOSTAT Food Balance Sheet (FBS) (FAO, 2017a). The characterization of drivers of change in crop production mixes, defined at the mesoscale (for example, for cereals, oil crops, vegetables, bovine products), relies on a forecasting algorithm calibrated to encompass the prediction discrepancies of established food demand forecasts. In general, predicting changes in food demand across decades and including but not limited to changes in dietary demand is a wicked task with hardly any two authorities in agreement (Valin et al., 2014). The uncertainty involved is exceptional. Individual forecasts for each food production mix were first trained on annual FBS data ranging, for twenty-one of the twenty-nine analyzed countries, from 1961–2013. For the eight remaining countries, namely Belgium, Croatia, Czech Republic, Latvia, Lithuania, Luxembourg, Slovakia and Slovenia, less historical data is available and time series start dates range between 1992 and 2000. Growth rate estimates for the demand of marginal food groups—defined as those groups with a consumption of less than 10 kg/capita/annum—are considered negligible. In this way, extreme growth outliers are avoided. Per capita changes in spice and stimulant demand, for example, are considered negligible. In all other cases, the Holt's linear trend forecasting algorithm (additive trend, double exponential smoothing) was used, selected as a general use heuristic and based on its proven effectiveness in the food demand context (Hyndman & Athanasopoulos, 2018; Makridakis et al., 1982). In addition to the baseline forecast, a confidence interval described using a normal distribution is considered as part of the assessment of parameter sensitivity. A 50% confidence level was selected, a determination made such that the resulting per capita growth factors encompass the breadth of predictions at the mesoscale described by the following relevant authorities: Alexandratos and Bruinsma (2012), EC (2017), Farm Europe (2015) and OECD and FAO (2017). In this sense, the sensitivity range of food demand changes is conservatively large. Its characterization uses established food demand predictions as a theory of inference, acknowledging that confidence intervals by themselves are neither indices of plausibility nor indices of reasonability (Morey *et al.*, 2016).

B.2.4 *Yield Estimates*

Changes in yield estimates include consideration of:

1) changes in technological efficiency, for example, innovation-driven advances in technology and techniques
2) changes in socio-economic factors, for example, increases or reductions of subsidies
3) drivers from the biosphere, for example, climate change and environmental degradation.

Constant average annual growth rates (AAGRs) for each of the mesoscale food commodities were characterized following the established literature (Alexandratos & Bruinsma, 2012; EC, 2017; OECD & FAO, 2017). High- and low-estimate bounds in Section B.3.1 are informed by the discrepancy range among the established estimates (*ibid.*). As was the case with food demand, designated yield ranges are conservatively large due to substantial discrepancies among existing yield estimates. Events such as catastrophic crop failure across commodity types are not included in the estimate's consideration.

B.3 EXTENDED FIGURES

B.3.1 *Sensitivity Ranges*

The following three figures accompany the figures presented in the results section (Section 5.3), presenting long-term anticipations individually for each of the EU member states plus the United Kingdom and Norway. High- and low-bounds (the sensitivity ranges) are determined following the methods described in Section 5.2.2 and Section B.2.1. Uncertainty emerging from parameter sensitivity is found not to be great enough to significantly affect the conclusions of the quantitative storytelling.

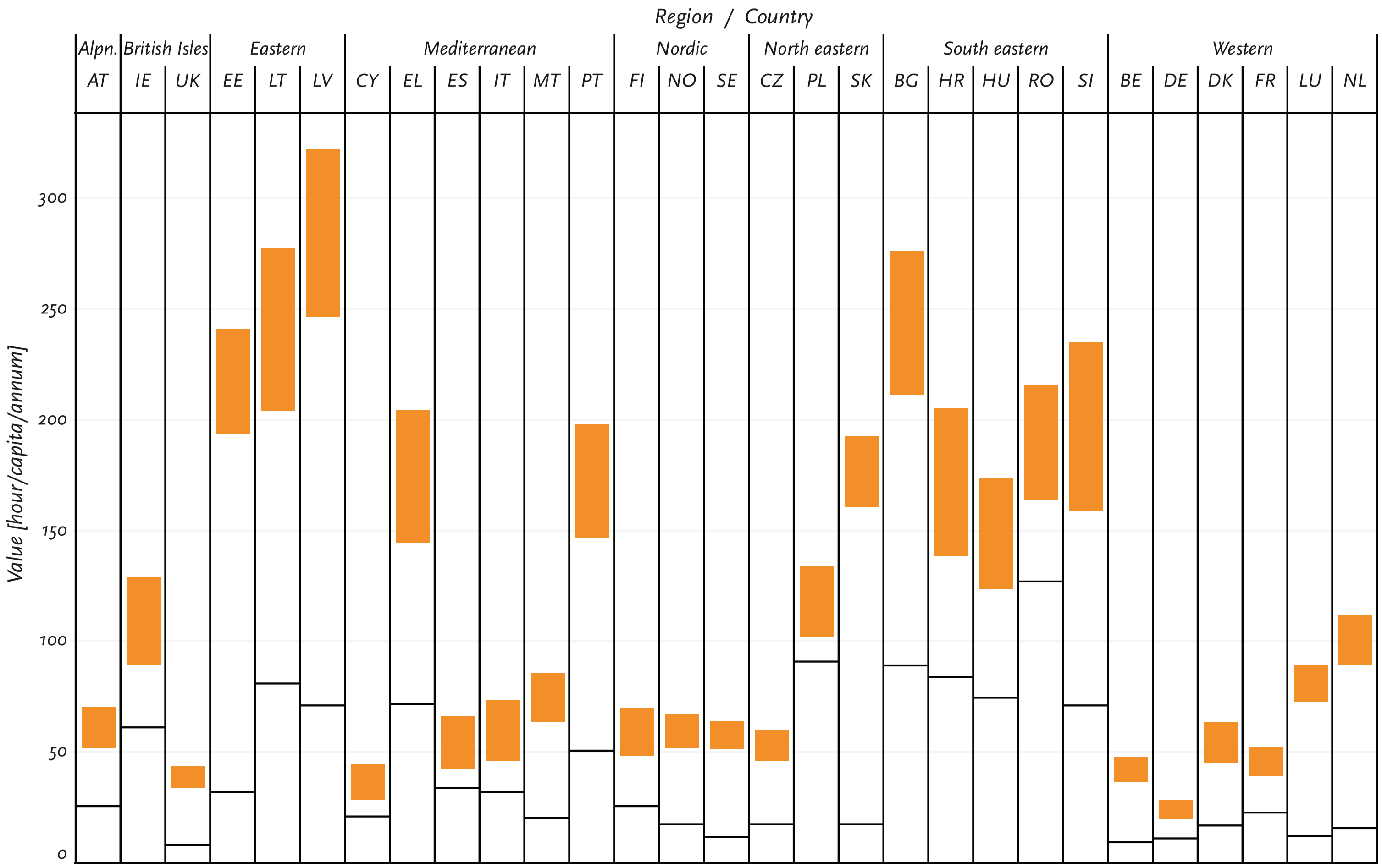


Figure 7 Anticipation of human activity in the agricultural sector over the long-term for the EU member states plus the United Kingdom and Norway. A re-internalization of 90% is anticipated in the long-term. Cell reference lines show the estimated value for 2012.

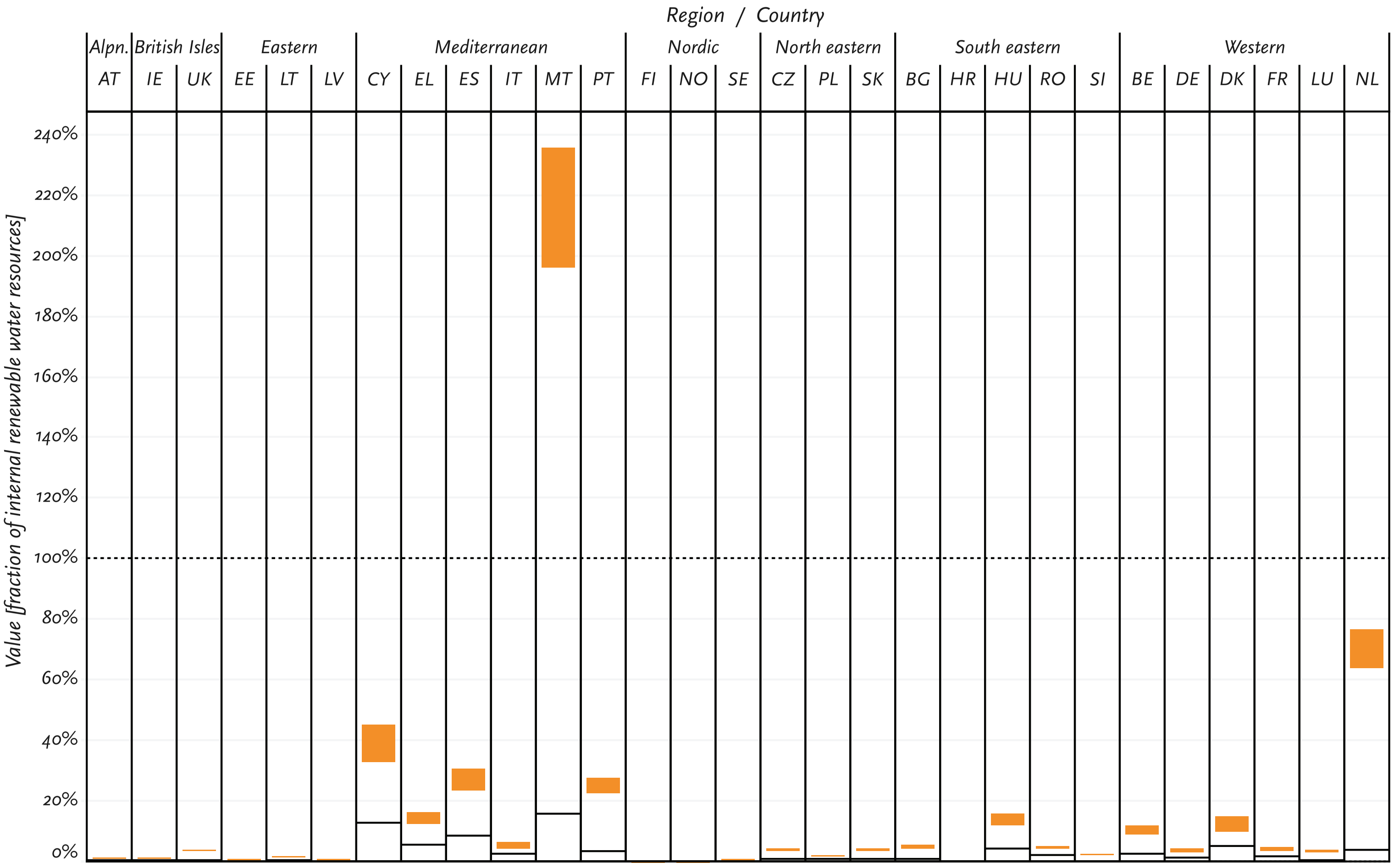


Figure 8 Blue water use in the agricultural sector per total internal renewable water resources (baseline 2012 estimate) over the long-term for the EU member states plus the United Kingdom and Norway, represented as a percentage of water use in the 2012 baseline estimate. A re-internalization of 90% is anticipated in the long-term. Cell reference lines show the estimated values for 2012, the table reference line represents a value of 100%. A deep understanding of this chart requires additional knowledge on water recharge rates—an aspect not readily available in a reliable form for all countries analyzed. In general, water recharge ratesare just a small fraction of total internal renewable water resources. In the case of many countries (Malta, the Netherlands, Cyprus, Spain, Portugal, for example), the internalization of the current agricultural paradigm is certainly infeasible.

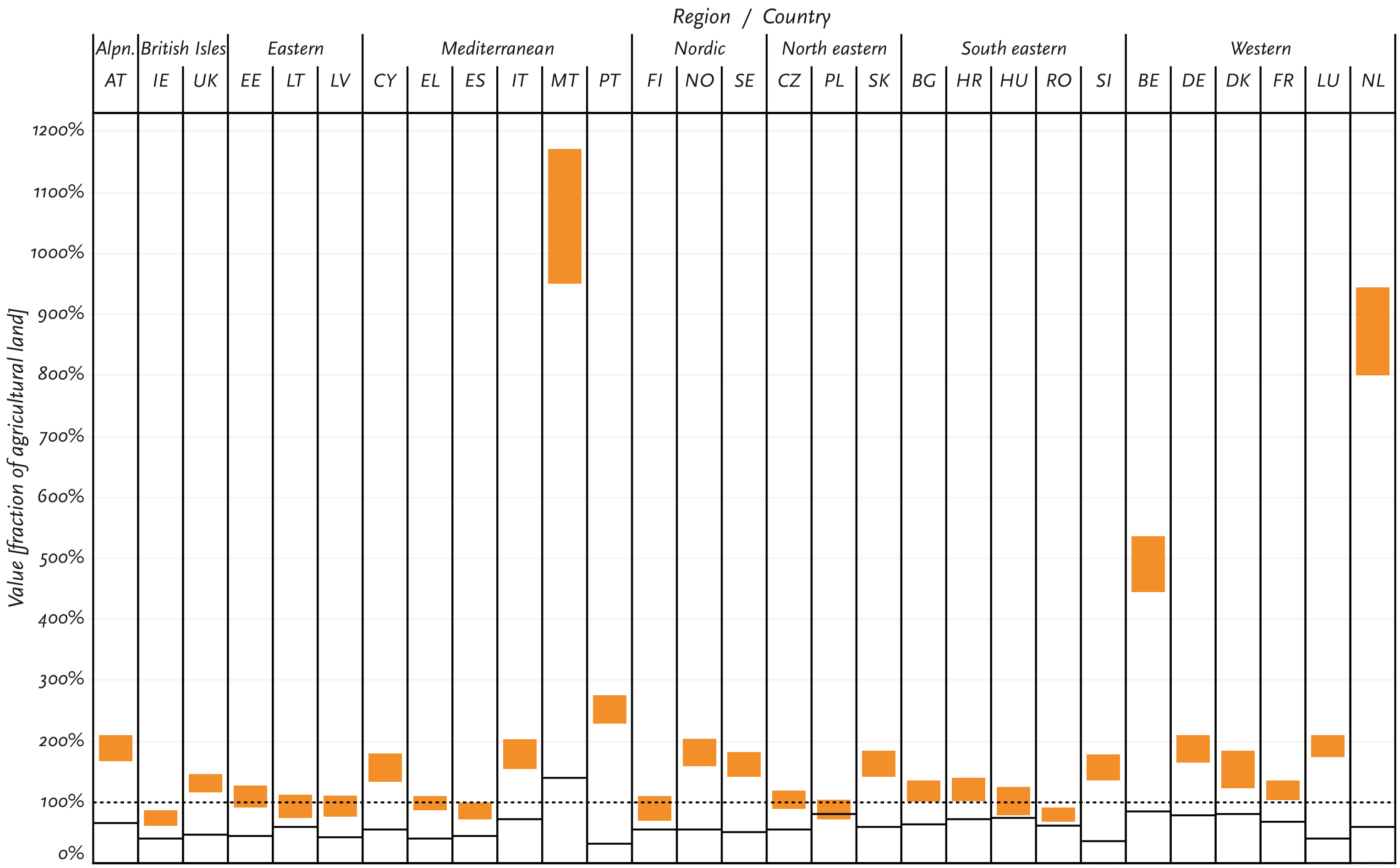


Figure 9 Anticipation of land use in the agricultural sector as a fraction of agricultural land (baseline 2012 FAO estimate) over the long-term for the EU member states plus the United Kingdom and Norway. Percentage values are conservative estimates, due to varying differences in the definition of agricultural land. A re-internalization of 90% is anticipated in the long-term. Cell reference lines show the estimated values for 2012, the table reference line represents the absolute feasible maximum (100%). Some small error in calculated baseline values is present, resulting both from this work's analysis and from official estimations. In the case of many countries (for example, Belgium, Malta and the Netherlands), internalization of the current agricultural paradigm is clearly infeasible, a reality resulting largely from animal trade.

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