



HAL
open science

Environmental assessment of territories through supply chain analysis : biophysical accounting for deliberative decision-aiding

Jean-Yves Courtonne

► To cite this version:

Jean-Yves Courtonne. Environmental assessment of territories through supply chain analysis : biophysical accounting for deliberative decision-aiding. Business administration. Université Grenoble Alpes, 2016. English. NNT : 2016GREAG004 . tel-01421664

HAL Id: tel-01421664

<https://theses.hal.science/tel-01421664v1>

Submitted on 22 Dec 2016

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

THÈSE

Pour obtenir le grade de

DOCTEUR DE LA COMMUNAUTÉ UNIVERSITÉ GRENOBLE ALPES

Spécialité : **Sciences de Gestion**

Arrêté ministériel : 7 août 2006

Présentée par

Jean-Yves COURTONNE

Thèse dirigée par **Denis DUPRÉ** et
codirigée par **Pierre-Yves LONGARETTI**

préparée au sein du **Laboratoire CERAG FRE 3748 CNRS/UGA**
dans **l'École Doctorale Sciences de Gestion**

Evaluation environnementale de territoires à travers l'analyse de filères

*La comptabilité biophysique pour l'aide à la décision
délibérative*

Thèse soutenue publiquement le **28 juin 2016**,
devant le jury composé de :

M. Nicolas BUCLET

Professeur des universités, Université Grenoble Alpes, Président du jury

M. Gilles BILLEN

Directeur de recherche CNRS, Université Pierre et Marie Curie,
Rapporteur

Mme Natacha GONDRAN

Maître-assistant HDR, École des Mines de Saint-Etienne, Rapporteur

M. Emmanuel RAUFFLET

Professeur, HEC Montréal - Canada, Membre du jury

M. Denis DUPRÉ

Maître de conférences HDR, Université Grenoble Alpes, Directeur

M. Pierre-Yves LONGARETTI

Chargé de recherche CNRS, Université Grenoble Alpes, Co-directeur



Jean-Yves Courtonne

PhD Thesis

Environmental assessment of territories through supply chain analysis

Biophysical accounting for deliberative decision-aiding

UNIVERSITÉ
GRENOBLE
ALPES

Inria
INVENTEURS DU MONDE NUMÉRIQUE


ARTELIA

Preface

"The hell of the living is not something that will be: if there is one, it is what is already here, the hell where we live every day, that we form by being together. There are two ways to escape suffering it. The first is easy for many: accept the hell and become such a part of it that you can no longer see it. The second is risky and demands constant vigilance and learning: seek and be able to recognize who and what, in the midst of the hell, are not hell, then make them endure, give them space."

Italo Calvino, *The invisible cities*, 1972.

Acknowledgments

This PhD thesis is for many reasons a joint achievement and I would like to thank all those who contributed to it in one way or another.

First, I was lucky enough to benefit from exceptional guidance with my two PhD directors Denis Dupré and Pierre-Yves Longaretti. Thank you both for your good spirit and cheerfulness, for your availability, for your scientific rigor, for helping me to tackle obstacles one by one, and of course for proofreading this manuscript, sometimes late into the night...

I also wish to thank the members of the jury committee, Nicolas Buclet, Gilles Billen, Natacha Gondran and Emmanuel Raufflet for accepting to review this thesis, and for their insightful comments.

I'm especially grateful to Julien Alapetite, without whom I might not have been able to eventually start this thesis, and who contributed greatly to many results presented here. Thank you for this rich and pleasant collaboration as well as for your training in programming!

I am grateful to Artelia for co-funding this PhD and for offering me many opportunities to confront academic knowledge and on-field studies. I especially thank Catherine Freissinet and Jérémy Gasc for their precious advice and enthusiasm all along the PhD. I also want to thank everyone from the Paris and Grenoble teams for their friendliness during my short-but-productive stays!

I consider myself extremely lucky to have spent all this time in the STEEP team of INRIA, which provided me with a friendly and intellectually stimulating working environment. Thank you to Emmanuel Prados whose dedication made this project (and many others) possible. Thank you to Marie-Anne for making our lives easy everyday (at least at the office!) and thank you to all my past and present colleagues and friends: Elise, Peter, Serge, Fausto, Thomas, Laurent, Luciano, Martí, Jérémy, Rémy, Anthony, Armel, Bérangère, Bappa, Jayasi, Brindusa, Luis, Lara, Pablo, Solange, Patricio... A special thanks to my sport coaches :) and ¡Gracias a todos los Argentinos que compartieron mate conmigo!

Thanks to the Aussois research group on territorial ecology and especially to Anne-Lorène, Daniela, Petros and Manuel from the energy team! Thank you to Jonathan Lenglet and Sylvain Cauria for the friendly and fruitful collaboration on the wood flow studies. Thank you to the DRAAF and DREAL Alsace-Champagne-Ardenne-Lorraine for allowing us to implement the model on a regional forest-wood supply chain and to share some results in this manuscript. Although I can't cite them all individually, I want to thank all the people from academic, public or private horizons who took the time to share their knowledge with me and to provide feedback on my work.

Of course, I finally wish to thank Florent, as well as my family and friends for their continued support throughout the years.

Résumé

Les conséquences de nos modes de production et de consommation sur l'environnement mondial sont reconnues et analysées depuis plusieurs décennies : changement climatique, effondrement de la biodiversité, tensions sur de nombreuses ressources stratégiques etc. Notre travail s'inscrit dans un courant de pensée visant à développer d'autres indicateurs de richesse. Dans une perspective de durabilité forte, nous nous concentrons sur une comptabilité biophysique (non monétaire), apte à pointer les externalités environnementales. Si une part importante des recherches dans ce domaine a été dédiée aux échelons nationaux, nous nous intéressons ici aux échelles locales, et en particulier aux régions françaises. Après avoir étudié les caractéristiques d'outils existants utilisés dans les domaines de l'économie écologique et de l'écologie industrielle, comme l'Empreinte Ecologique, l'Analyse de Flux de Matières (AFM), l'Analyse de Cycle de Vie ou l'Analyse Entrée-Sortie, nous nous focalisons sur les filières de production que nous analysons à partir des quantités de matières qu'elles mobilisent au cours des étapes de production, transformation, transport et consommation. La méthode développée, AFM Filière, permet de produire des schémas de flux cohérents au niveau national, dans chaque région, et quand les données le permettent, à des niveaux infra-régionaux. Ceux-ci sont basés sur un processus systématique de réconciliation des données disponibles. Nous évaluons la précision de ces données d'entrée, ce qui permet de fournir des intervalles de confiance sur les résultats, pouvant à leur tour pointer vers des manques de connaissance. En particulier, nous fournissons une évaluation détaillée de la précision de l'enquête permanente sur le transport routier de marchandises (TRM), une pièce maîtresse de l'AFM Filière. Nous montrons au passage que réaliser le bilan matières sur une période de plusieurs années permet non seulement de s'affranchir du problème des stocks, mais aussi de réduire significativement l'incertitude sur les échanges entre régions. Nous adaptons par la suite la méthode des chaînes de Markov absorbantes pour tracer les flux jusqu'à leur destination finale et allouer les pressions sur l'environnement produites tout au long de la filière. Les flux de matières peuvent également être couplés à des modèles économiques afin de prévoir leur évolution en réponse à certaines politiques. En collaboration avec le Laboratoire d'Economie Forestière (LEF), nous fournissons ainsi la première tentative de représentation des flux sur la filière forêt-bois française, et analysons l'impact de différentes politiques de réduction des exports de bois brut sur l'économie et sur les flux physiques. Enfin, nous montrons comment il serait possible d'articuler ces analyses de filières avec les méthodes d'analyse qualitative, en particulier celles déployées dans le domaine de l'écologie territoriale, pour analyser les jeux d'acteurs dans la filière. Nous situons notre travail dans le cadre normatif de la démocratie délibérative. A ce titre, nous réfléchissons aux apports de la comptabilité biophysique aux processus de décisions publiques incluant diverses parties prenantes. Nous dressons un panorama des étapes clé d'un processus d'aide à la décision, des méthodes multicritères mais également des différentes formes que peut prendre la participation des citoyens. Nous proposons finalement une méthode d'aide à la délibération conçue pour des contextes de décision caractérisés par de fortes incertitudes et des conflits de valeurs. Celle-ci est fondée sur l'élicitation de la satisfaction et du regret éprouvé par chaque partie prenante face à un futur donné. Enfin, en partant des principales critiques adressées à la quantification, nous proposons en conclusion une réflexion sur les conditions qui permettraient de mettre la comptabilité biophysique au service de l'émancipation démocratique.

Summary

The consequences of our modes of production and consumptions on the global environment have been recognized and analyzed for many decades: climate change, biodiversity collapse, tensions on numerous strategic resources etc. Our work follows a line of thought aiming at developing other indicators of wealth, alternative to the Growth Domestic Product. In particular, in a perspective of strong sustainability, we focus on biophysical (non-monetary) accounting, with the objective of pinpointing environmental externalities. A large part of existing research in this domain being targeted towards national levels, we rather focus on subnational scales, with on strong emphasis on French regions. With decentralization policies, these territories are indeed given increasing jurisdiction and also benefit from greater margins of action than national or international levels to implement a transition to sustainability. After studying the characteristic of existing tools used in the fields of ecological economics and industrial ecology, such as the Ecological Footprint, Material Flow Analysis (MFA), Life Cycle Assessment or Input-Output Analysis, we focus on supply chains that we analyze through the quantities of materials they mobilize during the production, transformation, transport and consumption steps. The method developed, the Supply-Chain MFA, provides coherent flow diagrams at the national scale, but also in every region and, when data allow it, at infra-regional levels. These diagrams are based on a systematic reconciliation process of available data. We assess the precision of input data, which allows to provide confidence interval on results, and in turn, to put the light on lacks of knowledge. In particular, we provide a detailed uncertainty assessment of the French domestic road freight survey (TRM), a crucial piece of the Supply-Chain MFA. By doing so, we show that undertaking the study on a period of several years not only solves the issue of stocks but also significantly reduces uncertainties on trade flows between regions. We then adapt the Absorbing Markov Chains framework to trace flows to their final destination and to allocate environmental pressures occurring all along the supply chain. For instance, in the case of cereals, we study energy consumption, greenhouse gas emissions, the blue water footprint, land use and the use of pesticides. Material flows can also be coupled with economic modeling in order to forecast how they will likely respond to certain policies. In collaboration with the laboratory of forest economics (LEF), we thus provide the first attempt of representing the whole French forest-wood supply-chain, and we analyze the impact of a set of policies on both the economy and physical flows. Finally, we show the possibilities of linking these supply-chain analyses with qualitative methods, in particular unfold in the domain of territorial ecology, to study actors interactions. We situate our work in the normative framework of deliberative democracy and are therefore interested in the contributions of biophysical accounting to public decision processes that include diverse stakeholders. We propose an overview of key steps of decision-aiding, of multicriteria methods, but also of the various forms taken by citizen participation. We eventually propose a deliberation-aiding method, designed for decision-making contexts characterized by high uncertainties and value conflict. It is based on the elicitation of each stakeholder's satisfaction and regret regarding a given future. Finally, based on the main criticisms addressed to quantification, we propose in conclusion thoughts on the conditions that could put biophysical accounting at the service of democratic emancipation.

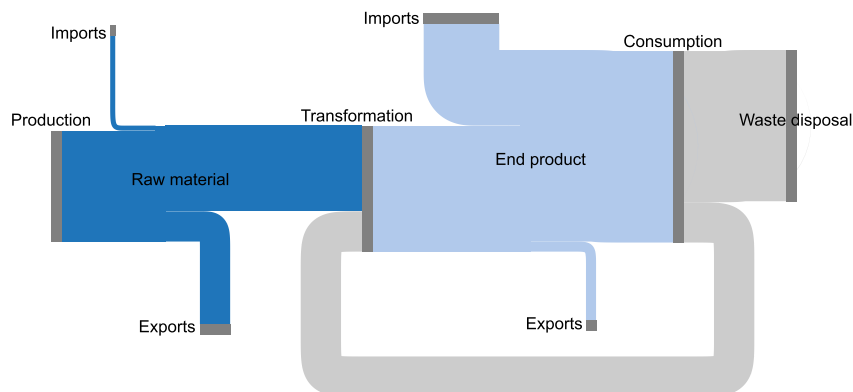
Practical considerations

The core of the manuscript is built upon four research articles that are put in context in dedicated chapters. These articles are the following:

- Chapter 3: Courtonne, J-Y, Alapetite, J, Longaretti, P-Y, Dupré, D, Prados, E, 2015. Downscaling material flow analysis: The case of the cereal supply chain in France. *Ecological Economics*, 118: 67-80.
- Chapter 4: Courtonne, J-Y, Longaretti, P-Y, Dupré, D. Uncertainties of domestic road freight surveys: insights for regional material flow studies. *Submitted for review*.
- Chapter 6: Courtonne, J-Y, Longaretti, P-Y, Alapetite, J and Dupré, D, 2016, Environmental Pressures Embodied in the French Cereals Supply Chain. *Journal of Industrial Ecology*, 20: 423-434.
- Chapter 7: Lenglet, J, Courtonne, J-Y, Cauria, S. Material flow analysis of the French forest-wood supply chain: a consequential approach of log export policies. *Working paper*.

Bibliographic references (including references of the above articles) are grouped between the conclusion and the appendix section. Articles' supplementary materials can be found in the appendix section.

How to read the diagrams. The flow diagrams presented in the thesis were drawn on an online open source sankey tool (available at http://www.eco-data.fr/tools/sankey/start_en.php). Since arrows are not yet implemented, here are some general guidelines to interpret them properly. Production, transformation, consumption and import-export operations are always represented with grey nodes. Horizontal links between two nodes correspond to flows occurring inside the system. From left to right, they indicate the progression from production to consumption. Vertical links always correspond to trade, with imports coming from the top and exports going down to the bottom. Finally, recycling flows (loops) may exist and must be read from right to left.



Contents

Preface	5
Introduction	25
1 Introduction	25
1.1 An unsustainable path	26
1.2 Biophysical accounting for strong sustainability	28
1.3 Knowledge and action	37
1.4 Structure of the thesis	41
I Analyzing regional supply chains through their material flows	43
2 A brief introduction to supply chain analysis	45
2.1 A wide range of approaches: from strategic management to industrial ecology .	45
2.2 Scope of our work	47
3 Downscaling material flow analysis: the case of the cereal supply chain in France	51
3.1 Introduction	51
3.2 Materials and methods	54
3.3 Results and discussion	66
3.4 Conclusion	78
4 Uncertainties of domestic road freight statistics: insights for regional material flow studies	81
4.1 Introduction	81
4.2 Materials and methods	83
4.3 Theoretical results	86
4.4 Case studies	90
4.5 Conclusion	96
II Coupling material flows with environmental and socio-economic aspects	101
5 Formal links between methods aiming at tracing flows	103
5.1 Tracing the origins and destinations of a single product	103
5.2 Input-Output Analysis	110
5.3 Absorbing Markov Chains	114

5.4	Linking IOA with AMC	120
5.5	Transforming SUT into a single square matrix	127
6	Environmental pressures embodied in the French cereals supply chain	129
6.1	Introduction	129
6.2	Materials and methods	131
6.3	Results	138
6.4	Conclusion	145
7	Material flow analysis of the forest-wood supply chain: a consequential approach of log export policies in France	149
7.1	Introduction	150
7.2	Materials and methods	152
7.3	Results	157
7.4	Conclusion	163
8	Territorial supply chains from a social sciences' perspective	165
8.1	Complementarity of existing frameworks	165
8.2	Characterizing employment	170
III Structuring public deliberation through multicriteria methods		181
9	Principles of multicriteria decision-aiding, participation and deliberation	183
9.1	A short introduction to decision theories	183
9.2	Multicriteria decision-aiding in a multi-stakeholders context	184
9.3	Participation and Deliberation	197
10	Proposition of a multicriteria deliberation-aiding procedure	203
10.1	A typology of decision-making contexts and possible decision-support tools	203
10.2	Deliberative multicriteria tools	208
10.3	Satisfaction and Regret	212
10.4	A procedure for deliberation-aiding	221
10.5	Application on Afterres 2050 scenarios	224
10.6	On the use of tools to improve the efficiency of public debates	226
Conclusion		231
11	Conclusion and outlook	231
11.1	Contributions and limits of the thesis	231
11.2	Perspectives for future work	233
11.3	How to count wisely? Biophysical accounting and democratic challenges	235
Bibliography		245
Bibliography		245

Appendix	265
A Supplementary material to Chapter 3	265
Supplementary material to the article Chapter 3	265
B Supplementary material to Chapter 4	283
Supplementary material to the article Chapter 4	283
B.1 Unequal probability survey sampling in a nutshell	283
B.2 Building all combinations of aggregates: an illustrative example	293
B.3 Estimating uncertainties for a single year based on explanatory variables	295
B.4 Uncertainty reduction when averaging over several years	298
C Supplementary material to Chapter 6	301
Supplementary material to the article Chapter 6	301
D Supplementary material to Chapter 7	305
Supplementary material to the article Chapter 7	305
E Appendix to Chapter 8	321
Appendix to Chapter 8	321
F Appendix to Chapter 10	325
Appendix to Chapter 10	325

List of Figures

1.1	Modeling collapse: a scenario from the limits to growth	27
1.2	A safe operating space for humanity	28
1.3	Weak vs. strong conceptions of sustainability.	29
1.4	Schematical representation of production and consumption responsibilities.	32
1.5	Questions related to modes of production and modes of consumption.	33
1.6	Knowledge, power, engagement and action.	39
1.7	Flowchart of the thesis	42
2.1	Industry value chain and value chain withing a firm.	46
2.2	Rice commodity chain in Thailand.	48
2.3	Main supply chains of the Belgian economic system.	49
2.4	Flows of iron in Belgium in 1974.	50
3.1	Principles of the livestock feed model.	63
3.2	Chain of computation and integration between softwares.	67
3.3	Steps taken to produce regional MFAs.	67
3.4	Cereals MFA at the scale of France: international trade and animal feed.	69
3.5	Cereals MFA at the scale of France: domestic use.	70
3.6	Map of cereal flows > 500 kt/year.	72
3.7	Nested territories under study.	73
3.8	Cereals MFA at the scale of France: aggregated results.	74
3.9	Cereals MFA at the scale of the Rhône-Alpes region: aggregated results.	75
3.10	Cereals MFA at the scale of the SCoT of Grenoble: aggregated results.	76
4.1	Piecewise models for estimating uncertainties based on the size of the subsamples.	88
4.2	Uncertainties of road freight at various spatial and product disaggregation levels	93
4.3	Uncertainties on wheat supply areas of Haute-Normandie and Alsace.	95
5.1	The perfect blend hypothesis made explicit	106
5.2	Example of MFA results for 1 raw material, 1 final product and 2 regions.	119
5.3	Example of Input-Output table of a national economy.	121
5.4	Diagram of resource flows.	123
5.5	Flows of embodied resources: production layers and consumption.	125
6.1	Fate of corn grown in the Midi-Pyrénées region.	139
6.2	The supply chain of bread consumed in the Provence-Alpes-Côte-d’Azur	140
6.3	Net virtual land export per French region.	143
7.1	Upstream part of the forest-wood MFA	158
7.2	Downstream part of the forest-wood MFA	159
8.1	A framework for studying social-ecological systems.	167

8.2	A stakeholder model of corporations.	170
8.3	A typology of stakeholders.	171
8.4	Main mechanisms of jobs creations and destructions	172
8.5	Wood flows and spatialization of associated employment in Lorraine.	175
9.1	DPSIR indicators.	188
9.2	Efficiency indicators using the DSPIR framework	188
9.3	Percentage distribution of MCDA methods by application areas.	196
9.4	The ladder of citizen participation.	197
10.1	Roles for scientists in policy and politics	204
10.2	The Pragmatic-Enlightened Model	205
10.3	Scale of technicality and scale of values	207
10.4	Flowchart for choosing decision-aiding tools.	207
10.5	Decision-aiding tools depending on systems uncertainties and conflict on values	209
10.6	The deliberation matrix in KerDST. Source: Chamaret et al. (2009).	210
10.7	Visualization of deliberation matrices with KerDST.	210
10.8	The satisfaction-regret matrix.	212
10.9	Flowchart of the ELECTRE I method.	213
10.10	Flowchart of the ELECTRE III method.	214
10.11	Flowchart of the Promethee method	216
10.12	Comparison of Electre and Promethee concordance indexes.	217
10.13	Flowchart of the Satisfaction-Regret	218
10.14	Result of the S-R III method.	220
10.15	Flowchart of the procedure.	223
10.16	Environmental performance matrix of business as usual and Afterres 2050 scenarios.	225
11.1	Complementarity between supply chain analysis and territorial analysis.	234
A.1	Supply and Use tables of the study.	266
A.2	Cereals MFA at the scale of Centre.	277
A.3	Cereals MFA at the scale of Bretagne.	278
A.4	Cereals MFA at the scale of Nord-Pas-de-Calais.	279
A.5	Cereals MFA at the scale of Ile-de-France.	280
A.6	Cereals MFA at the scale of Provence-Alpes-Côte-d'Azur.	281
B.1	Histogram of the distribution of the first-order inclusion probabilities	292
B.2	Example of 3 basic flows extrapolated from a survey on 9 trucks.	293
B.3	Existing combinations of aggregates based on the 3 basic flows	294
B.4	Number of class members in each class of defined by the size of the subsample .	295
B.5	Evolution of uncertainties depending on the number of observations	296
B.6	Evolution of uncertainties depending on the number of tonnes	298
B.7	Uncertainties of a 3-year average (2005-2007) depending on $2\sqrt{\hat{V}(T)}/T$	299
D.1	Input SUT for the wood MFA (France, expressed in 1000 m ³ (f).)	310
D.2	Output SUT for the wood MFA (France, expressed in 1000 m ³ (f).)	311
D.3	Comparison of material and monetary flows in the lumber chain.	312

D.4	Consequences of the <i>Exp</i> policy on material flows.	314
D.5	Consequences of the <i>Sub_C</i> policy on material flows.	315
D.6	Consequences of the <i>Sub_T</i> policy on material flows.	316
D.7	Evolution of social cost depending on the <i>Exp - Sub_T</i> policy mix.	317
D.8	Flows in the upstream part of the forest-wood chain in Lorraine.	318
D.9	Flows in the downstream part of the forest-wood chain in Lorraine.	319
E.1	Material vs. monetary flows associated with Argentinean soy	322
E.2	Second-tier variables from social-ecological systems.	323
E.3	Example of visualization by the MIT urban metabolism group	324
F.1	Decision making in a stabilized world.	325
F.2	Decision making in a controversial world.	325
F.3	Nature of the context and process or government styles.	326

List of Tables

3.1	Supply table and matrices notations.	54
3.2	Use table and matrices notations.	54
3.3	Available sources for data in weight unit.	60
3.4	Chosen proxies.	61
3.5	Bread consumption variability among different categories of towns in the mid 90's in France.	64
3.6	Characteristics of each run of the model.	66
3.7	Surface and population of the four territories under study.	73
4.1	Uncertainty estimation for given subsample sizes	87
4.2	Uncertainty reduction with a 3-year average	90
4.3	EW-MFA of the Bourgogne region	91
4.4	EW-MFA of Bourgogne's départements	92
4.5	Comparison of uncertainties in the French, Swedish and German road freight surveys	97
5.1	Production and consumption footprints in IOA and AMC	124
5.2	Resources embodied in flows between sectors in IOA and AMC	124
5.3	Resources embodied in each sector in IOA and AMC	124
5.4	IO and AMC formulas of flows in figure 5.5	126
5.5	Classical SPA: IO and AMC formulations.	127
6.1	Sizes of the model's variables.	136
6.2	Datasources for pressure estimation from the producer's viewpoint.	137
6.3	Contribution of each life-cycle stage to the environmental pressures under study.	140
6.4	Pressures and transport associated with the consumption of 1 kg of meat in Italy.	141
6.5	Paths from emissions of GHG to final consumption.	142
7.1	Data sources used for the MFA on wood products.	154
7.2	Variations in quantities produced (P) or consumed (C) in 2020 compared to the baseline scenario (without policy).	160
7.3	Variations in exports of raw products and imports of transformed products regarding baseline without policy in 2020.	160
7.4	Variations in surpluses (C: consumers surpluses; P: producers surpluses) regarding baseline scenario without policy in 2020.	161
7.5	Total welfare variations, budgetary costs and social costs.	161
8.1	A grid of analysis for studying local supply chains.	168
8.2	Sustainability indicators for agri-food supply chains.	169
8.3	Employment, turnover and material throughput in different sectors of the forest-wood chain.	174

10.1	Quantitative indicators available for the evaluation of each scenario.	219
10.2	Performance matrix expressed in qualitative terms.	219
10.3	Criteria weights.	219
10.4	Matrix of partial and global regrets.	220
10.5	Matrix of partial and global satisfactions.	220
A.1	Conversion factors used (kg of cereal output per kg of cereal input).	267
A.2	Contribution of production, trade and stock variation to apparent consumption.	267
A.3	Livestock feed in France	268
A.4	Estimation of livestock cereals intakes.	269
A.5	Chicken lifetime cereals intakes depending on carcass weight.	270
A.6	Estimation of cereals feed of milking cows depending on milk production quantity.	270
A.7	Impact of the operation of sea exports redistribution.	271
A.8	Bread consumption variability among French regions in the mid 90's.	272
A.9	Correspondence between the transport statistics classification and the product classification used the MFA study	275
B.1	Uncertainty estimation for different number of observations	297
B.2	Composition of the sample for each year of the survey	298
B.3	An independent sample between years 2003 and 2007	299
C.1	List of items implemented in the model.	301
D.1	Conversion factors to wood fiber equivalent (m3 (f))	307
D.2	Input-output coefficients used in the Leontief function of FFMSM	308
D.3	Supply table and matrices notations.	308
D.4	Use table and matrices notations.	308
F.1	Main characteristic of the Afterres 2050 scenario.	327

List of abbreviations

- ADEME: agence de l'environnement et de la maîtrise de l'énergie (French environment and energy management agency),
- AMC: absorbing Markov chains,
- CGDD: commissariat général au développement durable (French commission for sustainable development),
- EF: Ecological Footprint,
- EW-MFA: economy-wide material flow analysis,
- Exp: scenario with taxes on exports (chap. 7),
- fw: fuel wood (chap. 7),
- HRW: hard round wood (chap. 7),
- hsw: hard sawn wood (chap. 7),
- INSEE: institut national de la statistique et des études économiques (French national statistics and economic surveys institute),
- IO: input-output,
- IOA: input-output analysis,
- IW: industrial wood,
- LCA: life cycle assessment,
- MC: Markov chains,
- MCA: multicriteria analysis,
- MCDA: multicriteria decision-aiding,
- MFA: material flow analysis,
- NVC: nonviolent communication,
- pw: plywood (chap. 7),
- SC-MFA: supply chain material flow analysis,
- SFA: substance flow analysis,
- SitraM: système d'information sur le transport de marchandises (French information system on freight),
- SOeS: service de l'observation et de la statistique (French observation and statistics service),

- SPA: structural path analysis,
- SRW: soft round wood (chap. 7),
- ssw: soft sawn wood (chap. 7),
- Sub_C: scenario with subsidized consumption (chap. 7),
- Sub_T: scenario with subsidized transformation (chap. 7),
- TRM: enquête permanente sur le transport routier de marchandises (French permanent survey on road freight).

Introduction

Introduction

Territories, supply chains, environment, biophysical accounting, deliberation, decision-aiding... these are the key words that will accompany us throughout this thesis. Territory is a polysemous word; we use it to refer to a delimited geographical area, generally a subnational administrative unit, and to the people who live in it and transform it. With the recognition of global environmental issues, countries... and territories, asserted their will to transition towards more sustainable societies. When facing a problem, one of the things that comes in mind is to attempt to understand the underlying mechanisms it stems from (i.e. the causes and not the symptoms) in order to efficiently act upon them. In this view, there is a need for improving the understanding and evaluation of environmental impacts of human activities at all scales. Impacts (for example, biodiversity losses) are however particularly hard to forecast as they depend on a multiplicity of local factors. Environmental pressures (for instance carbon emissions) are easier to measure and can act as reasonable proxies for impacts (*if we decrease pressures we will decrease impacts*). These pressures need to be measured in physical units, which is what we call *biophysical accounting*¹. More broadly, as we will see, biophysical accounting is defined in opposition to monetary accounting in recognition of the fact the latter alone is not suited to monitor, nor foster, environmental sustainability. Going further on the analysis, most environmental pressures occur through production activities aiming at providing goods and services to consumers. These activities are organized into networks of processes called *supply chains*, which are simultaneously parts of local economies, connections between territories and links between producers and consumers. Supply chains therefore seem to be interesting subjects of study to understand the underlying mechanisms of environmental pressures... This way of structuring problems and improving knowledge may efficiently contribute to *decision-aiding*. Then, once one has reached enough knowledge on a problem, one can evaluate options if not in full, at least in brighter light. Sustainability issues being characterized by inter-connections between the environmental and socio-economic spheres, these options usually imply trade-offs which need to be arbitrated... if possible in a legitimate way. This legitimacy in turn arguably stems from *deliberation*, that is, the process of weighing alternatives, putting the emphasis on logic and reason, usually followed by a decision by vote or consensus. This is, in a few words, the path that we propose to investigate.

Throughout this manuscript, we will do our best not only to present the practical questions addressed in the thesis, but also to situate them in the wider normative conception of our research. The title of the thesis is attempting to reflect this dichotomy. While the first part, *Environmental assessment of territories through supply chain analysis*, summarizes the methodological option technically developed, in short, a focus on regional supply chains and

¹We chose these terms because they are commonly used in the field on economics and by the environmental assessment community, however, the terms *biogeochemical accounting* express what we do more accurately.

their links with local and global environmental pressures, the latter, *Biophysical accounting for deliberative decision-aiding*, rather informs on the reasons that guided this technical effort, again, in short, our wish to focus on physical indicators and to see how they can be integrated in public deliberation processes to advance towards more sustainable policies. It is noteworthy that similar technical developments could have been pursued with other motivations, for instance, to take a fashionable concept, in the perspective of *green growth*. Conversely, a number of other research leads could have been consistent with our goals, and we will present some of them in this introduction. Finally, the idea of a clear hierarchy, with a normative question guiding technical developments, is not a correct description of the actual research process. Indeed, we experienced in our own way that each technical development is partly self-propelled, and that research questions can evolve over time...

In this introduction, we first propose a short overview of global environmental stakes, then present the paradigms to which we relate and show why biophysical accounting matters in this context. After studying existing environmental assessment tools, we draw the contours of our work. Finally, in a perspective of collective action, we reflect on the links between scientific knowledge and decision-making on sustainability issues and frame our research lead in this area.

1.1 An unsustainable path

To a large extent, *unsustainability* is easier to apprehend and less polysemous than *sustainability*. Arguably, it is easier to recognize an unsustainable trend than to describe what a sustainable society would be like, or yet again, it is easy for most people to agree on what is not sustainable while the contours of a sustainable society can be controversial. We wish to dedicate our first lines to the description of such unsustainable trends. Various broad scale analyses of such trends are available in the literature (e.g., Brown 2011), therefore we will only provide a few illustrative examples and focus on environmental stakes.

1.1.1 From 1970's theories of environmental collapse...

In 1972, researchers from the MIT system dynamics group published *The Limits to Growth* (Meadows et al., 1972) where they attempted to model the consequences of rapid demographic and economic growth in a finite world. The world is modeled through five main variables: population, industrial output, food production, natural resources and pollution. Several tens of equations link those variables together; for instance pollution growth has a negative effect on life expectancy and therefore on population size, which in turn works in the direction of reducing pollution. Contrasted scenarios were tested and lead to the same long-term conclusion of collapse in the course of the 21st century: figure 1.1 for instance represents the model output for the reference scenario.

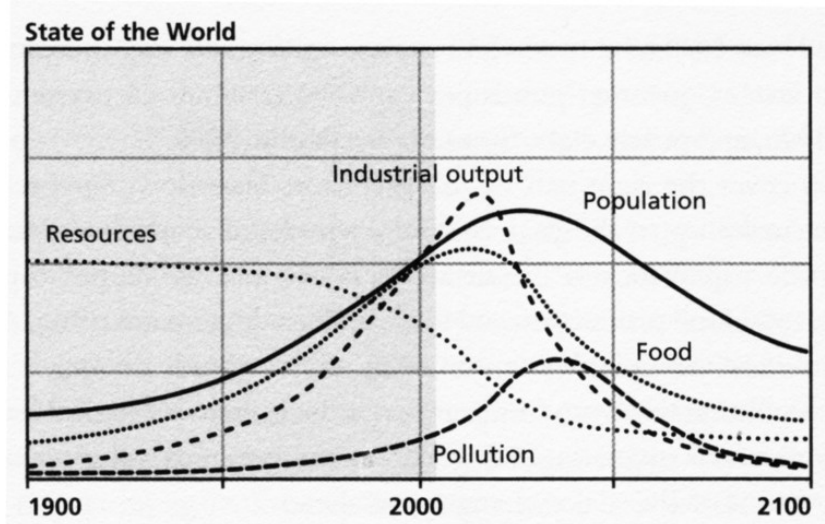


Figure 1.1: Scenario 1 of *The Limits to Growth*. “The world society proceeds in a traditional manner without any major deviation from the policies pursued during most of the twentieth century. Population and production increase until growth is halted by increasingly inaccessible nonrenewable resources. Ever more investment is required to maintain resource flows. Finally, lack of investment funds in the other sectors of the economy leads to declining output of both industrial goods and services. As they fall, food and health services are reduced, decreasing life expectancy and raising average death rates.” (Meadows et al., 2004)

The conditions of such collapse are eventually analyzed: overshoot of carrying capacity, delay in reaction, erosion of the environmental capacity during the overshoot phase, and finally, rapid variation (exponential growth). Interestingly, this understanding, acquired through computer simulations, is well in line with Jared Diamond’s description of the collapse of the Mayan, Greenland Vikings, or Sumerian civilizations, in the field of anthropology and evolutionary biology (Diamond, 2005).

1.1.2 ... To today’s environmental concerns

Scientists have forged a term, the *Anthropocene*, to designate a new geological era, where man has become the greatest force modifying the biosphere, the atmosphere, the hydrosphere and the geosphere (Lorius and Carpentier, 2011). In a 2009 article, Johan Rockström and colleagues attempt to identify and quantify planetary boundaries that must not be transgressed if one wants to prevent “*unacceptable environmental change*” (Rockström et al., 2009). Their results point to the fact that three boundaries have already been overstepped: biodiversity loss, climate change and interference with the nitrogen cycle. Noteworthy, neither current status nor sustainable thresholds are yet quantified for two out of nine boundaries (chemical pollution and atmospheric aerosol loading). The authors further underline that even if the notion of *safe distance* between current status and thresholds relies on social values, such as the degree of aversion to risk, many other boundaries (e.g. ocean acidification, global freshwater use, land use

change) may soon be reached. Figure 1.2, taken from their article, summarizes this situation.

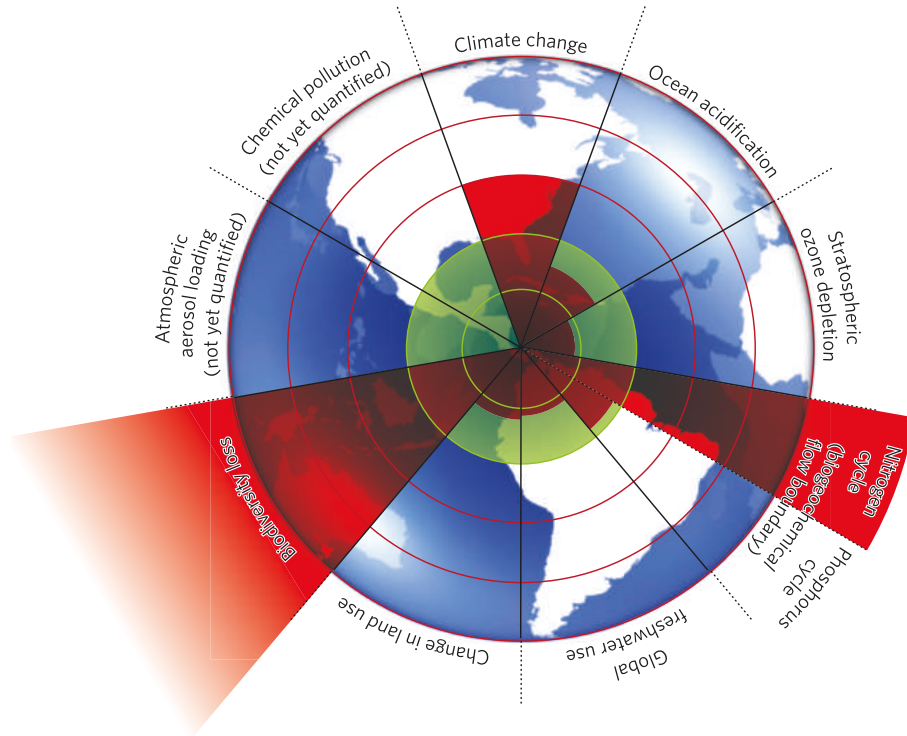


Figure 1.2: “Beyond the boundary. The inner green shading represents the proposed safe operating space for nine planetary systems. The red wedges represent an estimate of the current position for each variable. The boundaries in three systems (rate of biodiversity loss, climate change and human interference with the nitrogen cycle), have already been exceeded”. Source : Rockström et al. (2009).

1.2 Biophysical accounting for strong sustainability

Here, we first try to put in perspective the paradigms and research fields that we relate to; in doing so, we explain why we believe a focus on biophysical accounting is relevant.

1.2.1 The context: strong sustainability, ecological economics, industrial ecology and alternatives to GDP

Both the models of environmental collapse and the actual state of the environment suggest a head-on opposition between the economic and environmental spheres. Using the negotiation theory, Aurélien Boutaud precisely interprets the birth of the concept of *sustainable development* as a win-win solution to this opposition Boutaud (2005): sustainable development was imagined to unite all parties on one idea, solidarity with future generations. This is indeed what appears in the definition proposed by the World Commission on Environment and Devel-

opment: “a development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (Brundtland, 1987). The common representation of the three pillars of sustainable development, environmental, economic and social dimensions, derived from this agreement². However each party quickly re-appropriated this “soft concept” and put its own vision forward, leading to weak and strong conceptions of sustainability illustrated in figure 1.3. The main point of disagreement is the question of substitutability of natural capital by technical and financial capital³. Neoclassical economists thus argue that one can draw into the stocks of natural resources as long as one creates wealth and technological capital, whereas, for advocates of strong sustainability, human societies rely on nature services and would inevitably face collapse if those foundations were undermined. This distinction should however be qualified: everyone agrees that some environmental functions are irreplaceable, and that trespassing some limits (generally not known with precision) can only lead to catastrophic effects; only the perception of our ability to push those limits vary between the two points of view. Conversely, even without man, nature isn’t frozen: the real stake is not so much to leave nature unaltered as to interact with it in a slow enough way, preserving its capacity for adaptative change.



Figure 1.3: Weak vs. strong conceptions of sustainability.

In economics, this coarse distinction can be related to different fields. *Resource economics* as well as *environmental economics* are both subfields of neoclassical economics and respectively focus on the allocation efficiency of labor and capital devoted to extractive industries, and on the way allocation efficiency is disrupted by pollution externalities. They develop useful concepts, such as Pigovian taxes (that tackle undesirable externalities), but always think in terms of “right price, not sustainable scale” (Daly and Farley, 2011). On the contrary, *ecological economics*, aim at integrating, at least partially, economy with ecology. A focus is put on understanding the biophysics of the system: energy flows, material cycles, ecosystems structure and functions. The concept of throughput connects resource depletion and pollution, otherwise treated separately. More attention is also paid to impacts on ecosystems and to feedbacks

²Aurélien Boutaud notes that this is already an unbalanced representation: one dimension for *the environment* and two for *man*. This also presupposes that the economy is not concerned with social issues, a rather biased view in itself.

³The mere use of the term *capital* in fact indicates a preeminence of economic thinking on non-economic issues.

from these ecosystems on the economy. Finally, it is guided by a philosophical viewpoint, *non determinism* and *non-nihilism*, that is, “*it really is possible for things to be other than they are, and we really can distinguish better from worse states of the world*” (Daly and Farley, 2011).

We situate our work in the normative presuppositions of ecological economics and strong sustainability. In this view, monetary accounting appears insufficient to conduct proper analysis, although it is by far the most developed. We thus choose to concentrate our effort on biophysical accounting, that is accounting in physical, non-monetary, units. The 1980’s gave birth to a new research field precisely aiming at the study of material and energy flows through industrial systems, *industrial ecology* (Billen et al., 1983; Frosch and Gallopoulos, 1989). As one can guess from the name, the underlying belief behind it is that concepts and methods developed in ecology can be transposed to study industrial societies and bring about new knowledge that would be useful for policy-making. Metaphors of the economy as an ecosystem are often used: resources are drawn by extraction activities and are successively used by transformation industries, similar to trophic chains, before being distributed, consumed and ending-up as wastes that are recycled, or rejected in the environment. The term *metabolism* is also often used to refer to the functioning of the system, based on material and energy flows. The objective of closing the loops, that is, achieving less material and energy inputs, less wastes and pollution outputs and more efficiency and recycling, is at the core of industrial ecology’s identity (Allenby, 1992). Additionally, in France, the last few years have seen the emergence of *territorial ecology*, a field aiming at *downscaling* the conceptual frameworks of sustainability (Buclet et al., 2015). Territories are not only defined by their administrative limits, but also by their ecological, economic, social and identity coherence. In this sense, they are part of regional, national and global trajectories but retain singular dynamics that are worth studying. Territorial ecology uses both quantitative and qualitative analyses, and tries to connect them: once material and energy flows have been assessed, it is important to understand who are the actors behind these flows, how they are organized, what are their relationships of power, competition or cooperation and how they participate in the identity of the territory by valuing its material and immaterial resources. Buclet et al. (2015) indeed underline the risk for industrial ecologists to narrow their vision to engineering-optimization strategies and aim at a broader view, that would leave more room for social sciences and *heterodox* economics.

Finally, we relate our focus on biophysical accounting to reflections on other indicators of wealth, that is, alternatives to the *growth domestic product* (GDP). Mathis Wackernagel, co-founder of the Ecological Footprint, proposes his own definition of sustainability: “*living well within the means of one planet*”. This very short sentence clearly illustrates that a minimal set of two headlines indicators is needed for measuring progress in a society: one related to current well-being, and the other to sustainability. The Commission on the Measurement of Economic Performance and Social Progress also formulated this wish: “*The assessment of sustainability is complementary to the question of current well-being or economic performance, and must be examined separately. [...] To take an analogy, when driving a car, a meter that added up in one single number the current speed of the vehicle and the remaining level of gasoline would not be of any help to the driver. Both pieces of information are critical and need to be displayed in distinct, clearly visible areas of the dashboard*” (Stiglitz et al., 2009). If GDP itself has no pretension to measure either of those two dimensions, its common use as a target for

economic policy⁴ suggests that it is in practice routinely used as a proxy for well-being: *if we have growth then we will be fine*. The important amount of literature dedicated to the limits of, and misconceptions about GDP have so far had little impact on policy-makers. Interestingly, this illustrates the fact that for the human mindset, *knowing* that a statement is incorrect is not a sufficient incentive to stop using it... We will come back in conclusion to the question of statistics and alternatives to GDP, based in particular on the works of members of the Forum for other indicators of wealth (FAIR).

Now that we established that biophysical accounting was essential for measuring sustainability, but also for helping societies advance towards reduced environmental footprints, we will ask ourselves the following question: ***How can we complement existing environmental assessment tools, specifically at subnational scales?*** to which we devote the next section. The focus on local scales, consistent with the idea of territorial ecology, is additionally motivated by the fact that local territories, and regions in particular, are delegated increasing jurisdiction and seem less seem to benefit from unexploited opportunities to implement a transition to sustainability.

1.2.2 Existing environmental assessment tools: which tool for which question?

Evaluating the material basis of a territory is a way to identify relevant direct and indirect levers of action to improve the situation. Two angles can be mobilized in this perspective:

- The distinction between internal and external sustainability, described by Boutaud (2005), is based on the localization of environmental impacts. For instance, air pollution due to road traffic is rather an issue of internal sustainability while greenhouse gazes (GHG) emissions are an external, i.e. worldwide, issue. This distinction is relevant in the sense that a territory could be tempted to favor its internal sustainability (its local environment and livings conditions) at the expense of its external sustainability (the weight it places on the world).
- Producer and consumer responsibilities are complementary points of view to examine the two forms of environmental pressures: those physically occurring inside the administrative boundaries of a territory and those occurring worldwide in order to satisfy the consumption of this territory. The two perspectives, illustrated in figure 1.4 are useful to inform decision-makers. Taking the example of climate negotiations, China is for instance the first carbon emitter but a large part of its emissions can be associated with manufacturing of products for western consumers (Réseau-Action-Climat, 2013).

Highlighting the structure of the local economy and its inter-dependence with foreign economies has therefore the following purposes:

- Revealing critical links for both the economy itself and the environment,

⁴*"I will go and find growth with my teeth!"*, Nicolas Sarkozy during the 2007 presidential campaign (personal translation).

- Building *fair* environmental indicators that do not entirely allocate pressures based on the producer responsibility.

These aspects are summarized in figure 1.5.

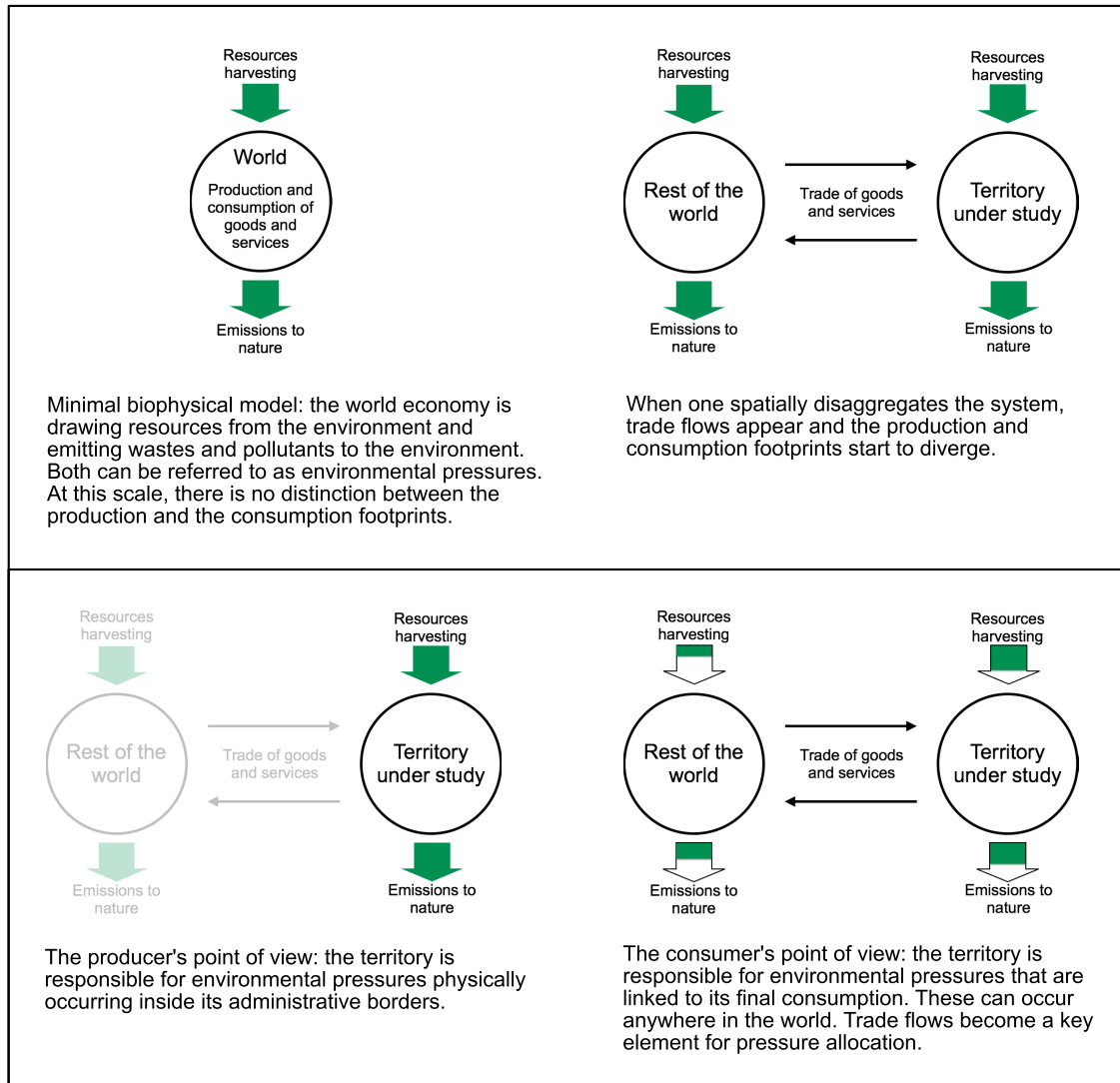


Figure 1.4: Schematical representation of production and consumption responsibilities.

Finally, a decision-maker should ideally be able to compare pressure with quantified sustainability thresholds, locally and globally. These thresholds are however generally difficult to establish and are partially normative.

Questions	Interest for decision-making
What environmental pressures are occurring on the territory? What activities produce them?	→ Diagnosis and identification of direct levers of action (modes of production)
What are the pressures virtually imported (hence externalized) by the territory to satisfy its consumption? What are the pressures virtually exported (hence internalized) by the territory to satisfy external demand?	→ "Equitable" allocation and identification of indirect levers of action (modes of consumption)

Figure 1.5: Questions related to modes of production and modes of consumption and potential interest for decision-making.

Which tools for which questions?

A relatively exhaustive review of methods for environmental assessment of territories was carried out by Loiseau et al. (2012); The authors express in the conclusion the wish to develop a synthetic tool that would benefit from the strengths of the different methods. Here, we reverse the perspective and try to situate tools in view of the questions in table 1.5. We then present how methods can be coupled to extend their potentialities. Four methods are described: Material Flow Analysis (MFA), Input-Output Analysis (IOA), Life-Cycle-Assessment (LCA) and the Ecological Footprint (EF). Each method is based on an explicit structural kernel: mass conservation for MFA, measure of economical sectors' inter-dependence for IOA, life-cycle accounting for LCA and measure of demand on a carrying capacity (referred to as biocapacity) for the EF. To this kernel is associated a preferred angle of inquiry: regenerative resources (products from agriculture, wood...) for the EF, end-products (seen as functional unit) for LCA, economical sectors for IOA, bulk materials, wastes and emissions for MFA. Methodological choices are determined by questions raised, available data, and methods of data acquisition at the scales of study. Independently of these methods, two strategies of data acquisition can be adopted: bottom-up and top-down. The first one provides a finer-grained resolution allowing clearer interpretation of results, but these results are often incomplete as precision prevents comprehensiveness. The second one studies systems in a comprehensive way but with high aggregation levels preventing a deep analysis of results.

Biocapacity: the singularity of the Ecological Footprint (EF)

The EF measures the pressure of human societies on nature's regenerative capacity by determining the bioproductive surface of land or sea necessary to sustain a given level of consumption (Wackernagel and Rees, 1996). This surface can be compared to the biocapacity (an adaptation of the carrying capacity concept) expressed in the same unit. If demand of bioproductive surface is higher than what nature has to offer, then there is a situation of ecological overshoot. The use of an accounting principle allowing to establish easily-transmissible profit and loss accounts is at the heart of the EF method. It explains the success of this concept and its relatively wide acceptance by governmental organizations, despite known methodological weaknesses (Van den Bergh and Verbruggen, 1999). In particular, the standard computation method (generally applied to countries), does not disaggregate results by final consumption categories, and does not take into account all indirect effects of trade; for instance imports and exports of services are

ignored.

Mass conservation: Material Flow Analysis (MFA)

MFA is based on the physical principle of mass conservation (Eurostat, 2001): for any given territory or industrial process (car production for instance), the difference between what goes in and what comes out of the system is equal to stock variation in this system during the period of study. This methodological constraint makes MFA easy to integrate into an accounting framework and also ensures, at least theoretically, not to forget anything in the balance sheet. In counterpart, MFA does not always cover all aspects of a territorial assessment. While Substance Flow Analyses (SFA), for instance applied to metals, traces a chemical component inside a system, economy-wide MFA (EW-MFA), results in aggregates that are not associated to processes existing in the territory. Moreover EW-MFA is not well-suited to inform on consumer responsibility: pressure occurring outside of the system, referred to as indirect flows or hidden flows, cannot be taken into account without calling for other tools, and are in fact often ignored in local scales studies. Kovanda et al. (2009) also criticize the use of the DMC (Domestic Material Consumption) indicator, that adds up quantities of different nature (raw materials and finished products). At regional and local scales, results moreover depend for a large part on the hypotheses used to remedy data shortage, and can only be assessed on a case-by-case basis. Nevertheless, MFA appears as a (paramount) preliminary to other methods.

Products from cradle to grave: Life-Cycle-Assessment (LCA)

LCA is the most "disaggregated" method since it was originally conceived for studying products, considered as functional units. Inversely to SFA, it starts from the product (or service) to get to the materials and pressures involved in each step of its manufacturing. Therefore, one has to choose where to truncate the study so that it be both relevant and feasible. For example, while SFA can help tracing the circulation of copper in the French economy (Bonnin et al., 2012), the LCA of a electric appliance will capture only a part of this circulation in its inventory (the copper physically present in the device as well as an estimate of the copper needed to produce the device), among other substances. The main appeal of this method lies in the fact that it allows to highlight impact transfers between stages of the life-cycle. It also allows to estimate a large panel of pressures and potential impacts, both local (air pollution, water pollution, waste production, and other nuisances) and global (contribution to climate change, contribution to ocean acidification, depletion of scarce resources). This helps showing which compromises must be found.

Inter-dependence of economic sectors: Input-Output Analysis (IOA)

Introduced by Wassily Leontief in the 30s, IOA is first an economic method measuring both direct and indirect flows between all economic sectors and all factors of production: work, capital, resources and pollutions. Leontief himself considered using Input-Output Tables (IOT) beyond pure economic matters (Leontief, 1970). The success of this extremely enriching approach and the adoption of IOT in the System of National Accounts (SNA) of most countries, which occurred in exchange of sensible simplifications (Duchin, 2009)⁵, helped spreading environmental applications. The last twenty years have thus seen a work of reappropriation of this formalism for environmental issues, as part of the development of industrial ecology (Duchin, 2009), the

⁵Standardized IOT in monetary units do not take into account all production factors, especially not those relevant to environmental issues, and are treating investments as exogenous.

most common application being the allocation of pressures between consuming sectors and final demand based on traded values. The introduction of physical IOT (PIOT) is an example of attempt to better capture the physical reality of economy. Their use is however subject to interpretation, as debated between Hubacek and Giljum (2003) Suh (2004), Giljum (2004) and Weisz and Duchin (2006). Additionally, those PIOT are very difficult to build given the lack of data and important simplifications have to be conducted, including materials aggregation, making a deep analysis of results harder. Finally, although monetary IOT are in many cases only available at the national scale, it is possible to regionalize them provided that local economic data are available and with the help of a number of *ad hoc* hypotheses (Cordier, 2011).

Toward an integration of methods

Progress can be obtained when these methods are combined. This combination can take different forms: complementarity, hybridization or complete integration. Understanding the explicit and implicit hypotheses of each method is a necessary preliminary to their integration.

For example, LCA results (or at least partial LCA results) can be used to complement material flow data in order to assess environmental pressures “embodied” in imported and exported products. This is for instance used to estimate hidden flows in MFA or also in the standard computation of EF (both for extraction factors and carbon emission factors).

Example of hybridization is given by coupling attempts between LCA and IOA (Treolar, 1997). One of the deficiencies of LCA is the truncation issue, that can lead to results ignoring up to 50% of impacts (Lenzen and Dey, 2000). Indeed, process analysis is precise for direct impacts but not feasible for the totality of indirect impacts, especially for high order ones⁶, which forces practitioners to fix a threshold *a priori* based on expert knowledge. On the contrary, IOA has the property to be very comprehensive and to take all pressures into account, at the expense of a detailed picture, due the need for aggregation of some economic sectors. In practice, the pressure attributed to a product are in fact the same for all product belonging to the same category. The hybridization between IOA and LCA involves accounting for direct impacts and the first order indirect impacts thanks to the precise LCA results, and completing them with IOA results on indirect impact linked to the same category of products. This is a good example of how the joint use of two methods enables to make the best of the comprehensiveness of a top-down approach and the precision of a bottom-up approach.

The phase of full integration is reached when the coupling of two tools gives birth to a new method. In their work, Nakamura et al. (2007) have extended IOA to take wastes into account and make a connection with MFA through the implementation of a mass conservation constraint. This implies a clear definition of the concepts of resource, material, product, by-product and waste in order to prevent double-counting. This extension allows to determine the different resources physically embodied in any complex end-product, although the authors studied the automotive industry in particular (Nakamura et al., 2011). their Waste Input-Output (WIO) model also assesses environmental pressures of a product during its production, use and end-of-life phases, offering an new alternative to LCA. Another approach, based on PIOT, was proposed in the European project FORWAST (Schmidt et al., 2010). Another example of strong integration between MFA and IOA is the adaptation of Absorbing Markov Chains (AMC), recently used to study the worldwide cycles of metals (copper, nickel, iron)

⁶When conducting LCA, one traces back production step upstream, that is from the final product to the (first-level) inputs required to make it, then to the (second-level) inputs required for these (first-level) inputs etc. Without a threshold, this can of course go on forever.

(Eckelman and Daigo, 2008). The question is then to understand the fate of a substance in the global economy once it has been extracted: where does it go? how is it used? how long does it stay in society? How many times is it used? How much energy is invested in it during its lifespan? More generally, Duchin and Levine (2013) insist on its assets to trace factors of production as well as polluting emissions in the economy and to identify critical dependence links towards a particular resource.

We finally want to stress the recent development of territorial LCA, pursued by Eleonore Loiseau in her PhD thesis, which we find quite close to our concerns (Loiseau, 2014). It is an attempt to adapt the LCA framework to territorial analysis and address both production and consumption viewpoints, making use of a bottom-up approach (i.e. use of local data) when possible, which is the case for most production activities, and a top-down approach (i.e. use of a proxy) in others cases, especially for household consumption of goods and services. In the latter case Environmentally-Extended IOA (EE-IOA) is used.

1.2.3 A focus on supply chains and biomass

Considering the above state of the art as well as our personal areas of interest, we believe a focus on supply chains can usefully supplement existing research efforts. A supply chain is by definition a group of sectors organized to produce, transform and distribute specific goods to consumers. It is therefore an obvious object of study when it comes to analyzing the links between production and consumption. In practice, there is an opportunity to develop tools that would more systematically take advantage of existing information, either drawn from national databases or local sources. Moreover, to our knowledge, there has been so far few attempts in France to assess uncertainties of material flow studies (Bonnin et al., 2012; Dubois et al., 2014), and thus to determine, given available data sources, the degree of precision worth pursuing with this methodology. Finally, it is clear that the relevant scale of study is defined by the problem and that there are in fact most of the time several relevant scales nested in one another (Debuissou, 2014). Although imperfect because constrained by administrative boundaries, we think a multi-scale approach providing results at the national, regional, departmental levels is likely to cover at least part of these concerns. We will thus aim at such a multi-scale view in a supply chain MFA (SC-MFA) model.

We will then show how environmental pressures can be associated to material flows but will not go as far as assessing their impacts on local and global ecosystems which would be a study in itself. Moreover, we believe knowledge on environmental pressures is already a good basis for enlightening sustainability policies. Beyond this main focus on environmental stakes, we are aware of the interest of decision-makers on issues of local employment and creation of wealth, especially in a time of economic crisis. Territorial supply chains, although they only partially cover these aspects (a territory is more than a juxtaposition of supply chains), can bring about relevant perspectives on them.

Thus, we wish to explore the feasibility, limitations and potentialities of coupling SC-MFA with existing models in environmental sciences and social sciences. We couldn't do so if we aimed at studying every supply chain of a territory, or even all the main ones. We therefore prioritize methodological developments over applications and only analyze two supply chains in this thesis: the French cereal supply chain and the French forest-wood supply chain. Beyond

our own interest in biomass and renewable resources, all the more so in the context of energy transition, this choice is motivated by the fact that the agri-food and forest-wood sectors are rooted in territories and based on local resources. More details are of course provided in the dedicated chapters.

In short, the work developed in Parts I and II of this thesis is complementary to that of territorial LCA in the sense that:

- We do not provide a holistic environmental assessment of a territory,
- Rather, we analyze a limited number of supply chains in a spatialized and multi-scale way (national, regional and sometimes local level),
- By doing so we not only tackle the production and consumption viewpoints but also provide the link between them, through transformation industries and transport.

In this section, we provided an overview of some existing tools for environmental assessment of territories and more specifically analyzed to what extent they could pinpoint externalities. We showed supply chains were a relevant subject of study for linking production to consumption and for analyzing the material basis and the creation of wealth of territorial economies. Our efforts will therefore be directed to developing a multi-scale supply chain material flow analysis (SC-MFA) model, and in a second step to extending it to environmental and socio-economic aspects. Aware of the fact that scientific information does not easily translates into policy-making, which is perhaps all the more true when science does not speak the monetary language, we consider the question: *How can we help to bridge the gap between knowledge and decision-making?* which we will now attempt to frame.

1.3 Knowledge and action

<p>“To know in order to predict, predict to enable action.”⁷ Auguste Comte</p>	<p>“Waiting to know enough in order to act in full light is to be condemned to inaction.”⁸ Jean Rostand</p>	<p>“Knowledge kills action, for in order to act we require the veil of illusion.” Friedrich Nietzsche</p>
---	--	---

Scientists played a key role in describing and raising awareness on environmental issues, such as biodiversity loss and climate change. Yet, triggering actions to solve these problems has proven to be a far more difficult enterprise. Our research being decision-oriented, linking knowledge and action is of particular interest to us which is why we propose here a short overview of studies on this question.

The rational-legal model that implicitly accompanied modern societies since the industrial revolution is based on the articulation between the man of science and the man of action (Weber, 2002). When confronted to a problem, the scientist provides a rational explanation of how the world works and the decision-maker uses this objective knowledge to implement the correct policy, in line with the above quotation from Auguste Comte. In this model, *experts* are defined

as men of science that intervene in a decision process, but still carry purely objective knowledge. The introduction of environmental issues however changes this deterministic representation of science: because of an infinite number of interactions, the system under study now escapes analytical modeling. The system is no longer complicated, it is complex; it can no longer be decomposed into small subsystems each of which would be easy to model. Uncertainty then becomes inseparable from scientific knowledge. This reversal of perspective, still not fully digested by public opinions, can lead to a feeling of powerlessness and to the rejection of science as a whole, whereas science can still provide key information for decision-making. For instance, in an update of *The Limits to Growth*, Meadows et al. (2004) state: “*We are not predicting that a particular future will take place. We are simply presenting a range of alternative scenarios: literally, 10 different pictures of how the twenty-first century may evolve. We do this to encourage your learning, reflection, and personal choice. We do not believe that available data and theories will ever permit accurate predictions of what will happen to the world over the coming century. But we do believe that current knowledge permits us to rule out a range of futures as unrealistic.*”

Funtowicz and Ravetz (1993) argue that in this new era, science should be based on assumptions of unpredictability and incomplete control. They define *post-normal* science in comparison with traditional problem-solving strategies (core science, applied science and professional consultancy) using two attributes: post-normal science is appropriate when both system uncertainties and decision stakes are high. Acknowledging that the “*old dichotomy between facts and values*” is transcended, and that there is a “*plurality of legitimate perspectives*”, they argue for an extension of peer communities to all stakeholders influenced by a decision.

In the same spirit, Van Kerkhoff and Lebel (2006) undertake a literature review of the links between research-based knowledge and action for sustainable development. Among conventional views, they identify the “*trickle down*” model, which holds that “*good research will be taken up by practitioners without additional effort*” and is illustrated by the Montreal Protocol which effectively tackled the problem of ozone depletion, and the “*transfer and translate*” model, which is still linear, “*founded on a one-way transfer of science to users*”, but additionally requires a translation, an adoption and a diffusion process among relevant users’ communities. For the authors, the latter model is for instance well-adapted to explain the massive adoption of intensive practices in agriculture. Its appeal is that “*it does not require a great deal of change on the part of the research community, does not conflict with academic goals or incentives, or challenge the view that technical solutions will provide the answers to sustainable development*”. Kerkhoff and Lebel then examine the critiques of these conventional representations. The main criticism of the linear model is probably the fact that science is socially and institutionally embedded. For instance, social and political processes can stimulate or deter research in some areas. Additionally, researchers may be tied to political and economic interests. Research therefore appears “*less autonomous, less certain, and more controversial*”. Although they acknowledge that “*actions toward sustainability are ultimately the result of social and political decisions*”, the authors identify participation, integration, negotiation and learning processes as possible responses to the critiques of conventional models as described in figure 1.6.

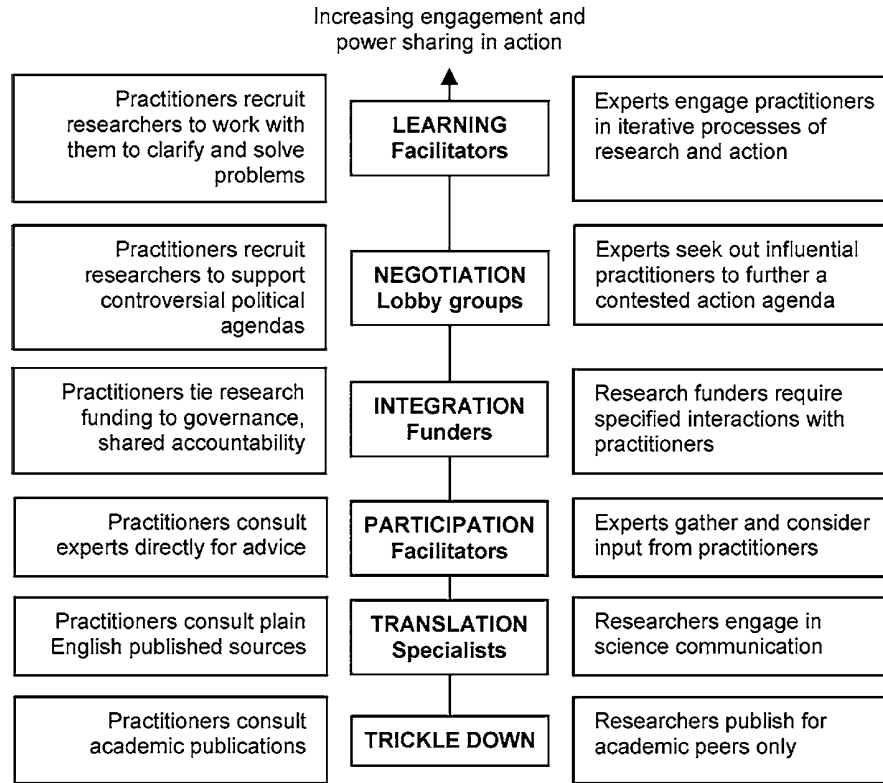


Figure 1.6: Knowledge, power, engagement and action. Source: Van Kerkhoff and Lebel (2006).

The key issues of uncertainty and pluralism of perspectives are also examined in the work of Pielke (2007). To the question of whether or not science can compel action, the author answers “*Yes, but only in particular circumstances characterized by shared values and low uncertainties about the relationship of alternative courses of action and those valued outcomes*”. On the contrary, he notes it is common that :

- Competing interests try to limit the scope of possible choices,
- Conflict exists about the desirability of different outcomes,
- Uncertainty exists on the relationship between actions and outcomes and there is little hope to reduce this uncertainty.

Paradoxically, Pielke shows that uncertainty can both play in favor or against democratic decision-making. On the one hand, it can be “*a resource for various interests in the process of bargaining*”, typically some interest groups can call for inaction until better knowledge is available. On the other, uncertainty may in some cases be considered as a realization of John Rawls’ *veil of ignorance* (Rawls, 2009) and help reaching a reasonable compromise: “*there may be greater room for political compromise when winners and losers are unknown or at risk*”.

We can derive a first conclusion from these analyses: regarding sustainability issues, a decision process limited to *experts* and decision-makers will unlikely be effective. As we will see in part III, participation has long been recognized as a central piece of sustainability policies, sometimes to the point of arousing hostility (Cooke and Kotiiari, 2001). At the same time, integrating stakeholders in the decision process of course complicates it. For instance, how much power should be transferred to them? On this matter, Rousseau and Martel (1996) distinguish between *consultation*, *negociation* and *concertation* (also referred as *participative decision*): in the case of consultation, stakeholders have no saying in the decision and can only express their opinion on a project; negociation implies a necessity of co-decision due to the interdependence of actors looking for acceptable agreements; *participative decision* is located somewhere in between, that is stakeholders can influence the decision but do not generally have the final say. In this case, they will likely support the decision if they originally agreed on the decision-making process. Interestingly, Manin (2002) argues there is no direct filiation between this form of procedural legitimacy, implemented by institutions to limit conflicts, and theoretical developments on *deliberative democracy*, which also holds that legitimacy stems from a procedure, in this case, from an argumentative deliberation process among equal citizens. Bases of the social choice theory and its relationship with deliberative democracy will be further presented in Part III.

Another highlighted difficulty is that consequences of policies can be difficult to predict. Again, a possible response to this issue is the involvement of a large-enough panel of stakeholders in a transparent decision process. Mistakes can be made, but it is easier to reconsider a choice when one can transparently trace back the decision process to see how it was previously justified, and specifically what values sustained it. Additionally, uncertainties may be large but one can attempt to quantify them. This effort should be pursued so that decision-makers can take into account the degree of confidence of information.

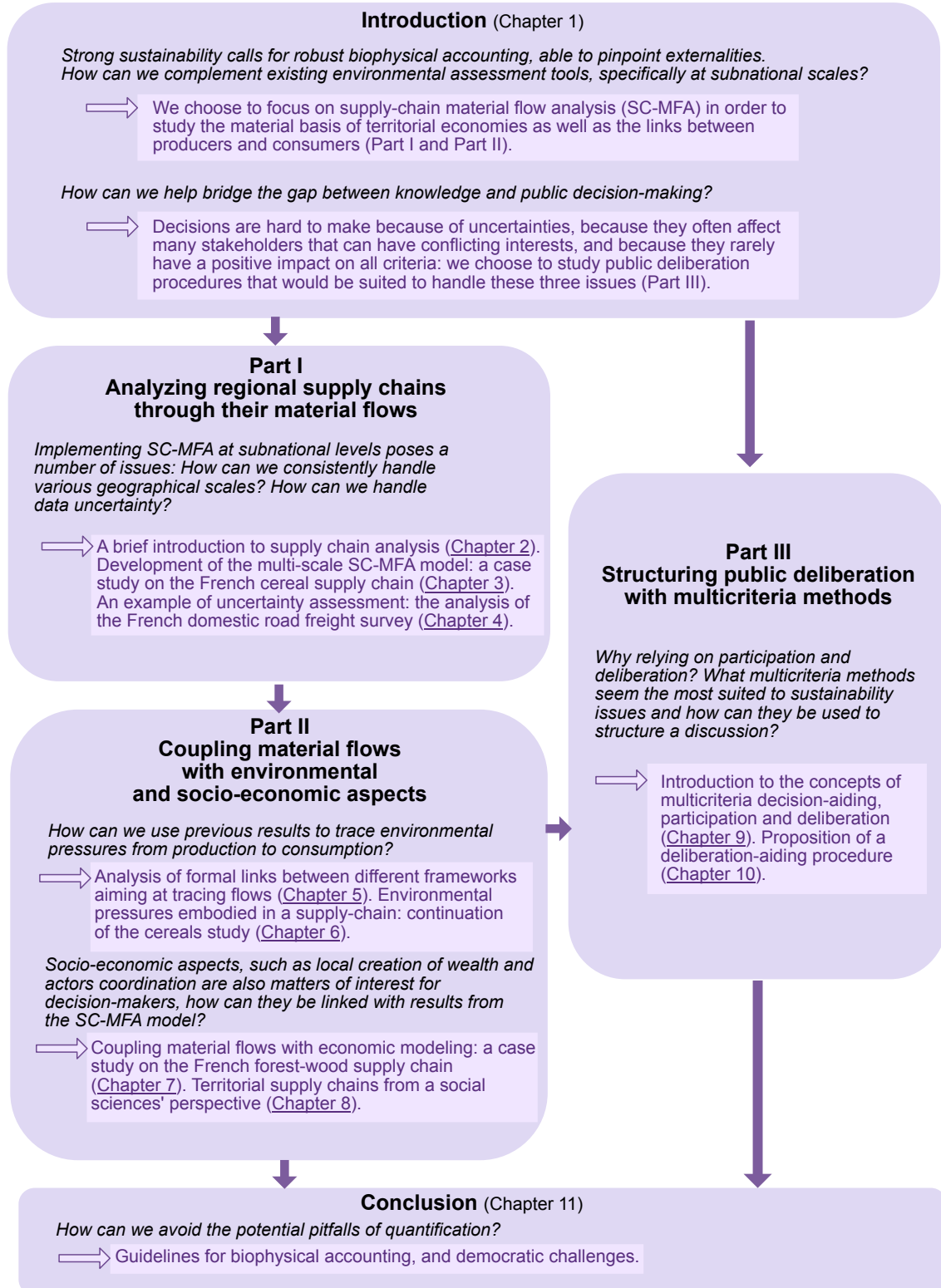
Finally, socio-ecologic systems, which are the subject of sustainability science, are not only difficult to predict but also difficult to describe because they are multi-dimensional. Classically, a first distinction can be made between the anthroposphere (man) and the environment. Clearly each of these two aspects are themselves multi-dimensional and the question arises of where to set the balance between the comprehensiveness of the description and the efficiency, or even the feasibility of the decision process: some dimensions need to be left out or aggregated while maintaining a reasonable distortion of reality. Dashboards of economic, social and environmental indicators have flourished, both in the corporate sector, following the *corporate social responsibility initiative*, and in the public sector, with official national sustainability indicators. The fact that actions rarely have positive impacts on all dimensions adds complexity to the decision process. How can one arbitrate between these different dimensions? In the field of corporate management, Michael Jensen argues that scorecards are flawed because ultimately, one can only maximize one criterion (Jensen, 2009). We will study to what extend multicriteria analysis can address to this argument in the context of public decision-making (Part III).

This section helped us to narrow our initial objective of bridging the gap between research results and decision-making. After defining basic concepts of decision-aiding, we will try

to study deliberation procedures between multiple stakeholders that encompass principles from multicriteria analysis and can handle uncertainty.

1.4 Structure of the thesis

Figure 1.7 explains the structure of the thesis in the form of a flowchart. In Part I and Part II, we will address the first research question presented in this introduction: we will present our developments on supply chain material flow analysis (SC-MFA) and its potential extensions to environmental and socio-economic aspects. More specifically, Chapter 2 will introduce different approaches of supply chain analysis and clarify the scope of our research, Chapter 3 (article) presents the SC-MFA model in the case of the French cereal supply chain, Chapter 4 (article) provides the uncertainty assessment of the French domestic road freight survey, a crucial part of the SC-MFA model. Chapter 5 studies formal links between different methods aiming at tracing flows upstream or downstream, Chapter 6 (article) implements it in the continuation of the study on cereals to analyze environmental pressures embodied in the supply chain. Chapter 7 (article) investigates the possibility of coupling SC-MFA with economic modeling in the case of the French forest-wood supply chain and Chapter 8 shows the links between SC-MFA and a few social sciences' approaches on the issue of actor analysis and local creation of wealth. Part III is dedicated to the second research question: helping bridging the gap between knowledge and policy-making. Chapter 9 introduces the principles of multi-criteria decision aiding, participation and deliberation, and Chapter 10 presents a deliberation-aiding procedure and discusses its possible implementation in the case of the Afterres 2050 sustainable agriculture scenarios. Finally, we summarize in the conclusion the contributions, limits and perspectives of our work, and ask ourselves, given the potential pitfalls of quantification, what guidelines could be useful in order to *count wisely*.



Part I

Analyzing regional supply chains through their material flows

A brief introduction to supply chain analysis

In the introductory chapter, we only presented methods related to biophysical accounting and environmental footprints. Here, we rather propose an overview of approaches used to analyze supply chains, which as we will see, originate from many different disciplines.

2.1 A wide range of approaches: from strategic management to industrial ecology

The term *value chain* was popularized by Michael Porter in the 1980's in the field of strategic management (Porter, 2011). It focuses on the firm level and consists in decomposing the firm's activities into successive tasks required to bring their product or service from its original design to its delivery to consumers. These tasks not only include "*primary*" activities (operations, logistics, marketing, after-sale services), but also all "*support*" activities such as human resources management and quality control. The idea is to study each link in order to understand which ones positively contribute to the competitive advantage of the company and which ones would be best provided by others. In other words, the goal is to identify activities that add the most value to the final product in order to reduce costs and increase differentiation. This concept has been extended to *industry value chain*, which situates the firm as part of a whole supply chain as figure 2.1 shows.

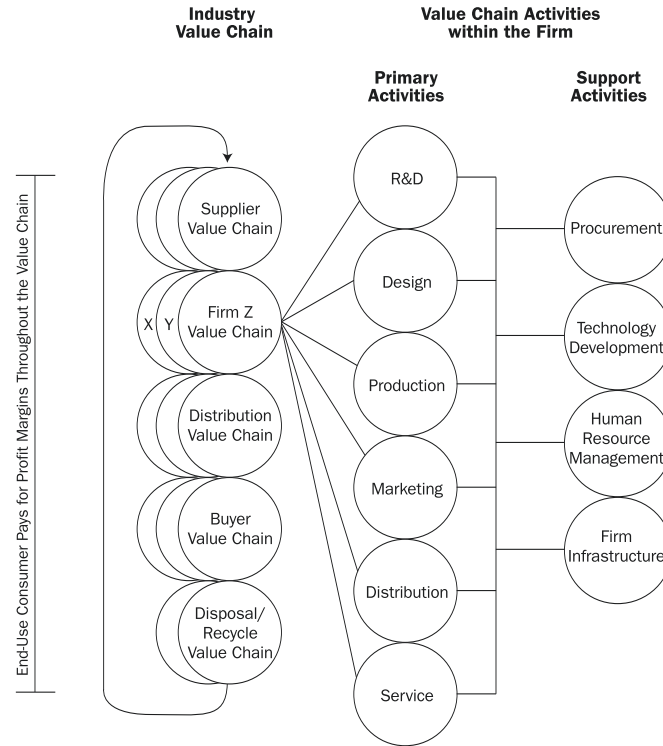


Figure 2.1: Industry value chain and value chain withing a firm. Source: IMA (1996).

In the prolongation of *industry value chains*, a second approach, called *Global commodity chain*¹, or *Global value chain*, analysis was introduced by Gereffi (1994). It studies the increasing economic integration of production and marketing chains in the context of globalization. Its specificity is to emphasize relations of power in the supply chain based on a distinction between two governance patterns: *buyer-driven* and *producer-driven* commodity chains. For instance, most supply chains related to non-durable goods (e.g. food) are buyer-driven because retailers are usually the dominant actors while when products require high technical competences (e.g. aircrafts), chains tend to be producer-driven. Typically, dominant agents out-source upstream or downstream low-profit activities to networks of suppliers or retailers, often located in developing countries, who compete to keep or improve their position in the chain. This framework has been used to study many commodity chains including apparels, fruits and vegetables, cocaine, electronic products or automobiles, with however little quantitative analysis (Raikes et al., 2000).

A third approach, to which we relate more, is that of the French *Approche filière* translated in English by *Commodity chain analysis*. It was originally developed by research institutions² with the objective of analyzing agricultural supply chains. Since the 1960's, many application

¹A global commodity chain is defined by Hopkins and Wallerstein (1994) as "a network of labour and production processes whose end result is a finished commodity".

²Institut National de la Recherche Agronomique (INRA) and Centre de coopération internationale en recherche agronomique pour le développement (CIRAD).

have concerned ex French colonies, with a particular focus on exports of agricultural commodities (e.g. cotton, rubber, coffee) to France. It is now promoted by the Food and Agriculture Organization (FAO) as a way of “*assessing how public policies, investments and institutions affect local production systems*” (Tallec and Bockel, 2005) and according to Raikes et al. (2000), the method was used to justify interventionist measures against liberalization policies carried out by the World Bank. Tallec and Bockel (2005) define the term *commodity chain* as: “*the name given to the succession of operations and of agents which, starting upstream with a raw material, eventually emerge downstream, after several stages of transformation and increases in value, with one or more final products at consumer level. A chain is thus a series of operations (transformations) of agents and of markets, which lead to physical flows and their counterparts in monetary value*”.

The first implementation step is to identify relevant activities as well as boundaries of the study: one usually follows a primary product *downstream*, that is through its successive transformations, until final consumer or export. One can also start from a final commodity and identify providers at each stage of production, however “*the general rule is that only agents who deal directly with the commodity [...] should be included in the chain*”, which excludes for instance providers of fertilizers, pesticides and machinery. Then, one identifies agents behind the activities and group them in homogeneous technical and socio-economic functions. Last, a flowchart is drawn as illustrated in figure 2.2 and one attempts to quantify both physical and monetary flows and to analyze them.

Finally, coming back to the field of industrial ecology, a biophysical approach on supply chains was proposed in the 1983 study entitled “*L’écossystème Belgique - Essai d’écologie industrielle*”³ (Billen et al., 1983). In this work, the authors focus on the Belgian economy by decomposing it into supply chains, as shown in figure 2.3. They analyze material flows and stocks of some of these supply chains in detail, using Sankey diagrams representations (an example of the iron supply chain is given in figure 2.4). In addition, in the second part of the essay, environmental pressures linked to the Belgian economy are quantified (waste generation, energy flows and emission of pollutants) and associated to specific supply chains when possible. Beyond the scientific endeavor, the authors express the wish to use this more global perspective on the economy, pinpointing environmental externalities, to rethink what is and what is not profitable, and to open a debate on the productive system’s reorientation.

2.2 Scope of our work

Our work can be directly affiliated to this last approach of territories and supply chains. It also bears some similarities with the *Approche filière*, however differences need to be pointed out. Firstly, we do not wish to restrict our analysis to agricultural supply chains. Secondly, the method used allows us to study flows between industrial sectors but not through collection or distribution networks. Thirdly we do not distinguish large from small agents nor production practices, for instance we don’t distinguish organic from conventional supply chains. These limits will be further discussed in Chapter 8.

Furthermore, we adopt the following strategic bias: we want to explore the possibility of relying only on existing datasets and not on a bottom-up, survey-based, data collection process. This

³The ecosystem Belgium - Essay of industrial ecology.

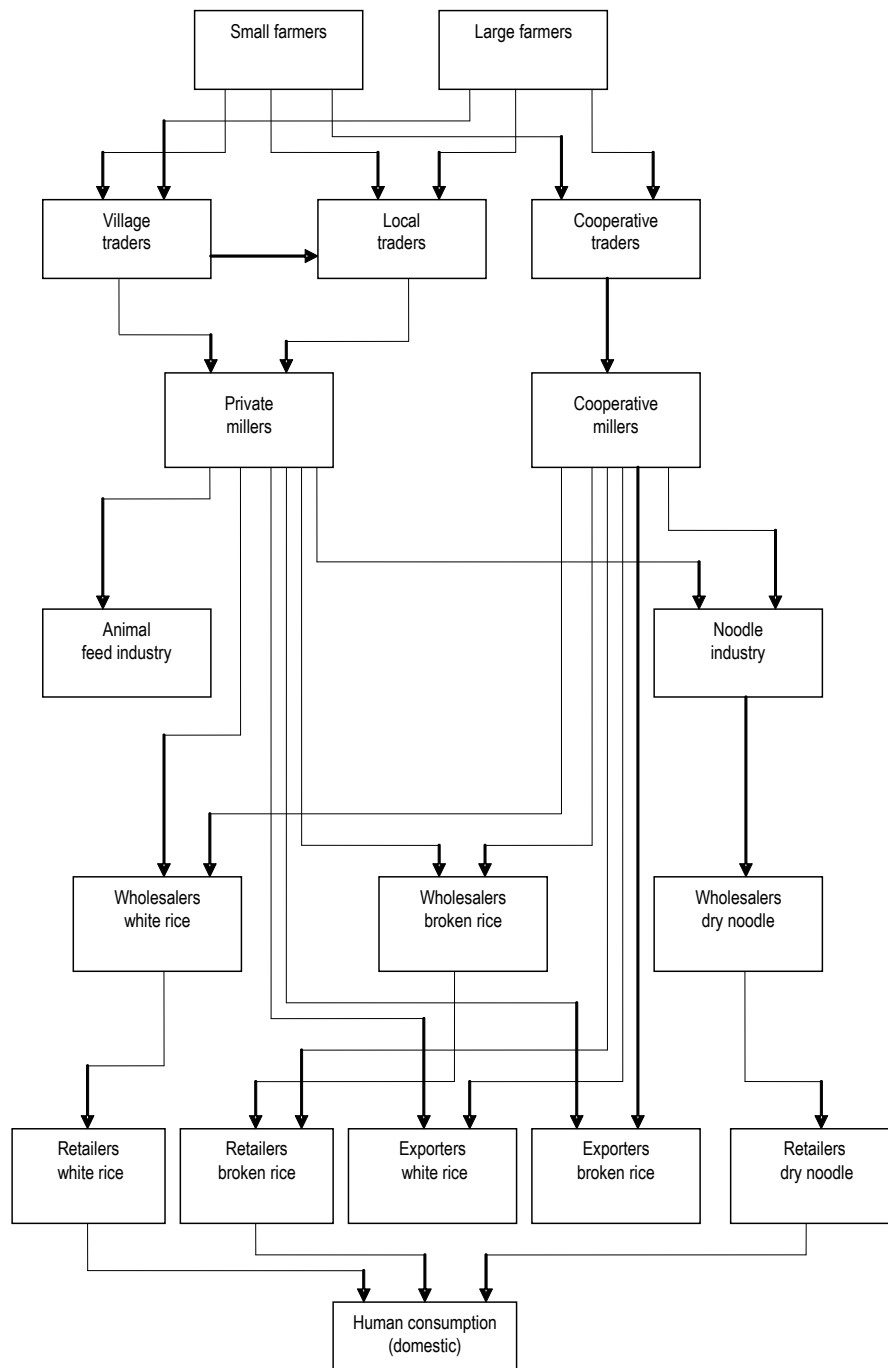


Figure 2.2: An example of implementation of the *Approche filière*: the rice commodity chain in Thailand. Source: Tallec and Bockel (2005).

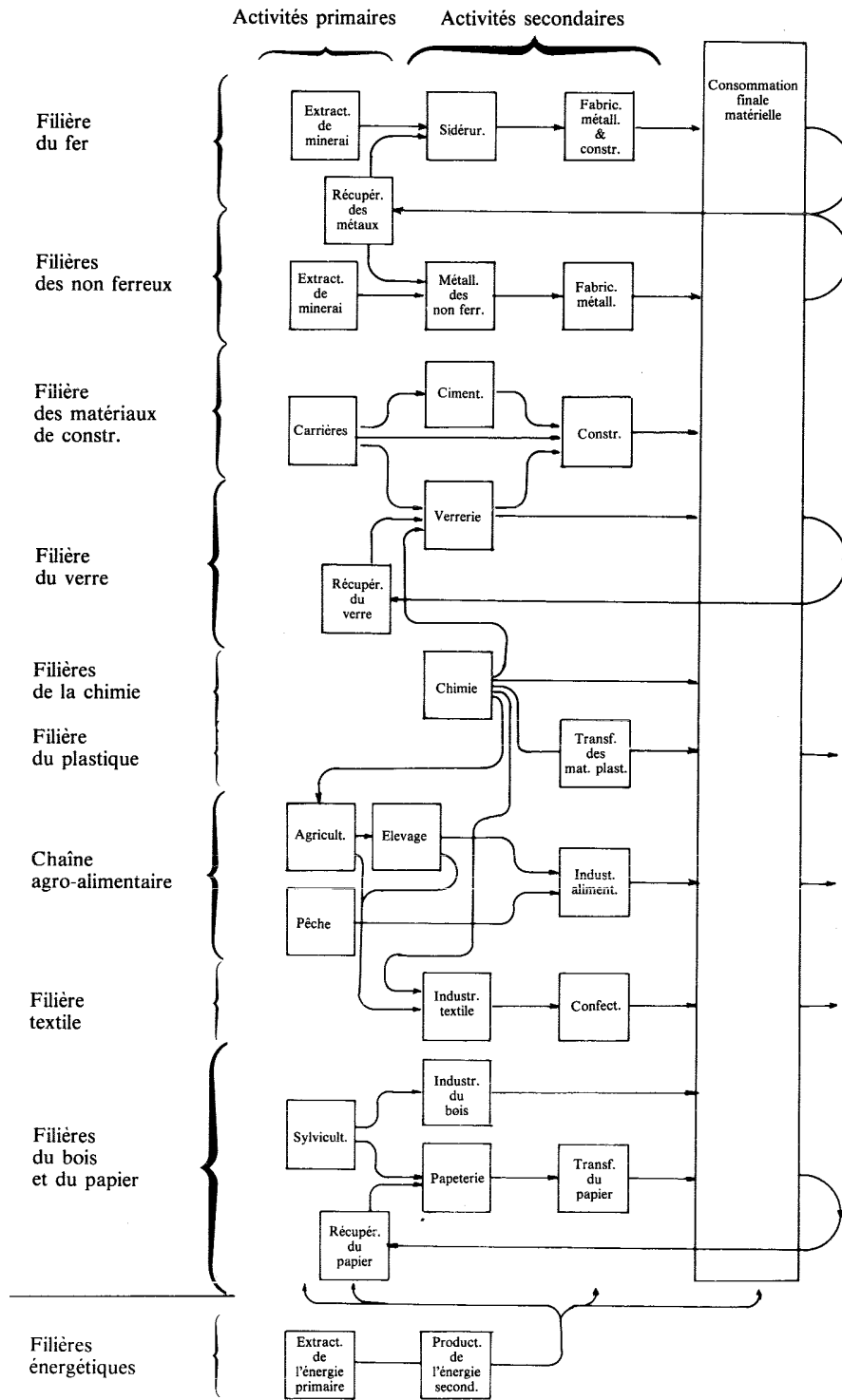


Figure 2.3: Main supply chains of the Belgian economic system. Source: Billen et al. (1983).

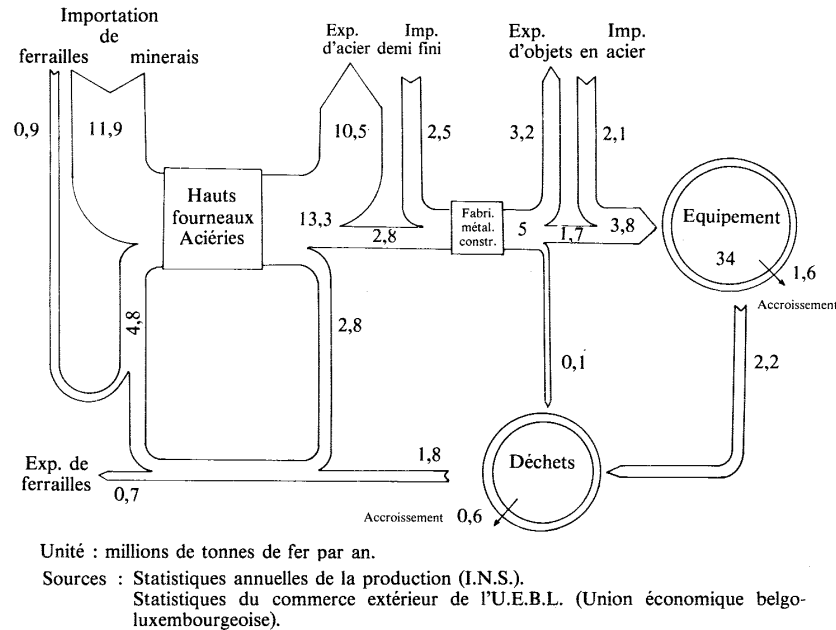


Figure 2.4: Flows of iron in Belgium in 1974. Source: Billen et al. (1983).

of course sets the finer scale we can study, systematic information only being available down to a certain level. We will see that, while we can have reasonable confidence in results at the regional level, it is not always the case at the department level, and going deeper cannot be done without coarse simplifications. **Our main purpose is to produce SC-MFAs at the level of France and of all French regions in an efficient, semi-automatic way, with the assumption that they could then provide a basis for deeper territorial analyses.** In a longer-term perspective, it can be pointed out that:

- Only two chains were studied in this thesis, but the goal would be to analyze all the main chains (much like what was done in Billen et al. 1983, but at regional scales),
- In practice though, supply chain analyses have intrinsic limits (because of data availability, and because human activities cannot be fully studied through supply chains),
- Strategies to develop more comprehensive environmental assessments of territories are discussed in the conclusion.

Our first effort, presented in Chapter 3, aims at introducing the SC-MFA methodology, on the case of the French cereal supply chain. Chapter 4 is then oriented towards uncertainty assessment of available data, and more specifically of domestic road freight statistics which we consider the *weakest link* of local MFA studies.

Downscaling material flow analysis: the case of the cereal supply chain in France

Courtonne, J.-Y., Alapetite, J., Longaretti, P.-Y., Dupré, D., Prados, E., 2015. Downscaling material flow analysis: The case of the cereal supply chain in France. *Ecological Economics* 118, 67 - 80.

Abstract The spatial reconstruction of the production, trade, transformation and consumption flows of a specific material, can become an important decision-help tool for improving resource management and for studying environmental pressures from the producer's to the consumer's viewpoint. One of the obstacles preventing its actual use in the decision-making process is that building such studies at various geographical scales proves to be costly both in time and manpower. In this article, we propose a semi-automatic methodology to overcome this issue: we describe our multi-scalar model and its data-reconciliation component and apply it to cereals flows. Namely, using official databases (Insee, Agreste, FranceAgriMer, SitraM) as well as corporate sources, we reconstructed the supply chain flows of the 22 French regions as well as the flows of four nested territories: France, the Rhône-Alpes région, the Isère département and the territory of the SCoT of Grenoble. We display the results using Sankey diagrams and discuss the intervals of confidence of the model's outputs. We conclude on the perspectives of coupling this model with economic, social and environmental aspects that would provide key information to decision-makers.

Keywords:

Material flow analysis, supply chain, downscaling, data reconciliation, cereals, France.

3.1 Introduction

Material flow analysis (MFA) is a systematic assessment of the flows and stocks of materials within a system defined in space and time (Brunner and Rechberger, 2003). Depending on the pursued objective (e.g. detoxification, dematerialization etc.), this framework has been

*PhD students at CERAG (University of Grenoble).

‡Members of STEEP team (INRIA Grenoble).

†Artelia Eau & Environnement.

§UJF-Grenoble 1 / CNRS-INSU, Institut de Planétologie et d'Astrophysique de Grenoble (IPAG) UMR 5274.

¶Professor of ethics and sustainable development, University of Grenoble.

implemented for various scopes de facto creating a family of methodologies, ranging from Substance Flow Analysis to Economy-Wide Material Flow Accounting (Bringezu and Moriguchi, 2002). In this paper, we are interested in mapping the flows of specific resources throughout the economy, both from a spatial and a processing point of views; i.e., we aim to trace the associated flows from the extraction of raw materials to the processing, trade and consumption of the derived products based on the resource under consideration. These studies are known as MFA on the level of goods, as defined by Baccini and Brunner (2012)¹. In their original work, Billen et al. (1983) conducted such MFA on 6 supply chains at the scale of Belgium (iron, glass, plastic, lead, wood and paper, and food products). Since then, MFA has been mostly applied to metals² (Ciacci et al., 2013; Eckelman and Daigo, 2008; Liu and Müller, 2013; Dahlström and Ekins, 2006; Bonnin et al., 2012) to cite only a few. Some studies were also undertaken on construction materials (Smith et al., 2003) and wood (Hashimoto and Moriguchi, 2004; Binder et al., 2004; Cheng et al., 2010; Liu, 2014). Regarding food products, few studies actually quantified flows between the production, transformation and consumption stages (Wirsenius, 2003; Blezat-Consulting, 2010), rather focusing on the supply of a product unit (Narayanaswamy et al., 2003; Mintcheva, 2005; Virtanen et al., 2011), on nitrogen flows (Billen et al., 2009), or on land embodied in trade (Hubacek and Giljum, 2003).

Binder et al. (2009) raised the important issue of the practical usefulness of large-scale MFA studies for policy-making. Three main obstacles were identified in comparison with MFA at the scale of an industrial unit: “(i) the numbers of stakeholders involved increases [...] and it becomes unclear who is responsible for taking action; (ii) the uncertainty of the data increases; and (iii) the goals [...] are not always clearly defined”. In order to bridge the gap between research findings and policy-making, many authors have rightly argued that MFA should be coupled with social, economic or/and environmental models (Binder, 2007). This kind of coupling was for instance successfully implemented by Rochat et al. (2013) who combined MFA, Life Cycle Assessment (LCA) and multi-scenarios, multi-criteria, multi-stakeholders analysis to address the issue of PET plastic management in Columbia. One could also refer to the study carried out by Bouman et al. (2000) who used SFA, LCA and partial equilibrium models to evaluate industrial systems and compare pollution management scenarios. Coupling MFA with a social model aims at better understanding the behaviors of stakeholders and the interactions between them in order to study how to improve resource management. For instance, Binder et al. (2004) used a multi-agent model to study the management of regional wood flows in Switzerland. As mentioned by Kytzia et al. (2004), the coupling of MFA with an economic model can be performed to study economic consequences of environmental policy, or on the contrary, to study the effectiveness of economic tools to tackle environmental issues. Finally, the coupling with an environmental model, for example with LCA, makes it possible to build environmental accounts (such as footprints) from the producer’s and from the consumer’s perspective. As underlined by many authors (Peters and Hertwich, 2006b; Skelton et al., 2011), these points of view are both complementary and paramount for policy-making. The producer’s point of view informs on environmental pressures that occur on a territory: a variety of measures (incentives, regulations, information...) can be taken to address these pressures. The consumer’s point of

¹Two kind of materials are distinguished: substances, that is *any chemical element or compound composed of uniform units*, and goods, that is *economic entities of matter with a positive or negative economic value [...] made up of one or several substances* (Brunner and Rechberger, 2003).

²Many investigations dedicated to metals life-cycle flows are linked to the Stocks and Flows (STAF) project at Yale university.

view informs on the responsibility of the consumer for environmental burdens occurring locally or far away (end products purchased by final consumers trigger global supply chains and thus it can be argued that consumers bear the subsequent environmental pressures).

The present paper is the first step of a project aiming at analyzing local supply chains from an economic, social and environmental perspective for decision-aiding. In particular we aim at analyzing environmental pressures along supply chains, i.e. from the producer's to the consumer's viewpoint. The paper has two main objectives. The first one is to assess the feasibility of downscaling a national MFA to simultaneously obtain MFAs on every subterritory the country is composed of (e.g. every regions). This makes the study more time-efficient while also ensuring the comparability of the data and the consistency of aggregated results (the regional data will sum up to the national data). This also helps to get a better grasp on inter-regional trade, which is rarely known with precision. These results can then serve as a basis for discussion and refinements with local stakeholders. The second goal is to undertake a multi-scale MFA. We strongly believe that multi-scale analysis is a powerful decision-help tool given social-environmental issues are unlikely to be resolved at any single administrative level. Indeed, each level has specific jurisdictions and discusses with specific actors. We further discuss the potential of multi-scale analysis at the end of the results section. Such a perspective has already been adopted in France in the case of Paris and its region where economy-wide MFAs were produced on three different geographical scales (from the city to the région level; Barles (2009)). Here, we undertake studies at the national, regional, departemental and SCoT³ scales.

In order to illustrate the interest of the tool we have developed, we have chosen to apply it to a basic class of commodities, i.e., cereals. This choice is motivated by the following considerations:

- At the world's scale, but more generally at any scale, the supply of cereals and cereals products is strategic given their direct and indirect (through meat consumption) role in human diets and their increasing use for other purposes (e.g. bioethanol),
- Cereals are, in terms of weight of production, the most important agricultural good in France; the supply chain is represented all over the territory and, at the same time, a strong heterogeneity can be observed between regions,
- The supply chain is well structured making it easier to model and collect the necessary data.
- Finally, it is possible to account for most end-products derived from cereals with a limited set of descriptive product categories, bread being the most obvious one in the case of France.

The paper is organized as followed: the first section depicts the methodological framework and the sources and hypotheses used in the modeling phase, we present and discuss the results in the second section before concluding on the perspectives for further research in the field of MFA.

³Schéma de cohérence territoriale: the SCoT is an urban-planning document dedicated to a group of towns or urban areas.

3.2 Materials and methods

3.2.1 Methodological framework

In order to semi-automatically produce MFAs at subnational scales, we start by building a consistent MFA at the country level. For this purpose, we use on the one hand a supply and use tables (SUTs) framework as a way to present and organize the data, and on the other hand a constraint optimization algorithm aiming at reconciling inconsistent data. We underline here that while we use a typical Input-Output framework, we don't go into any IOA (e.g. computation of the Leontief matrix)⁴.

It is worth noting our resource-specific MFA based on SUTs is close to the concept of Material System Analysis (MSA) introduced by Moll et al. (2005) on the case of European iron and steel flows, and taken up by OECD (2008b). However, while MSA is considering all material inputs and outputs along the supply chain (i.e. life-cycle-wide), we only focus at this step on one good: cereals⁵.

3.2.1.1 Supply and use tables

Handling a large quantity of data is a major difficulty in MFA and calls for a proper way of organizing the information. SUTs appear to be the most convenient framework to achieve this goal. They comprise a Supply table, which indicates the origin of the goods (either sector-wise or geographically) and a Use table, which indicates the destination of the goods.

	industry 1 .. industry m	imports
product 1 .. product n	$V_{ij} (n,m)$	$I_i (n,1)$

Table 3.1: Supply table and matrices notations. The numbers in brackets indicate the dimensions of the matrices.

	industry 1 .. industry m	exports	consumption
product 1 .. product n	$U_{ij} (n,m)$	$E_i (n,1)$	$C_i (n,1)$

Table 3.2: Use table and matrices notations.

As shown above, the supply table comprises the supply matrix V and the imports vector I whereas the use table comprises the use matrix U , the exports vector E and the (final) consumption vector C . For instance U_{ij} refers to the quantity of product i that is used by sector j and C_i refers to the quantity of product i that is consumed by end-users on the territory. The constraints linking these elements are discussed in section 3.2.1.3.

⁴French IO tables indeed come into a too aggregated form to reach the level of detail we are interested in here.

⁵The study of specific material/environmental flows associated with it will be tackled in a next step as described in the introduction.

Using SUTs implies to make a list of the goods deriving from the primary resource under study, i.e. the primary material itself, semi-products, by-products and end-products. Finding the appropriate level of details for both products and industries is an iterative process between looking for sources of information and trying to fill the tables. With a small number of highly aggregated product categories, the study isn't likely to provide useful information and with a very detailed list of products and industries, filling the data, especially at local scales, won't be feasible. A good knowledge of existing classifications in the national statistical system, for instance economic sectors, products or traded commodities classifications, is also required because correspondences between them will be needed. We used the most precise level of classification of economic sectors available in France for most of the sectors in the study: the NAF 2008 classification (732 sub-classes). For some important products such as bioethanol, this classification was however not precise enough. In those cases, we created our own sectors, knowing information on factories location was available from the cereals' supply chain federation. This initial step of supply-chain structure analysis is the most time-consuming and cannot be automatized. In fact, it consists in building a model of the supply chain: a too coarse model will not make sense while a too detailed one will be intractable. The final version of our study includes 19 products and 18 sectors (displayed in figure A.1 in Supplementary Material section A).

3.2.1.2 Boundaries of the study, units and allocation choices

We used a typology proposed by Nakamura and Kondo (2009) to define the scope of the study. Inputs from sector a to sector b can take three different forms: primary material inputs, that will be physically incorporated in the production of sector b (e.g. wheat for flour production), material ancillary inputs, that are necessary for production of sector b but not part of it (e.g. machines), and finally flows of services. For this MFA on cereals we track the flows from product to product until cereal grains are no more physically present in the output of the process. Thus, we go for instance from wheat to flour and to bread and biscuits while we stop the study at animal feed without analyzing the embodied cereals in the meat finally consumed (which would be virtual allocation and not a physical flow of cereals).

Like other MFA studies on the level of goods, we converted all flows to a common unit⁶. Here, flows are expressed in cereals grains equivalent (c.g.e.). The c.g.e. weight equals the real weight when the product under consideration is entirely made out of cereals (e.g. flour), otherwise (e.g. bread, beer...), it represents the weight of the cereal content of the product.

To sum things up, our SUTs framework distinguishes itself from SUTs traditionally used in national accounts by the finer-grained description of the products and industries categories, by the fact that it focuses on a single supply chain and by the choice of the unit.

3.2.1.3 Data reconciliation

The principle of mass conservation provides a few constraints on the SUTs. When the data comes from distinct sources, these constraints are of course very unlikely to be fulfilled. Making the original data fit the constraints is commonly referred to as the data reconciliation process. The constraints are discussed below.

We first apply the law of mass conservation on each product: the amount of product that was used during the considered time period by transforming industries, exports and final consump-

⁶For instance, Binder et al. (2004) and Cheng et al. (2010) convert all flows of wood-related products into their equivalent in cubic meters of round-wood.

tion, had to be supplied by local industries or by imports (*constraint 1*). The corresponding equation is:

$$\sum_j \hat{V}_{ij} + \hat{I}_i = \sum_j \hat{U}_{ij} + \hat{E}_i + \hat{C}_i \quad i = 1..n \quad (3.1)$$

We use hats above letters to refer to the data resulting from the reconciliation process (original data are represented without a hat). In the general case, equation D.1 should contain additional terms to account for initial and final stocks (or alternatively one term of stock variation). We however go around this issue as explained in section 3.2.2.5. Moreover, losses are treated as a sector (without outputs) in matrices U and V .

We apply a similar principle of conservation to every transforming industrial sector (*constraint 2*): the sum of a sector's inputs is equal to the sum of its outputs:

$$\sum_i \hat{V}_{ij} = \sum_i \hat{U}_{ij} \quad j = 1..m \quad \text{and } j \text{ is a transforming sector} \quad (3.2)$$

A sector producing raw materials is not concerned by this constraint because it only has outputs. We moreover implement a few process constraints to verify classical technical conversion factors between products (*constraint 3*). These equations link one or more inputs of a transforming sector with one or more of its outputs. For instance the yield of conversion of wheat grains into flour translates into the following constraint for the milling sector : $S_{flour,mills} = 0.77 * U_{wheat,mills}$. We present those equations in table A.1 in section A of Supplementary Material. Finally, we want all terms to remain positive (*constraint 4*) and most of the terms to remain null (*constraint 5*) because of the supply chain modeling choices (for instance the primary production sector cannot produce transformed products).

Our goal is to minimize the discrepancy between original data and estimated/final data while respecting the constraints. This problem can be expressed in many ways depending on the expression of the distance between original and final data. We choose here one of the simplest, a weighted least square problem under constraints:

$$\begin{aligned} \min \quad & \left(\sum_i \sum_j \frac{(\hat{V}_{ij} - V_{ij})^2}{\sigma_{V_{ij}}^2} + \sum_i \sum_j \frac{(\hat{U}_{ij} - U_{ij})^2}{\sigma_{U_{ij}}^2} + \sum_i \frac{(\hat{I}_i - I_i)^2}{\sigma_{I_i}^2} + \sum_i \frac{(\hat{E}_i - E_i)^2}{\sigma_{E_i}^2} \right. \\ & \left. + \sum_i \frac{(\hat{C}_i - C_i)^2}{\sigma_{C_i}^2} \right) \\ \text{subject to the set of constraints 1 to 5} \end{aligned} \quad (3.3)$$

In equation 3.3, σ refers to the assumed standard deviation of the data. They make it possible to treat data sources differently depending on the assumed (or possibly measured, or constrained) uncertainties on the data. The chosen weights are discussed later in the paper.

3.2.1.4 Downscaling technique

From an administrative point of view, metropolitan France is currently divided in 22 administrative régions. Each région is further subdivided into départements (96 in total), the next and last administrative authority being towns and cities (about 36000 in total). The lack of data at local scale is problematic. The smaller the scale, the less the availability of the data. For

this reason, one can try to estimate the missing data using other existing variables along with data available at a larger scale, by defining appropriate proxies.

The general proxy expression of the estimation of local data would be:

$$Y^{n+1} = f(Y^n, X_1^{n+1}, \dots, X_k^{n+1}) \quad (3.4)$$

Here the exponents refer to the geographical level of the data (for instance, if n represents the country level, $n + 1$ represents the regional level). f is the model linking the quantity of interest at level n , Y^n (known), and k explanatory variables available at level $n + 1$, X_j^{n+1} , to the quantity of interest at level $n + 1$ that we are looking for: Y^{n+1} .

The possibilities of testing complex proxy models are of course very limited by the scarcity of the information. Researchers who faced the lack of data in their local MFA studies actually used a single proxy (or explanatory variable) to estimate missing data (Barles, 2009; Kovanda et al., 2009; Niza et al., 2009). This is usually based on reasonable hypotheses such as ‘‘consumption is almost proportional to the population’’. We applied the same approach here and conducted linear regression tests whenever the sample existed and was of sufficient size⁷. We studied the possibility of having a multiple explanatory variables model but concluded it wasn’t robust enough given the limited size of the geographic sample (Smaranda, 2013). Moreover, we found that the R^2 index, which represents the proportion of the variability of the sample that has been explained by the model, was high enough in the case of a simple one-explanatory-variable-linear model to consider it satisfactory. Results are presented in Table 3.2.2. For instance, if we want to estimate the regional use of wheat by the milling industry in region i , $U_{wheat,mills}^{ri}$, with the number of employees working in this sector E_{mills} , equation 3.4 becomes:

$$U_{wheat,mills}^{ri} = U_{wheat,mills}^{fr} * E_{mills}^{ri} / E_{mills}^{fr} \quad (3.5)$$

Once enough direct data or proxies have been gathered, it is possible to fill the SUTs. New columns are added to consider inter-regional trade of good. By construction, the imports of product i to region a from region b , $Ir_i^{a,b}$, are equal to the exports of product i from region b to region a , $Er_i^{b,a}$, so we only use the Ir variable (matrix) in the program. We then apply the same data reconciliation process as the one described above. An additional constraint however needs to be implemented: one wants to ensure the coherence of the results regarding aggregation and disaggregation. The regional data must sum up to the national total. With the same notations as above for the exponents, the general expression of the aggregation constraint (*constraint 6*) is:

$$\sum_i \hat{X}^{n+1, i} = \hat{X}^n \quad \text{where } \hat{X} \text{ represent matrix } \hat{V}, \hat{U}, \hat{I}, \hat{E} \text{ or } \hat{C} \quad (3.6)$$

In equation 3.6, I and E refer to international imports and exports only: there is no aggregation constraint on inter-regional trade.

There exists no trade database at subnational scales that perfectly matches our products classification. Therefore, a few traded categories are more aggregated than our own categories. For instance the *wheat* category in the transport database includes both our *common wheat* and *durum wheat* categories. Table A.9 in section B of Supplementary Material shows the full correspondence and section B depicts the changes that had to be made to take this limitation into account.

⁷The fact that the sample size is small (96 individuals at best) has to be balanced by the fact that it is exhaustive.

Finally, no trade data is available below the level of the département. Therefore, at this scale, we only compute production and consumption (intermediate and final) flows, using the usual proxies and then apply the resource equals use constraint on each product to determine the amount of net imports (or net exports). Thus, we no longer use any optimization or data reconciliation process below the scale of the département.

3.2.2 Data sources and hypotheses

Figure A.1 in Supplementary Material section A shows the classifications used in this study for product and sector categories together with the chosen model of the supply chain: it indicates for instance that the starch industry uses common wheat and maize and supplies starch and residues. In order to fill the SUTs, the information we are looking for fall into different categories: primary production, intermediate consumption, stocks, trade, livestock consumption and final consumption. As mentioned in the previous section, we use direct data when it exists and proxy data otherwise. Each type of information is discussed below in relationship to table 3.2.2 that summarizes the sources and table 3.2.2 that presents the chosen proxies. The question of data uncertainties is discussed in the last paragraph of the section.

Item	Source	Smallest scale available
Production of each type of cereals (common wheat, durum wheat, maize, barley...)	Statistique Agricole Annuelle (Agreste): http://aces.agriculture.gouv.fr/disar/faces/	département (better resolution can be purchased as long as it does not go against statistical secret)
Production of intermediate products (flour, bread, biscuits, starch, semolina, pasta, malt, beer...)	Bilans d'approvisionnement http://agreste.agriculture.gouv.fr/enquetes/bilans-d-approvisionnement/cereales-riz-pomme-de-terre/ , cereales' inter-profession http://asset.keepeek.com/permalinks/domain39/2013/06/04/927-B18-Des-chiffres-et-des-cereales__edition_2012-2013__page_a_page.pdf	country
Animal feed (for cattle, poultry and pigs)	Bilans d'approvisionnement (Agreste) Inputs used by the animal feed industry (Agreste)	country most of the régions
International trade of raw materials and transformed products	Bilans d'approvisionnement (Agreste) Sitram database (based on French customs' data)	country département of origin/destination - country of origin/destination
National road freight	Sitram database (based on the TRM survey)	département of origin/destination - département of origin/destination
National railroad freight	Sitram database (based on reports from SNCF - available until 2006)	région of origin/destination - région of origin/destination
National river freight	Sitram database (based on reports from VNF)	département of origin/destination - département of origin/destination
Cereals' consumption patterns	Babayou et al. (1996)	régions

Table 3.3: Available sources for data in weight unit. All recent years are available when applicable.

Item	Proxy and source	Sample size	R^2 (and p-value)	Used for scales...
Cereals production	Recensement Général Agricole 2000 and 2010 (Agreste) ^a	95	0.98 ($<2.2 \cdot 10^{-16}$)	$<$ département
Total livestock feed	Livestock at subnational scales - Statistique Agricole Annuelle (Agreste) for régions and départements, Recensement Général Agricole 2000 and 2010 (Agreste) for groups of cities	see the livestock feed section		$<$ country
Flour production	Employment (sector 10.61A)	12	0.75 ($2 \cdot 10^{-4}$)	$<$ country
Production of semolina	Number of factories		not tested	$<$ country
Production of cornmeal	Number of factories		not tested	$<$ country
Rice transformation	Number of factories		not tested	$<$ country
Production of canned corn	Number of factories		not tested	$<$ country
Starch production	Employment (sector 10.62Z)	3	0.96 (0.13)	$<$ country
Industrial bread production	Employment (sector 10.71A)		not tested	$<$ country
Production of bread in supermarkets	Employment (sector 47.11F)		not tested	$<$ country
Craft bread production	Employment (sector 10.71C)		not tested	$<$ country
Biscuits production	Employment (sector 10.72Z)		not tested	$<$ country
Pasta production	Employment (sector 10.73Z)		not tested	$<$ country
Livestock compound feed production	Employment (sector 10.91Z)	18	0.96 ($1 \cdot 10^{-12}$)	$<$ région
Malt production	Employment (sector 11.06Z)	3	0.99 (0.06)	$<$ country
Beer production	Employment (sector 11.05Z)		not tested	$<$ country
Bioethanol production	Number of factories		not tested	$<$ country
Final consumption	Population coupled with consumption pattern - Population census (Insee), Babayou et al. (1996)		not tested	$<$ country

Table 3.4: Chosen proxies. R^2 can be interpreted as the fraction of the sample's variability that is explained by the linear model. The p-values (in brackets) represent the probability of obtaining a similar or better R^2 value if the null hypothesis is true (i.e. if there is no relationship between the explanatory and response variables). One usually assumes the null hypothesis is false when the p-value is below 0.05. Here, we can validate the explanatory models for cereals, flour and livestock feed production whereas the samples are too small to validate the starch and malt production models. Insee's CLAP database is used to get the number of employees; number and location of factories come from the yearly report of the *Passion Céréales* association (inter-profession). Hypotheses were not tested when no data was found at the regional scale.

^aIn other european countries where such census is not available, results from the Capri-Dynaspat model (Leip et al., 2008) could be used.

3.2.2.1 Primary production

Detailed data on cereals production is published in the annual agricultural statistics available down to the level of the département. We therefore used a land-use proxy (see table 3.2.2) to estimate the production of cereals at the scale of a group of cities.

3.2.2.2 Intermediate consumption

The annual report of the French inter-profession of cereals (Passion-Céréales, 2013) provides information on the quantities used and produced by different industries in the supply chain. Based on this data, we established conversion factors between products (table A.1 in Supplementary Material section A), that are used to constrain the problem (see section 3.2.1.3). When the data couldn't be found in specific regional reports, which is the general case, we estimated the subnational intermediate consumptions using the downscaling technique presented in the previous section and the proxies in table 3.2.2.

3.2.2.3 Losses and by-products

In the current version of the supply chain model, losses are only considered at the farm and during grain storage, because these losses are the most significant and are estimated by the ministry of agriculture. We additionally take into account by-products (residues from transformation industries). In a sustainability perspective, the material efficiency of the supply chain can be estimated (it could be defined as a ratio of $1 - losses/inputs$), as well as the fate of by-products in order to make sure they are recovered.

3.2.2.4 Livestock feed

Regional consumption of cereals for livestock feed are not directly known, mainly because the cereals are distributed in various forms: mostly self-consumption at the farm and consumption of industrial compound products, and marginally grains bought by the farmer. We therefore designed a model to estimate these consumptions. Figure 3.1 presents the general principle of the model: we estimate the local livestock consumption of cereals based on the data on livestock and slaughter and on the nutritional needs of the animals. Data source for livestock, slaughter and production figures are shown in table 3.2.2. We estimated the nutritional needs based on zootechny guidebooks (see table 3.2.2) and then scaled them in order to make them consistent with the total cereals animal consumption provided in the national accounts of the ministry of agriculture. Table A.3 in Supplementary Material section A shows the modeled distribution of cereals feed among the main categories of animals before and after this adjustment process: the scaling ratio obtained is moderate (1.13), indicating that the model is probably robust. In order to derive this table, we distinguished about 20 different types of animals and products. Tables A.4, A.5 and A.6 in Supplementary Material section A show the original feed intakes per type of animal or product. Care was taken in order to avoid double-counting: either the lifecycle or the annual approach was used for each product. For instance, we use the lifecycle approach for pigs (meaning we multiply the number of pigs slaughtered during one year by the cereals intake of one pig during its lifespan) and the annual approach for nursing cows (meaning we multiply the livestock at the end of the year by the per capita annual feed intake). Once

local cereal feed consumption is estimated, we split it between compound feed and raw feed thanks to information and hypotheses on the animal feed industry (tables 3.2.2 and 3.2.2).

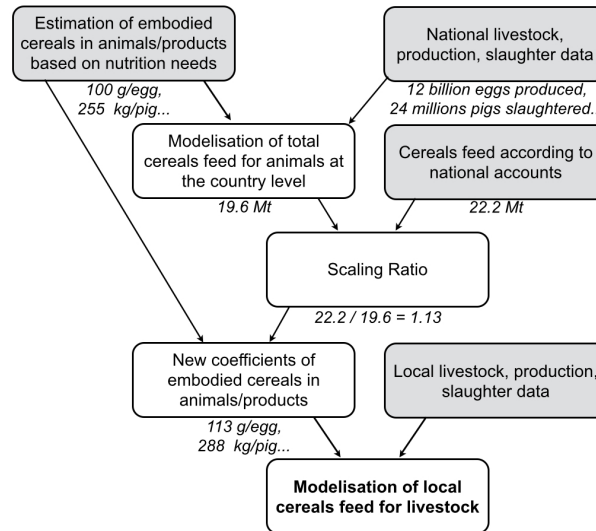


Figure 3.1: Principles of the livestock feed model. Input data is shown in grey.

3.2.2.5 Stocks

Information about stock is partial, notably because of confidentiality issues. Averaging the figures over several years solves this issue since the variations of stock tend to compensate one year after another. For instance, table A.2 in Supplementary Material section A shows that stock variation explains up to 12% of the national apparent consumption in 2003 whereas this number falls to -0.6% over the period average. In this work we therefore study the period 2001-2009.

3.2.2.6 Trade

As shown in table 3.2.2, for the national MFA, we use the imports and exports data of the ministry of agriculture, providing information with detailed product categories directly in weight of grain equivalent. For MFAs at subnational scales, we use the SitraM database, maintained by the French ministry of ecology. We underline 3 main difficulties with this data :

1. We had to design a correspondence table between the transport statistics classification and our own product classification : table A.9 in Supplementary Material section A.
2. Assumptions had to be made regarding the national trade by railway since the classification is not as detailed as for the other modes of transport: we assume that cereals represent 75% of the "Agricultural products and living animals" category. This is the proportion found for international export by railroad in 2005.

3. Theoretically, there is a compatibility issue between data from the customs (international trade) which provides the first origin and final destination of a product and the national data which provides the last loading or unloading of the merchandise. This issue can lead to double counting for regional imports and/or for exports⁸. We partially solved the problem by redistributing the international trade by sea using the market shares of French harbors for cereals exports. This means in particular that sea exports of regions without any harbors were entirely reallocated to regions with harbors. We were not able to do the same for road, river or railway transport. Still, this operation is significant since more than half the French exports of cereals are made by sea: on average, between 2001 and 2009, France exported about 14 Mt of cereals by sea, 6 Mt by road, 5 Mt by river, and 1,5 Mt by railroad. Table A.7 in Supplementary Material section A shows the impact of this operation on the total international exports of every regions.

3.2.2.7 Final consumption

Final consumption of cereal products occurs in two forms: food products (bread, biscuits, pasta...) and industrial products (bioethanol and many products derived from starch). In France, local consumption patterns are not precisely documented, at least not precisely enough to be used in this study. For most of the products, we considered the per capita consumption to be equal all over France. Regarding bread, we used a study depicting the diversity of food consumption patterns in France in the mid 1990's that presents statistical information on the gap between regional and average consumption of bread per household (Babayou et al., 1996). This consumption estimation is not built as an apparent consumption (resulting from the difference between production, stock variation and trade) but on direct households surveys. Table A.8 (supplementary material) presents the adopted regional adjustment factors for per capita bread consumption, reconstructed from this report. For subregional scales, no data was found in the report. Following the conclusions of Babayou et al. (1996), that the urban vs. rural and north vs. south typology was the most suited to explain the variability in the bread consumption patterns (rather than regional cultural differences for instance), we estimated the gap between local and average consumptions based on this typology. Table 3.5 shows the corresponding adjustment factors.

	Urban	Rural
North	-10%	+21%
South	-7%	+25%

Table 3.5: Per capita bread consumption variability among different categories of towns in the mid 1990's in France. The table makes the distinction between cities in the north and in the south of France and between urban and rural cities (cities with less than 2000 inhabitants are considered rural). According to Babayou et al. (1996), this typology is the most suited to explain the differences between bread consumption patterns in France.

⁸For instance, French wheat loaded in the Centre région, transported by road to the Rouen harbor and then exported by sea to Algeria will be counted in the customs statistics as *from the Centre région to Algeria* and in the national transport statistics as *from the Centre région to Rouen*, leading to a double-counting of exports of the Centre région.

According to the national MFA, bread accounts for about 40% of the consumption of cereals for food purposes, and for one third of the total consumption of cereals. This adjustment on local bread consumption is therefore significant.

3.2.2.8 Data uncertainty

Uncertainties on input data

Laner et al. (2014) review existing literature regarding uncertainty handling in MFA and provide recommendations relatively to the goals of each study. Our case study typically falls in the category of descriptive MFA as they describe it and we use an approach similar to the one implemented in software STAN (Cencic and Rechberger, 2008): input data are expressed by a mean and a standard deviation reflecting the level of confidence in the data. As we mentioned in section 3.2.1.3, the weighted least squares optimization leads to higher alteration (difference between output and input data) of variables with higher uncertainties. Since none of the sources used provides detailed information on data uncertainty, this step is based on assumptions and on educated guesses. Following Danius (2002), we treat data differently depending on its origin. Below, we list the different origins from the ones we trust the most to the ones we trust the less:

1. official statistics at local, regional or national scale, based on cross-checking of surveys (some of which are exhaustive) : e.g. agricultural production, employment...
2. statistics based on declarations (and punctual control): e.g. customs, reporting from the supply chains' federations...
3. modeled local data, based on downscaling,
4. extrapolation of statistical surveys on sub-populations

The last one typically applies to road freight statistics which are based on a survey⁹. The estimation of total road freight in the country (all goods combined) is quite accurate (less than 1% of error according to the calculation of the statistical office (SOeS, 2012)), however the extrapolation on subpopulations, meaning on specific goods in specific regions, can be deteriorated a lot because of the small size of the sample. Collaboration with the statistical office is in progress in order to estimate the intervals of confidence on these subpopulations. Generally we consider that small flows have a larger relative error than large ones for data extracted from the same source, but we prevent null flows from having a vanishing standard deviation (this would be unrealistic).

Although the attribution of uncertainty weights is based on objective elements such as the source of the data, this part of the process is not the most robust and the model would benefit from a sensitivity analysis that would show the impact of a change for each input variable. This was however too demanding to accomplish in this paper (this would require to rewrite our Matlab code in a more efficient language such as C for the simulations for the computational time to remain within reasonable bounds).

Uncertainties on output data

Using common terminology in statistics, we can describe our problem as follow: if we call a supply-use table with uncertainties on each parameter a supply-use table distribution (STUD),

⁹This survey is mandatory for all European Union members.

then our goal is to obtain a posterior STUD from our prior STUD. Given the number of constraints we know our result is of much lower dimension than the number of variables and a direct sampling of the posterior STUD is then possible by Monte-Carlo simulations. The intervals of confidence of output variables are thus inferred from these simulations. Numerous input datasets are randomly generated knowing the standard deviation of input data, and assuming a Gaussian distribution (although this is not a requirement). After a while, typically in our case, a few tens of simulations, the process reaches convergence. The confidence intervals represented on the diagrams correspond to two standard deviations (95% of possible values if the actual distributions are indeed gaussian). We analyze the results in section 3.3.

3.2.3 Software integration

We wrote a program to properly integrate our databases, the original SUTs, the optimization and Monte-Carlo processes, and the visualization of results. As table 3.2.3 illustrates, it made it possible to implement a model with a large quantity of variables, simultaneously computing all sub-entities of a given territory. Figure 3.2 presents the software background on the study in relation to figure 3.3 which shows the manual and automatic steps conducted to produce regional results.

Geographical scope	Scale	Number of MFAs (territories) computed	Number of output variables (of which are forced equal to zero)	Execution time
France	France	1	741 (637)	about 10 secs
France	Regions	22	25498 (14428)	about 3 min
Rhône-Alpes	Departements	8	13832 (5582)	about 1 min

Table 3.6: Characteristics of each run of the model. One line corresponds to one run. We first obtain the national MFA, then downscale it to obtain results in every region, and finally downscale the Rhône-Alpes results in every departement of the region. The 741 variables of the first run are decomposed as follow: 361 variables for the supply table (19 products * 18 sectors + 19 variables for international imports) and 380 variables for the use table (19 products * 18 sectors + 19 variables for international exports + 19 variables for consumption). The 25498 variables of the second (regional) simulation are decomposed as follow: 16302 for the "basic" supply and use tables (22 regions * 741 variables), 9196 variables for inter-regional trade. We use sparse matrices for the computation as many variables are null (see constraint 5 in section 3.2.1.3)

3.3 Results and discussion

We use Sankey diagrams to display our results¹⁰. They have long been used in flow studies and are very efficient in wrapping a large quantity of information (Schmidt, 2008). We use the

¹⁰There is a clear link between SUTs and their representation in Sankey diagrams. Products, and activities (industries, imports, exports and consumption) are the nodes of the diagram. The values in the supply table are represented by links going from activity nodes to product nodes and the values in the use table are represented by links going from product nodes to activity nodes. For the purpose of this study we developed a Sankey

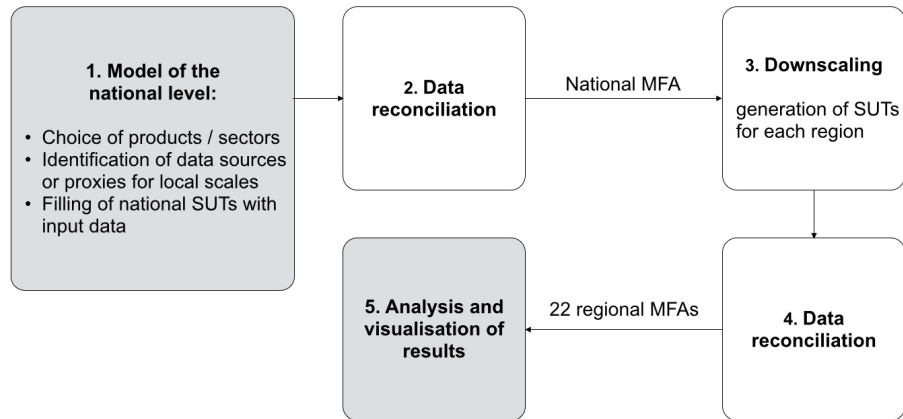
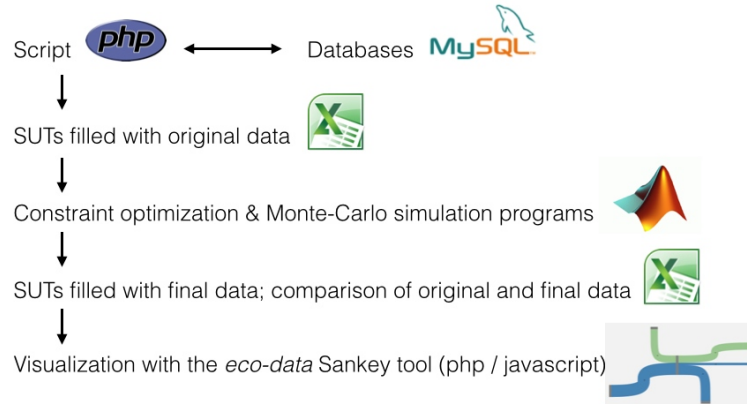


Figure 3.3: Steps taken to produce regional MFAs. Automatized parts are shown in white. SUTs: supply-use tables.

following convention: flows circulating inside the territory are represented by horizontal lines while flows entering or leaving it are represented by vertical lines. Although the core of the paper only shows results under this form, all input and output datasets are available by request to the authors.

3.3.1 Results for France and French regions

We split the national results into two diagrams in order to make them more readable. Figure 3.4 shows the production, imports and exports of cereals as well as the flows related to livestock consumption (raw or compound feed). With a yearly average of 34 Mt of grains produced, common wheat is the most commonly grown cereal in France (53% of the total cereal production) before corn (23%) and barley (16%). This production of about 65 Mt is mainly dedicated to exports (about 27 Mt or 42%). Although the information does not appear on the diagram, about 2/3 of these exports go to European countries and 1/4 to African and middle-east countries, according to customs data. The rest of the production goes to livestock feed (about 22 Mt or 34% evenly divided between raw and compound feed) and other domestic use (about 16 Mt or 25%). Imports are almost negligible (less than 1 Mt)¹¹. Cereals grouped in the *other cereals* category are only used for exports and for livestock, except for rice. Finally, residues of agro-industries play a significant role in the material efficiency of the supply chain: with 4 Mt, they account for about 1/6th of cereals fed to livestock.

software that can be used on http://www.eco-data.fr/tools/sankey/start_en.php

¹¹It can be noted that French livestock depends a lot on imports of soycakes (nearly 5 Mt are imported each year, mostly from Brazil and Argentina) but this is not in the scope of the cereals study.

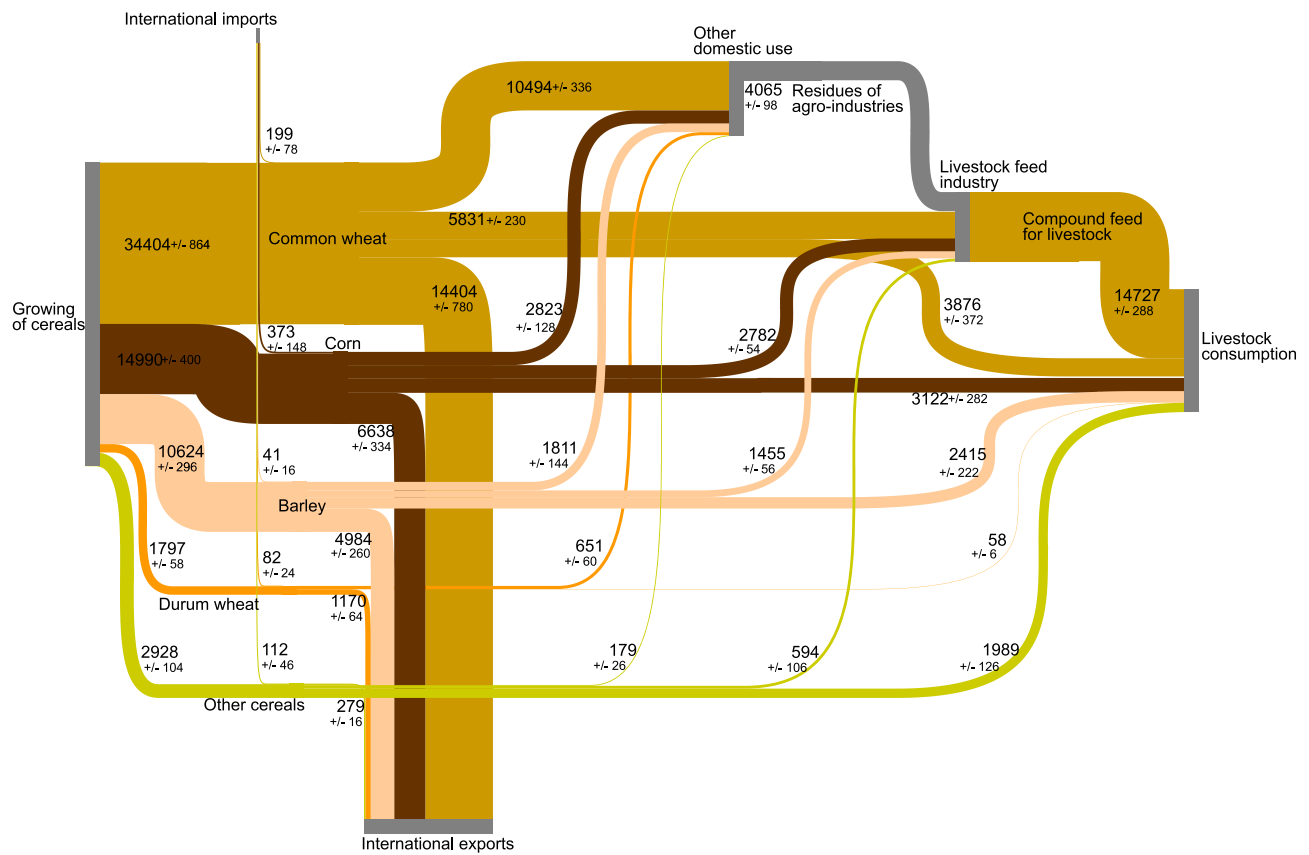


Figure 3.4: Cereals MFA at the scale of France: international trade and animal feed. Results are shown in kilotonnes for an average year over the period 2001-2009.

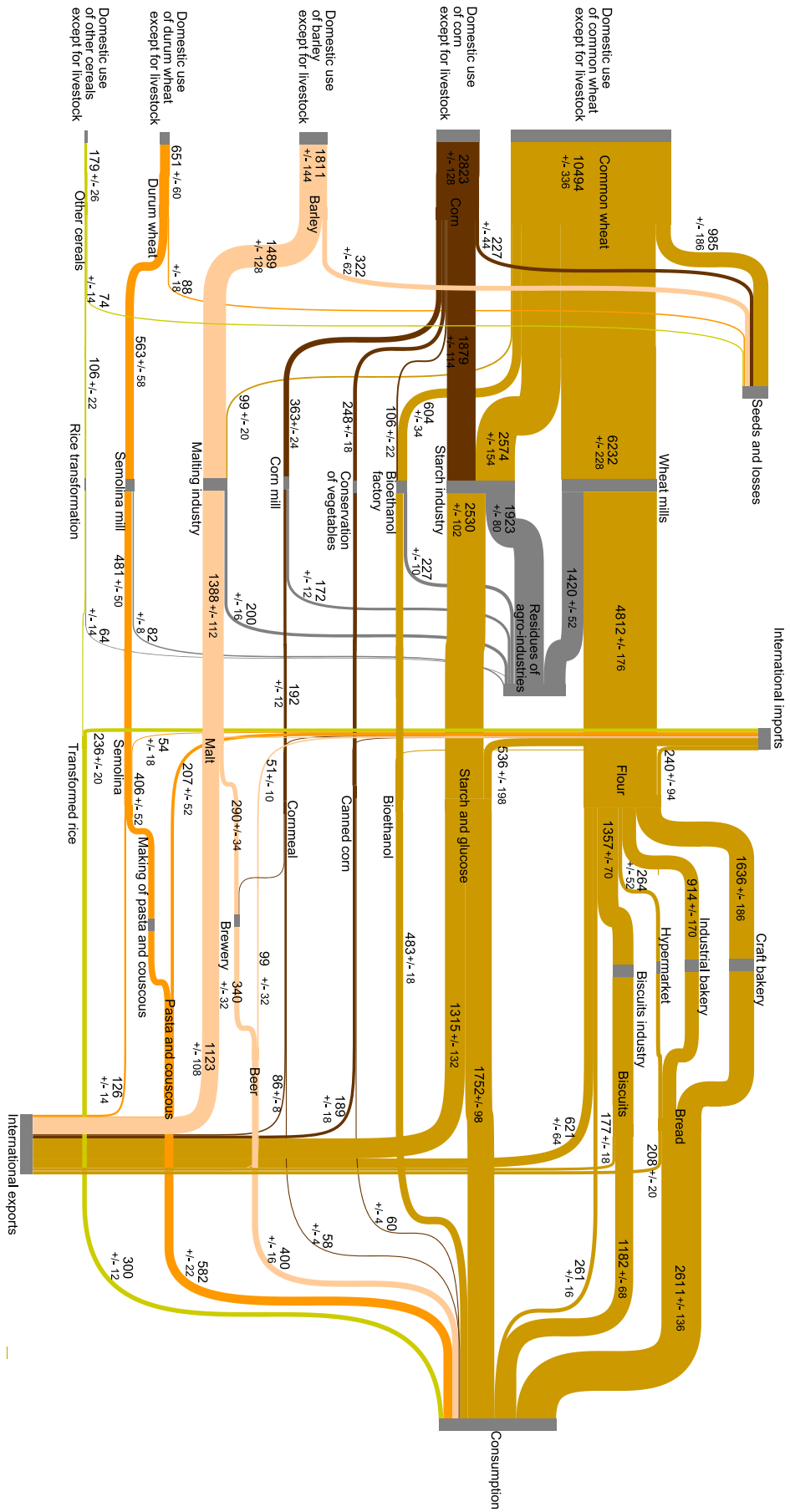


Figure 3.5: Cereals MFA at the scale of France: domestic use. Results are shown in kilotonnes for an average year over the period 2001-2009.

Figure 3.5 shows the domestic use of each cereal along with imports and exports of transformed products, until final human consumption on the territory. Starch and wheat mill industries clearly stand out as the two main supply chains with respectively 6.2 Mt and 4.4 Mt of grain (wheat and corn) processed. They also produce most of the by-products (3.3 Mt or 81% of the residues). Then comes the malting industry with about 1.6 Mt of barley processed. Other supply chains (bioethanol, pasta and couscous, rice, canned corn, cornmeal) are less significant although together, they add up to 2 Mt¹². On the imports side, the main flows correspond to flour, starch and glucose, pasta and rice, adding up to 1.1 Mt or 85% of the total imports of transformed products. On the exports side, the main flows correspond to starch and glucose, malt and flour adding up to 2.9 Mt or 78% of the total exports of transformed products. On the consumption side, the main flow corresponds to bread (with 2.6 Mt or 34%), starch and glucose (with 1.8 Mt or 23%), and biscuits (with 1.2 Mt or 16%). Pasta, beer, rice, bioethanol, flour, canned corn add up to 2.2 Mt. 83% of cereals are consumed through food and drink products and 17% through other industrial products¹³. All these figures provide convenient points of comparison for sub-national geographic levels.

One thousand Monte-Carlo simulations were conducted for the national model. The convergence is very quick: on average, the average standard deviation reaches 95% of its final value after less than 100 simulations. According to the Monte-Carlo process, the range of coefficients of variation goes from 1% to 20%, small flows having a larger relative interval of confidence (i.e. a bigger relative uncertainty) in the general case. The output uncertainty has been reduced compared to the input uncertainty through the enforcement of the constraints, for instance wheat production uncertainty (expressed as the coefficient of variation) goes from 2% in the input to 1% in the output. Finally, we checked that each output value belong to the 95% confidence interval of the input.

Figures A.2, A.3, A.4, A.5 and A.6 in supplementary materials show MFAs of five regions (among the 22 computed) each of which present a specific profile (producing region, livestock region, region with a large transformation activity, exporting region...). Considering the whole dataset, figure 3.6 show the most important flows accross regions. Three types of flows stand out: most of them are linked to international exports, some other to livestock activities in Bretagne and the rest to transformation activities in Nord-Pas-de-Calais. These flows result from the model, they are not the mere visualization of the trade database. Firstly, the model output flows distinguish between products that are otherwise grouped in the trade classification: for instance common and durum wheat as well as residues and livestock feed are initially grouped. Secondly, given their high uncertainty compared to other flows (e.g. production), output inter-regional trade flows sometimes differ significantly from input values: for instance the original database does not mention any export above 500 kt from the Centre region while the map shows 4 flows leaving this region.

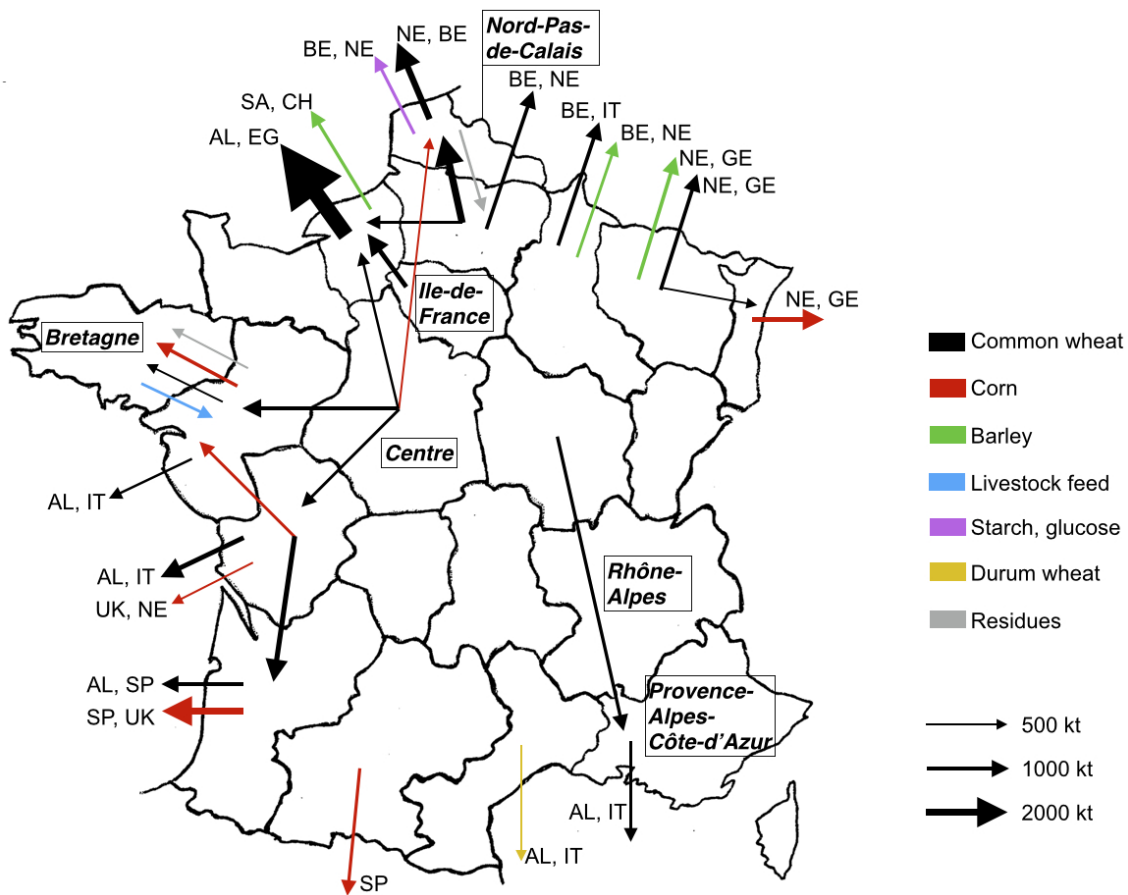


Figure 3.6: Flows of cereals > 500 kt/year (average during the 2001-2009 period). The main two countries of destination are shown for each international export flow. AL: Algeria, BE: Belgium, CH: China, EG: Egypt, GE: Germany, IT: Italy, NE: Netherlands, SA: Saudi Arabia, SP: Spain, UK: United Kingdom.



Figure 3.7: Nested territories under study. From left to right: France, Rhône-Alpes région, Isère département and the territory of the SCoT of Grenoble.

3.3.2 Multi-scale analysis

Territory	Area (km ²)	Population (thousands of inhabitants in 2007)
France (metropolitan area)	547030	61796
Rhône-Alpes region	44749	6066
Isère département	7882	1179
SCoT of Grenoble	3720	714

Table 3.7: Surface and population of the four territories under study.

We show diagrams in an aggregated form in order to make the comparison between geographical scales clearer¹⁴. As indicated in section 3.2.1.4, results at the level of the SCoT (that is, below the level of the département) are not obtained through the usual optimization process and only show net trade. Results for the Isère département are skipped, because they were close to what is observed at the SCoT level, but are available upon request.

¹²Bioethanol production increased a lot from the end of the 2000-2010 decade: in 2013, about 2.2 Mt of cereals were used for this purpose, compared to the 0.5 Mt that appear in our results for the 2001-2009 yearly average.

¹³Following Passion-Céréales (2013), we consider that half of the starch production serves non-food purposes.

¹⁴The graphical scale (i.e. width of line per kt) is different in diagrams 3.8, 3.9 and 3.10 in order to improve the readability of the figures.

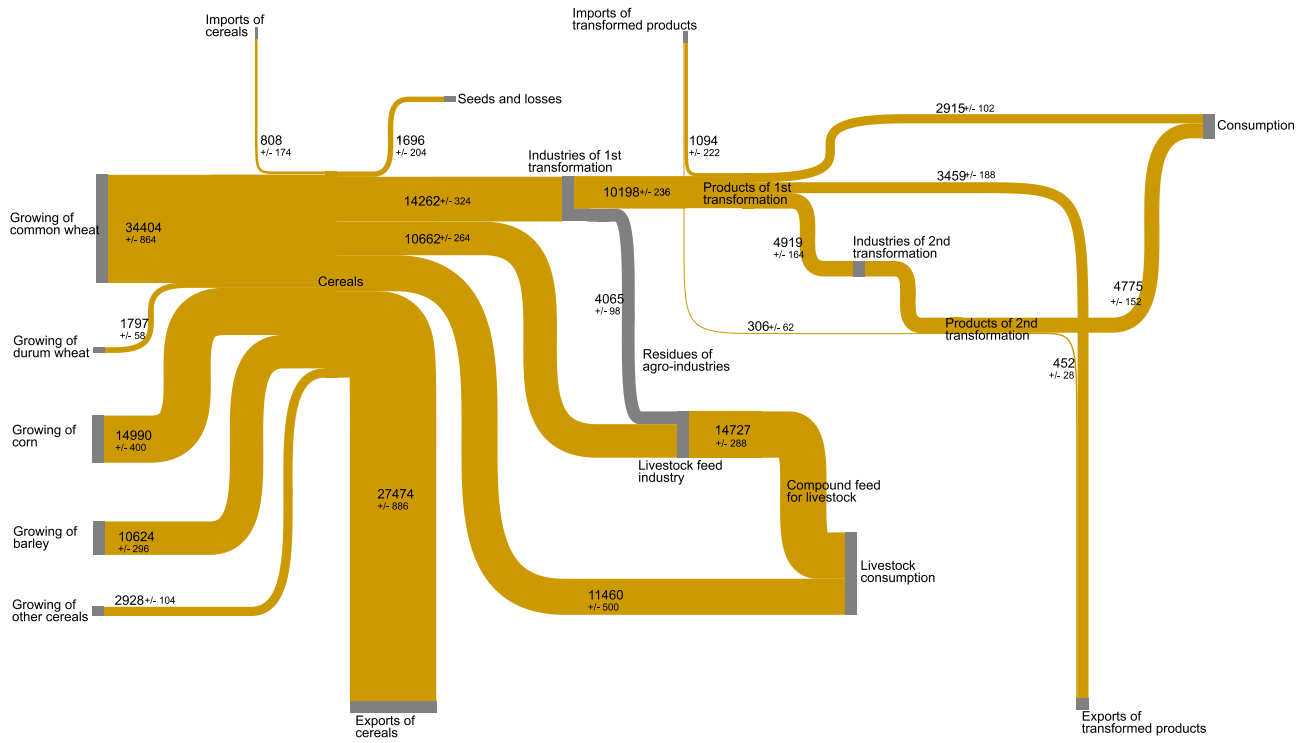


Figure 3.8: Cereals MFA at the scale of France: aggregated results shown in kilotonnes for an average year over the period 2001-2009.

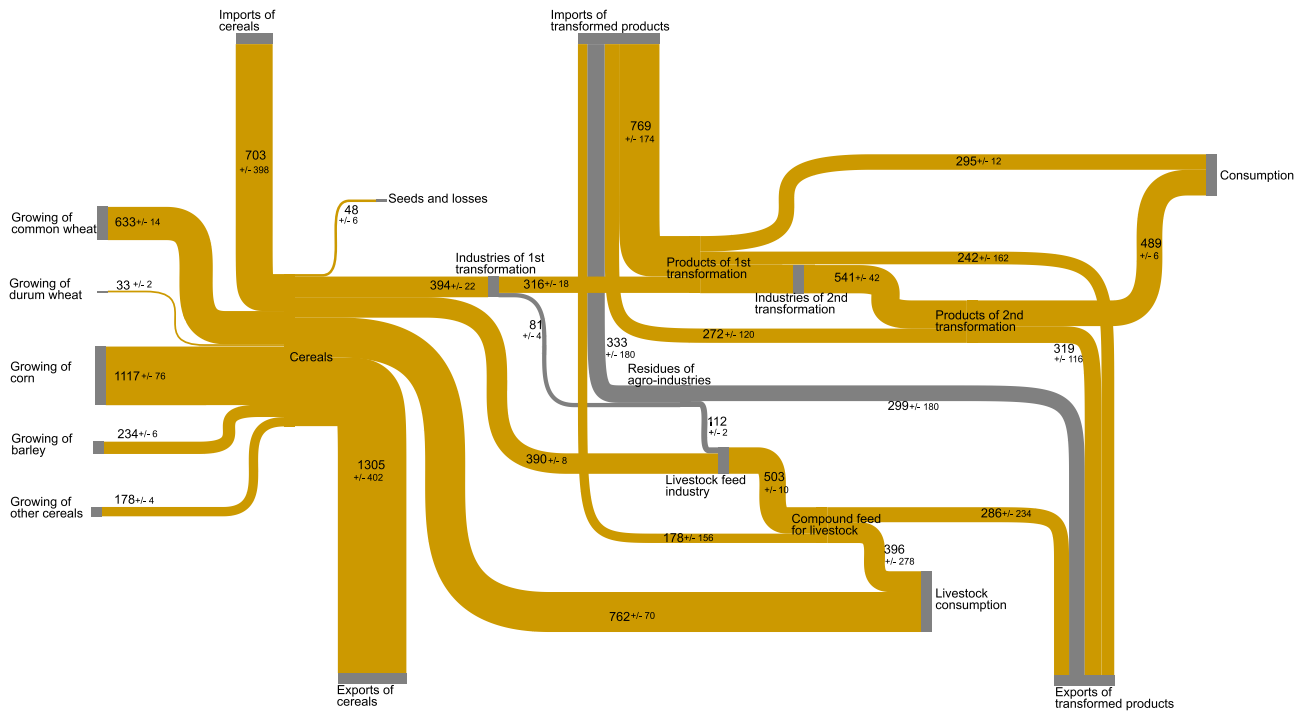


Figure 3.9: Cereals MFA at the scale of the Rhône-Alpes region: aggregated results shown in kilotonnes for an average year over the period 2001-2009.

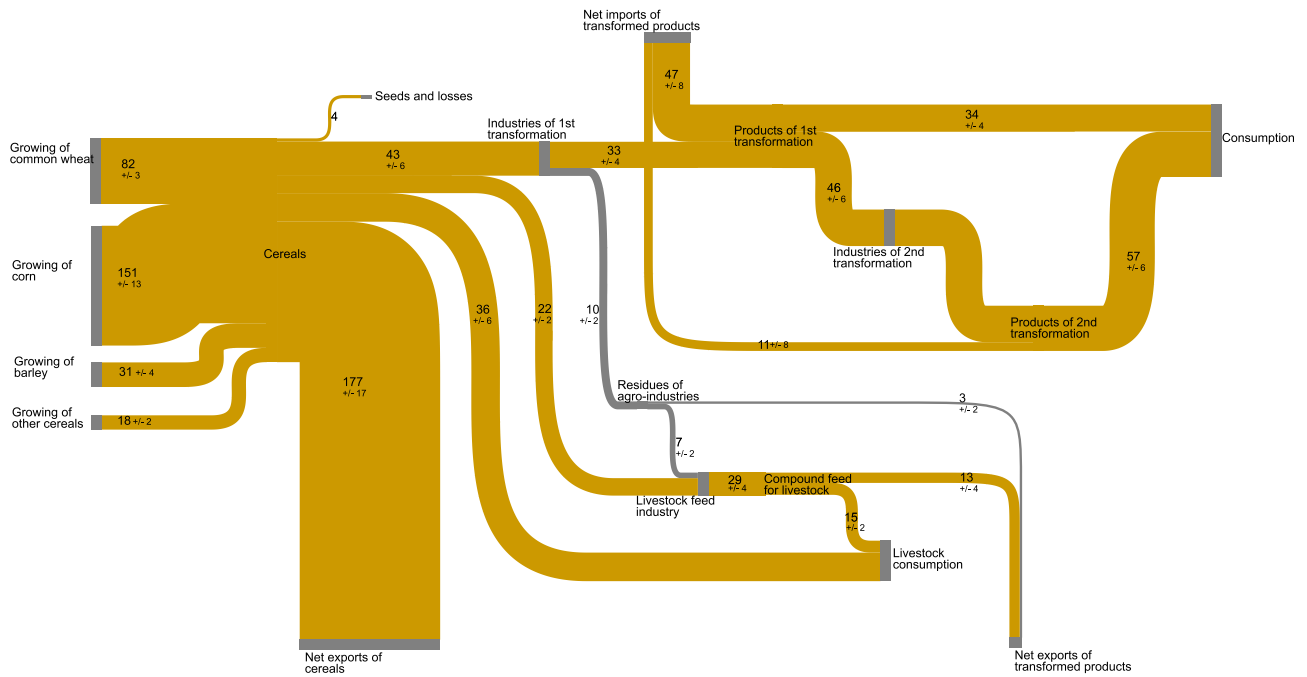


Figure 3.10: Cereals MFA on the territory of the SCoT of Grenoble: aggregated results shown in kilotonnes for an average year over the period 2001-2009.

The comparison of figures 3.8 and 3.9 shows that the supply chain's structure at the level of France and Rhône-Alpes are very different¹⁵. Indeed, unlike France:

- With a yearly average of 1.1 Mt of grains produced, corn is the most commonly grown cereal in Rhône-Alpes (51% of the total cereal production) before common wheat (29%),
- The region is not characterized by a significant net export capacity, human and livestock consumption almost adding up to local production, however, inter-regional trade has a important role in the working of the supply chain. In particular, the region is a net exporter of corn, inter-regional exports being the biggest outlet of the corn supply (with 55%), whereas it is a net importer of common wheat (38% of the supply comes from outside the territory),
- Many industries, such as the starch industry, are not represented in the region, which leads to significant imports of transformed products (in fact, regional industries almost exclusively process common and durum wheat).

One thousand Monte-Carlo simulations were run at the regional level¹⁶. Each flow from one region to another has been computed by the model. We however only show aggregated results because they come with a smaller uncertainty range. As we can see on figure 3.9, uncertainty ranges of trade flows (even aggregated) are usually quite large. For instance the 95% confidence interval of imports of cereals indicates that the flow can reasonably take values from 305 kt to 1101 kt, the most likely being 703 kt. Of course this reflects the choices made for the uncertainty of input data, where region-to-region flows were given a high uncertainty for the reasons discussed in section 3.2.2.8.

If we now turn to the comparison of the Rhône-Alpes and of the SCoT of Grenoble's supply chains, we can see that they share many characteristics. One of the possible explanation is that the territory of the SCoT is a small image of the region itself, since it comprises both mountain and plain areas. Two differences are however worth pointing out: the relative net exports capacity of the SCoT is larger than the region's, and contrarily to what happens in Rhône-Alpes, in the SCoT, human consumption is larger than livestock consumption. Corn is the most commonly grown cereal in the SCoT whereas wheat is the only cereal processed for human consumption purposes. This implies that the territory depends on imports for the supply of many transformed products. This is not necessarily problematic in itself (the smaller the area the less likely it is to be self-sufficient), but we point out that the multi-scale analysis provides information, e.g., on the range of scale this situation can be found.

3.3.3 Potential interest for practical policy-making

The national MFA as well as the study of interregional flows points to the fact that the cereals supply chain is export-oriented. The fact most exported goods are raw materials can raise the question of lost added value and employment on the national territory. Furthermore, being able to compare regions is important for national objectives. For instance, it makes it possible to assess the pros and cons of regional specialization strategies on the three fronts of sustainability (economic, social and environmental).

¹⁵A few elements also come from the detailed results that are not shown here.

¹⁶After only 100 simulations, 96% of the standard deviations are within +/- 20% of their final value.

From another angle, the type of tool described here is potentially helpful for a better integration of the different levels of decisions through the ability to analyze more and more detailed geographical scales. In the case of France, various administrative levels have leverage on some parts of the supply chain, and each one on a different aspect. For instance, local (group of cities) levels can foster or discourage the development of certain type of activities, either through subsidies, public orders (e.g. organic food in schools) or by administrative authorizations. The regional level is often in charge of coordinating local initiatives while the global strategy and objectives are established at the national level. A multi-scale tool can help in identifying more efficiently the most appropriate type and level of decisions for a given objective.

Generally speaking, through the analysis of the most important supply chains present at the various geographic scales (a substantial endeavor in itself) one opens up the possibility of addressing a number of social and environmental issues and of identifying potential lock-ins and/or leverages for a sustainability transition; we briefly mention a few key questions here. What are the critical supply chains in terms of employment for a given territory? What are their weaknesses and opportunities relatively to the territory's resources (in a wide meaning of the word)? What type of environmental impacts are associated to them, and where do they occur (is the territory externalizing major impacts)? Regarding the case of cereals, energy use / emission of greenhouse gases, use of water and use of pesticides are of particular interest. A production map coupled with ecosystem services analyzes¹⁷ will show what are the critical areas/productions, while the supply chain point of view will show how impacts can be shared between producers and consumers. A supply chain perspective may also help decision-makers anticipate climate change impacts (e.g., how a change in cereal production type and pattern affects employment and/or consumption on the territory?) Conversely, how can consumer-driven sustainability demands (local production, for example, or reduction of demand for meat-based products) affect existing supply chains and promote new ones, both in terms of employment and (local and distant) environmental impacts? Addressing a number of these questions will of course require a scenario approach, or at least an analysis of contrasted options.

3.4 Conclusion

Regarding our first objective, that is assessing the feasibility of constructing non-survey MFA at local scales, we argue that the proposed methodology is an efficient investment: efforts are needed to design the initial model (in relation to the downscaling objective) but results are then available almost directly for any territory covered by the data. Moreover, the data reconciliation process provides consistent and comparable results among territories. The method could be adapted in other countries, at least in European countries, providing data sources are adapted. Secondly, we tested our multi-scale model and analyzed its results in the case of the cereals supply chain of four nested territories: France, the Rhône-Alpes région, the Isère département and the SCoT of Grenoble. This example shows that it is possible to identify the key differences in local supply chains and to understand how they are currently articulated. It would be interesting to compare these downscaling results with local surveys: this could inspire future research especially in regions providing detailed supply/use or input-output tables, which is not currently the case in France.

Uncertainties are unavoidable in this kind of studies and it is important to assess them

¹⁷One author is involved in this type of program which critically complements the one undertaken here.

(Rechberger et al., 2014). We tried to do so, although acknowledging that the evaluation itself is still imperfect. In order to improve it, at least three elements would be useful: an iteration with local stakeholders and experts during the design of the model and the choice of data inputs, a better knowledge on the interval of confidence of statistical data used as input (work is for instance under way regarding road freight statistics), and finally, a sensitivity analysis to understand the weight of each input variable in the results of the model.

As underlined in the introduction, we consider MFA as a first step towards a broader analysis of economic, social and environmental aspects of local supply chains. Additional work has to be conducted to reach this goal. For instance, regarding environmental aspects, studying the coupling between material flows and the associated major environmental footprints (energy use, greenhouse gases emissions, water use, use and emission of pollutants...) provides relevant leads for our future investigations of this topic. MFA helps to bridge the geographical gap between producers and consumers and can provide good insights on their shared responsibility.

Calame and Lalucq (2009) argue that subnational territories and supply chains are the two key players for organizing a sustainable society in the 21st century thus replacing the the couple state - company, which played a pivotal role in the 20th century, but which they find ill-suited to face the new challenges of sustainability). In their opinion, they could organize both territorial coherence (from city to regional scale) and production chains. There are several underlying ideas to these statements. Firstly, by insisting on supply chains rather than on the companies, one brings the collaborative aspect of exchanges to the forefront to balance the competitive aspects of free markets. Secondly, the focus on territories is driven by the necessity of building on local strengths to balance local weaknesses in the undertaking of a sustainability transition. Finally, local/regional levels are more reactive, and closer to actual social needs and environmental threats, although of course a multiplicity of approaches targeted at the whole spectrum of decision scales is needed to address sustainability issues.

The present MFA study is one of the tools that can be used to foster such a view, as it has the potential to meet decision-makers concerns by providing key information on local supply chains viewed from the economic (creation of wealth), social (local employment) and environmental (flows of environmental pressures from producers to consumers) perspectives. In a time when the fragility of the complex globalized system makes it mandatory for all to strengthen their capacity of absorbing exogenous shocks, the development of such tools at the service of subnational institutions is a necessity.

Acknowledgments: This research has been funded by grants from Inria and Artelia Eau & Environnement.

Uncertainties of domestic road freight statistics: insights for regional material flow studies

Courtonne, J.-Y., Longaretti, P.-Y., Dupré, D. Uncertainties of domestic road freight surveys: insights for regional material flow studies. Submitted for review.

Abstract

Because they depict the physical inter-dependencies of territories and allow to link worldwide productions and consumptions, freight statistics are at the core of many studies in the field of industrial ecology. Recent studies have been increasingly focusing on subnational scales, often relying on domestic freight data. In this perspective, this article analyses the uncertainties of the French domestic road freight survey, road being by far the most common mode of transport in the country. Based on a statistical analysis of the survey, we propose a model to estimate the uncertainty of any given flow . We also assess uncertainty reduction when averaging the flows over several years, and obtain for instance a 30% reduction for a 3-year average. We then study the impact of the uncertainties on regional material flow studies such as the Economy-Wide Material Flow Analysis of the Bourgogne region. Overall the case studies advocate for a systematic assessment of freight uncertainties, as neither the disaggregation level nor the quantities traded are good enough predictors. This justifies the need for an easy-to-implement estimation model. Finally, basic comparison with the German and Swedish surveys tend to indicate that the main conclusions presented in this article are likely to be valid in other European countries.

4.1 Introduction

Material flow analysis (MFA) is a systematic assessment tool used to assess the flows and stocks of a system during a period of time. Either focusing on specific substances or on the whole economy, it has been widely applied to countries and more recently to subnational scales (Binder et al., 2004; Kovanda et al., 2009; Niza et al., 2009). Regarding these studies, Rechberger et al. (2014) raise two key questions: “*What level of precision do we achieve, and what level of precision do we require?*” These questions can be related to the remarks of Binder et al. (2009) regarding the lack of implementation of MFA in policy making: indeed, if the precision of results is not properly analyzed, the reliability of the studies may be questioned. On the

contrary, analyzing uncertainties helps preventing premature conclusions and points to the main lacks of information. For instance, it would not make sense to try to explain a 10% difference on the per-capita consumption of two regions if it can be explained by an overlapping of confidence intervals. Laner et al. (2014) review the existing MFA literature and propose a classification of uncertainty management methods into three types of approaches: qualitative and semi-quantitative approaches (e.g., Graedel et al. 2004), approaches based on data quality classification (e.g., Weidema and Wesnæs 1996; Hedbrant and Sörme 2001; Danius 2002) and statistical approaches (e.g., Cencic and Rechberger 2008; Dubois et al. 2014). They insist on the distinction between “random” uncertainty (that cannot be reduced) and “epistemic” uncertainty (that is due to a lack of knowledge). Patricio et al. (2015) provide uncertainty quantifications of Economy-Wide Material Flow Analysis (EW-MFA) for different spatial levels in Sweden: national, regional and urban levels¹. Uncertainties of input data are estimated based on available statistical information, expert judgment and empirical estimates to account for imputation errors, for instance when a proxy is used. Domestic transport is identified as a major source of uncertainty when tackling regional and urban levels. Generally speaking, they underline that the lack of direct information implies larger uncertainties as the spatial resolution increases. They also insist on the fact that evaluating uncertainties is more common in Substance Flow Analysis (SFA) studies than in EW-MFA where they are generally treated qualitatively.

In France, the statistical service of the ministry of ecology (SOeS) compiles information from various sources to provide centralized data updated every year on both international and domestic freight (Sitram database). As about 85% of merchandises transported between French regions travel by road, a specific survey, called the TRM² survey, is dedicated to domestic road freight. It consists of a poll on French trucks (more details are provided in the methods section). Uncertainties being inherent to polls, the SOeS assesses every year the precision of the survey for the total aggregated result, that is, whatever the good transported and whatever the regions of loading and unloading. For instance, the 2010 quality assessment indicates a precision of about 1.5% on a total of about 2 Gt, which can be interpreted as: *there is a 95% chance for the real value to belong to an interval between 1970 Mt and 2030 Mt*. Until now, however, uncertainties have never been estimated for disaggregated flows whereas these information are becoming more and more used. For instance, among the 22 French regions³, 4 have already undertaken an EW-MFA and several other are launching studies. Typically, domestic freight data can be obtained by NST 2007 positions (382 categories) up to the NUTS 3 levels (96 French départements) for loading and unloading. Extrapolations for each flow are provided along with the number of observations they are based on (see the glossary next section for a proper definition). The SOeS warns that results based on less than 10 observations shouldn't be used because they are probably not significant. This article is aiming at a more precise assessment of the uncertainties. Especially, we try to:

- Check whether or not our results lead to a similar threshold of 10 observations,
- Quantify uncertainties above this threshold.

¹Note that the uncertainties reported in their article correspond to one standard deviation (68% confidence interval), whereas here we chose to express them as two standard deviations (95% confidence interval).

²*Enquête permanente sur le Transport Routier de Marchandises*: permanent survey on road freight.

³Note that since January 1st 2016, metropolitan France is divided into 14 regions.

We believe this information can directly benefit ongoing and future MFA studies in France, and also foster research on similar topics in other countries, especially in Europe. Indeed, following the Council Regulation No 1172/98 on statistics on the carriage of goods by road, EU countries as well as candidate countries must carry surveys on road freight similar to the TRM survey. If uncertainty calculation seems to be a common practice in some countries (as Sweden and Germany as we show in the case studies), it may not be the case everywhere and it is especially unlikely for uncertainties to be available for any possible aggregation level of the flows. Moreover, to our knowledge, the question of uncertainty reduction through a multi-year average MFA has not been fully explored yet, while in some cases providing more accurate results for a 3-year average (for instance) may be more relevant than providing less precise annual results.

The article is structured into three sections. Data sources and methods are depicted in a first section. A second section is dedicated to theoretical results, and provides formulae to compute uncertainties for a single year and for a multi-year average. Because the precision required of course depends on the problem, case studies ranging from EW-MFA to MFA focusing on specific products are presented in a third section. This last section also includes a basic comparison of the French, Swedish and German surveys. Finally, a summary of the main findings and perspectives for future research are proposed in the conclusion.

4.2 Materials and methods

4.2.1 Glossary

For the sake of clarity, we provide definitions of the following terms that are used throughout the article:

- *Population.* All vehicles-weeks in France (typically 52 times the number of vehicles). The population total size is N (a quantity that varies from year to year), and elements of this population are denoted i ($1 \leq i \leq N$). Vehicles-weeks are elements obtained by considering that each vehicle provides an independent elementary unit each week of the year. An element is therefore one vehicle surveyed for a single week.
- *Subpopulation.* Vehicles-weeks that meet specific criteria for at least one of their travels: specific loading area, specific unloading area and specific type of merchandise transported. We are interested in well-defined subpopulations, identified by a given origin (o), destination (d) and category of goods (c) transported. These subpopulations are symbolically represented by an index δ_i^c , taking two values: $\delta_i^c = 1$ if i belongs to the desired $c = (o, d, c)$ subpopulation, and $\delta_i^c = 0$ otherwise.
- *Sample.* Vehicles-weeks surveyed. A sample is noted s and is a collection of elements of the population, usually of predetermined size S . The number of times a given element i is represented in a sample is noted S_i . For a sampling method without replacement (as is the case for the TRM survey), $S_i = 0$ or 1 .
- *Subsample.* Subpopulation restricted to a sample; subsample sizes are denoted n . Note that the selection of a subsample is a post-selection procedure once the sample is drawn, and not a subsequent resampling of the sample. This definition does not conform with the conventional use of the word.

- *Number of observations.* Number of elementary operations of loading/unloading meeting specific criteria (specific loading/unloading/good); a single vehicle-week can report several observations of the same good between the same loading and unloading places.
- *Characteristic quantity.* Any quantity of interest on the total population, for example the total quantity transported per year (tonnes) corresponding to specific criteria (loading-unloading-good). Quantities of interest are denoted y in a generic way. The most important quantity one tries to estimate through survey sampling is the total of a quantity of interest on the whole population

$$T = \sum_{i=1}^N y'_i, \quad (4.1)$$

where $y'_i = N_w y_i$ and $N_w = 52$ is the number of weeks of the annual survey. The number of weeks scaling is due to the fact that elements are vehicles-weeks and not vehicles-year (see the *Supplementary material* first section for more details). In the probabilistic description adopted here, y_i are parameters, not random variables.

For a subpopulation, the associated total is

$$T^c = \sum_{i \in c} y'_i = \sum_{i=1}^N \delta_i^c y'_i. \quad (4.2)$$

- *Inclusion probability.* The inclusion probability π_i relates to element i and defines its probability of being present in the sample. By construction the probability of absence is $\bar{\pi}_i = 1 - \pi_i$. Unequal probability sampling methods are characterized by the fact the π_i is not constant (not independent of i); it is the form of sampling adopted in the TRM survey.
- *Coefficient of variation.* Also known as relative standard deviation, it is a measure of dispersion equal to the ratio of the standard deviation sigma (σ) to the mean mu (μ).
- *Uncertainty.* In this article, only uncertainties due to the sampling methodology are taken into account⁴. They are provided in the form of 95% confidence intervals, that is nearly twice (1.96) the coefficient of variation, given an hypothesis of Gaussian distribution. We therefore use the notation $\mu \pm 2\sigma/\mu$ (expressed in %). Uncertainties above 100% mean the extrapolation (μ) is not significant and shouldn't be used.
- *Extrapolation.* procedure allowing us to estimate the quantities of interest in the whole population from a sample.

4.2.2 Description of the methodology of the TRM survey

The TRM survey focuses on motor vehicles registered in France, less than 15 years old, belonging to one of the two following categories: lorries of loading capacity (LC) higher than 3.5 tonnes and road tractors of maximum permissible laden weight (MPLW) above 5 tonnes.

⁴This excludes for instance mistakes in the answers from truck drivers, possible errors during the treatment of the forms or bias due to the handling of nonresponse. These sources of error are quite difficult to quantify. Nonresponse is handled by a simple correction factor.

The design experiment is constructed with an unequal probability sampling method, taking advantage of known contextual information about the vehicles. The unequal drawing probabilities are defined based on three factors: the age of the vehicle, the loading capacity of the vehicle and the activity of the owner. The goal is to draw more "young" vehicles and vehicles which have a high loading capacity because they have a higher contribution in the total tonnes and tonnes-kilometers transported. Half of the sample is renewed every year in order to make the year-to-year evolution more reliable.

Once the answers are collected, sampling weights are corrected for non-response and improved by a calibration procedure (CALMAR method), aiming at reconciling data estimated from the survey with otherwise known totals, for instance the number of trucks registered in each region, the number of trucks of each type etc. More information about this procedure can be found in CGDD-SOeS (2011).

The owners (or users) of the vehicles drawn for the survey are asked about the use of the vehicle during one week (the answer is mandatory). The unit of the survey is therefore the vehicle-week.

In 2010, the survey had the following characteristics (CGDD-SOeS, 2011):

- population size: 527,403
- sample size: 77,921
- number of usable forms: 49,933
- sampling rate: (sample size / population size) \times 1/52 weeks = 0.28%

4.2.3 Formulae for totals and associated uncertainty estimation

We only collect here the relevant expressions for total estimators and their variance. Some details about these expressions and their justification is provided in the first section of this paper's *Supplementary material*.

The extrapolation of the annual characteristic totals is performed with the help of the Horvitz-Thomson (HT) estimator:

$$\hat{T} = \sum_{i \in s} \frac{y'_i}{\pi_i}, \quad (4.3)$$

The HT estimator variance can itself be estimated by

$$\hat{V}_s(\hat{T}) = \sum_{i \in s} (1 - \pi_i) \left(\frac{y'_i}{\pi_i} - \frac{\sum_{k \in s} (1 - \pi_k) y'_k / \pi_k}{\sum_{k \in s} (1 - \pi_k)} \right)^2. \quad (4.4)$$

For a subpopulation c , the HT estimator can be expressed as

$$\hat{T}^c = \sum_{i \in s} \frac{y'_i \delta_i^c}{\pi_i}, \quad (4.5)$$

with the associated variance estimator

$$\hat{V}_s(\hat{T}^c) = \sum_{i \in s} (1 - \pi_i) \left(\frac{y'_i \delta_i^c}{\pi_i} - \frac{\sum_{k \in s} (1 - \pi_k) y'_k \delta_k^c / \pi_k}{\sum_{k \in s} (1 - \pi_k)} \right)^2 \quad (4.6)$$

The 95% confidence limit is readily obtained from the variance of the estimator under a Gaussian distribution assumption⁵

$$\hat{e}_{95\%} = 2 \frac{\sqrt{\widehat{V}_s(\widehat{T})}}{\widehat{T}}. \quad (4.7)$$

4.2.4 Data processing

The study is based on data from the French road freight surveys from 2002 to 2010; the data have been made anonymous for confidentiality purposes. For each truck of the samples, the following three types of information are given:

- targeted information: location of loading, location of unloading, category of good transported, reported tonnes, reported tonnes-kilometers,
- sampling information: statistical weight of each truck,
- contextual information (used for the sampling): age of the vehicle, type of vehicle, activity of the transporter, region of registration.

From this disaggregated information, we recreated all existing combinations of aggregation levels, distinguishing between:

- 3 levels of loading: 1 country (nuts 1), 22 régions (nuts 2), 96 départements (nuts 3),
- 3 levels of unloading (same),
- 3 levels of product category: all goods, 10 groups of goods (NSTR between 2002 and 2008) / 20 groups of goods (NST 2007 between 2009 and 2010), 176 detailed goods (NSTR between 2002 and 2008) / 382 detailed goods (NST 2007 between 2009 and 2010).

An illustration of such combinations is provided in the accompanying *Supplementary Material* file. We computed confidence intervals for each extrapolation (about 900,000 extrapolations in total for the period 2002-2010) with a C++ program implementing Eq. (4.7).

4.3 Theoretical results

4.3.1 Estimating uncertainties based on subsample sizes

We built a file based on the surveys from 2002 to 2010 containing the following fields for each extrapolation:

- n : size of the subsample used for the extrapolation (see *subsample* in the glossary),
- e : 95% error (see *uncertainty* in the glossary), computed from Eq. (4.7).

⁵The service producing the survey also uses a 95% confidence interval to compute the uncertainty on the total (all flows aggregated).

Extrapolations were first sorted out in 15 classes depending on the size of the subsample they are based on. 5%, 50% and 95% quantiles of uncertainties were then computed for each class⁶.

Power law fits to the data are proposed in figure 4.1. Applying these models, table 4.1 provides the values for lower, median and upper uncertainty estimations for different values of subsample sizes. The R^2 of the median model, that is the proportion of variability it explains, is equal to 0.87, which is satisfactory. We conducted similar studies for two other predictor variables, that are available in the supplementary material. First, we took the number of observations (see glossary) as predictor variable, since it is currently the default variable provided by the French statistical office. The derived model has an R^2 of 0.77, which is still acceptable but indicates that the size of the subsample is a better predictor and should be preferred when available. Finally, we tested the hypothesis "*the higher the quantity transported the smaller the uncertainty*", using the number of tonnes transported as the explicative variable. This last model is the least efficient, with an R^2 of only 0.63⁷.

Subsample size	Uncertainty (%)		
	Lower bound	Median	Upper bound
5	75	92	136
10	57	73	110
15	49	64	98
20	44	58	90
50	31	43	68
100	24	34	56
150	21	30	49
200	19	27	45
500	13	20	34
1000	10	16	24
2000	8	13	16
5000	5	7	9
10000	3	4	6
20000	2	3	4

Table 4.1: Lower, median and upper uncertainties estimations for given subsample sizes (rows). We see that below a size of 15 vehicles-week, there is risk for the statistic not to be significant (above 100% of uncertainties), although it can be significant in some cases. Above 150 vehicles-week, there is a 95% chance that the uncertainty is lower than 50%, the median estimation being 30%.

⁶The combinatorial effect implies that the vast majority of the studied extrapolations have small subsample sizes. Therefore data has to be organized into subsample size classes to prevent a ponderation bias during the analysis. More details are available in the *Supplementary Material* file.

⁷All the R^2 indexes are computed with the formula $R^2 = 1 - SS_{residuals}/SS_{total}$.

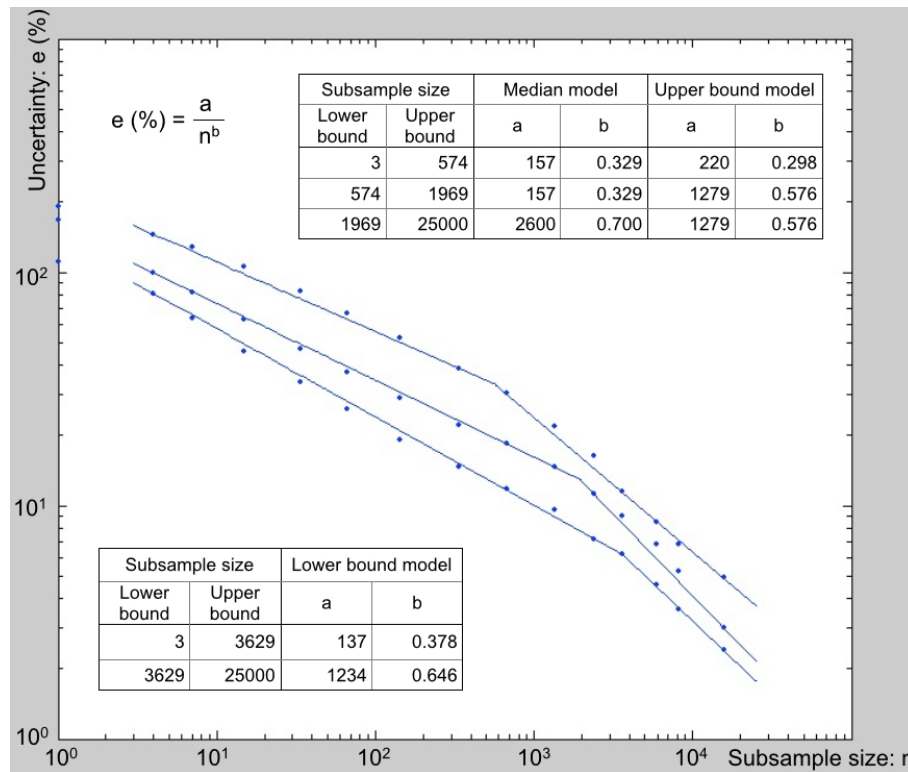


Figure 4.1: Piecewise models for estimating lower bound, median and upper bound uncertainties based on the size of the subsamples (NB: this is a log-log plot). Extrapolations were classified in size classes as explained in the text: each class is represented by three dots (aligned vertically). Lower dots correspond to 5% percentiles, middle dots to medians and upper dots to 95% percentiles. Explanatory models were calibrated in order to properly fit the dots. The piecewise models $e(\%) = a/n^b$ are drawn in blue lines and the parameters are provided in the two tables. The R^2 of the median model is 0.87. It is interesting to notice that for the three models, the slope increases when the size of the subsample reaches a threshold: upper bounds are the first to decrease, followed by median (for nearly 2000 individuals) and lower bounds.

4.3.2 Estimating the reduction of uncertainty when averaging over several years

Let T_i be the estimation of tonnes transported for a given subsample (given loading and unloading locations, and transported product) during the year α . The average over several years n_y is:

$$\bar{T} = \frac{1}{n_y} \sum_{\alpha} T_{\alpha}. \quad (4.8)$$

Assuming T_{α} are independent variables, we would have:

$$V(\bar{T}) = \sum_{\alpha} V\left(\frac{T_{\alpha}}{n_y}\right) = \frac{1}{n_y} \frac{\sum_{\alpha} V(T_{\alpha})}{n_y} = \frac{1}{n_y} \bar{V}(T), \quad (4.9)$$

where $\bar{V}(T)$ is the mean of the $V(T_{\alpha})$ over n_y years. Then:

$$\sigma(\bar{T}) = \left(\frac{\bar{V}(T)}{n_y}\right)^{1/2}, \quad (4.10)$$

and the associated error (twice the coefficient of variation):

$$e = 2 \frac{\sigma(\bar{T})}{\bar{T}} = \frac{2}{\bar{T}} \left(\frac{\bar{V}(T)}{n_y}\right)^{1/2}. \quad (4.11)$$

In reality one cannot assume that the annual totals T_{α} are independent variables because every year, half of the sample is reconducted. To recover statistical independence, we chose to build alternative independent samples by removing redundant vehicles-weeks. If we call p the size of a full sample for one year and consider that this size is stable over the n_y years considered, we see that the full sample over n_y years will have a size of $n_y p$ while any independent sample over n_y years will have a size of $p + (n_y - 1)p/2$ (see the table 3 of the *Supplementary Material* file and its accompanying comment).

This argument suggests to substitute $[p + (n_y - 1)p/2]/p$ to n_y in the last expression of Eq. (4.11), leading to the following predictor for the error e :

$$e = \frac{2}{\sqrt{1 + (n_y - 1)/2}} \frac{\sqrt{\sum_{\alpha} V(T_{\alpha})/n_y}}{\sum_{\alpha} T_{\alpha}/n_y}. \quad (4.12)$$

This relation is plotted on figure 7 of the *Supplementary Material* for an average over 3 years, where the uncertainty e is represented as a function of $x = 2\sqrt{\bar{V}(T)}/\bar{T}$ with $\bar{V}(T) = \sum_{\alpha} V(T_{\alpha})/n_y$ and $\bar{T} = \sum_{\alpha} T_{\alpha}/n_y$. The linear behavior holds with good accuracy, with the correct slope predicted by Eq. (4.12). To obtain this plot, we sorted out observations depending on the value of the predictor and in each class and computed the median of the uncertainties obtained by applying Eq. (4.6) to the independent sample.

The results displayed in table 4.2 allow us to validate this model over all the possible number of years one could use for this averaging procedure. To construct this table, we have constructed the samples as explained above for each averaging option, and compared a fitted slope with the predicted one; the difference between the two is clearly negligible for all practical purposes. Theoretically, the uncertainty of the average could still be lowered because the part of the sample removed is not 100% correlated with the part kept. However, it is not possible to know the level of correlation between these sample parts, so that we advise to break the sample over several years as explained in this section and use Eq. (4.12) as a basic predictor.

Average over n_y years	Observed slope (fitted model)	Suggested model $1/\sqrt{1 + (n_y - 1)/2}$	R^2 of the fitted model	R^2 of the suggested model
n=2 (2006-2007)	0.82	0.82	0.97	0.97
n=3 (2005-2007)	0.70	0.71	0.98	0.97
n=4 (2004-2007)	0.60	0.63	0.98	0.96
n=5 (2003-2007)	0.55	0.58	0.98	0.96
n=6 (2002-2007)	0.52	0.53	0.98	0.97

Table 4.2: Fitted slopes versus modeled slopes in a $e = slope \times 2\bar{V}(T)/T$ model. The R^2 index of the fitted model shows that $[\bar{V}(T)]^{1/2}/T$ is a very good predictor of the error. The suggested model produces slopes very close to that of the fitted model and its R^2 index stays very high. Note that the value $1 - slope$ can be interpreted as the reduction of uncertainty obtained thanks to the averaging operation (e.g. for a 3 year-average, we can expect a reduction of uncertainty of about 30%).

4.4 Case studies

4.4.1 Implications for regional EW-MFA: the case of the Bourgogne region

The methodology for Economy-Wide Material Flow Analysis was standardised by Eurostat (2001). Its objective is to quantify the physical inputs into an economic system, material accumulation in this system and outputs to other economies or back to nature, as illustrated by table 4.3. This table shows the material balance of the Bourgogne region as computed by Alterre-Bourgogne (2013).

We only consider the uncertainties of road freight statistics and we use Gauss's law of propagation to capture their impact on EW-MFA results. Of course this requires the use of a correspondence table between freight and EW-MFA classifications: we use the table provided by the French official guide for regional EW-MFA (CGDD, 2014).

Regional (Eurostat nuts 2 level) results are presented in table 4.3. We can see that at this level road freight uncertainties are very low for total imports and exports (about 5%) and low to moderate when we start disaggregating by product categories (between 5% and 21%). Also note that with 95% intervals of confidence of respectively 2.5% and 6% DMI (Domestic Material Input) and DMC (Domestic Material Consumption) indices seem robust to road freight uncertainties, although DMC is more subject to variations. This conclusion is confirmed by the results for the four départements of Bourgogne (nuts 3 levels) displayed in table 4.4: while DMI uncertainties vary between 5% and 8%, DMC uncertainties vary between 12% and 21%. At this geographical level, DMCs should therefore be compared with great care and intervals of confidence should be given. This higher sensitivity of the DMC index to input data uncertainties was already underlined in Patricio et al. (2015).

4.4.2 The *disaggregation effect*: a focus on agro-products and wheat

In this section, we show the results for two categories of products: all products from agriculture, forestry and fishery on the one hand and wheat on the other hand (in the NST 2007 classification

Flow type	Flow	Value (Mt)	Uncertainty
Inputs (Mt)	Balancing inputs	15.8	
	Domestic extraction (unused)	20.1	
	Domestic extraction (used)	27.8	
	Imports	27.1	+/- 5%
	products from agriculture and fisheries	5.4	+/- 11%
	products from sylviculture	1.4	+/- 16%
	metallic minerals and derived products	2.4	+/- 5%
	non metallic minerals and derived products	4.9	+/- 21%
	fossil fuels and derived products	3.8	+/- 7%
	other products	9.2	+/- 7%
	Indirect flows associated to imports	131.4	
System (Mt)	Net addition to stock	11.0	
	Recycling	4.0 to 5.5	
Outputs (Mt)	Balancing outputs	15.1	
	Domestic extraction (unused)	20.1	
	To air	11.2	
	To nature (others)	6.6	
	Exports	26.8	+/- 4%
	products from agriculture and fisheries	8.0	+/- 7%
	products from sylviculture	1.6	+/- 16%
	metallic minerals and derived products	2.1	+/- 17%
	non metallic minerals and derived products	5.4	+/- 11%
	fossil fuels and derived products	0.8	+/- 13%
other products	8.8	+/- 7%	
	Indirect flows associated to exports	120.6	
Indicators	DMI	33.5 t/cap	+/- 2.5%
	DMC	17 t/cap	+/- 6%

Table 4.3: Economy-Wide Material Flow Analysis of the Bourgogne region (Alterre Bourgogne, 2013). Uncertainties of trade flows (95% interval of confidence) are computed by the authors.

Flow type	Flow	Côte d’Or	Nièvre	Saône et Loire	Yonne
Inputs (Mt)	Balancing inputs	4.5	2.5	6	2.8
	Domestic extraction (un-used)	7.1	3.1	4.4	5.5
	Domestic extraction (used)	7.8	5.9	7.8	6.3
	Imports	9.4 +/- 6%	3.8 +/- 17%	12.8 +/- 9%	6.5 +/- 14%
System (Mt)	Net addition to stock	2.5	1.8	4.0	2.7
Outputs (Mt)	Balancing outputs	3.2	3.1	6.3	2.5
	Domestic extraction (un-used)	7.1	3.1	4.4	5.5
	To nature	5.3	2.6	6.3	3.5
	Exports	10.7 +/- 8%	4.6 +/- 18%	10.0 +/- 7%	7.0 +/- 10%
Indicators	DMI	33 t/cap +/- 5%	44 t/cap +/- 8%	37 t/cap +/- 7%	37 t/cap +/- 8%
	DMC	12 t/cap +/- 15%	23 t/cap +/- 21%	19 t/cap +/- 12%	17 t/cap +/- 20%

Table 4.4: Economy-Wide Material Flow Analysis of the départements (nuts 3 levels) of Bourgogne (Alterre Bourgogne, 2013). Uncertainties (95% interval of confidence) of trade flows and of the indicators are computed by the authors.

these correspond respectively to the codes 01 and 0111). In addition, we distinguish between three levels of spatial disaggregation: total domestic road freight, total road imports and total road exports of each French region and inter-regional road freight. The results presented in figure 4.2 clearly show that geographical and product disaggregation rapidly lead to loss of precision given the decrease in the size of the subsample. The most disaggregated results (inter-regional trade of wheat) show that there is a very large variability of uncertainties depending on the flows (here, depending on loading and unloading regions), ranging from 31% to 183%.

This clearly shows that the disaggregation level is not enough to characterize uncertainty, but that there is a large regional variation. As a consequence, uncertainties should be evaluated in each MFA study to check whether or not road freight is reliable enough depending on the question tackled. Data reconciliation techniques that couple transport data with production, transformation and consumption data seem well adapted to take advantage of available trade data while still taking its (lack of) precision into account, as shown by the authors in a previous article (Courtonne et al., 2015).

4.4.3 Uncertainty propagation: studying wheat supply areas of French regions

Another common way of using transport databases is to estimate the origin or the destination of products (see, e.g., Kastner et al. 2011; Billen et al. 2009; Courtonne et al. 2016 to name only a few). In this section, we analyze the case of supply areas.

Following Kastner et al. (2011), we define a matrix R whose terms R_{ij} represents the

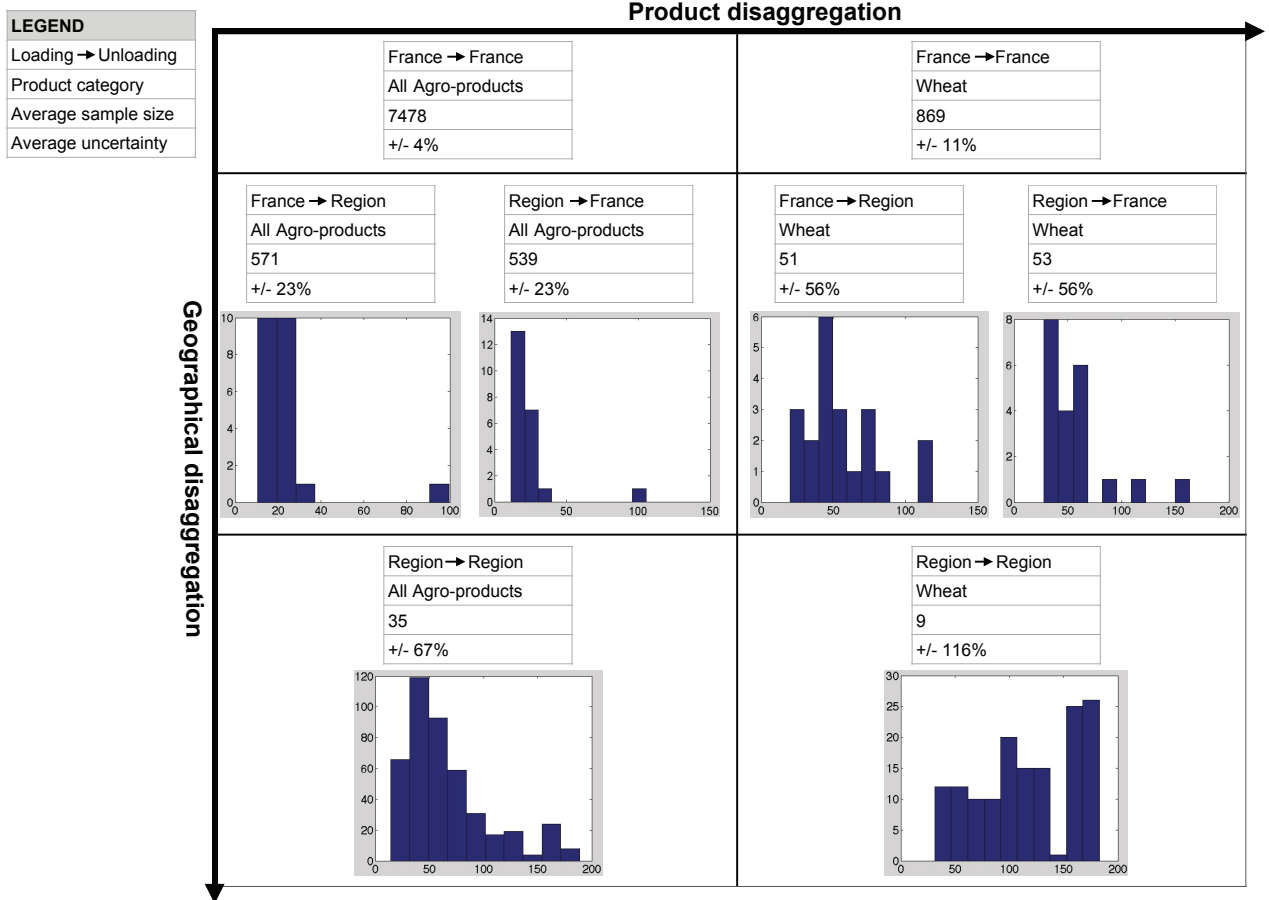


Figure 4.2: Analysis of uncertainties of road freight at various spatial and product disaggregation levels. Distributions are shown, with the x axis representing uncertainties computed for the year 2010 and the y axis representing the number of occurrences. Distributions are not drawn for total domestic freight (loading and unloading in France, whatever the region) since there is only one occurrence per product category. Uncertainties above 100% correspond to non-significant extrapolations. Flows between French départements (nuts 3 levels) are not shown but display an even larger level of uncertainty.

percentage of region i supply initially originating from region j . It is computed as follows:

$$R = (I - Z\hat{x}^{-1})^{-1}\hat{p}, \quad (4.13)$$

$$x = p + Z \cdot \mathbb{I}. \quad (4.14)$$

In these relations, I is the identity matrix; p the vector of regional productions; Z the transport matrix (with Z_{ij} the exports of country j to country i); \mathbb{I} a vector of ones so that $Z\mathbb{I}$ is the vector of total imports for each region; and \hat{x}^{-1} a diagonal matrix whose i th diagonal elements is x_i^{-1} . Note that term R_{ij} takes into account an infinite regression of imports and exports between all regions (e.g., region j exports to region k which in turn exports partly to region i while importing its own supply from other regions, etc), under an assumption of perfect blend⁸.

For the study of uncertainty propagation we use Monte-Carlo simulations and only consider uncertainties of domestic road freight statistics⁹. For each simulation, road freight data (symbolized by the r superscript on matrix Z) are generated and satisfy the four following constraints:

- all terms must remain positive,
- random draws of trade between two regions are generated from a Gaussian distribution centered on the estimated value and within the 99% confidence interval (3 sigmas).
- total imports and total exports of a region computed with the random draws of inter-regional trade must be within the 99% confidence interval of the estimated total imports and total exports
- total domestic trade computed with the random draws of inter-regional trade must be within the 99% confidence interval of the estimated total domestic trade.

The distributions mean value are extracted from the TRM survey extrapolated values and the confidence interval from our error analysis.

These constraints are necessary due to the fact that aggregated data is more reliable than disaggregated data. They translate into the following inequalities:

- For each couple of regions (i, j) , $Z_{ij}^r \geq 0$, with Z^r the random draw of road freight,
- $|Z_{ij}^r - Z_{0ij}^r| \leq 3\sigma_{ij}^{(0)}$ with Z_0^r the initial road freight data, of estimated standard deviation $\sigma^{(0)}$,
- $|(Z^r\mathbb{I})_i - (Z_0^r\mathbb{I})_i| \leq 3\sigma_i^{(1)}$,
- $|(\mathbb{I}^t Z^r)_j - (\mathbb{I}^t Z_0^r)_j| \leq 3\sigma_j^{(2)}$,
- $|\mathbb{I}^t Z^r \mathbb{I} - \mathbb{I}^t Z_0^r \mathbb{I}| \leq 3\sigma^{(3)}$.

⁸This hypothesis states that the proportion of production going to local consumption (which is unknown) is the same as the proportion of total supply going to local consumption (which is known). The same applies to the proportion of production directed to exports. This assumes constant stocks on the long run.

⁹This means that uncertainties of production, international trade and domestic trade by other modes of transport are not considered. It is however very likely that domestic road freight data are the less precise.

Here, $\sigma^{(0)}$ is a matrix, $\sigma^{(1)}$ and $\sigma^{(2)}$ are vectors and $\sigma^{(3)}$ is a number.

Figure 4.3 shows the supply areas for wheat of two French region (Haute-Normandie and Alsace), chosen for their high level of inter-regional imports. These two examples show that the supply uncertainty is often but not always small: for instance, the supply of Alsace coming from Franche-Comté is estimated inside of a wide 2%-22% interval. Turning to the analysis of all regions, we find that the average uncertainty for regions contributing to more than 5% to another region's supply is equal to 28% (the median is 18%) but the dispersion is quite high. Again, this suggests that uncertainty evaluation for input data as well as for output results should be generalized as emphasized by Laner et al. (2014).

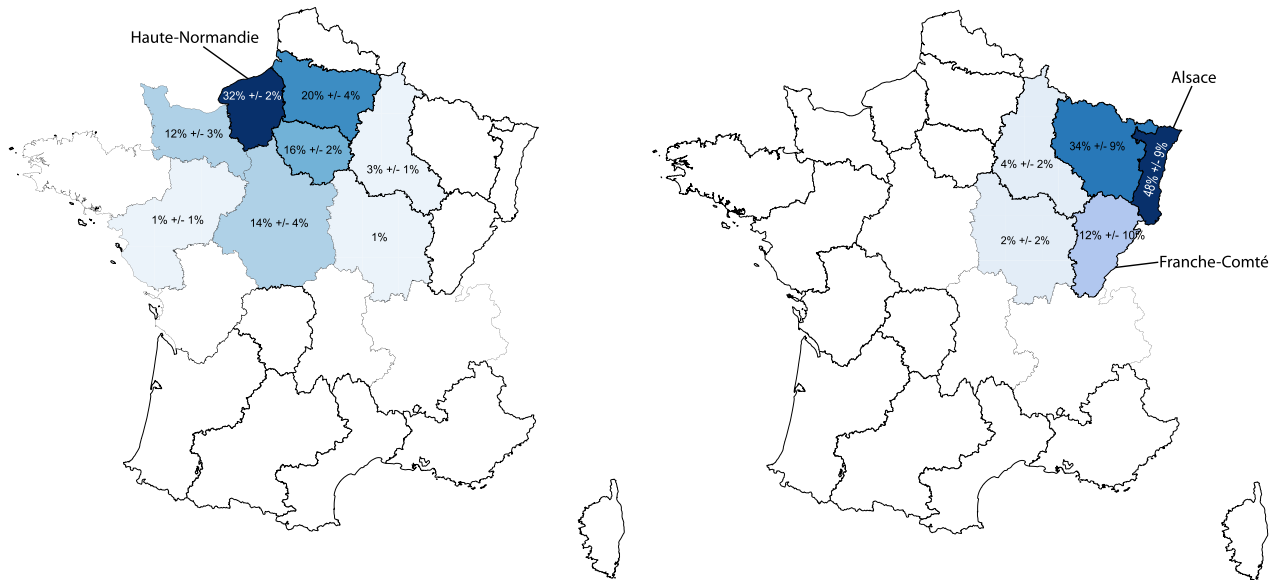


Figure 4.3: Wheat supply areas of region Haute-Normandie (left) and Alsace (right). Note that for each region x , the first percentage gives the fraction of supply of region y (Haute-Normandie or Alsace) produced in region x . 95% Confidence intervals are shown in the second percentage and are expressed in absolute value (which is a percentage since the quantity of reference is a percentage). Most of the uncertainties do not twist the conclusions that could be made based on central values alone, except for the case of supply of Alsace originating from Franche-Comté which can in fact vary between 2% and 22%.

4.4.4 Comparison between the French, Swedish and German surveys

It is interesting to compare freight error analysis between countries, when possible. For Sweden, following Patricio et al. (2015), we retrieved data from the Swedish statistics office and built table 4.5. Note that the uncertainties presented correspond to total domestic freight (a regional resolution will have higher uncertainties as we saw previously). For Germany, the German statistics office in charge of the survey only provides extrapolations meeting minimum quality

criteria: the subsample size must be above 35 and the uncertainty below 40%. It also highlights extrapolations that are based on less than 50 trucks or whose uncertainties are above 20%. The uncertainty of the total in Sweden is about four times larger than in France, the latter being itself about twice as large as in Germany. Although a more comprehensive study would be necessary, these first results suggest that the conclusions drawn from case studies in France are likely to be valid in other European countries.

4.5 Conclusion

This article addresses the complex and technical issue of uncertainties of domestic road freight data in the context of material flow studies. Since uncertainties are not currently computed by the French statistics office, we have conducted our own uncertainty analysis of the sampling procedure performed in France, and proposed a model to estimate the resulting errors, based on available predictor variables, the subsample size or the number of observations. We also proposed a computation rule to assess uncertainty reduction when averaging over n_y years. Results suggest that conducting MFA studies on period of several years instead of a single year would lead to more reliable results. For instance, we can expect a 3-year average to reduce the uncertainty of road freight by 30%.

Turning to specific material flows, we first analyzed the impact of domestic road freight uncertainties on the EW-MFA of the Bourgogne region. On this example, we showed that the relative uncertainty of the DMC index (Domestic Mass Consumption) is between 2 and 3 times higher than that of the DMI index (Domestic Mass Input). Results should therefore be interpreted with caution, especially when comparing subnational territories (for instance, eurostat nuts 2 and nuts 3 levels). We illustrate the *data disaggregation effect* on the case of agro-products, and then the *propagation effect* of determining regional supply areas for wheat. Results show it is not possible to assert up to which disaggregation level the data can be exploited: computing uncertainties should be done on every flow studied (which justifies the need for reliable and easy-to-implement computation rules). Of course, uncertainties are generally lower when large quantities are involved, however this is not always true. We indeed show that the subsample size (or the number of observations) is a much better predictor than the total tonnes estimated.

Although the analysis is conducted for the French domestic transport survey, many conclusions are likely to be valid in other European countries since they all make use the same kind of surveys for assessing road freight. The basic comparison conducted at the national level for the main product categories between France, Sweden and Germany tends to confirm this hypothesis.

Future perspectives would include conducting similar analysis in other European and non-European countries, implementing the models developed in this article in new regional material flow studies, and finally, conducting uncertainty analysis on other data sources used in MFA (production data, custom data...), when feasible.

With the large amounts of data and computational power available nowadays, it is tantalizing to elaborate evermore sophisticated tools without taking the time to question to what extent they provide useful new contributions to our knowledge and understanding. Analyzing uncertainties helps putting such results in perspective, avoiding premature conclusions, pointing to current lack of information, in line with this famous quote from Read (1920): *“it is better*

Product category	Uncertainty of the 2010 French survey	Uncertainty of the 2010 Swedish survey	Uncertainty of the 2013 German survey
01 - Products of agriculture, hunting, and forestry; fish and other fishing products	4%	10%	< 20%
02 - Coal and lignite; crude petroleum and natural gas	18%	114%	20% < e ≤ 40% or 35 < # trucks ≤ 50
03 - Metal ores and other mining and quarrying products; peat; uranium and thorium ores	4%	16%	< 20%
04 - Food products, beverages and tobacco	4%	13%	< 20%
05 - Textiles and textile products; leather and leather products	22%	56%	< 20%
06 - Wood and products of wood and cork (except furniture); articles of straw and plaiting materials; pulp, paper and paper products; printed matter and recorded media	7%	19%	< 20%
07 - Coke and refined petroleum products	7%	30%	< 20%
08 - Chemicals, chemical products, and man-made fibers; rubber and plastic products; nuclear fuel	8%	25%	< 20%
09 - Other non-metallic mineral products	4%	24%	< 20%
10 - Basic metals; fabricated metal products, except machinery and equipment	10%	21%	< 20%
11 - Machinery and equipment n.e.c.; office machinery and computers; electrical machinery and apparatus n.e.c.; radio, television and communication equipment and apparatus; medical, precision and optical instruments; watches and clocks	8%	29%	< 20%
12 - Transport equipment	10%	31%	< 20%
13 - Furniture; other manufactured goods n.e.c.	12%	62%	< 20%
14 - Secondary raw materials; municipal wastes and other wastes	8%	26%	< 20%
15 - Mail, parcels	9%	21%	< 20%
16 - Equipment and material utilized in the transport of goods	14%	15%	< 20%
17 - Goods moved in the course of household and office removals; baggage and articles accompanying travelers; motor vehicles being moved for repair; other non-market goods n.e.c.	15%	43%	< 20%
18 - Grouped goods: a mixture of types of goods which are transported together	4%	8%	< 20%
19 - Unidentifiable goods: goods which for any reason cannot be identified and therefore cannot be assigned to groups 01-16	17%	-	< 20%
20 - Other goods n.e.c.	55%	39%	$e > 40%$ or # trucks ≤ 35
TOTAL (all product categories)	1.5%	6%	0.8%

Table 4.5: Comparison of the 95% uncertainties in the 2010 French and Swedish road freight surveys and the 2013 German survey for the main categories of products (NST 2007 classification). Uncertainties of the French survey are computed by the authors as described in methods section, except for the total which is provided in CGDD-SOeS (2011). Uncertainties of the Swedish survey are computed based on table 7A of Swedish-Transport-Administration (2011). Uncertainties of the German survey were taken from the table p. 60 of Kraftfahrt-Bundesamt (2014), except for the total which was directly provided to the authors by the statistics office.

to be vaguely right than exactly wrong".

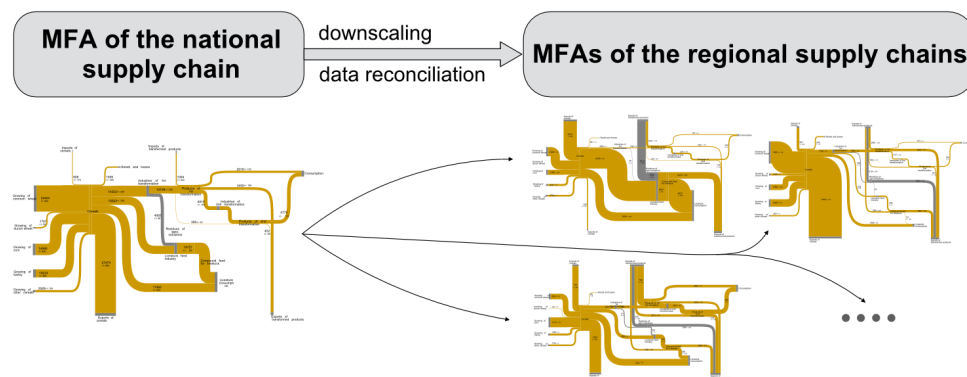
Acknowledgments

This research was funded by grants from Inria and Artelia Eau & Environnement. The authors would like to thank the freight statistics team from the French Ministry of Ecology, and especially Mr Mahmoud Jlassi, for their kind collaboration, which was essential to the study.

Part one recap

The first part was devoted to:

- Situating our methodological developments in comparison with existing approaches of supply chain analysis (Chapter 2).
- Presenting the bases of the SC-MFA model (Chapter 3). Important features include the data reconciliation process, that exploits information on data sources' uncertainty, the downscaling process, that allows us to provide simultaneous and comparable assessment on all sub-territories, and the process of uncertainty propagation, based on Monte-Carlo simulations, allowing us to display confidence intervals on Sankey diagrams. Data is organized in the form of Supply and Use Tables (SUT) and submitted to the constrained optimization presented in Eq. (3.3) of the article. While such data reconciliation is a common process in MFA, we propose to use it at a greater quantitative scale. For instance, the multi-regional model handles about 15,000 variables for characterizing productions and consumptions in each of the 22 French regions as well as inter-regional and international trade.



- Applying the model on the French cereal supply chain: we obtained SC-MFAs for all French regions, that underline regional specialization strategies in a striking way. We further tested the downscaling process down to the department and ScoT levels (Isère department and Grenoble area), and showed what simplifications had to be made.
- Presenting an example of uncertainty assessment with what we consider the weakest link of local MFA studies: domestic road freight statistics (Chapter 4). We provide a simple model linking sample sizes with confidence intervals. A conclusion is worth noting, and probably applies beyond the case of France: uncertainties can be significantly reduced

when a study is carried out on a multi-year period (for instance, uncertainty reduction for a 3-year average was estimated to 30%).

As pointed out in Chapter 3, we consider material flows as a basis for further analysis that includes environmental and socio-economic aspects associated to territorial supply chains. Part II is dedicated to this endeavor.

Part II

Coupling material flows with environmental and socio-economic aspects

Formal links between methods aiming at tracing flows

This chapter serves as a preliminary to the coupling of the SC-MFA model with environmental pressures. As we saw in the introduction, we are particularly interested in building environmental footprint accounts from the producer's and consumer's perspectives. Here, we introduce formal methods for tracing physical flows, be it between regions or between economic sectors:

- In order to get used to the type of reasoning mobilized in this section, we start by detailing how one can formally trace the geographical origin or destination of a single product,
- We then present two common frameworks, Input-Output Analysis (IOA) and Absorbing Markov Chains (AMC) that help to efficiently organize data; we provide proofs of these frameworks' classical interpretations,
- We show the links between IOA and AMC using Leontief's minimal example (a two-sectors economy, Leontief 1970),
- Finally, we briefly discuss how the Supply Use Tables (SUT) used in the SC-MFA model can be adapted to fit the IOA and AMC frameworks.

5.1 Tracing the origins and destinations of a single product

When tracing the geographical origin of a product, one refers to the origin *at the first order* when one only considers its last loading area, to the origin *at the second order* when one considers the transit that may have occurred before this last loading, and so on. Thus, the origin *at the infinity order* corresponds to the product's production area. The order is denoted k in the matrix formulation of this infinite order ($k = \infty$) that is exposed below. Let us first introduce some definitions and notations:

- The expression "*the part of quantity X...*" always refers to an absolute quantity; the expressions "*the fraction of quantity X...*" and "*the proportion of quantity X...*" always refer to percentages.
- n : number of regions.
- I : identity matrix of size (n, n) .
- $\mathbf{1}$: column vector of ones of contextual size (used for line or column summation of vectors and matrices).

- M^t : transposed of any vector or matrix M .
- \hat{V} : the diagonal matrix obtained from any column vector, i.e., $\hat{V}_{ij} = V_i \delta_{ij}$ where δ_{ij} is the Kronecker delta symbol. $V = \hat{V} \cdot \mathbf{1}$ and $V^t = \mathbf{1}^t \cdot \hat{V}$.
- T : (n, n) matrix of trade between regions, T_{ij} represents the amount of good transported from region i to region j , intra-regional flows (diagonal elements) are omitted.
- C : $(n, 1)$ vector of consumption in each region,
- P : $(n, 1)$ column vector of production in each region.
- S : $(n, 1)$ column vector of total supply (production plus imports) in each region:

$$\begin{aligned} S_i &= P_i + \sum_j T_{ji}, \\ S &= P + (\mathbf{1}^t \cdot T)^t. \end{aligned}$$

- U : $(n, 1)$ column vector of total use (consumption plus exports) in each region:

$$\begin{aligned} U_i &= C_i + \sum_j T_{ij}, \\ U &= C + T \cdot \mathbf{1}. \end{aligned}$$

- X and \hat{X} : $(n, 1)$ vector and (n, n) diagonal matrix representing the proportion of direct local supply in each region:

$$\begin{aligned} \hat{X} &= \hat{P} \hat{S}^{-1}, \\ X_i &= \frac{P_i}{S_i}. \end{aligned}$$

- Y and \hat{Y} : $(n, 1)$ vector and (n, n) diagonal matrix representing the proportion of direct local consumption in each region:

$$\begin{aligned} \hat{Y} &= \hat{C} \hat{S}^{-1}, \\ Y_i &= \frac{C_i}{S_i}. \end{aligned}$$

- A : (n, n) matrix with null diagonal terms, such that A_{ij} is the proportion of supply in region j directly coming from region i , with $j \neq i$:

$$A = T \hat{S}^{-1}.$$

or in coordinate form, $A_{ij} = T_{ij}/S_j$. The column sum of each column of $(A + \hat{X})$ is equal to one (as it corresponds to the total supply of the corresponding region):

$$\mathbf{1}^t \cdot (A + \hat{X}) = \mathbf{1}^t,$$

- \tilde{A} : (n, n) matrix with null diagonal terms, such that \tilde{A}_{ij} is the proportion of supply of region i directly *going* to region j , with $j \neq i$:

$$\tilde{A} = \hat{S}^{-1}T,$$

so that $\tilde{A} = \hat{S}^{-1} \cdot A \cdot \hat{S}$ and $\tilde{A}_{ij} = T_{ij}/S_i$. The row sum of each row of $(\tilde{A} + \hat{Y})$ is equal to one (as it corresponds to the total use of the corresponding region):

$$(\tilde{A} + \hat{Y}) \cdot \mathbf{1} = \mathbf{1}.$$

- $R^{(k)}$: (n, n) redistribution matrices, defined such that $P_i R_{ij}^{(k)}$ is the part of region j supply which one can trace as produced in i , by considering a maximum of k successive transport operations. This matrix relates the *production row vector* to the *supply column vector*. In other words, $P_i R_{ij}^{(k)}$ is the part of products P_i in the supply S_j that has undergone at most k inter-regional operations of exports or imports. $R_{ij}^{(k)}$ can also be interpreted as the average number of times one unit of i has transited through j at order k ; note that the same product unit can be exported and reimported, which is to say R_{ij} may be greater than one¹. $R^{(k)}$ is the redistribution matrix of order k ; $R^{(\infty)}$ is the redistribution matrix after an infinite series of inter-regional exchanges.
- $O^{(k)}$: (n, n) defined such that $O_{ij}^{(k)}$ is the fraction of region j supply coming from the production of region i , at transport order k . It embodies the information of $R^{(k)}$ in fractional form: $O_{ij}^{(k)} = P_i R_{ij}^{(k)} / S_j$. $O_{ij}^{(\infty)}$ is the fraction of region j supply produced in region i at infinite order.
- $\Phi^{(k)}$: (n, n) matrices linking productions and consumptions at transportation order k . More specifically $\Phi_{ij}^{(k)}$ is the part of production P_i that is consumed in region j after undergoing at most k transport operations. Similarly, $\Phi_{ij}^{(\infty)}$ gives the contribution of P_i to C_j at infinite transportation order. By construction, and in the absence of stock variation, $P_i = \sum_j \Phi_{ij}^{(\infty)}$ and $C_j = \sum_i \Phi_{ij}^{(\infty)}$.

One can compute $R^{(k)}$ and $R^{(\infty)}$ by induction, with the help of a *perfect blend* hypothesis. This hypothesis states that the proportion of production going to local consumption (which is unknown) is the same as the proportion of total supply going to local consumption (which is known). The same applies to the proportion of production directed to exports. The mathematical meaning of this statement is made explicit in figure 5.1.

For the sake of clarity and precision, the induction reasoning is presented in coordinate form, and then stated in matrix form. To alleviate notations, it is often conventional to omit summation signs over repeated indices; for example, for a matrix M connecting to vectors V

¹Time is conspicuously absent from this definition. A reimported product unit can only have been exported at an earlier time. Trade is usually monitored for a given time period, typically a year. over this period, only a finite number of imports and exports has taken place. The underlying approximation can be justified in the following way. First, the number of multiple imports and exports of the same product unit has a smaller and smaller probability at each successive order, as indicated by the decreasing magnitude of the k order trade flow calculated below so that only the first few orders matter (generally the first two). Second, trade flows today are similar to the flows from earlier time periods (stationary hypothesis). In this approximation, summing to all orders has little effect on the result and provides simple closed form formulae.

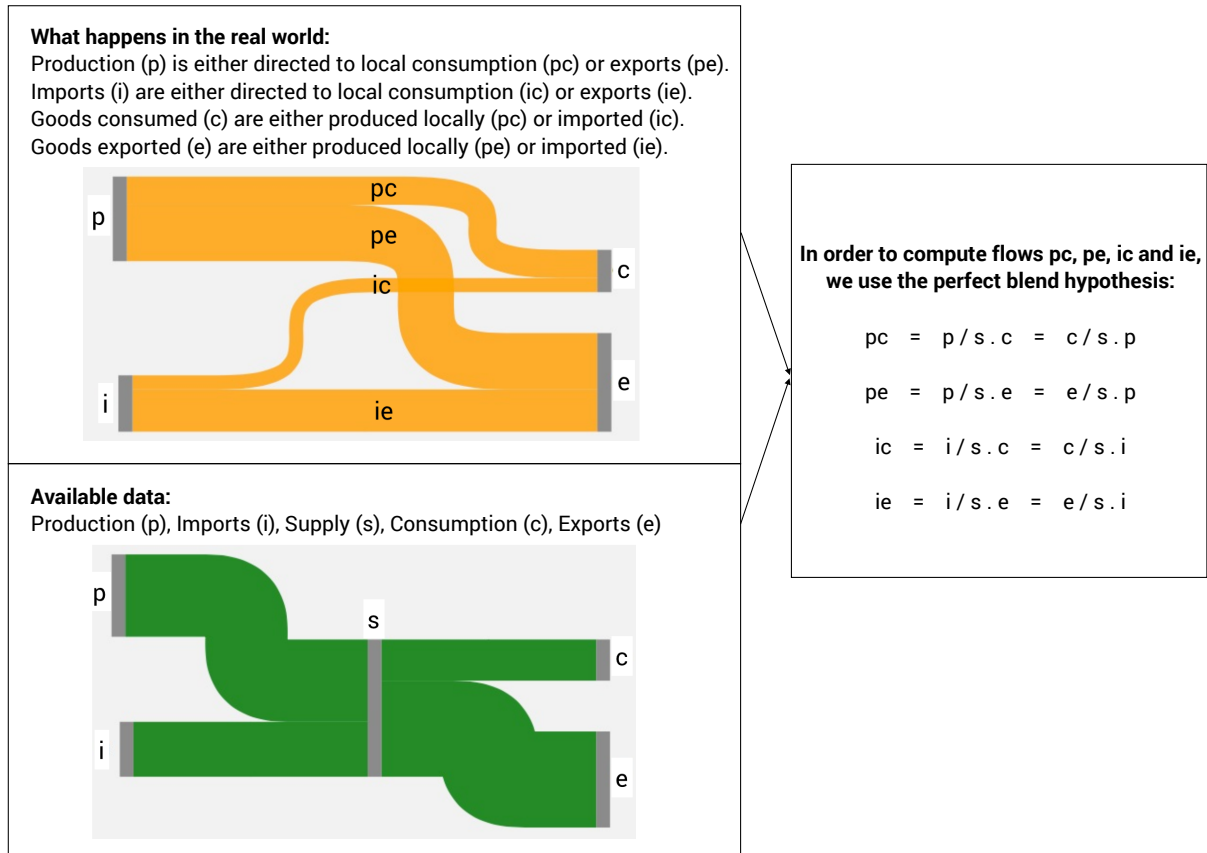


Figure 5.1: The perfect blend hypothesis made explicit. One formulation is the following: the proportion of production going to local consumption (which is unknown) is the same as the proportion of total supply going to local consumption (which is known).

and W : $W_i = \sum_j M_{ij} V_j = M_{ij} V_j$. This convention is used below to derive Eq. (5.1) and is given up afterwards.

The induction starts with a tautological recursive substitution²:

$$\begin{aligned}
S_{i_1} &= P_{i_1} + \sum_{i_2} T_{i_2 i_1} \\
&= P_{i_1} + \sum_{i_2} S_{i_2} \frac{T_{i_2 i_1}}{S_{i_2}} \\
&= P_{i_1} + \sum_{i_2} \left[P_{i_2} + \sum_{i_3} T_{i_3 i_2} \right] \tilde{A}_{i_2 i_1} \\
&= P_{i_1} + P_{i_2} \tilde{A}_{i_2 i_1} + S_{i_3} \tilde{A}_{i_3 i_2} \tilde{A}_{i_2 i_1} \\
&= P_{i_1} + P_{i_2} \tilde{A}_{i_2 i_1} + P_{i_3} \tilde{A}_{i_3 i_2} \tilde{A}_{i_2 i_1} + \cdots + P_{i_k} \prod_{j=k}^2 \tilde{A}_{i_j i_{j-1}} \\
&\quad + S_{i_{k+1}} \prod_{j=k+1}^2 \tilde{A}_{i_j i_{j-1}}.
\end{aligned} \tag{5.1}$$

This is where the perfect blend assumption comes in to interpret the tautology: all terms represent part of the production that is exported. For example, under this assumption, $P_{i_2} \tilde{A}_{i_2 i_1}$ is the part of the production of region i_2 that is exported to region i_1 . Indeed, as there is no preference in the origin of the product for their exportation, the exported production is proportional to what production represents in the exporting country's supply; the same conclusion holds as well for $T_{i_3 i_2} \tilde{A}_{i_2 i_1}$, which embodies the part of the importations of i_2 in its exportation to i_1 . Consequently, all the P_{i_j} terms in the preceding sum represent the contribution of region i_j to the supply of region i_1 . This is the central result of this analysis.

The preceding relation can be put in vector form as

$$S^t = P^t \cdot \left[I + \sum_{q=1}^k \tilde{A}^q \right] + S^t \cdot \tilde{A}^{k+1}. \tag{5.2}$$

This implies that

$$\begin{aligned}
R^{(k)} &= I + \sum_{q=1}^k \tilde{A}^q = I + \sum_{q=1}^k \left(\hat{S}^{-1} \cdot A \cdot \hat{S} \right)^q, \\
R^{(\infty)} &= \left(I - \tilde{A} \right)^{-1} = \left(I - \hat{S}^{-1} \cdot A \cdot \hat{S} \right)^{-1}.
\end{aligned}$$

where the limit $k \rightarrow \infty$ has been taken to obtain the last equality.

²A similar formula was also derived by Kastner et al. (2011).

One can recast Eq. (5.1) to obtain the $O^{(k)}$ and $O^{(\infty)}$ matrices. Indeed, as $P_{i_k} \prod_{j=k}^2 \tilde{A}_{i_j i_{j-1}} = X_{i_k} \prod_{j=k}^2 A_{i_j i_{j-1}} S_{i_1}$, Eq. (5.1) implies that (no summation over repeated indices)

$$\begin{aligned} O_{ji}^{(k)} &= X_j \delta_{ji} + X_j \left[\sum_{q=1}^k A^q \right]_{ji}, \\ O_{ji}^{(\infty)} &= X_j \delta_{ji} + X_j [I - A]_{ji}^{-1}. \end{aligned}$$

These relations are more compactly written in matrix form as (with the convention that $A^0 = I$)

$$\begin{aligned} O^{(k)} &= \hat{X} \cdot \left[\sum_{q=0}^k A^q \right], \\ O^{(\infty)} &= \hat{X} \cdot [I - A]^{-1}, \end{aligned} \quad (5.3)$$

Let us now turn to the connection between consumption and production. This is again achieved with the help of the perfect blend assumption, which implies:

$$\begin{aligned} \Phi_{ij}^{(k)} &= O_{ij}^{(k)} C_j, \\ \Phi_{ij}^{(\infty)} &= O_{ij}^{(\infty)} C_j. \end{aligned} \quad (5.4)$$

Remember the closing relation:

$$\begin{aligned} P_i &= \sum_j \Phi_{ij}^{(\infty)} = \sum_j O_{ij}^{(\infty)} C_j, \\ P &= O^{(\infty)} C. \end{aligned}$$

Note that at any order k , one can make an approximation [derived from Eq. (5.2)] and use formula (5.6) to link productions and consumptions:

$$\begin{aligned} P &= O^{*(k)} C, \quad \text{with} \\ O^{*(k)} &= O^{(k)} + A^{k+1}, \\ O^{*(k)} &= \hat{X} \cdot \left[\sum_{q=0}^k A^q \right] + A^{k+1} \end{aligned} \quad (5.5)$$

For instance, at order 1 (meaning only products that have been transported one time before being consumed have been traced back to their real area of production):

$$O^{*(1)} = \hat{X} \cdot [I + A] + A^2 = \hat{X} + \hat{X}A + A^2.$$

Eq. 5.6 is in fact the matrix formulation of the formula proposed by Billen (2010), and since then implemented in a number of French studies [e.g. Le Noë et al. (2016)]. In many cases, this approximation is indeed justified as $O^{*(1)} \approx O^{(\infty)}$. In our study, we will however use the infinite order directly since it does not bring any computational overhead.

The same general relation between productions and consumptions can also be obtained directly in matrix form³. This way of proceeding is a lot quicker but less intelligible at first.

³Still using the perfect blend hypothesis and assuming that stock variations are null. This stock hypothesis is a common assumption that is justified on average over a few years, especially in a just-in-time production economy.

From the equality of supply and uses, $S = U = C + T\mathbf{1}$, one can express the production vector as:

$$\begin{aligned} P = \hat{P} \cdot \mathbf{1} = \hat{X} \cdot \hat{S} \cdot \mathbf{1} &= \hat{X} \cdot C + \hat{X} \cdot T \cdot \mathbf{1} \\ &= \hat{X} \cdot C + \hat{X} \cdot T \cdot (\hat{S}^{-1} \cdot \hat{S} \cdot \hat{P}^{-1} \cdot \hat{P}) \cdot \mathbf{1} \\ &= \hat{X} \cdot C + \hat{X} \cdot A \cdot \hat{X}^{-1} \cdot P. \end{aligned}$$

Then:

$$\begin{aligned} (I - \hat{X} \cdot A \cdot \hat{X}^{-1}) \cdot P &= \hat{X} \cdot C, \\ (I - A) \cdot \hat{X}^{-1} \cdot P &= C, \\ P &= \hat{X} \cdot [I - A]^{-1} \cdot C \end{aligned}$$

$O_{ij}^{(\infty)}$ being defined as the proportion of supply of j produced in i but also as the proportion of consumption of j produced in i (due to the perfect blend hypothesis), we have:

$$\begin{aligned} P &= O^{(\infty)}C, \text{ with} \\ O^{(\infty)} &= \hat{X} \cdot [I - A]^{-1} \end{aligned} \quad (5.6)$$

which is consistent with Eq. (5.3).

Now, we can define the destination matrix $D^{(\infty)}$, where $D_{ij}^{(\infty)}$ is the proportion of production i consumed in j . Using Eq. (5.4) and remembering that Φ_{ij} is the production of i consumed in j , we have:

$$\begin{aligned} \Phi_{ij}^{(\infty)} &= O_{ij}^{(\infty)}C_j, \\ D_{ij}^{(\infty)} &= \Phi_{ij}^{(\infty)}/P_i = O_{ij}^{(\infty)}C_j/P_i. \end{aligned}$$

Or in matrix terms:

$$\begin{aligned} \Phi^{(\infty)} &= O^{(\infty)}\hat{C}, \\ D^{(\infty)} &= \hat{P}^{-1}\Phi^{(\infty)}, \\ D^{(\infty)} &= \hat{P}^{-1}\hat{X} \cdot [I - A]^{-1} \hat{C}, \\ D^{(\infty)} &= \hat{S}^{-1} \cdot [I - A]^{-1} \hat{C}. \end{aligned}$$

And eventually, since $[I - A]^{-1} = \hat{S} \cdot [I - \tilde{A}]^{-1} \cdot \hat{S}^{-1}$:

$$D^{(\infty)} = [I - \tilde{A}]^{-1} \hat{Y}. \quad (5.7)$$

TO SUM THINGS UP, matrix $O^{(\infty)}$, where $O_{ij}^{(\infty)}$ is the proportion of supply (or consumption) of region j produced in i , is defined in Eq. (5.6), matrix $D^{(\infty)}$, where $D_{ij}^{(\infty)}$ is the proportion of region i production consumed in region j , is defined in equation (5.7) and:

$$\Phi^{(\infty)} = O^{(\infty)}\hat{C} = \hat{P}D^{(\infty)}$$

where $\Phi_{ij}^{(\infty)}$ is the production of region i consumed in region j .

Hopefully, this rather heavy section helped the reader to get used to the type of calculation used to trace flows. It is directly related to the formalism of IOA and AMC, which we will now present.

5.2 Input-Output Analysis

5.2.1 General formulation: quantity vs. price IO models

Introduced in their modern form by Wassily Leontief, Input-Output Tables (IOT)⁴ depict the links between factors of production, economic sectors (intermediate consumption) and final demand⁵. As emphasized by Duchin (2009), one can build two IO models based on these relationships: a quantity model and a price model: “*the quantity model follows the supply chain, for an individual product or an entire bill of goods; the price model makes it possible to track the value chain for the same final deliveries*”. The following material presents the core of IO theory needed for this thesis. More details can be found in Miller and Blair (2009).

In order to describe the two IO models, we introduce the following notations⁶:

- n is the number of economic sectors,
- $\mathbf{1}$ is a summation vector (of ones) of contextual size,
- \hat{M} is the diagonal matrix formed from vector M : $\hat{M}_{ij} = \delta_{ij}M_i$,
- Z is the (n,n) matrix of intermediate consumption with Z_{ij} the quantity of sector i production used by sector j . Each row i of Z can be quantified in the most *natural* unit (e.g. tonnes of wheat, tonnes of pig iron, kWh, ...or dollars when the product mix is too heterogeneous⁷),
- Y is the (n,1) vector of final demand for goods and services produced by economic sectors; each term Y_i is expressed in the same unit as row Z_i ,
- X is the (n,1) vector of total output per economic sector, $X_i = \sum_j Z_{ij} + Y_i$, or in matrix form $X = Z \cdot \mathbf{1} + Y$,
- $A = Z \cdot \hat{X}^{-1}$ is the (n,n) matrix of technical coefficients, with $A_{ij} = Z_{ij}/X_j$ the amount of sector i production directly consumed by sector j per unit of sector j output,
- P is a (n,1) vector of unit prices for each economic sector,
- V is a (n,1) vector of added value per unit of each sector’s output.

⁴François Quesnay’s *Tableau Economique* (1758), is recognized as an earlier, cruder form of IOT; the former laid the foundation of Physiocratic economics, i.e. a French school of thoughts putting land and agriculture at the center of wealth creation.

⁵Final consumption of households and administrations and most often investments (considered a final demand category for the sake of simplification).

⁶Note that we use the terms production and output indifferently.

⁷In fact, confusion between the quantity and price models may occur when the quantity model is only expressed in monetary units, as it is the case in most national accounts.

The quantity model aims at explaining outputs from all sectors based on the level of final demand. It is classically derived as follows:

$$\begin{aligned} X &= Z \cdot \mathbf{1} + Y \\ X &= A \cdot \hat{X} \cdot \mathbf{1} + Y = A \cdot X + Y \\ X &= (I - A)^{-1} \cdot Y \end{aligned} \quad (5.8)$$

The price model aims at explaining the unit price of a particular good (or service) based on the level of value-added of each sector contributing directly or indirectly to the supply of this good. For deriving the price model, we start by writing that the added value of a sector is equal to the turnover of this sector (the money made from selling production) minus all the expenditures on intermediate consumption (NB: we note M^t the transposition of matrix M):

$$\begin{aligned} V_i \cdot X_i &= P_i \cdot X_i - \sum_j P_j \cdot Z_{ji} \\ V_i \cdot X_i &= P_i \cdot X_i - \sum_j P_j \cdot A_{ji} X_i \\ V_i &= P_i - \sum_j P_j \cdot A_{ij}^t \\ V &= P - A^t \cdot \hat{P} \cdot \mathbf{1} = (I - A^t) \cdot P \\ P &= (I - A^t)^{-1} \cdot V \end{aligned} \quad (5.9)$$

Finally, one can derive from Eqs. (5.8) and (5.9) that:

$$P^t \cdot Y = V^t \cdot X$$

This means that the total value-added of the economy is equal to total final expenditures⁸. Let us now introduce factors of production. Again, these are present in the quantity and in the price model: in fact, value-added is used to pay each production factor (labor, capital, land, natural resources etc.). We define the following elements:

- m is the number of production factors,
- F is a $(m,1)$ vector of production factors with F_i the amount of production factor i used by the whole economy. Each element of F can be expressed in the most *natural* unit (e.g., tonnes of ressources, number of working hours etc.),
- f is a (m,n) matrix of production factors per unit of output with f_{ij} the quantity of production factor i used per unit of output of sector j ,
- π is a $(m,1)$ vector of unit prices for each factor of production.

We can then extend the quantity and price models to production factors:

$$\begin{aligned} F &= f \cdot X \\ F &= f \cdot (I - A)^{-1} \cdot Y \end{aligned} \quad (5.10)$$

⁸Note that in macro-economics there are three equivalent ways of computing the growth domestic product: providing some adjustments (e.g., taking depreciation, taxes on added-value and subsidies into account), GDP is (i) the sum of sectoral growth value-added (value of output minus intermediate consumption expenditures), (ii) the sum of final expenditures, and (iii) the sum of salaries and corporate profits.

$$\begin{aligned}
V_i &= \sum_j \pi_j \cdot f_{ji} \\
V &= f^t \cdot \pi \\
P &= (I - A^t)^{-1} \cdot f^t \cdot \pi
\end{aligned} \tag{5.11}$$

And from Eqs. (5.8) and (5.11) comes:

$$P^t \cdot Y = \pi^t \cdot f \cdot X = \pi^t \cdot F$$

meaning total final expenditures are paying for total use of production factors.

The interest of Eqs. (5.8), (5.9), (5.10) and (5.11) is not readily obvious. Indeed, total outputs, unit prices, total use of production factors (vectors X , P and F) are known from the start. These models are however very enriching for two reasons:

- *Forecasting.* Under the assumption that the *economic recipe* (structure) does not change, one can forecast how the use of production factors will evolve (e.g., number of job creations) consecutively to a change of final demand; with the price model, one can similarly estimate how prices of products will evolve following a change of unit prices of production factors.
- *Analyzing the current situation.* These models allow *analytical accounting*, that is, allocating a global quantity to a series of elementary processes. In doing so they help identify critical links in the economy (in our case, critical links related to environmental pressures).

In this thesis, we only concentrate on the second point. Coming back to Eq. (5.8), we can for instance compute matrix \tilde{X} whose ij th term represents the production of sector i used to satisfy final demand for sector j :

$$\begin{aligned}
X &= (I - A)^{-1} \cdot Y \\
\tilde{X} &= (I - A)^{-1} \cdot \hat{Y}
\end{aligned}$$

Here, it is noteworthy that $\tilde{X} \cdot \mathbf{1} = X$, however $\tilde{X} \neq \hat{X}$. In the next section, we show ways of further decomposing the links between production and consumption.

5.2.2 Taylor decomposition of $(I - A)^{-1}$ and Structural Path Analysis

Since $A \cdot X = X - Y$, the column sum of each row of matrix A is lesser or equal to one and at least one row is strictly inferior to one: $\forall i, \sum_j A_{ij} \leq 1$ and $\exists k, \sum_j A_{kj} < 1$. This last condition simply means that final demand Y is strictly positive for at least one economic sector. These conditions imply that: $\lim_{n \rightarrow \infty} A^n = 0$. One can therefore use the Taylor series decomposition of matrix $(I - A)^{-1}$, often referred to as the *Leontief matrix* and noted L :

$$L = (I - A)^{-1} = \sum_{k=0}^{\infty} A^k = I + A + A^2 + \dots + A^n + \dots$$

Eq. (5.8) can then be rewritten as:

$$X = Y + A \cdot Y + A^2 \cdot Y + \dots + A^n \cdot Y + \dots$$

This formulation is interpreted as follows: in order to deliver quantities of Y to final demand, one must at least produce Y (order 0); the production of Y in turn requires intermediate consumptions of $A \cdot Y$ (order 1), and therefore the production of $A \cdot Y$, which in turn requires the intermediate consumption of $A \cdot A \cdot Y = A^2 \cdot Y$ (order 2), ... and so on. On the right-hand side of the equation, matrices correspond to successive orders (layers) of production where flows are traced upstream (direct inputs, inputs for inputs, inputs for inputs for inputs etc.) as the power of A increases, and eventually vanish.

We can also decompose matrix $f \cdot \tilde{X}$, whose ij th term provides the quantity of production factor i directly and indirectly used to satisfy final demand for sector j :

$$f \cdot \tilde{X} = f \cdot \hat{Y} + f \cdot A \cdot \hat{Y} + f \cdot A^2 \cdot \hat{Y} + \dots + f \cdot A^n \cdot \hat{Y} + \dots$$

Each term of the right-hand side of the equation then corresponds to direct uses of production factors (at order 0, 1, 2 etc.). Finally, using the notation⁹ $T(f)_k = \hat{f}_k$, one can track which sector used production factor k at each order:

$$\hat{f}_k \cdot \tilde{X} = \hat{f}_k \cdot \hat{Y} + \hat{f}_k \cdot A \cdot \hat{Y} + \hat{f}_k \cdot A^2 \cdot \hat{Y} + \dots + \hat{f}_k \cdot A^n \cdot \hat{Y} + \dots$$

The ij th term of matrices $\hat{f}_k \cdot A^n \cdot \hat{Y}$ is the quantity of production factor k directly used by sector i at order n , in order to ultimately satisfy final demand for sector j .

The latter formulation already provides a fine understanding of the links between production factors (for our concerns, environmental pressures) and final consumption. However, it is possible to go one step further by decomposing the ij th terms of matrices A^n . This is what is called Structural Path Analysis [SPA, (Peters and Hertwich, 2006b)]:

$$\begin{aligned} I_{ij} &= \delta_{ij} \\ A_{ij} &= A_{ij} \\ A_{ij}^2 &= \sum_k A_{ik} \cdot A_{kj} \\ &\vdots \\ A_{ij}^n &= \sum_{k_1} \sum_{k_2} \dots \sum_{k_{n-1}} A_{ik_1} \cdot A_{k_1 k_2} \cdot \dots \cdot A_{k_{n-2} k_{n-1}} \cdot A_{k_{n-1} j} \end{aligned}$$

A Structural Path describes a particular succession of processes that leads to embody of certain quantity of production factor k in final demand:

$$f_{ki} \cdot Y_i \tag{5.12}$$

$$f_{ki} \cdot A_{ij} \cdot Y_j \tag{5.13}$$

\vdots

$$f_{ki} \cdot \sum_{k_1} \sum_{k_2} \dots \sum_{k_{n-1}} A_{ik_1} \cdot A_{k_1 k_2} \cdot \dots \cdot A_{k_{n-2} k_{n-1}} \cdot A_{k_{n-1} j} \cdot Y_j$$

Paths of type (5.12) are interpreted as follows: final demand Y_i for sector i requires the production of Y_i units by sector i , for which the sector uses $f_{ki} \cdot Y_i$ units of production factor k . Paths

⁹In other words, $T(f)$ is a 3-dimensional tensor and its ij th element corresponds to the diagonal matrix of size (n,n) formed with the ij th row of matrix f .

of type (5.13) are interpreted as follows: final demand Y_j for sector j requires the production of Y_j units of j , in turn requiring the production of $A_{ij} \cdot Y_j$ units of sector i , for which sector i uses $f_{ki} \cdot A_{ij} \cdot Y_j$ units of production factor k . And so on. In practical uses, structural paths are ranked according to their values, which makes it possible to identify which paths contribute the most to the use of a production factor.

5.3 Absorbing Markov Chains

5.3.1 Markov chains

5.3.1.1 An introductory example: weather forecast

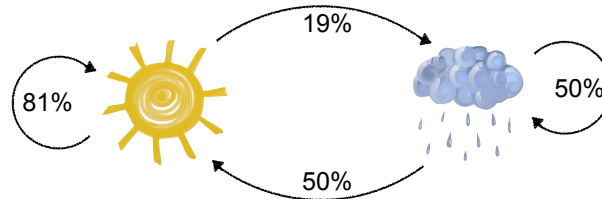
In a given city, the weather can only take two forms: it can be sunny or rainy. After a one year (365 days) observation, one has counted 265 sunny days and 100 rainy days. Among the 265 sunny days, 215 were followed by another sunny day and 50 by a rainy day. Among the 100 rainy days, 50 were followed by a sunny day and 50 by another rainy day as the following table shows:

Day_n / Day_{n+1}	sun	rain	total
sun	215	50	265
rain	50	50	100
total	265	100	365

The city's data scientist then computes the probabilities of transitioning from one type of weather to another:

Day_n / Day_{n+1}	sun	rain
sun	0.81	0.19
rain	0.5	0.5

... and provides the following graphical representation of his model:



Note that in this weather forecast model, tomorrow's weather only depends on today's weather (e.g., it does not matter if it rained 5 days in a row or just today). Let us call M this probability transition matrix and $M^{(m)}$ the matrix encompassing the probabilities to have sunny or rainy weather on day $n + m$ knowing only the weather on day n . By definition $M^{(1)} = M$ and, for instance, the probability to have a rainy day on day $n + 1$ knowing there is a sunny day on day n is:

$$P(Day_{n+1} = \text{rain} \mid Day_n = \text{sun}) = M_{\text{sun},\text{rain}}^{(1)} = M_{\text{sun},\text{rain}}$$

We now wish to compute the probability to have a rainy day on day $n + 2$ knowing there is a sunny day on day n . Two courses of events can lead to this situation: Day_{n+1} can be either sunny or rainy. Mathematically, this translates into:

$$\begin{aligned}
 P(Day_{n+2} = \text{rain} \mid Day_n = \text{sun}) &= M_{\text{sun},\text{rain}}^{(2)} \\
 &= P(Day_{n+1} = \text{rain} \mid Day_n = \text{sun}) \cdot P(Day_{n+2} = \text{rain} \mid Day_{n+1} = \text{rain}) \\
 &\quad + P(Day_{n+1} = \text{sun} \mid Day_n = \text{sun}) \cdot P(Day_{n+2} = \text{rain} \mid Day_{n+1} = \text{sun}) \\
 &= M_{\text{sun},\text{rain}} \cdot M_{\text{rain},\text{rain}} + M_{\text{sun},\text{sun}} \cdot M_{\text{sun},\text{rain}} \\
 &= M_{\text{sun},\text{rain}}^2
 \end{aligned}$$

Following the same computation steps, one can readily show by induction reasoning that for any positive integer m , $M^{(m)} = M^m$. Moreover we know that M^m converges because M is a regular stochastic matrix¹⁰. Since this limit M^∞ exists, we can write:

$$\begin{aligned}
 M^\infty \cdot M &= M^\infty \\
 M^\infty \cdot (M - I) &= 0
 \end{aligned}$$

And M^∞ can be computed by solving the system of equations (all terms of matrix $M^\infty \cdot (M - I)$ must be null). We obtain the following matrix:

$Day_n / Day_{n+\infty}$	sun	rain
sun	0.73	0.27
rain	0.73	0.27

Each term ij represents the probability of having weather j on $Day_{n+\infty}$ knowing that the weather on Day_n was i . We can see that the type of weather on Day_n does not influence the result. The interpretation of this matrix is quite logic: according to the model, the probability of having a sunny day in a far future is independent of today's weather and is merely the probability of having a sunny day, nothing else considered (e.g. 265/365); the same of course goes for rainy days as well.

5.3.1.2 General formulation

The theory of Markov chains is presented, e.g., in Kemeny and Snell (1976). In what follows, we present what is needed for this thesis purposes.

A Markov chain is a random process that undergoes transitions from one state to another on a state space, that is, on the set of values the process can take (in our previous example, $\{\text{sun}, \text{rain}\}$). A process is characterized by:

- a state space,
- a transition matrix describing the probabilities of particular transitions,
- an initial state (or initial distribution).

¹⁰A real square matrix is stochastic if its rows or columns are each summing to one. Square matrix A is regular if there exists an integer $k > 0$ with all A_{ij}^k terms > 0 .

Here, we call the transition matrix P (M in the previous example). P_{ij} represents the probability of being in state j at step $n + 1$ knowing that the process is in state i at step n . Following the probabilities' definition:

$$\begin{aligned} P_{ij} &\geq 0 \\ \sum_j P_{ij} &= 1 \end{aligned}$$

The Markov process is formally described as a sequence of random variables (row vectors) $X^{(n)}$ indicating the probabilities of being in each state at step n (implying that $\sum_i X_i^{(n)} = 1$), where $X^{(n+1)}$ depends only on $X^{(n)}$ and on the transition matrix P :

$$X^{(n+1)} = X^{(n)}.P$$

Induction reasoning readily shows that:

$$X^{(n)} = X^{(0)}.P^n$$

where $X^{(0)}$ is a column vector describing the initial state of the system. Finally, the theorem of stochastic matrices indicates that if P is regular (P moreover being stochastic by construction), then the Markov sequence converges (the system eventually reaches a steady-state):

$$\begin{aligned} \lim_{n \rightarrow \infty} X^{(0)}.P^n &= X^{(\infty)} \\ \text{with } \sum_i X_i^{(\infty)} &= 1 \end{aligned}$$

In our previous example, we for instance computed that, whatever the initial state:

$$X^{(\infty)} = (0.73 \quad 0.27)$$

5.3.2 Absorbing Markov Chains

5.3.2.1 General formulation

This section is derived from the book by Kemeny and Snell (1976) dedicated to *Finite Markov Chains*, that is Markov chains characterized by a finite, discrete state space¹¹. The authors distinguish two equivalence classes of states, transient states and ergodic states: “*the former, once left, are never again entered; while the latter, once entered, are never again left*”. In situations characterized by n states and s ergodic states (i.e. $n - s$ transient states), the authors propose to organize matrix P in the following canonical form:

$$P = \begin{matrix} & \begin{matrix} s & n - s \end{matrix} \\ \begin{matrix} s \\ n - s \end{matrix} & \begin{pmatrix} S & 0 \\ R & Q \end{pmatrix} \end{matrix}$$

S is the transition matrix between ergodic states, R is the transition matrix from transient to ergodic states and Q is the transition matrix between transient states. Note that the definition

¹¹Chapter 3 of this book : “*Absorbing Markov Chains*”.

of the equivalence class of transient states implies that¹², $\lim_{n \rightarrow \infty} Q^n = \mathbf{0}$. Furthermore, "if a state is the only element of an ergodic state, then it is called an absorbing state". In other words, a particular state i is called an *absorbing state* if and only if:

$$\begin{aligned} P_{ii} &= 1 \\ P_{ij} &= 0 \quad \forall j \neq i \end{aligned}$$

The canonical form of P can then be rewritten:

$$P = \begin{matrix} & \begin{matrix} s & n-s \end{matrix} \\ \begin{matrix} s \\ n-s \end{matrix} & \begin{pmatrix} I & 0 \\ R & Q \end{pmatrix} \end{matrix}$$

Under this form, computing the powers of P is straightforward:

$$P^n = \begin{matrix} & \begin{matrix} s & n-s \end{matrix} \\ \begin{matrix} s \\ n-s \end{matrix} & \begin{pmatrix} I & 0 \\ (I+Q+\dots+Q^n).R & Q^n \end{pmatrix} \end{matrix}$$

As we saw before, P_{ij}^n can be interpreted as the probability for the process to be in state j if it started in state i and underwent n transitions. Since $\lim_{n \rightarrow \infty} Q^n = \mathbf{0}$, we can compute the infinity order:

$$P^\infty = \lim_{n \rightarrow \infty} P^n = \begin{matrix} & \begin{matrix} s & n-s \end{matrix} \\ \begin{matrix} s \\ n-s \end{matrix} & \begin{pmatrix} I & 0 \\ (I-Q)^{-1}.R & 0 \end{pmatrix} \end{matrix}$$

Let us call N the matrix $(I-Q)^{-1}$. The interpretation of P^∞ is (i) that there is a probability of one for the process to end up in an absorbing state and (ii) that $(N.R)_{ij}$ is the probability for the process to end up in absorbing state j if it started in transient state i . This important result will be proven in two other ways in a moment. Before, we wish to provide an interpretation of matrix N by proving N_{ij} is the average number of time the process is found in transient state j if it started in transient state i .

Let us call n_{ij} the random variable corresponding to the number of times the process is in transient state j if it started in transient state i . Let us also define $u_{ij}^{(k)}$ the random variable worth 1 when the process is in state j after k transitions and 0 otherwise, with again a start in

¹²If that wasn't the case, once entered, transient states would never be left, which would imply they are not transient but ergodic states.

state i . Finally, we note $E(X)$ the expectation of random variable X . We then have:

$$\begin{aligned} n_{ij} &= \sum_{k=0}^{\infty} u_{ij}^{(k)} \\ E(n_{ij}) &= E\left(\sum_{k=0}^{\infty} u_{ij}^{(k)}\right) = \sum_{k=0}^{\infty} E(u_{ij}^{(k)}) \\ E(n_{ij}) &= \sum_{k=0}^{\infty} (1 - P_{ij}^k) \cdot 0 + P_{ij}^k \cdot 1 = \sum_{k=0}^{\infty} P_{ij}^k \\ E(n_{ij}) &= \sum_{k=0}^{\infty} Q_{ij}^k = (I - Q)_{ij}^{-1} = N_{ij} \end{aligned}$$

which proves our initial assertion. Let us now define B_{ij} the probability that a process starting in transient state i ends up in absorbing state j . The probability of being captured in a single step is $P_{ij} = R_{ij}$. If that does not happen, the process can either end up in another absorbing state (in which case it will never reach state j) or go to transient state k . In this latter case, the probability it will end up in absorbing state j is by definition B_{kj} . Therefore:

$$\begin{aligned} B_{ij} &= P_{ij} + P_{ik} \cdot B_{kj} \\ B &= R + Q \cdot B \\ B &= (I - Q)^{-1} \cdot R = N \cdot R \end{aligned}$$

An alternative way of proving this relies on the following observation: each time the process is in transient state k , it has a $P_{kj} = R_{kj}$ chance to be absorbed in state j . Given N_{ik} represents the average number of times a process starting in state i passes through state k before being absorbed, this translates into:

$$\begin{aligned} B_{ij} &= \sum_k N_{ik} \cdot P_{kj} \quad \text{with } k \text{ in the set of transient states} \\ B_{ij} &= \sum_k N_{ik} \cdot R_{kj} \\ B &= N \cdot R \end{aligned}$$

5.3.2.2 Interpretation in industrial ecology

Industrial ecology studies the circulation of material and energy flows through human societies, with a perspective of reducing throughput (upstream resource extraction and downstream emissions to nature). As we saw in the introduction, *virtual flows* linked to the consumer's responsibility cannot be measured; only *physical flows* linked to the producer's responsibility can be. The purpose of the MFA process described in Chapter 3, was precisely to assess the physical flows linked to the extraction, transformation and consumption of a specific material. Figure 5.2 is an illustration of what can be obtained with an MFA.

Based on diagram on figure 5.2, we can define the following *states* in which the material can be found:

- a. Extracting sector in region A,

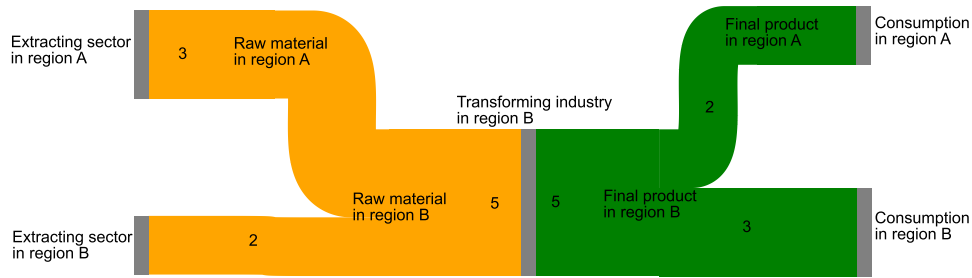


Figure 5.2: Example of MFA results for 1 raw material, 1 final product and 2 regions.

- b. Raw material in region A,
- c. Extracting sector in region B,
- d. Raw material in region B,
- e. Transforming sector in region B,
- f. Final product in region B,
- g. Consumption in region B,
- h. Final product in region A,
- i. Consumption in region A

and we can build the following matrix of flows (where flows always go from rows to columns and empty cells mean *no flow*):

$$\begin{array}{c}
 a \quad b \quad c \quad d \quad e \quad f \quad g \quad h \quad i \\
 \begin{pmatrix}
 a & & & & & & & & \\
 b & & & & & & & & \\
 c & & & & & & & & \\
 d & & & & & & & & \\
 e & & & & & & & & \\
 f & & & & & & & & \\
 g & & & & & & & & \\
 h & & & & & & & & \\
 i & & & & & & & &
 \end{pmatrix}
 \end{array}$$

We can adopt a probabilistic interpretation of these flows, for instance there is a 60% chance ($3/(2+3)$) that materials in state f (final product in region B) then moves to state g (consumption in region B) and a 40% chance ($2/(3+2)$) it will move to state h (final product in region A). Noting g and i are absorbing states, we can use this probabilistic interpretation to build

matrices Q and R :

$$Q = \begin{matrix} & a & b & c & d & e & f & h \\ \begin{matrix} a \\ b \\ c \\ d \\ e \\ f \\ h \end{matrix} & \begin{pmatrix} 1 & & & & & & & \\ & & & & & & & \\ & & & & & & & \\ & & & & & & & \\ & & & & & & & \\ & & & & & & & \\ & & & & & & & \\ & & & & & & & \end{pmatrix} \end{matrix} \quad R = \begin{matrix} & g & i \\ \begin{matrix} a \\ b \\ c \\ d \\ e \\ f \\ h \end{matrix} & \begin{pmatrix} & \\ & \\ & \\ & \\ 0.6 & \\ & 1 \end{pmatrix} \end{matrix}$$

$$N = \begin{matrix} & a & b & c & d & e & f & h \\ \begin{matrix} a \\ b \\ c \\ d \\ e \\ f \\ h \end{matrix} & \begin{pmatrix} 1 & 1 & & 1 & 1 & 1 & 0.4 \\ & 1 & & 1 & 1 & 1 & 0.4 \\ & & & 1 & 1 & 1 & 0.4 \\ & & & & 1 & 1 & 0.4 \\ & & & & & 1 & 0.4 \\ & & & & & & 1 & 0.4 \\ & & & & & & & 1 \end{pmatrix} \end{matrix} \quad B = \begin{matrix} & g & i \\ \begin{matrix} a \\ b \\ c \\ d \\ e \\ f \\ h \end{matrix} & \begin{pmatrix} 0.6 & 0.4 \\ 0.6 & 0.4 \\ 0.6 & 0.4 \\ 0.6 & 0.4 \\ 0.6 & 0.4 \\ 0.6 & 0.4 \\ & 1 \end{pmatrix} \end{matrix}$$

Finally, following the proofs provided in the previous section, we will from now on directly use the following results:

- It is interesting to put the AMC problem in canonical form (thus defining matrices Q and R),
- The $ijth$ term of Matrix $N = (I - Q)^{-1}$ represents the average number of time one unit of i passes through j before being embodied in an absorbing state (usually a final consumption),
- The $ijth$ term of Matrix $B = N.R$ represents the fraction of one unit of i that ends up embodied in absorbing state j .

5.4 Linking IOA with AMC

The main motivation of this section is to apply IOA and AMC on a simple example (Leontief, 1970) in order to illustrate the links between the two. In particular, Duchin and Levine (2013) state that “*the explicit exposition in Peters and Hertwich (2006b) makes clear that the SPA paths [structural paths deriving from IOA] bear no direct relation to the AMC network that joins origin and destination nodes*”, which can be misinterpreted as a close relationship indeed exists between IOA and AMC.

5.4.1 Leontief's example and basic notations in IOA

From	Into	Sector 1 Agriculture	Sector 2 Manufacture	Final Demand Households	Total Output
Sector 1					
Agriculture		25	20	55	100 bushels of wheat
Sector 2					
Manufacture		14	6	30	50 yards of cloth

Figure 5.3: Example of Input-Output table of a national economy. Source: Leontief (1970).

Numbers of figure 5.3 can be interpreted as follows: among the 100 bushels of wheat produced, 45 serve intermediate consumption (25 for agriculture and 20 for manufacture), and 55 are destined to final consumption. We define the following notations:

- Z is the matrix of intermediate consumption,
- Y is the vector of final demand,
- X is the vector of production (total output),
- $A = Z.\hat{X}^{-1}$, is the matrix of technical coefficients (representing the economic "recipe").

We saw that:

$$X = Z.\mathbf{1} + Y = A.X + Y$$

and that the Leontief matrix L is defined by:

$$X = L.Y \quad \text{with} \quad L = (I - A)^{-1}$$

L_{ij} is the production of sector i needed to sustain one unit of final demand of sector j .
 $\tilde{X}_{ij} = (L.\hat{Y})_{ij}$ is the production of sector i needed to sustain final demand of sector j .

We now extend the model to environmental pressures. These can either be resource use or emissions of pollutant: in both cases, these can be seen as production factors (they play a role similar to labor or capital). In the following, we take the example of resource use and we define the following elements:

- f is a row vector representing the intensity of resource use per unit of production in each sector; here it is considered as input data,
- $F = f.\hat{X}$ is a row vector with F_j representing the total use of resource by sector j ,
- $m = f.L$, is a row vector with m_j the amount of resource needed to sustain one unit of final demand of sector j ,
- $\varphi = m.\hat{Y}$, with φ_j the amount of resource needed to sustain final demand of sector j ,

- $F_{tot} = \varphi \mathbf{1} = F \cdot \mathbf{1}$, with F_{tot} the total amount of resource extracted and consumed¹³.

In our example, results are the following:

$$\begin{aligned} Z &= \begin{pmatrix} 25 & 20 \\ 14 & 6 \end{pmatrix} & Y &= \begin{pmatrix} 55 \\ 30 \end{pmatrix} & X &= \begin{pmatrix} 100 \\ 50 \end{pmatrix} \\ A &= \begin{pmatrix} 0.25 & 0.4 \\ 0.14 & 0.12 \end{pmatrix} & L &= \begin{pmatrix} 1.46 & 0.66 \\ 0.23 & 1.24 \end{pmatrix} & L\hat{Y} &= \begin{pmatrix} 80.13 & 19.87 \\ 12.75 & 37.25 \end{pmatrix} \\ f &= (0.5 \quad 0.2) & F &= (50 \quad 10) \\ m &= (0.77 \quad 0.58) & \varphi &= (42.62 \quad 17.38) & F_{tot} &= 60 \end{aligned}$$

For later purposes, we extend every matrix to incorporate the resource sector:

$$Z_{ext} = \begin{pmatrix} 0 & F \\ 0 & Z \end{pmatrix} \quad Y_{ext} = \begin{pmatrix} 0 \\ Y \end{pmatrix} \quad X_{ext} = \begin{pmatrix} F_{tot} \\ X \end{pmatrix} \quad A_{ext} = \begin{pmatrix} 0 & f \\ 0 & A \end{pmatrix} \quad L_{ext} = \begin{pmatrix} I & m \\ 0 & L \end{pmatrix}$$

5.4.2 Basic AMC notations and application to the same example

Based on results from section 3, we directly compute matrices Q , R , N and B . Remember that the proportions of direct flows among the transient states (trade between industries) are represented by matrix Q , and those from transient to absorbing states (final consumption) are represented by matrix R .

$$\begin{aligned} Q &= \bar{A} \quad \text{with} \quad \bar{A} = \hat{X}^{-1}Z = \hat{X}^{-1}A \hat{X} \\ R &= \hat{X}^{-1}\hat{Y} \\ Q \cdot \mathbf{1} + R \cdot \mathbf{1} &= \mathbf{1} \\ N &= \sum_{k=0}^{\infty} Q^k = (I - Q)^{-1} = (I - \bar{A})^{-1} = \hat{X}^{-1} L \hat{X} \\ B &= N \cdot R \end{aligned}$$

Remember that the term B_{ij} is the proportion of sector i eventually embodied in final product j . We then define the following elements to consider environmental pressures (again, here we only consider a single resource¹⁴):

- $\bar{f} = F/F_{tot}$ is a row vector with \bar{f}_j the proportion of total resource extraction directly used by sector j ,
- $\alpha = \bar{f}N = m\hat{X}/F_{tot}$ is also a row vector, with α_j representing the average number of time one resource unit passes through sector j before being embodied in final consumption,

¹³Note that vector F used in section 2 corresponds to F_{tot} in this section.

¹⁴When several pressures are studied, one simply needs to add rows to f and \bar{f} : one row then correspond to one pressure.

- $\beta = \bar{f}NR = \bar{f}B = \alpha R = m\hat{Y}/F_{tot}$ is also a row vector, with β_j the proportion of resource eventually embodied in final consumption of sector j .

Numerical results are the following:

$$Q = \begin{pmatrix} 0.25 & 0.2 \\ 0.28 & 0.12 \end{pmatrix} \quad R = \begin{pmatrix} 0.55 & 0 \\ 0 & 0.6 \end{pmatrix}$$

$$N = \begin{pmatrix} 1.46 & 0.33 \\ 0.46 & 1.24 \end{pmatrix} \quad B = \begin{pmatrix} 0.80 & 0.20 \\ 0.25 & 0.75 \end{pmatrix}$$

$$\bar{f} = (0.83 \quad 0.17) \quad \alpha = (1.29 \quad 0.48) \quad \beta = (0.71 \quad 0.29)$$

Note that, as for the IOA case, we can incorporate the resource sector directly in the matrices:

$$Q_{ext} = \begin{pmatrix} 0 & \bar{f} \\ 0 & Q \end{pmatrix} = X_{ext}^{-1} A_{ext} X_{ext} \quad R_{ext} = \begin{pmatrix} 0 \\ R \end{pmatrix}$$

$$N_{ext} = (1 - Q_{ext})^{-1} = \begin{pmatrix} I & \alpha \\ 0 & N \end{pmatrix} = X_{ext}^{-1} L_{ext} X_{ext} \quad B_{ext} = \begin{pmatrix} \beta \\ B \end{pmatrix}$$

Now that basic vectors and matrices have been defined and interpreted, we can build correspondences between the two approaches.

5.4.3 Upstream and downstream perspectives

We schematize the national economy of Leontief's example in figure 5.4.

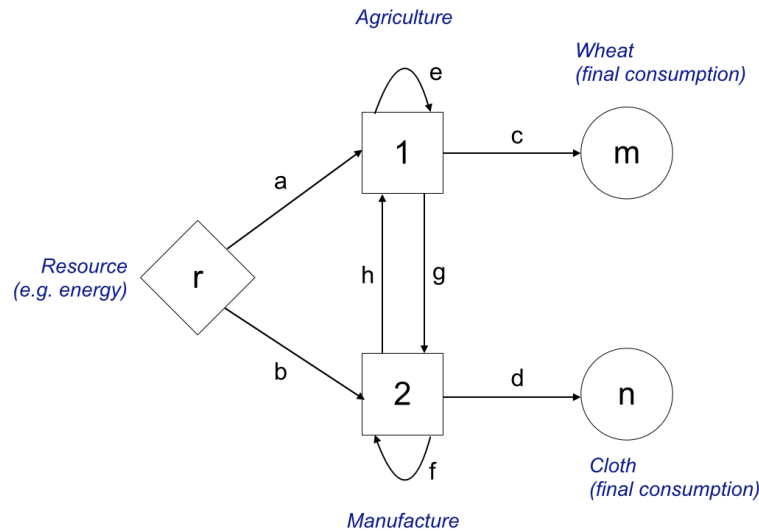


Figure 5.4: Diagram of resource flows. r is the resource sector, 1 and 2 are economic sectors, m and n are consumption sectors. The goal is to quantify resources flows (from a to h) that are embodied in trade between sectors. Resources embodied in nodes (sectors) can be quantified as well.

It is noteworthy that flows a and b correspond to the producer's point of view, while flows c and d correspond to the consumer's point of view. Corresponding formulas are presented in table 5.1.

Point of view	IOA		AMC	
Production	$a = F_1 = f_1 X_1$	$b = F_2 = f_2 X_2$	$a = F_{tot} \bar{f}_1$	$b = F_{tot} \bar{f}_2$
Consumption	$c = \varphi_1 = m_1 Y_1$	$d = \varphi_2 = m_2 Y_2$	$c = F_{tot} \beta_1$	$d = F_{tot} \beta_2$

Table 5.1: Production and consumption footprints in IOA and AMC for sectors 1 and 2.

Formulas for flows and nodes on figure 5.4 are then provided in tables 5.2 and 5.3.

Flow	IOA	AMC	Value
a	$F_1 = f_1 X_1$	$F_{tot} \bar{f}_1$	50
b	$F_2 = f_2 X_2$	$F_{tot} \bar{f}_2$	10
c	$m_1 Y_1$	$F_{tot} \beta_1$	42.62
d	$m_2 Y_2$	$F_{tot} \beta_2$	17.38
e	$m_1 A_{11} X_1 = m_1 Z_{11}$	$F_{tot} \alpha_1 Q_{11}$	19.37
f	$m_2 A_{22} X_2 = m_2 Z_{22}$	$F_{tot} \alpha_2 Q_{22}$	3.48
g	$m_1 A_{12} X_2 = m_1 Z_{12}$	$F_{tot} \alpha_1 Q_{12}$	15.50
h	$m_2 A_{21} X_1 = m_2 Z_{21}$	$F_{tot} \alpha_2 Q_{21}$	8.11

Table 5.2: Embodied resources in flows between sectors: analytical formulas in IOA and AMC frameworks and numeric application.

Node	IO	AMC	Value
r	F_{tot}	F_{tot}	60
1	$F_1 + m_1 Z_{11} + m_2 Z_{21}$	$F_{tot} \alpha_1$	77.48
2	$F_2 + m_2 Z_{22} + m_1 Z_{12}$	$F_{tot} \alpha_2$	28.97
m	$m_1 Y_1$	$F_{tot} \beta_1$	42.62
n	$m_2 Y_2$	$F_{tot} \beta_2$	17.38

Table 5.3: Resources embodied in each sector (node) in IOA and AMC frameworks and numeric application. The value of a node is equal to the sum of flows entering (or leaving) the node.

These formula show that the IO model can be seen as “*demand-driven*”: one starts from intermediate or final consumption (Z or Y) and multiplies it by coefficients accounting for up-stream resource requirements. On the contrary, the AMC model appears as “*resource-driven*”: one starts from the total resource extraction (F_{tot}) and applies transition coefficients to account for the fact that the resource flows from sectors to sectors until final consumption.

In their article, Skelton et al. (2011) propose an alternative representation of the system, by decomposing production layers¹⁵. They argue this representation is useful because it provides

¹⁵These production layers can be viewed as the Taylor decomposition of the Leontief matrix: $L = (I - A)^{-1} = I + A + A^2 + A^3 + \dots$

intermediate points of view between production and consumption. We use it to represent our problem (figure 5.5). The authors already provide the expression of each flow in the IOA framework. We start by expressing them in the AMC framework (table 5.4).

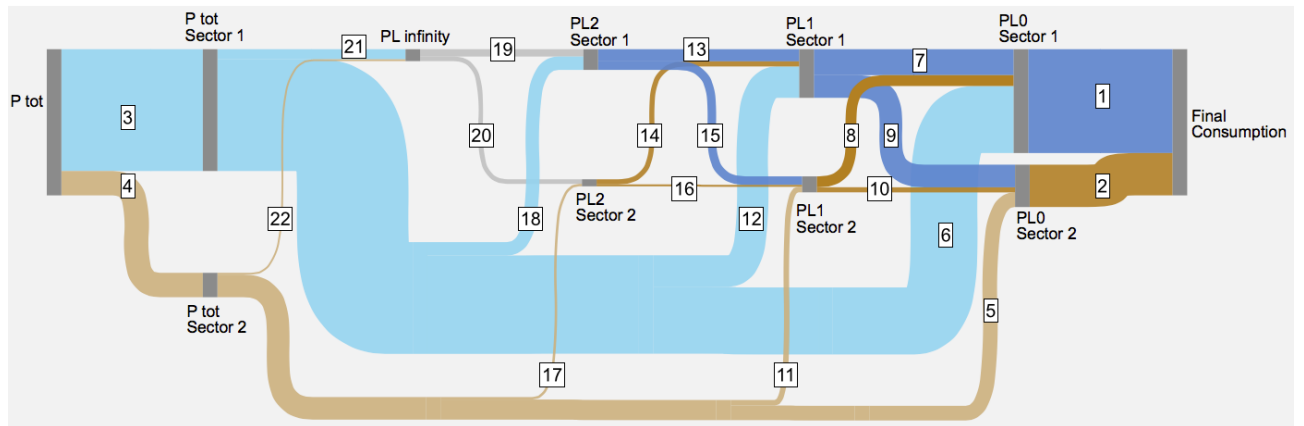


Figure 5.5: Flows of resources from consumption, through production layers, to original production. Light shades correspond to direct resource use by sectors and dark shades to resources embodied in products. For instance, in order to provide product 1 to final consumption (flow 1), sector 1 directly uses resources (flow 6) but also requires inputs from sector 1 and sector 2 that embody a certain amount of resources (flows 7 and 8) and so forth.

Flow	IO	AMC	Value
1	$\varphi_1 = m_1 Y_1$	$\varphi_1 = F_{tot} \beta_1$	42.62
2	$\varphi_2 = m_2 Y_2$	$\varphi_2 = F_{tot} \beta_2$	17.38
3	$F_1 = f_1 X_1$	$F_1 = F_{tot} \bar{f}_1$	50
4	$F_2 = f_2 X_2$	$F_2 = F_{tot} \bar{f}_2$	10
5	$f_2 Y_2$	$F_2 R_{22} = F_{tot} \bar{f}_2 R_{22}$	6
6	$f_1 Y_1$	$F_1 R_{11} = F_{tot} \bar{f}_1 R_{11}$	27.5
7	$m_1 A_{11} Y_1$	$F_{tot} \alpha_1 Q_{11} R_{11} = F_{tot} Q_{11} \beta_1$	10.65
8	$m_2 A_{21} Y_1$	$F_{tot} \alpha_2 Q_{21} R_{11}$	4.46
9	$m_1 A_{12} Y_2$	$F_{tot} \alpha_1 Q_{12} R_{22}$	9.30
10	$m_2 A_{22} Y_2$	$F_{tot} \alpha_2 Q_{22} R_{22} = F_{tot} Q_{22} \beta_2$	2.09
11	$f_2 A_2:Y$	$F_2 Q_{21} R_{11} + F_2 Q_{22} R_{22} = F_2 Q_2:R1$	2.26
12	$f_1 A_1:Y$	$F_1 Q_{11} R_{11} + F_1 Q_{12} R_{22} = F_1 Q_1:R1$	12.88
13	$m_1 A_{11} A_1:Y$	$F_{tot} \alpha_1 Q_{11} (Q_{11} R_{11} + Q_{12} R_{22}) = F_{tot} \alpha_1 Q_{11} Q_1:R1$	4.99
14	$m_2 A_{21} A_1:Y$	$F_{tot} \alpha_2 Q_{21} (Q_{11} R_{11} + Q_{12} R_{22}) = F_{tot} \alpha_2 Q_{21} Q_1:R1$	2.09
15	$m_1 A_{12} A_2:Y$	$F_{tot} \alpha_1 Q_{12} (Q_{21} R_{11} + Q_{22} R_{22}) = F_{tot} \alpha_1 Q_{12} Q_2:R1$	3.5
16	$m_2 A_{22} A_2:Y$	$F_{tot} \alpha_2 Q_{22} (Q_{21} R_{11} + Q_{22} R_{22}) = F_{tot} \alpha_2 Q_{22} Q_2:R1$	0.79
17	$f_2 A_2:AY$	$F_2 Q_2:QR1$	0.99
18	$f_1 A_1:AY$	$F_1 Q_1:QR1$	5.48
19	$(m_1 - f_1) A_1:AY$	$(F_{tot} \alpha_1 - F_1) Q_1:QR1$	3.01
20	$(m_2 - f_2) A_2:AY$	$(F_{tot} \alpha_2 - F_2) Q_2:QR1$	1.88
21	$3 - (6 + 12 + 18)$	$3 - (6 + 12 + 18)$	4.15
22	$4 - (5 + 11 + 17)$	$4 - (5 + 11 + 17)$	0.75

Table 5.4: IO and AMC formulas of flows from figure 5.5. The notation M_k : refers to the kth row of matrix M, that is, a row vector.

Finally, we provide the link between representations from figures 5.4 and 5.5. If PL_i^k represents the amount of resources embodied in the production layer of sector i at order k (shown in figure 5.5) and $Flow_{ij}$ and $Node_i$ correspond to what is shown in figure 5.4, then:

$$\sum_{k=0}^{\infty} Flow_{PL_i^{k+1} \rightarrow PL_j^k} = Flow_{ij} = \text{total resources embodied in flows from sector } i \text{ to sector } j,$$

$$\sum_{k=0}^{\infty} PL_i^k = Node_i = \text{total resources embodied in sector/node } i.$$

As a proof, we sum the interlayers flows between sectors i and sector j . Again, we note A_j : the j th row of matrix A :

$$m_i A_{ij} Y_j + \sum_{k=0}^{\infty} m_i A_{ij} A_j: A^k Y = m_i A_{ij} (Y_j + A_j: X) = m_i A_{ij} X_j = m_i Z_{ij} = Flow_{ij}$$

We see that providing different representations of the same object enables a better understanding of its functioning. Depending on the question tackled, one representation may be better suited. We want to end this section with the correspondence between structural path analysis in IOA and AMC¹⁶. As explained by Peters and Hertwich (2006b), these structural paths pro-

¹⁶Supplementary material for Chapter 6 describes an algorithm to compute these path in the case of AMC.

vide the detailed linkage between production and consumption activities. In Leontief’s example we saw that the final consumption of 55 bushels of wheat required the use of 42.62 units of resource. As explained in section 2.2, Structural Paths (SP) in fact correspond to the finest decomposition of these 42.62 units. The order of the SP corresponds to the production layer where the initial resource extraction occurred. SPA are often expressed using IOA notations, but not, to our knowledge, using AMC notations. We show the equivalence between the two in table 5.5.

SPA order	IO	AMC	Application
0	$f_i Y_i$	$f_i X_i / X_i Y_i = F_i R_{ii}$	$\forall i$
1	$f_i A_{ij} Y_j$	$f_i Q_{ij} X_i / X_j Y_j = F_i Q_{ij} R_{jj}$	$\forall i, j$
2	$f_i A_{ij} A_{jk} Y_k$	$f_i Q_{ij} Q_{jk} X_i / X_k Y_k = F_i Q_{ij} Q_{jk} R_{kk}$	$\forall i, j, k$
...
Total	$mY = F_{tot}$	F_{tot}	sum of all possible paths

Table 5.5: Classical SPA in IOA: IO and AMC formulation. Again, we note that paths must be interpreted upstream in the IOA formulation and downstream with the AMC formulation.

5.5 Transforming SUT into a single square matrix

In the course of the presentation of the SC-MFA model (Chapter 3), we showed the Supply-Use Tables (SUT) framework was very well suited to organize MFA data. SUT, however, are not square matrices, which is a requirement when one wants to undertake IOA or AMC (because of matrix inversion). To make this transformation, a first option is to move from product-by-industry matrices to product-by-product (M_p), or industry-by-industry matrices (M_i). The construction of these matrices (as well as underlying hypotheses) is discussed in chapter 5 of Miller and Blair (2009). However, matrices M_p and M_i contain less information than the original SUT. In order to conserve all the information, it is possible to build either of the two following matrices:

$$M_{ip} = \begin{matrix} & \begin{matrix} industries & products \end{matrix} \\ \begin{matrix} industries \\ products \end{matrix} & \begin{pmatrix} 0 & S^t \\ U & 0 \end{pmatrix} \end{matrix} \quad M_{pi} = \begin{matrix} & \begin{matrix} products & industries \end{matrix} \\ \begin{matrix} products \\ industries \end{matrix} & \begin{pmatrix} 0 & U \\ S^t & 0 \end{pmatrix} \end{matrix}$$

This is the option chosen in the next Chapter.

The concepts presented in this chapter will be implemented in Chapter 6 to trace cereal flows and associated environmental pressures. As we hope we achieved to show, there is a direct correspondence between IOA and AMC, so either framework could have been used. However, using AMC seems more natural when the main concern is to trace flows

downstream, which is the case for an export-oriented supply chain as the French cereal chain.

Environmental pressures embodied in the French cereals supply chain

This article was published in the special issue of the Journal of Industrial Ecology *Linking local consumption to global impacts*.

Courtonne, J.-Y., Longaretti, P.-Y., Alapetite, J. and Dupré, D. (2016), Environmental Pressures Embodied in the French Cereals Supply Chain. *Journal of Industrial Ecology*, 20: 423-434.

Abstract. France is the second largest exporter of cereals in the world. Although the cereals supply chain is an asset for the country's economy and employment, it is at the same time responsible for a number of pressures on the local and global environment including greenhouse gases (GHG) emissions and stresses on water quality and quantity. This article aims at evaluating this situation from an environmental point of view by linking productions occurring in French regions with consumptions occurring in France and abroad. Based on previous work on Material Flow Analysis, we use an Absorbing Markov Chain model to study the fate of French cereals and link worldwide consumptions to environmental pressures along the supply chain, that is, induced by production, transformation or transport. The model is based on physical supply and use tables and distinguishes between 21 industries, 22 products, 38 regions of various spatial resolution (22 French regions, 10 countries, 6 continents) and 4 modes of transport. Energy use, GHG emissions, land use, use of pesticides and blue water footprint are studied. Illustrative examples are taken in order to demonstrate the versatility of the results produced, for instance: Where and under what form does local production end up? How do regions compare relatively to their production and consumption footprints? These results are designed to be a first step towards scenario analysis for decision-aiding that would also include socio-economic indicators. Examples of such scenarios are discussed in the conclusion.

6.1 Introduction

The producer-centric approach to environmental impacts of economic activities was historically the first developed. Lenzen et al. (2007) suggest it may be because questioning consumer preferences was not in line with a free-market philosophy. A complementary explanation is that the producer's responsibility is the most easily and objectively traceable as it concerns flows that can be physically observed on site; on the contrary, a series of allocation hypotheses are needed in order to trace consumer's responsibility. In today's economy, intensively relying on international trade, environmental accounts from both perspectives are a necessity to guide decision-making and prevent a simple externalization of impacts. In the past two decades, an important research effort was put on the development of Input-Output Analysis (IOA) in order

Chapter 6. Environmental pressures embodied in the French cereals supply chain

to associate final consumption expenditures of households and administrations with the worldwide production of goods and services they trigger. Of all environmental pressures, greenhouse gases (GHG) emissions were the most studied (Peters and Hertwich, 2006a) (Wiedmann et al., 2010), although research also targeted water use (Guan and Hubacek, 2007), land use (Yu et al., 2013) or material flows (Bruckner et al., 2012) to name only a few. Socio-economical aspects were also studied (Simas et al., 2014). The second path of research to link producer's and consumer's responsibilities is the coupling of Material Flow Analysis (MFA) with Life Cycle Assessment (LCA), or more simply with ratios of pressure intensity (Rochat et al., 2013). This is for instance the approach followed in the classical calculation of the Ecological Footprint (Wackernagel et al., 2005). Each method having its own drawbacks (typically, trade of services is not accounted for in the MFA-based approach, while IOA can sometimes lead to questionable results (Kastner et al., 2014)), the choice between the two relies on the research question and on data availability. Our study is based on supply chain material flows because of our focus on the regional level and of the level of detail we aim at¹.

A supply chain is by definition a group of sectors organized to produce, transform and distribute specific goods to consumers. It is therefore an obvious object of study when it comes to analyzing the links between production and consumption. Leigh and Li (2014) propose a literature review on environmental approaches to sustainable supply chain management, that includes environmental management, design for environment, product stewardship, green purchasing, reverse logistics, recycling, reuse and remanufacturing. This body of literature studies the supply chain from a company's perspective. In a complementary way, the present work adopts a territorial point of view and is primarily intended for institutional decision makers at regional and national levels. Cazcarro et al. (2014) propose a similar perspective by focusing on footprints and scenario analysis of the agro-industry of a Spanish region. They underline the importance of articulating regional and national strategies, stressing Spanish regions have major competences regarding the local economy and environment. While France remains more centralized than Spain, the jurisdiction of local territories tends to expand. Calame and Lalucq (2009) insists on the pivot role territories and supply chain could play in a transition to sustainability at local, national and international scales, benefiting from both horizontal (territorial coherence) and vertical (chain of production) integration. Moreover, they argue that these two actors are well adapted to a cooperative vision of the economy.

The present article is the second step of a project aiming at analyzing local supply chains from an economic, social and environmental perspective for decision-aiding. Here, our goal is to analyze environmental pressures along supply chains, that is from the producer's to the consumer's viewpoint, to see what pressures are internalized or externalized by French regions and foreign countries. This article follows a study which produced Material Flow Analysis (MFA) on every regional level by downscaling the national MFA (Courtonne et al., 2015). We shortly present these results in the methodology section as they are the starting point of the present work.

Although the methodology developed here could be applied to any supply chain or region, we implement it on the case of the French cereals supply chain. Cereals are, in terms of weight of production the most important agricultural good in France. The supply chain is a significant contributor to the national economy with a turnover of more than 50 billion euros and 500,000 jobs. It is also the largest contributor to the positive trade balance of the country's agro-

¹IO tables are not compiled at the level of French regions and the national table only distinguishes between 65 sectors.

industrial sector, along with wine (FranceAgriMer, 2012). Orientations for the development of the supply chain were recently proposed by the ministry of agriculture and confirmed this strategic role of exports. The model is focused on French regions: total productions, trade and consumptions of foreign countries are not studied, only the portion linked to the French supply chain is, that is, either imports of French products or exports of local production to France. According to FAO statistics, France was the 7th largest cereals producer in the world in 2011 (after China, the United States, India, Russia, Indonesia and Brazil) but the 2nd largest exporter (after the USA). Our study therefore encompasses about 3% of global production and 11% of global trade of cereals.

We study five environmental pressures that are especially relevant for the cereals supply chain: energy consumption, GHG emissions, land use, use of pesticides and blue water consumption. Both global (for instance GHG emissions) and local (for instance use of pesticides) environmental pressures were included in order to aim at a holistic view of the situation. A recent assessment of the implementation of the Water Framework Directive in France revealed that rivers' contamination with pesticides was especially high in cereals-growing regions (SOeS, 2015a). With about 90 Mt CO₂ eq., agriculture is responsible for nearly one fifth of French greenhouse gases emissions² (SOeS, 2015b). Transport and of transformation industries are also responsible for emissions through their use of energy. According to Ercin et al. (2012), crop growing accounts for half of the French blue water footprint of production. Cereals represent 59% of this half, corn representing 50% on its own (the last 9% are shared between rice, wheat, triticale, barley and oats). Production of corn ranks first in the causes of water scarcity in the summer months in many regions, especially in Midi-Pyrénées, Aquitaine, Poitou-Charentes and Centre.

The first section is dedicated to the presentation of the methodology and of the datasources. We present the results in the second section laying the emphasis on the types of questions can be tackled with the model: *What is the fate of the regional production? What are the supply areas of the regional consumption? What pressures are associated to each life-cycle stage? What pressures are embodied in a specific consumption? What are the production and consumption footprint of a region? What are the main paths between production and consumption? How do regions compare relatively to their per-capita footprint of consumption?* We then discuss the limits and potential leads to improve the model. The concluding section summarizes the main features of the method developed for the present paper as well as some important findings, before outlining how such results can be used for actual decision-help, in particular through the discussion of energy transition and land use scenarios for France at the 2050 time horizon.

6.2 Materials and methods

Studying how environmental pressures flow from producers to consumers is done in 3 steps:

- Reusing and extending an existing MFA model at the level of French regions,
- Tracking flows downstream using an AMC model with transport sectors,
- Coupling material flows with associated pressures on the environment all along the supply

²This number includes livestock and crop farming (most of the emissions accounted for occur under the form of methane and nitrogen protoxide).

Chapter 6. Environmental pressures embodied in the French cereals supply chain

chain, that is pressures generated for the production of raw materials, pressures generated by transformation industries and pressures generated by freight.

Coupling of MFA with Markov chains modeling was for instance previously done by Eckelman and Daigo (2008) (for a discussion on the relationships between AMC, IOA and MFA see Eckelman et al. (2012)). This methodology can be applied to any type of product; here it is specifically applied to the French cereals' supply chain.

6.2.0.1 An MFA on cereals in every French region

We base the model on previous results of the authors (Courtonne et al., 2015). MFAs on the cereals supply chain in the 22 French regions were produced in the form of reconciled physical supply and use tables by downscaling the national MFA. 19 products (raw materials, intermediate and end-products) and 18 industries were taken into account. The period studied was the annual average between years 2001 and 2009 and is therefore the same in the present article.

In this previous work, these MFAs were limited to physical cereal flows, for instance flows of bread were considered because they physically embody cereal grains but flows of livestock products were left out, meaning that the model considered livestock consumption as a final consumption. This makes sense in a pure MFA study but becomes problematic when one is interested in studying and allocating environmental pressures: typically, husbandry regions would then have a high consumption footprint even if their animal products are consumed elsewhere.

In order to overcome this issue, three animal products were included in this extension of the model: meat, milk (including milk products) and eggs. Balanced MFAs at the level of French regions were obtained using the methodology described in Courtonne et al. (2015) and data sources from the French Ministry of Agriculture, from customs data and from the SitraM database for inter-regional trade. All details regarding the classifications used are available in supplementary material.

6.2.0.2 An AMC model to track flows from producers to consumers

The next step is to study the fate of cereals products and the paths they take in the economy. Typical questions are: *Where and under what form does a grain of wheat produced in region A end? What productions and transports were needed in order to consume 1 kg of bread in region B?* Here, the two questions respectively adopt a downstream and an upstream perspective. The AMC model implemented is inspired by the one proposed by Duchin and Levine (2013). The main difference is that we build the tables directly from our MFA data and not from Input-Output tables. A smaller difference is in the way we deal with transport sectors (we associate each transport flow with the product traded whereas they rather model the trade of transport services between regions).

Flows through a (spatialized) supply chain can be seen as changes of state of the quantities involved. After being normalized, they can be interpreted as transition probabilities. Note that the underlying assumption here is a *perfect blend* between local production and imports: without additional information we assume once a product is available in a region, its use is independent from its geographical origin. As explained by Duchin and Levine (2010), "for any system represented by n states, the parameters of an AMC are the probabilities of directly

transitioning from one state to another; they are contained in an $n \times n$ transition matrix M . M_{ij} describes the likelihood of transitioning from state i to state j . Therefore the sum of any row equals 1. State i is called an absorbing state if M_{ii} equals 1, meaning it can no longer be exited. In our model, this is the case for end-products that are consumed and for losses. The M matrix can be put into the following canonical form (Kemeny and Snell, 1976):

$$M = \begin{pmatrix} Q & R \\ 0 & I \end{pmatrix} \quad (6.1)$$

In equation 6.1, Q_{ij} represents the proportion of flows in transient state i directly moving to transient state j . This is the case when an industry supplies a product, when a product is used by an industry and when a product is exported from one region to another. Similarly, R_{ij} is the proportion of flows from transient state i directly moving towards absorbing state j .

Below we give more details on the content on the Q and R matrices. We define the following elements:

- $\mathbf{1}$ is a summation vector (column vector filled with 1). Its size is contextual.
- n is the number of regions.
- p is the number of products.
- q is the number of industries.
- t is the number of transport modes.
- S^r is the domestic supply matrix of region r of size (p,q) .
- $\overline{S^r} = S^r \mathbf{1}$ is a column vector representing the local supply of each product whatever the producing industry.
- $\overline{(S^r)^T} = (S^r)^T \mathbf{1}$ is a column vector representing the total production of each industry of region r , whatever the product.
- U^r is the domestic use matrix of region r of size (p,q) .
- $\overline{U^r} = U^r \mathbf{1}$ is a column vector representing the use of each product by industries of region r , whatever the consuming industry.
- $E^{r,s}$ vector of exports from region r to region s of size p .
- $T^{r,s}$ matrix of transport from region r to region s of size (t,p)
- $T^r = \sum_s T^{r,s}$ matrix of transport from region r to all other regions.
- $\overline{T^r} = T^r \mathbf{1}$ is a column vector representing for each transport mode the total transport from region r .
- C^r is the vector of consumption of region r of size p .
- Z^r is the vector of total supply of region r of size $q + p + t$.

Chapter 6. Environmental pressures embodied in the French cereals supply chain

Vectors Z^r are composed of 3 parts:

$$Z^r = \begin{matrix} 1 \\ q \\ p \\ t \end{matrix} \begin{pmatrix} Z_1^r \\ Z_2^r \\ Z_3^r \end{pmatrix} \quad Z_1^r = \left[(\overline{S^r})^T \right] \quad Z_2^r = \left[\overline{S^r} + \sum_s E^{s,r} \right] = \left[\overline{U^r} + \sum_s E^{r,s} + C^r \right] \quad Z_3^r = \left[\overline{T^r} \right]$$

Matrices $T^{r,s}$ are computed based on 3 elements:

- $E^{r,s}$ trade flows from region r to region s , not necessarily expressed in real weight, for instance we use the cereals grain equivalent unit, of size $(p,1)$,
- w vector of conversion ratios from trade unit to real weight, of size $(p,1)$,
- $D^{r,s}$ matrix representing distances of transport between regions, of size (t,p) : each mode of transport is one row of the matrix and each product is a column. For international flows, we estimate the distance from/to the country of loading/unloading based on the mode of transport. Equation 6.2 therefore illustrates the properties of matrices $D^{r,s}$ for international transport. For domestic inter-regional flows, we exploit the SitraM database providing information both in tonnes and tonnes.kms for each good, mode of transport, origin and destination. Hence it is possible to compute average distances (*tonnes.kms / tonnes*) for each group defined by a good, mode of transport, region of origin and of destination. These distances are good estimates of distances from facilities to facilities.

The following properties only hold when r or s are foreign regions, they don't in the case of French interregional trade:

$$D^{r,s} = D^{s,r} \quad D_{m,j}^{r,s} = D_{m,k}^{r,s} \quad \forall \text{ products } j, k \quad (6.2)$$

The transport matrices, which show results in weight.distances (typically tonnes.kms) are then computed as follow (note that we use the hat symbol to refer to the diagonal matrix created from a vector):

$$T^{r,s} = D^{r,s} \hat{w} \hat{E}^{r,s}$$

The Q and R matrices presented below are respectively of size $(n.(q+p+t), n.(q+p+t))$ and $(n.(q+p+t), n.p)$. Q can be partitioned:

$$Q = \begin{bmatrix} Q_{11} & \dots & Q_{1r} & \dots & Q_{1n} \\ & \ddots & & & \\ Q_{r1} & \dots & Q_{rr} & \dots & Q_{rn} \\ & & & \ddots & \\ Q_{n1} & \dots & Q_{nr} & \dots & Q_{nn} \end{bmatrix}$$

with

$$Q_{rr} = \begin{matrix} q & p & t \\ q \\ p \\ t \end{matrix} \begin{pmatrix} 0 & (\hat{Z}_1^r)^{-1} (S^r)^T & 0 \\ (\hat{Z}_2^r)^{-1} U^r & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

and

$$Q_{rs} = \begin{matrix} & q & p & t \\ \begin{matrix} q \\ p \\ t \end{matrix} & \begin{pmatrix} 0 & 0 & 0 \\ 0 & (\hat{Z}_2^r)^{-1} \hat{E}^{r,s} & 0 \\ 0 & (\hat{Z}_3^r)^{-1} T^{r,s} & 0 \end{pmatrix} \end{matrix}$$

R is also partitioned

$$R = \begin{bmatrix} R_{11} & \dots & 0 & \dots & 0 \\ & & \vdots & & \\ 0 & \dots & R_{rr} & \dots & 0 \\ & & \vdots & & \\ 0 & \dots & 0 & \dots & R_{nn} \end{bmatrix}$$

with

$$R_{rr} = \begin{matrix} & p \\ \begin{matrix} q \\ p \\ t \end{matrix} & \begin{pmatrix} 0 \\ (\hat{Z}_2^r)^{-1} \hat{C}^r \\ 0 \end{pmatrix} \end{matrix}$$

Then two matrices of interest can be computed, N and B :

$$N = (I - Q)^{-1} \quad B = NR \quad (6.3)$$

Each row i of matrix B can be interpreted as the fate of sector/product i . For instance, the B_{ij} term is the proportion of i that is finally embodied in region-product j . As we will show it in the next section, it is interesting to aggregate the terms either by product type or by region. If we define the Z vector as equation 6.4, we can compute matrix $\hat{Z}B$, with the ij^{th} term representing the amount of i finally embodied in region-product j . Finally, we can compute matrix L^3 as defined in equation 6.5⁴ and its ij^{th} term will be interpreted as the amount of i needed in order to consume one unit of region-product j .

$$Z = \begin{bmatrix} Z^1 \\ \vdots \\ Z^n \end{bmatrix} \quad (6.4)$$

$$L = \hat{Z} B \hat{C}^{-1} \quad \text{with } C = \begin{bmatrix} C^1 \\ \vdots \\ C^n \end{bmatrix} \quad (6.5)$$

Table 6.1 presents the size of the main variables/matrices used.

³We deliberately name this matrix L because it can be seen as an equivalent of the traditional Leontief matrix in IOA.

⁴Elements equal to zero in vector C are replaced by ones in order to make \hat{C} invertible ; the same is done on Z^r vectors. This operation is purely technical and has no impact on the results.

Chapter 6. Environmental pressures embodied in the French cereals supply chain

Variable	Size	Comment
n	38	22 French regions, 10 countries, 6 continents
p	22	19 cereals products, 3 animal products
q	21	1 livestock farming sector
t	4	sea, road, railroad, river
Q, N	1786, 1786	the Q matrix is sparse
$R, B, \hat{Z}B, L$	1786, 836	the R matrix is sparse

Table 6.1: Sizes of the model's variables.

6.2.0.3 Coupling material flows with environmental pressures

Data sources to inform environmental stakes of the supply chain

As explained in the introduction, we study five environmental pressures that are especially relevant for the cereals supply chain: energy consumption, GHG emissions, land use, use of pesticides and blue water consumption. Berger and Finkbeiner (2013) show drawbacks of volumetric water footprints, arguing that numerically smaller footprints can cause higher impacts. In particular they criticize the aggregation of green and blue water footprints by questioning the definition of water consumption. In this work, we build on previous diagnosis about regional water stress, and study the blue water footprint of cereals, that is the withdrawals of surface or groundwater. Table 6.2 presents the data sources used for estimating pressures from the producer's viewpoint.

Extension of the AMC model to environmental pressures

Let α be the number of environmental pressures under study, 5 in our case. We define matrix F so that F_{ij} represents the direct emission of environmental pressure i by sector-region j . F_i is the total environmental pressure i emitted, whatever the sector or region. Finally, f matrix is defined as: $f_{ij} = F_{ij}/F_i$. We then extend our Q and R matrices as follow, in line with Duchin and Levine (2010):

$$Q' = \begin{matrix} \alpha & dim_Q \\ \alpha & dim_Q \end{matrix} \begin{pmatrix} 0 & f \\ 0 & Q \end{pmatrix} \quad R' = \begin{matrix} dim_R \\ \alpha & dim_Q \end{matrix} \begin{pmatrix} 0 \\ R \end{pmatrix} \quad Z' = \begin{matrix} 1 \\ \alpha & dim_Q \end{matrix} \begin{pmatrix} F \\ Z \end{pmatrix}$$

We compute matrices N' , B' the same way as explained above:

$$N' = \begin{matrix} \alpha & dim_Q \\ \alpha & dim_Q \end{matrix} \begin{pmatrix} I & fN \\ 0 & N \end{pmatrix} \quad B' = \begin{matrix} dim_R \\ \alpha & dim_Q \end{matrix} \begin{pmatrix} fB \\ B \end{pmatrix}$$

The i^{th} row of B' ($i \leq \alpha$) indicates in what consumption environmental pressure i is eventually embodied, summing all the paths taken from production to consumption. Similarly to IOA, it is however interesting to compute the main paths contributing to this sum, using the Taylor decomposition of matrix N' . We describe the algorithm used for this purpose in the Supplementary Material.

Pressure	Production	Transformation	Transport
Energy	Agribalyse, national average (ratio per kg of product)	Agreste survey on energy consumption in the agro-industry (regional data)	Base Carbone (ratio per t.km)
Greenhouse gases	Agribalyse, national average (ratio per kg of product)	Energy use times emission factors	Base Carbone (ratio per t.km)
Land use	Agreste (French regions), FAO (foreign countries)	-	-
Pesticides use	Agribalyse, national average (kg of active substance per ha), Agreste survey on farming practices (regional Treatment Frequency Indices)	-	-
Blue water footprint	Mekonnen and Hoekstra (2011), Ercin et al. (2012)	IREP database	-

Table 6.2: Datasources for pressure estimation from the producer’s viewpoint. The production stage refers to the production of raw materials (called extraction in the MFA terminology). Agribalyse (Ademe, 2015a) an official Life-Cycle-Inventory and Life-Cycle Assessment database for French agricultural products. Base carbone (Ademe, 2015b) is an official database for greenhouse gases emission factors. Agreste is the statistical service of the French Ministry of Agriculture. The IREP database (Ineris, 2015) provides water withdrawals of industrial sites that reach registration thresholds; extrapolations for each sector of the agro-industry were computed on this basis.

6.3 Results

In this section we present a range of questions than can be tackled with the model described above, stating each time what matrices are used. It is meant to be illustrative and therefore focuses on a few examples only. More comprehensive results are available in the Supplementary Material. The same methodology could be applied to other supply chains, territories and environmental pressures. We then discuss the limits of the model and some potential leads to improve it.

Studying the fate of a specific product

As explained before, the model is focused on France and its main goal is to track resources and pressures downstream. In order to illustrate this, we show the fate of corn grown in the Midi-Pyrénées region. This example is of particular interest because water is becoming a major stake in this region both in terms of quality (in particular, pollution by pesticides) and quantity. We use matrix B to produce the results. They indicate that nearly two thirds of the corn is embodied in the consumption of foreign countries, pointing to the internalization of environmental impacts in Midi-Pyrénées. Figure 6.1 shows the regions of destination. It is also interesting to study under what form the corn is eventually consumed. 49% remains under the form of grain, meaning it is exported, lost or used for seeds. Animal products account for 48% of the total (43% for meat only, 4% for milk and 1% for eggs). Since the fate of exported grains is not modeled, this number is underestimated, given most of the exported corn is likely to be fed to livestock. Finally starch and canned corn respectively represent 2% and 1%.

Studying the supply area for a specific product

Another way to exploit the results is to estimate supply areas for specific products. Starting from a final product, it is interesting to trace back earlier production stages and to compute average supply distances at each stage. This gives an idea of the degree of dependency of the region regarding the consumption of this final product. To illustrate this, we use matrix L along with distances matrices to analyze the supply of bread in the Provence-Alpes-Côte-d'Azur region (PACA). Figure 6.2 shows that the more we go back in the supply chain the further supply areas are located: average supply distances for bread, flour and wheat are respectively 55 km, 195 km and 470 km (distance is considered null for products originating from the PACA region itself).

Identifying the main life-cycle-steps producing environmental pressures

Table 6.3 shows total amounts of pressures produced (whatever the region of production) and splits them among the production, transformation and transport phases using matrix $\hat{F}f$. In all cases, the production phase clearly stands out as the most critical. Still, in the case of GHG, transformation and transport are significant with nearly one third of total emissions. Regarding the transport sector, road freight ranks first as GHG emitter (79% of the emissions with 28% of the tonnes kilometers), followed by sea freight (19% of the emissions with 66% of the tonnes kilometers). Domestic transport only represents 16% of total tonnes kilometers although it amounts to 64% of the tonnage traded. The production phase represents a larger part in energy consumption than in GHG emissions because of a biomass-based energy consumption at the farm, according to the LCA database. Regarding the blue water footprint of transformation

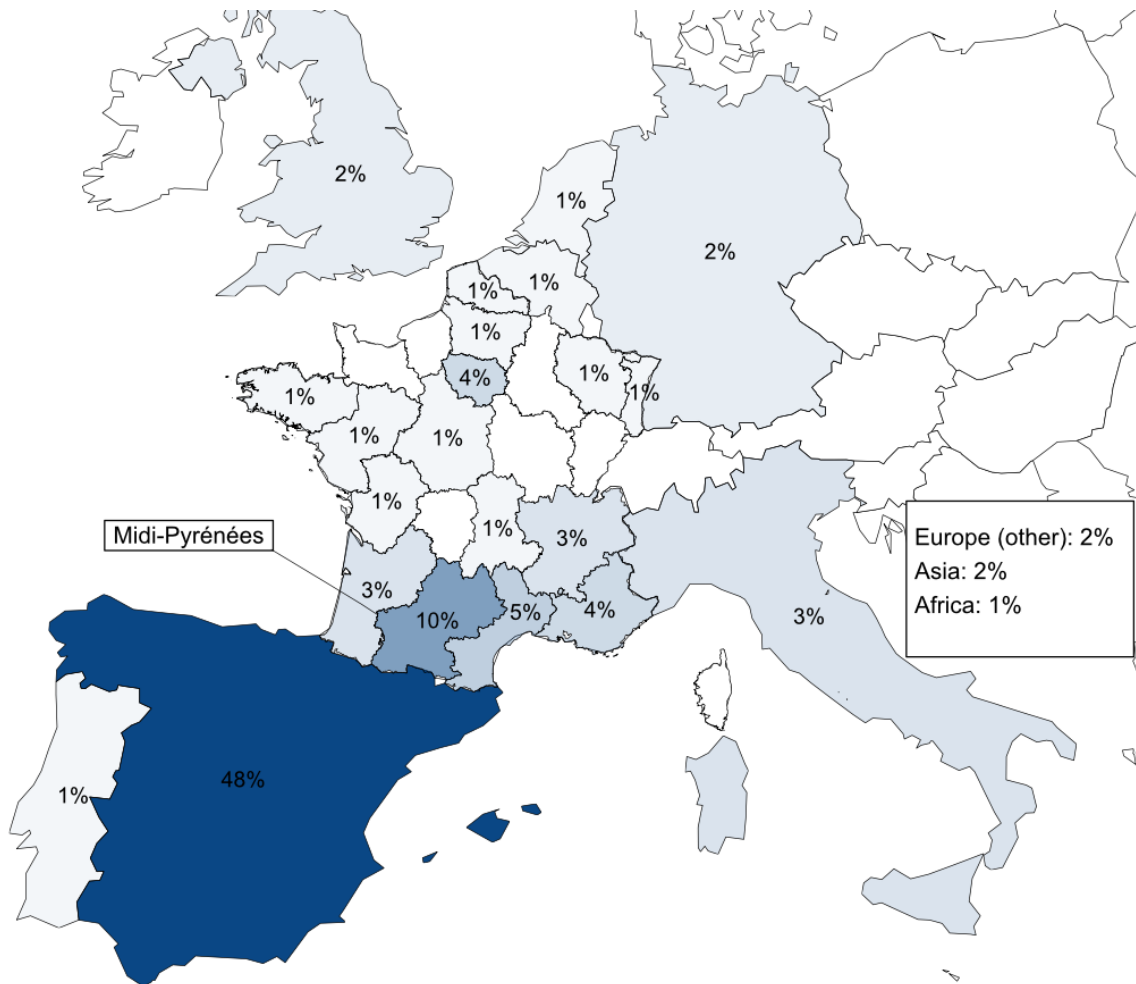


Figure 6.1: Fate of corn grown in the Midi-Pyrénées region. Darker color means greater consumption of corn or corn products. With nearly half of the regional production, Spain is by far the main destination. Additional cross-check with FAO statistics shows that Spain only exports about 1% of its corn supply. 10% of the production of corn in Midi-Pyrénées eventually serves local consumption, mostly under the form of meat (7%), seeds and losses and milk products accounting respectively for 2% and 1%.

Chapter 6. Environmental pressures embodied in the French cereals supply chain

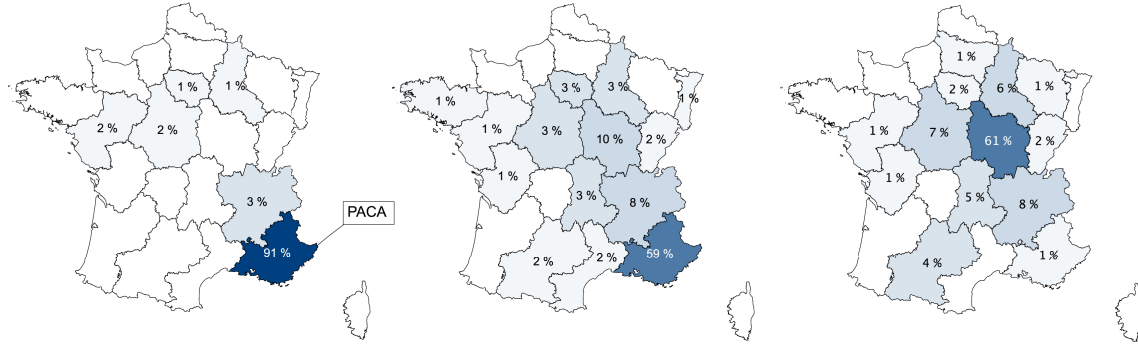


Figure 6.2: The supply chain of bread consumed in the Provence-Alpes-Côte-d’Azur (PACA) region. From left to right: supply areas for bread, flour used for bread and wheat used for bread. Darker color means greater contribution. Supply coming from abroad is negligible (less than 1% in each case).

industries, starch factories rank first with about two thirds of the water consumption⁵.

Pressure	Production	Transformation	Transport	Total
Energy use	86 %	5 %	9 %	407 TWh
GHG emissions	68 %	8 %	24 %	42.0 Mt CO ₂ eq.
Land use	100 %	-	-	10.3 Mha
Pesticides use	100 %	-	-	20.0 kt
Blue water footprint	96 %	4 %	-	2.58 Gm ³

Table 6.3: Contribution of each life-cycle stage to the environmental pressures under study. Pesticides use are expressed in weight of active substance.

Studying the needs associated to a specific consumption

Matrix L is used to compute productions needed in every region to satisfy the consumption of a specific product in a specific region. We illustrate this with the example of French meat consumed in Italy⁶, Italy being the first trade partner of France for this product. Table 6.4 presents the results. The order of magnitude of GHG emissions per kg seems a bit low compared to other LCA results⁷. Indeed, results here only encompass the portion of the emissions linked to the cereals supply chain (emissions from livestock digestion are for instance excluded). 4 m² were used to grow 2.8 kg of cereals needed to feed the livestock⁸, in particular in the Centre

⁵Starch but also bioethanol, beer and canned corn factories were identified as major water consumers per unit of production.

⁶More precisely the meat considered here originates from the meat supply of France (both national production and imports).

⁷For instance emissions factor for cattle, pork and chicken meats are respectively 12, 2.3 and 2.2 kg CO₂ eq. per kg according to ?.

⁸This does not include soy feed as explained in the discussion. Given national use of soy cakes for livestock consumption, the order of magnitude is 1 kg of soy per kg of meat (expressed in carcassee-weight equivalent), most of this soy originating from Brazil and Argentina.

region (for 14%). 13800 kcal are embodied in 1 kg of meat; by comparison, the caloric value of this kg of meat is about 2000 kcal. We compared pressures associated with Italian consumption with other regions and saw that indices do not vary a lot (generally more or less 10%) except for the ones related to blue water footprint and transport. This is explained by the fact that the production phase is the most significant one, as we saw above. The difference in blue water footprint intensities can be explained by the variability in cereal mix fed to livestock (corn being a lot more water-intensive than wheat).

Topic	Quantities associated to 1 kg of meat
Energy	16 kWh
GHG	1.6 kg CO ₂ eq.
Land use	4.0 m ²
Pesticides use	0.75 g (of active substance)
Blue water footprint	130 L
Sea freight	0.6 t.km
Road freight	2.0 t.km
Rail and river freight	0.2 t.km

Table 6.4: Environmental pressures and transport associated with the consumption of 1 kg of meat from France in Italy.

Identifying the main paths linking production to consumption

We use a structural path analysis (SPA) algorithm, inspired by Peters and Hertwich (2006b), on matrix B in order to extract the main links between production of environmental pressures and final consumption of products. The algorithm is described in Supplementary Material. Table 6.5 presents the top five paths linked to GHG emissions as well as three other paths illustrating different emission patterns. The first 30 paths are linked to exports and contribute to nearly 10% of total GHG emissions of the supply chain. The largest path for freight emission is the one representing exports of corn from Aquitaine to Spain by road. The path of emissions due to the growing of wheat in Bretagne, to feed animals for meat consumption in Ile-de-France, is the main emission path related to French consumption. Finally the main path related to pressures occurring during the transformation step is the emission of craft bakeries in Ile-de-France for local consumption. The first 100 paths (listed in Supplementary Material) account for 17% of total emissions.

Building environmental accounts from the producer's and from the consumer's perspective

For each region, we can build environmental accounts from the producer's (what is emitted/used by the productive activity of the region) and consumer's (what is emitted/used to satisfy the final consumption of the region) perspectives. For this purpose we respectively use matrices $\hat{F}f$ and $\hat{F}fB$. For instance, results regarding the land use footprint indicate that Centre (FR) and Poitou-Charentes (FR) have the two largest footprints of production with respectively 1.25 Mha (12% of the total) and 720 kha (7%), whereas Ile-de-France (FR) and Italy have the two largest footprints of consumption with respectively 834 kha (8% of the total) and 741 kha (7%). These footprints can be seen as Ecological Footprints of cropland from the production

Chapter 6. Environmental pressures embodied in the French cereals supply chain

Rank	Path	Contribution
1	Growing of wheat in Picardie > Consumption of wheat in Belgium	0.56 %
2	Growing of wheat in Picardie > Consumption of wheat in the Netherlands	0.56 %
3	Growing of corn in Aquitaine > Consumption of corn in Spain	0.49 %
4	Road freight from Aquitaine to Spain > Consumption of corn in Spain	0.45 %
5	Growing of wheat in Haute-Normandie > Consumption of wheat in Algeria	0.42 %
...
31	Growing of wheat in Bretagne > Making of compound feed in Bretagne > Animal farming in Bretagne > Consumption of meat in Ile-de-France	0.18 %
...
44	Production of bread in craft bakery in Ile-de-France > Consumption of bread in Ile-de-France	0.14 %

Table 6.5: Paths from emissions of GHG to final consumption. The column *contribution* shows the portion of total GHG emissions explained by each path. Picardie, Aquitaine, Haute-Normandie, Bretagne are French regions, Ile-de-France is the Parisian region (with the largest population).

and consumption perspectives (Wackernagel et al., 2005), although results are presented in real surface and not in surface of average bioproductive land. Of course, we can check that the total footprint of production is equal to the total footprint of consumption. Accounts for all regions and pressures are shown in supplementary material: it can be noted that rankings vary little except for the case of the blue water footprint, which is mostly driven by corn production and consumption.

Assessing net internalization of environmental pressures and identifying main trade partners at national and regional scales.

A net-export footprint can be computed as follows based on the production and consumption footprints: $Footprint_{net\ exports} = Footprint_{production} - Footprint_{consumption}$. A positive value indicates that the region under study internalizes more environmental pressures than it externalizes and vice-versa. Results show that France is a net exporter of (that is internalizes) about 175 TWh of energy, 17.7 Mt CO₂ eq. of GHG emissions, 4.41 Mha of land, 8.98 kt of pesticides, 550 Mm³ of blue water. In the case of land use, the main trade partners contributing to the net export balance are European countries (67%) followed by Africa (25%) and Asia (8%), net trade being almost negligible with north and south America and with Oceania. Finer resolution can be obtained by looking at regional results as shown in Figure 6.3, and is available in supplementary material.

Comparing environmental efficiency of different regions' consumptions

Knowing the population of each region, we can then estimate per-capita consumption footprints: detailed results are available in Supplementary Material. On average the French per-capita footprint linked to the cereals supply chain is about 3.1 MWh, 0.33 t CO₂ eq., 780 m², 0.15 kg of active substance of pesticides and 20 m³ of blue water. The two main French regions in terms of population are Ile-de-France and Rhône-Alpes (with respectively about 11.6 millions and 6.1 millions inhabitants in 2007). Looking at these two regions, per capita footprints are the same in the case of GHG emissions and the maximum difference is obtained in the case of blue water

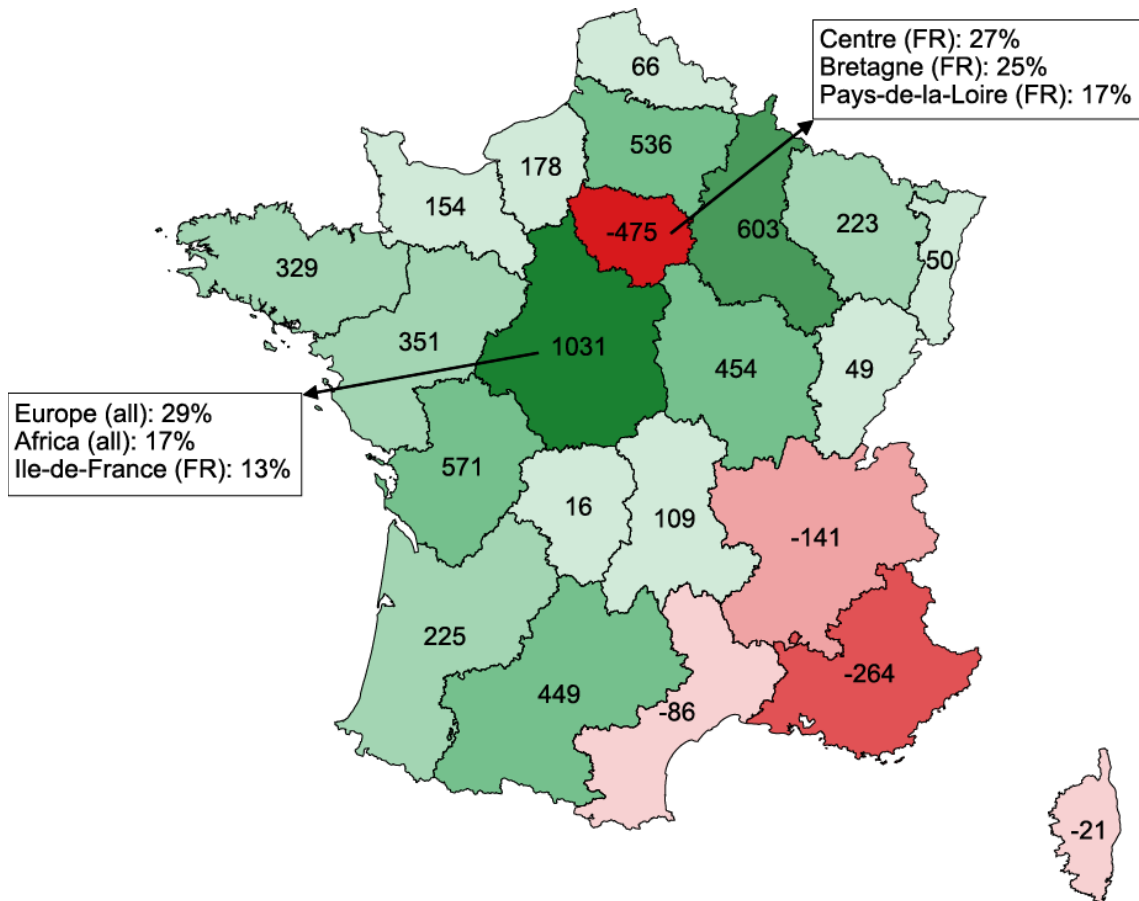


Figure 6.3: Net virtual land export per French region, expressed in kha of real surface. Shades of red correspond to net importing regions while shades of green correspond to net exporting regions. Ile-de-France (in dark red) and Centre (in dark green) are respectively the largest net importer and largest net exporter. The results can be disaggregated per trade partner: for instance, the top three trade partners of Ile-de-France and Centre are shown.

Chapter 6. Environmental pressures embodied in the French cereals supply chain

with 12%. Given the differences may be in the range of the model's uncertainties, it would be premature to draw precise conclusions based on these results. However, they show French regions have relatively homogeneous footprints of consumption.

Limits of the model and perspectives of improvement

In this section, we discuss the limits of the model and some leads for future developments.

- The model is limited to the study of the cereals supply chain. For instance, soy cakes fed to livestock are not taken into account because they are oleaginous. Two levels of improvement can be targeted in the future to overcome this limitation. The first one is to apply the methodology on all the main agri-food supply chains (oleaginous, sugar, wine, fruits and vegetables, animal breeding) in order to have a comprehensive view on the food issue. The second one would be to extend the model to the main industrial supply chains (such as energy, wood, concrete, steel and chemistry). The obtention of such physical, highly disaggregated supply/use table is of course a longer-term project.
- The model is focused on France. Foreign countries are only considered for their role of outlet or provider and their interior supply chain is not fully depicted; nor is trade between them. Including each country/continent's supply chain would be useful to track downstream flows to their final destination, although *a priori* it wouldn't be possible to reach the same level of disaggregation as in the case of France. FAO statistics could be used to implement this idea.
- On a similar topic, the model could be compared and enriched with the works of Kastner et al. (2011) and Godar et al. (2015) that depict methods for enhanced tracing of international trade and subnational footprints.
- Intra-regional freight is not taken into account because of a lack of information: the distance between local crop fields and transformation industries in the same region is neglected, only inter-regional and international distances are estimated. The fact that French regions have developed specialization strategies, consequently relying a lot on inter-regional trade, makes it less problematic.
- Transport of consumers to local shops or to supermarkets is not considered. Rather than a technical impossibility, it was left out of the model because the authors did not find useful for policy-making to study the part of the travel to the supermarket that should be allocated to cereal products. It is however an important question once the scope of the study widens to the full basket of a household.
- Currently, part of the pressures related to inputs at the farm are not traced back to their geographical origin since LCA results are directly applied. This is for instance the case for GHG emissions occurring during the production of fertilizers, which may be located elsewhere.
- Uncertainties associated with MFA results were previously estimated. Adding confidence intervals to environmental pressure ratios would make it possible to compute interval of confidence of the model's outputs which would be useful for a better interpretation of the results. Work is underway to estimate the missing intervals of confidence.

6.4 Conclusion

The goal of this article was to show the potentialities of coupling supply chain MFA with AMC and environmental pressures. Adopting a downstream perspective through the use of AMC seems well-adapted to exporting regions. The implementation of the methodology on the case of French cereals leads to interesting results that could serve as a starting point for decision-aiding. The supply chain object is well adapted to understand what life-cycle stages (production, transformation, transport) are predominant regarding each environmental pressure: regarding GHG, it appears for instance that the transport of goods, mostly through road freight, is not negligible, which raises the question of fostering rail and river transport between French regions and between France and its direct neighbors. Given the relatively small variability of cultural practices in France, land use appears to be a good proxy of other pressures such as the use of pesticides. On the contrary, the blue water footprint is driven by corn production and therefore concentrates on specific regions. While previous studies have pointed out the major responsibility of corn production regarding water scarcity in these regions (Ercin et al., 2012), the analysis of the fate of corn production leads to two lines of thoughts. First, consumption of animal products is by far the main driver of production, and prospective scenarios of dietary changes should therefore be examined. Second, Spain appears as the main importer of French corn and consequently externalizes the associated pressures on the local environment: in particular qualitative and quantitative stresses put on water resources through the use of pesticides and irrigation. This situation points to a limit of the study: only one supply chain was taken into account so we lack information on "net trade of pressures" all activities considered. For instance, in return, France imports a lot of fruits and vegetables from Spain, grown in regions with even greater water-scarcity. Hence, a comprehensive view with a multi-supply chains approach is needed in order to be more policy-relevant. Linking this study with recent works on Spanish agri-food industries and multi-regional input-output tables is a promising perspective (Cazcarro et al., 2013, 2014).

The choice of a subnational spatial resolution was motivated by the existence of leverages of regional administrative levels but also by the potentialities it opens to analyze impacts of specialization strategies or to compare environmental efficiencies of regional consumptions. Given the model's uncertainties, results are not conclusive regarding inter-regional comparison of efficiencies except for the specific aspect of transport for which we observe a large variability of regional profiles. On the contrary, results are useful for the environmental evaluation of regional strategies, starting with the diagnosis. The level of detail of the model provides a concrete picture of each territory, all the more so as a finer spatial resolution is achievable. As stated in the introduction, the present work is part of a larger project aiming at the analysis of local supply chains from the environmental, economic and social points of view for decision-aiding. In this perspective the next step is to include socio-economical indicators (a minimum set of indicators being a labor footprint and an index on added value) to the model and to evaluate possible alternatives of development. Relevant areas of investigations related to cereals include the study of trade-offs of exports, adaptation to climate change (given water scarcity is planned to worsen in regions that are already enduring water stress) and trade-offs between food use and energy-use (for instance, bioethanol production has known a constant increase in recent years). The Afterres scenario (Solagro, 2014) envisions the future of land use in France in 2050 in concordance with the Negawatt scenario of energy transition (Négawatt, 2013). Changes in both modes of production and in modes of consumption are proposed. On the consumption

Chapter 6. Environmental pressures embodied in the French cereals supply chain

side, 3 actions are implemented: reduction of protein intake (currently in surplus), reduction of food waste and reduction of the proportion of animal proteins in the total intake. Concretely this translates into more direct cereal intake but eventually less cereals need for food purposes. On the production side, the scenario suggest a 50% proportion of organic agriculture by 2050, a division of corn export by two because of water stress and a partial reaffectedation of arable land (mostly prairies) freed from animal production towards energy production. The work of regionalization of this scenario is in progress and it will eventually be useful for regional and national decision-makers to be able to compare this vision of the future with a business as usual scenario. The model and leads of development presented here are an important step towards this goal.

Acknowledgments

This research was funded by grants from Inria and Artelia Eau & Environnement.

Introduction of Chapters 7 and 8

Understanding and quantifying what activities produce pressures on the environment and for the satisfaction of which end-consumers, was the main concern of our work. We saw the supply chain approach could in particular help identify what life-cycle stage (production, transformation, transport) should be targeted first to improve the overall situation. As underlined in Chapter 6 's conclusion though, measures implemented to reduce environmental footprints would also impact on local employment and distribution of wealth, positively or negatively. In a decision-aiding perspective, information on socio-economic aspects cannot be neglected. We do not attempt to develop new concepts on the subject. Rather, we wish to provide an overview of how the SC-MFA model could be coupled with existing economic and social models. Chapters 7 and 8 are dedicated to this endeavor. Chapter 7 focuses on linking MFA with economic modeling and Chapter 8 is studying how existing frameworks and theories stemming from social sciences could usefully complement MFA and also provide a better grasp on the issue of employment.

Material flow analysis of the forest-wood supply chain: a consequential approach of log export policies in France

The article below is the result of a collaboration between the Laboratory of Forest Economics (LEF; INRA, AgroParisTech, Nancy) and the STEEP team (INRIA, Grenoble). The SC-MFA methodology was applied to the French forest-wood supply chain as part of a mission funded by the DRAAF Lorraine (regional direction of food, agriculture and forest of the Lorraine region) and directed by Mélanie Lucas. The demand was to “*Assess and analyze wood flows in the Grand-Est area*” which is composed of 5 regions (Alsace, Champagne-Ardenne, Lorraine, Bourgogne, Franche-Comté). The effort was concentrated on the six-month internship of Jonathan Lenglet (AgroParisTech), scientifically supervised by Sylvain Caurla (LEF) and us. The article itself focuses on the national scale and on the attempt to couple MFA with economic modelling. Regional results for Lorraine are however shown in Appendix of Chapter 7 as another illustration of the downscaling procedure.

Lenglet, J, Courtonne, J-Y, Caurla, S. *Material flow analysis of the French forest-wood supply chain: a consequential approach of log exports policies.*

Abstract. In the context of national policies for climate mitigation and energy transition, the forest-wood sector is drawing increasing attention, not only for energy wood but also for longer-life timber products. At the same time, part of the French timber transformation industry suffers from difficulties to adapt to recent changes on global markets, which translates into net exports of raw wood and imports of transformed products, detrimental to both the trade balance and the local creation of wealth. This article first aims at objectifying this situation by undertaking the first material flow analysis of the French forest-wood supply chain. We then evaluate the potential consequences of various scenarios of raw wood exports reduction policies, namely subsidies for consumption or transformation and taxation of exports, on both economic outcomes for the different actors and material flows. We thus provide an example of coupling material flow analysis with economic modeling in an attempt to move from the diagnostic phase to the assessment of possible actions within a decision-making perspective.

7.1 Introduction

For the last two decades, the forest sector has been increasingly involved in the climate mitigation policy portfolio. Since CO₂ emissions from wood combustion are considered to be null by the Kyoto Protocol (IPCC, 2006), climate policies in the forest sector have so far mostly favored the energy wood sector at the global level. For the last few years, however, the *cascading* use of wood products, defined by Sathre and Gustavsson (2006) as the sequential use of a resource for different purposes, as the resource quality degrades over time on its path towards thermodynamic equilibrium, has been recognized as the first best option to take advantage of the entire mitigation potential of forests (Bellassen and Luyssaert, 2014; Sikkema et al., 2013; Dornburg and Faaij, 2005). This implies the production of long-life wood products that sequester carbon over a long period of time (Fortin et al., 2012; Perez-Garcia et al., 2005; Pingoud et al., 2001; Profft et al., 2009). These products generally come from extended-rotations forests that favor carbon sequestration in situ compared to energy-oriented types of management (Liski et al., 2001). The use of wood as a replacement for other products then makes it possible to reduce carbon emitted at manufacturing stages (Petersen and Solberg, 2005; Perez-Garcia et al., 2005). Eventually, using end-of-life wood products as an energy source instead of landfilling makes it possible to avoid carbon emissions from fossil sources, via the energy substitution process (Petersen, 2006).

This transition from policies that stimulate energy wood sectors alone toward policies that promote the multipurpose cascading use of wood goes hand-in-hand with the promotion of roundwood products to tackle climate issues. Since official recommendations in France encourage the use of products made from roundwood, such as sawnwood, veneer and plywood, the question of the capacity of log provision has arisen (Alexandre, 2014). This is all the more questionable given that wood is a material that requires a long time to grow and that global and national roundwood sectors have undergone several structural changes during the last two decades.

Indeed, the globalization of the wood products chain has shifted the centers of transformation in view of shifting comparative advantages (Uusivuori and Tervo, 2002). In addition, the relaxation of trade and the containerization of transportation have dramatically facilitated the trade and exchange of raw and transformed products. Moreover, new engineered materials based on wood chips and fibers have emerged and lumber has lost its historic dominance as the primary raw product for secondary products (Hansen et al., 2013).

These economic and technological changes have deeply transformed the French roundwood sector. Today, the country is a net exporter of roundwood and a net importer of processed wood products. This trade pattern is recognized as a source of value added loss and trade deficit (Koebel et al., 2016; Levet et al., 2014).

Beyond these immediate economic implications, the current situation also raises mid and long-term issues. First, the mid-term efficiency rationale of the current situation is, to a large extent, due to the low transportation costs and the exclusion of environmental externalities in prices. These two factors may change in the future since transportation costs are expected to increase in line with fossil fuels depletion (Capellán-Pérez et al., 2014) and transportation may face a progressive inclusion of environmental externalities. Second, outsourcing by the manufacturing industry may decrease the economic resilience of national and sub-national forest sectors. Defining resilience as “*the capacity [of a system] to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity,*”

and feedbacks" (Holling, 1973; Walker et al., 2004), lead us to assume that the loss of wood timber industries makes territories more vulnerable.

Relocating sawmill activities on the national territory can therefore be a solution to ensure the provision of sawnwood products in an efficient and resilient way. However this raises questions such as which sawmill industries should be relocated, to what extent and what would be the consequences over the rest of the wood sector, in terms of competition, trade-offs and/or synergies.

With this in mind, we strongly believe that any recommendation to relocate sawmill activities, either by stimulating private investments or by implementing public policies, should rely on a comprehensive pattern of wood harvests, flows and uses. The primary goal of this paper is therefore to assess wood product flows in a comprehensive manner, following their pathway from the time the wood is harvested in the forest, along the transformation process, and ending with the consumption of transformed products. We particularly focus on outgoing and ingoing flows. This endeavor typically falls in the field of Material Flow Analysis (MFA), that is, a systematic assessment of the flows and stocks of materials within a system defined in space and time (?). To our knowledge, so far, only Bais et al. (2015) have so far extensively quantified wood flows at the global scale, suggesting that there are still considerable uncertainties about the extraction of wood at the global level and especially of woodfuels. Other identified wood flow studies have focused on regional levels (?Mantau, 2015), national levels (Hekkert et al., 2000) for the Netherlands, ? for Japan, Piskur and Krajnc (2007) for Slovenia, Knaggs and O Driscoll (2008) for Ireland, ? for China, METLA (2011) for Finland, Weimar (2009) for Germany, Parobek et al. (2014) for Slovakia), as well as on the European Union as a whole (Mantau, 2012). Such studies are currently lacking in France where no consistent and homogeneous accounts for wood product production and consumption exist at this time. Forest management and wood extraction are generally treated separately from wood transformation (which is itself organized into many different federations). Different units are used in official reports (cubic meters of roundwood, cubic meters of product, metric tons, number of units produced) making it difficult to cross-check the data. In addition, large uncertainties prevail in some existing databases, especially regarding woodfuels that are known to be largely under-reported in official statistics (Chevallier et al., 2014). This article is a first attempt to fill this gap and provide a comprehensive view of the flows in the French forest-wood supply chain. In order to reconcile data from various sources, we rely on the MFA framework depicted in ?, which uses the wood fiber equivalent (presented in Section 2) as a basic accounting unit.

The second goal of this paper is to assess the impacts of the relocation of sawmill activities on other forest sectors such as the fuelwood and pulp sectors, as well as on the economic outcomes for the sector agents. To address this issue, we couple the MFA with a partial equilibrium forest sector model, the French Forest Sector Model (Lobianco et al., 2015; Caurla et al., 2013,?; Lecocq et al., 2011) and we explore the economic consequences of three policy options that reduce roundwood export.

By combining a MFA and a partial equilibrium framework, this paper makes it possible to bridge the gap between the diagnosis phase and the recommendation phase for policy makers through a multi-scenarios analysis. Indeed, as ? and ? recall, the impact of MFA on policy making is not clear since most studies stop at the diagnostic phase. We propose to go beyond the diagnosis in order to provide policy relevant information by using a partial equilibrium model that projects the evolution of the forest sector at the same scale and for the same prod-

ucts as those described in the MFA. Compared to ? who focused on how different approaches (LCA, MFA and partial equilibrium model) independently contribute to elucidating a research question, we undertake the coupling of MFA with economic modeling. Note that in the title, we refer to this as a *consequential approach* in reference to consequential Life Cycle Assessment (LCA) that, contrary to attributional LCA, models economic links between processes and is therefore able to account for the indirect effects of a change. In practice, this generally translates into nonlinearities, because of the existence of thresholds or scaling effects.

The article is organized as follows. The first section is dedicated to the presentation of the data sources, hypotheses and methodologies used, both for the MFA and the parts dealing with economic prospectives. Results are presented and discussed in a second section before concluding on the main findings of the study and on future research perspectives within the context of a transition to sustainability.

7.2 Materials and methods

7.2.1 Material Flow Analysis (MFA)

7.2.1.1 Boundaries of the study

We focus on the upstream part of the forest-wood supply chain, which is the most relevant to our research questions. Firstly, this makes it possible to analyze to what extent the country is exporting raw products and importing products of first transformation. Secondly, it provides information on log outlets, a key question, for example, being: *is there a reason to worry that firewood is cannibalizing log resources at the expense of the lumber industry?* As a consequence, the model implemented does not aim to represent some second or third transformation industries such as the furniture industry. More precisely, our MFA covers all log products (distinguishing hardwood from softwood), wooden pallets, sawnwood, veneer, plywood and wood panels, as well as energy wood, sawmill residues, pulp and paper products and niche products such as wood staves. A full list of the products considered is presented in Table D.1 in the Supplementary Material. The geographic boundary of the study is metropolitan France.

7.2.1.2 Reference unit

To make the MFA consistent we need to define a homogeneous unit for the entire wood chain. This is all the more important given that wood products data are reported in various units. Bösch et al. (2015) note that when quantities of wooden products are converted into the same unit in order to compare them, the cubic meter of roundwood equivalent is often used. It is defined as the volume of roundwood necessary to make one unit of processed product. However, we share their opinion that it cannot be directly used in MFA studies since it leads to double-counting of by-products such as sawmill residues. Using cubic meters or tonnes also raises consistency issues since other constitutive materials such as adhesives in panels or additives in paper products are then considered to be wood, whereas, volume changes due to drying would not be accounted for.

We therefore use the wood fiber equivalent as the reference unit. This unit was defined by Weimar (2009) and used by Bösch et al. (2015). The wood fiber equivalent (referred to as m³

[f] in the text) is the volume of the wood fibers that are contained in the product at the fiber saturation point Weimar (2009). For each wood-based product (e.g., fiber board, plywood, pulp), a specific conversion factor is calculated depending on its primary measurement units. A section of the Supplementary Material is dedicated to a presentation of the formula and hypotheses used for this unit, with Table D.1 providing conversion factors for each product studied. Although similar in principle, our theoretical formula slightly differs from the one provided by Weimar (2009) in order to actually provide results expressed at the fiber saturation point. However, in practice, the lack of data (particularly concerning on moisture rates) leads us to use the same factors for many products.

7.2.1.3 Data sources

Table 7.2.1.3 summarizes the sources used to build the MFA model. Data is taken from a number of different sources, which makes it very unlikely that it will “fit” the mass conservation law. However, to take advantage of all of the information available, we used a data reconciliation technique inspired by ?.

7.2.1.4 Uncertainty of input data and period of study

Data quality is assessed either by directly retrieving precision indicators from the statistic sources, or, in most of the cases, on expert judgments based on the way data is built (source, type of survey or poll, scope of the study). Note that what matters the most for MFA results is the relative difference between data sources (*e.g. source a is twice as precise as source b*). Estimated 95% confidence intervals range from 1.4% (forest primary production) to 50% (wood logs used for individual heating, in official circuits).

Additionally, we chose to study the annual average between the years 2011, 2012 and 2013. This presents at least two advantages: first, it reduces the uncertainty of data from polls), and second, it allows us to neglect stock variations, which would be very difficult to quantify otherwise.

7.2.1.5 Supply and use tables and data reconciliation

Physical Supply and Uses Tables (SUT) have a long tradition of being used in the fields of ecological economics and industrial ecology ?. They consist of product-industry matrices indicating:

- which local industries and/or foreign territories are supplying the product to the studied system (Supply Table),
- which local industries and/or foreign territories are using the product available in the studied system (Use Table).

Data reconciliation is used to phase out inconsistencies. The model imposes mass conservation laws, which implies constraints on the supply-use tables. In particular, supply equals use constraints must be verified for each product and for each transformation industry (the materials that enter an industry must also exit this industry, regardless of the products they are embodied in) as well. Equations of the constraints are provided in the Supplementary Material. As we explained before, these constraints are unlikely to be met by input data so we resort to data

Item	Source	Comments
Biological increment / Total harvest / Mortality	French Geographic Institute (IGN)	Year average for the 2009-2013 period. Available for each department (nuts 3 level)
Harvest (commercial) and harvest residues	Annual agricultural statistics (SSP)	Available for each department and for groups of species (coniferous and broadleaves) and groups of uses (roundwood, pulpwood and energy wood)
Firewood self-consumption	Ademe (2013)	Survey on household wood consumption
Production of sawnwood and residues	Annual agricultural statistics (SSP)	Available for each department and for groups of species (coniferous and broadleaves)
Production of other transformed products	Annual reports from federations (e.g. FCBA)	Available at the country level, quantities reported in specific units
Consumption of paper / paper recycling rate	Federation of paper producers	Available at the country level
Outcome of wood wastes	INSEE	The order of magnitude is highly variable among available reports underlining the fact that these quantities are not known with precision. For this study, we chose the official Insee statistics.
International trade	SitraM database (based on French customs)	Available for 382 positions (NST 2007), department of origin/destination, country of destination/origin.

Table 7.1: Data sources used for the MFA on wood products.

reconciliation. While details are provided in supplementary material, the principle can be summarized as follow: in order for the constraints to be fulfilled, output data (results) are allowed to differ from input data but the less uncertainty there is about the input data the smaller the distance between output and input data will be. SUTs at the level of France are provided in the Supplementary Material both before and after the data reconciliation process (Tables D.1 and D.2).

7.2.1.6 Uncertainty propagation

We use Monte Carlo simulations to evaluate uncertainties of output results. Each random draw corresponds to a set of input data. This set is composed as follows: for each input value, we assume a truncated Gaussian distribution (plus or minus infinity would have no meaning in our context) centered on this value, and whose standard deviation depends on the previously assessed uncertainty. We run the reconciliation model for each random set of input data and obtain the sets of output data. Uncertainties, presented in the form of 95% intervals of confidence, are computed by analyzing the dispersion of the distribution of each output variable.

7.2.2 French Forest Sector Model (FFSM)

7.2.2.1 An overview of the model

FFSM is a bio-economic recursive model of the French forest sector. The version used in this article is FFSM 1.0 (Caurla et al., 2013,?; Lecocq et al., 2011),¹. This version is composed of two modules: an inventory-based dynamics forest module (FD) and a partial equilibrium market module (MK). The FD module represents the dynamics of the French forests that accounts for natural growth and mortality (Colin and Chevalier, 2009) and wood removals from human harvest.

The optimal harvest level is computed by the MK module on a yearly and regional basis, starting from 2006 as the base year. To do this, the MK module solves a partial equilibrium problem, annually taking the demands for transformed products, wood availabilities in forest, and the costs of transportation from one region to another into account, according to Samuelson (1952) spatial price equilibrium framework.

The model represents the demand of processed products: sawnwood (hard and softwood, respectively hereafter referred to as hsw and ssw), plywood (pw), fuelwood (fw), pulp, panels and the supply of raw products: roundwood (hard and softwood, respectively hereafter referred to as HRW and SRW) and industrial wood (IW). A Leontief function represents the transformation of raw products into processed products. The model considers sawmills and harvest residues as by-products of primary activities.

While interregional trade is modeled through the spatial price equilibrium framework, international trade is computed through an Armington framework assuming that domestic and foreign products are not fully substitutable. The international trade is modeled using exoge-

¹The most recent version of the model (FFSM++; Lobianco et al. (2015, 2016)) involves a third module, referred to as the micro-based Area-Allocation module (AA) making it possible to project over longer horizons, and accounting for forest resource heterogeneity and the degree of forest owners expectations as well as their degree of risk-aversion.

nous international prices derived from the FAO (2013) and elasticities of substitution between local and international products specifically estimated for FFSM in Sauquet et al. (2011).

7.2.2.2 Consistency with MFA and input-output calibration in FFSM

The number of products represented in FFSM is lower than in MFA analysis. To make the modeling framework consistent, results from MFA are aggregated to match the definition of products in FFSM. Input-output coefficients used in the Leontief function of FFSM are then calibrated using MFA results for each group of products. They are presented in Table D in the Supplementary Material.

7.2.2.3 Prospective: simulating policies to relocate sawmill activities

Several papers assess the impacts of export restrictions on global and national forest sectors. Using a global log-lumber trade model, Van Kooten and Johnston (2014) show that moving an export tax at the national level (Canada or Russia) has a small impact on the global forest sector welfare. Using data for the State of Washington, Johnson et al. (1995) suggest that domestic mills and consumers clearly benefit from the ban while the welfare of Japanese consumers and the export industry is reduced. The same conclusion holds in Van Kooten and Johnston (2014) for British Columbia (BC). They report that, while free trade of logs might maximize global wellbeing, it might also reduce the domestic welfare of economic forest sector agents. While these papers clearly suggest that export bans are beneficial to the domestic forest sector, neoclassical economy judges them inefficient at the global scale (Goodland and Daly, 1996). However, these studies focus on the impacts of a restriction without analyzing the different design of policy options to reduce export and their implications on forest sectors. This is precisely the aim of the prospective part of this paper. To do this, we tested three alternative policies. Two of them consist in subsidizing transformed products made of roundwood: *Sub_C* is a subsidy to domestic sawnwood and plywood consumption, while *Sub_T* is a subsidy to sawnwood and plywood transformation. The other policy, referred to as *Exp*, is an extra-cost to roundwood export. *Sub_C* and *Sub_T* differ from their transmission channels: while *Sub_C* acts through processed product consumers, *Sub_T* directly irrigates the upstream and the downstream of the roundwood sector through the reduction of transformation costs. *Exp* acts differently and models an extra cost for plant-health control and preventive treatment. Such a policy already exists for wood packaging material (Strutt et al., 2013) as a tool to limit the diffusion of pests and diseases. We assume that this policy costs 10 €/m³ which is close to the export tax equivalent imposed by Canada on its exports to the U.S. (Van Kooten and Johnston, 2014) and which is considered as plausible by the French government. In the model, this value leads to a reduction of roundwood log exports of 20% regarding a baseline scenario without policy. To make the comparison between policies meaningful, we based them on the same level of export reduction derived from the *Exp* policy result (-20% for roundwood, either hardwood or softwood). We calibrated the levels of subsidies *Sub_C* and *Sub_T* consistent with this objective by a trial and error process (55% and 110%, respectively).

7.3 Results

7.3.1 Wood flow analysis

MFA results are presented in two figures: Figure 7.1 provides a global view of the upstream part of the supply chain (forest stock, increment, harvest, self-consumption of households, etc.) and Figure 7.2 focuses on the transformation of lumber and pulpwood. Every flow comes with a figure that specifies the quantity of wood in m³(f). Confidence intervals are also represented as well as some quantities in a more intelligible unit, e.g., paper production is expressed in tonnes.

Six main outcomes stem from the diagrams. First, Figure 7.1 shows that, at the national level, the stock of standing wood is increasing since the total of harvested wood (including self-consumption) represents about half of the annual increment. Although this result is in line with figures published elsewhere (Colin and Thivolle-Cazat, 2016), it must be qualified since all biological production at the national level cannot be harvested. Indeed, some species or diameters do not have a commercial outlet and some areas, such as mountainous ones, are inaccessible. This can explain the paradoxical situation encountered in many French regions where forest stocks increase while wood harvest seems to reach a ceiling. In addition, as suggested by its wide confidence interval, the production of energy wood remains difficult to assess. The majority of energy wood flowing in anthropogenic activities is composed of self-consumption energy wood. These self-consumption volumes are estimated by Pouet and Gauthier (2013) based on a poll taken on some 1,500 households. Even if the total household consumption probably gives a fair idea of the situation, quantifying the share of the different firewood supply chains is more difficult since some suppliers may have an interest in under-reporting their sales. In addition, the core business of energy wood suppliers is often logging or sawmilling, which makes the identification of energy wood flows even more complex (INSEE, 2014).

Second, although the standing wood resource at national level is mostly composed of broadleaves (about 63% (FCBA, 2013)), it appears that HRW represents 9.5% of log volumes, whereas SRW accounts for 28%. This result is explained by the higher adequacy of softwood with the process industry requirements. Indeed, sawmills consume about four times more SRW than HRW, and the panel and paper pulp industries nearly twice as much.

Third, France is a net exporter of logs. This is all the more true for hardwood. Exports represent 22% of total HRW and 7% of total SRW. France is also a net exporter of pulpwood since about 15% of the pulpwood harvest is exported.

Fourth, Figure 7.2 suggests that ssw represents the largest production in volume closely followed by panels production. Half of the sawmill residues are used in the pulp and panel industries as raw material, which reveals a well-established recovery chain and potential competition with new additional fuelwood demand. The pulp and paper sectors have a large recycling chain: more than 80% of papers consumed are sorted to be recycled, representing about 55% of the resources of the paper industry (expressed in volume of wood fiber equivalent). These sectors determine the economic value of the wood sector in France. It can be noted that France also exports large quantities of paper wastes that are therefore not valued in the country.

Fifth, Figure D.3 in the Supplementary Material shows that niche products such as stave woods and plywood, even if negligible from a volume point of view, remain important from a value-added perspective. Conversely, the weight of sawmill residues is strongly reduced. Note

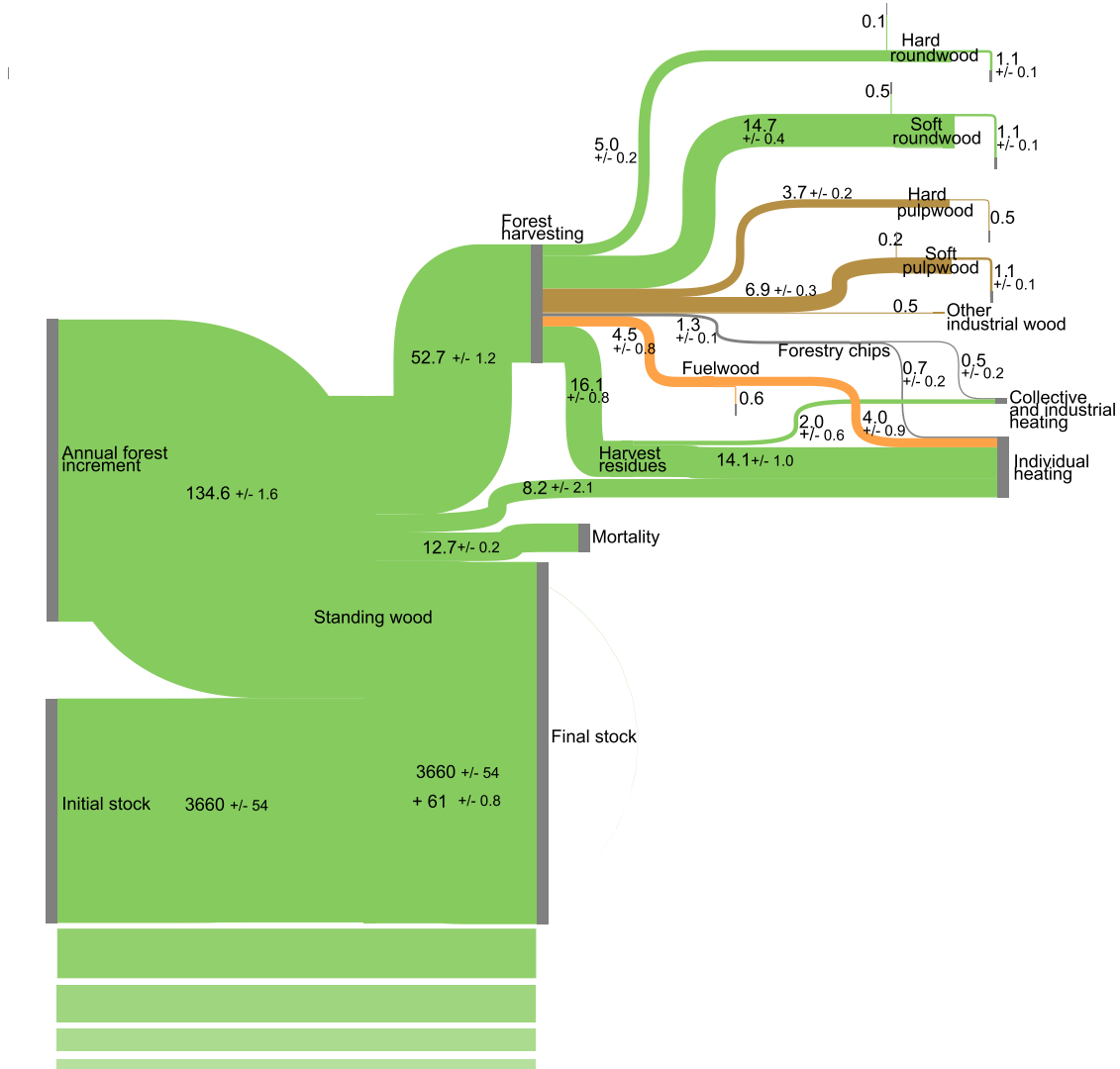


Figure 7.1: Sankey diagram of the upstream part of the forest-wood MFA. Flows are expressed in $Mm^3(f)$ and correspond to a one-year average during the period 2011-2013. Wood stock is not represented at the same scale as the other flows. Besides, initial stock and its associated uncertainty is not an output from the model (that does not handle stocks) but is directly retrieved from IGN.

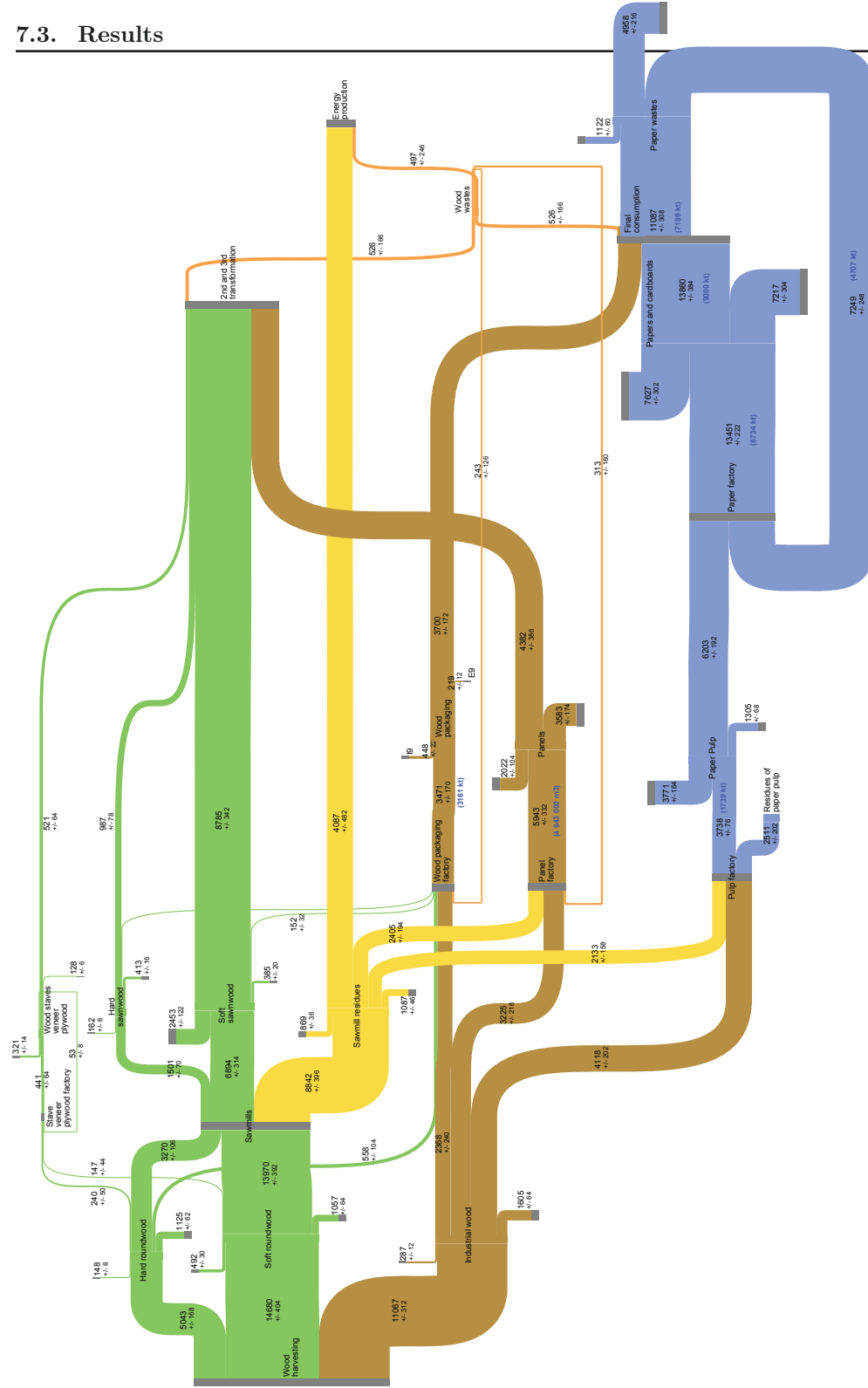


Figure 7.2: Sankey diagram of the downstream part of the forest-wood MFA. Flows are expressed in 1000m³ (f) and correspond to a one-year average during the period 2011–2013.

that these niche products are mainly produced from HRW and could become interesting outlets from the point of view of export reduction.

Sixth, from a trade balance perspective, we can notice that panels and paperboards are largely exported (resp. 60% and 54% of the total production is exported). Hardwood sawmilling is also a net exporter, which shows a possible commercial outlet for producing hsw in France for export. On the contrary, 28% of total ssw consumed in France is imported which shows an inadequacy between local supply and demand. Imported products are likely to be species and/or diameters that are not produced in France (even if data cannot corroborate this assumption).

These results mask important regional differences. For example, about half of the wood harvest takes place in only five regions (of the 22 French regions). These regions are not analyzed in this article, which focuses on diagnosis and prospective for the national forest-wood supply chain, although they constitute major leads for future work. We will come back to this question in the conclusion.

7.3.2 Prospective

We assessed the impacts of the policies described above on two groups of economic indicators: (i) the variations in prices and quantities produced, consumed, imported and exported, and (ii) the budgetary cost and the variations in economic agent surpluses. Variations are given for the year 2020. Sankey diagrams outlining the potential impact of each policy on material flows are proposed in the Supplementary Material (Figures D.4, D.5 and D.6).

7.3.2.1 Variations in quantities

	HRW (P)	SRW (P)	IW (P)	fw (C)	hsw (C)	ssw (C)	pw (C)	pulps (C)	panels (C)
<i>Sub_C</i>	+42%	+23%	-20%	+6%	+73%	+33%	+26%	+2%	+1%
<i>Exp</i>	-5%	-2%	+1%	0%	0%	0%	0%	0%	0%
<i>Sub_T</i>	+42%	+20%	-18%	+4%	+38%	+11%	+45%	+1%	+1%

Table 7.2: Variations in quantities produced (P) or consumed (C) in 2020 compared to the baseline scenario (without policy).

	HRW (E)	SRW (E)	IW (E)	fw (I)	hsw (I)	ssw (I)	pw (I)	pulps (I)	panels (I)
<i>Sub_C</i>	-20%	-20%	-3%	-2%	+83%	+42%	+29%	-1%	0%
<i>Exp</i>	-20%	-20%	0%	0%	0%	0%	0%	0%	0%
<i>Sub_T</i>	-20%	-20%	-3%	-2%	0%	-7%	-24%	-1%	0%

Table 7.3: Variations in exports of raw products and imports of transformed products regarding baseline without policy in 2020.

Table 7.2 shows the impacts of the three policies on production and consumption of wood products in the sector. Three outcomes stem from these results. First, while *Sub_C* and *Sub_T* largely modify production and consumption patterns, *Exp* does not have a major impact on

	HRW (P)	SRW (P)	IW (P)	fw (C)	hsw (C)	ssw (C)	pw (C)	pulps (C)	panels (C)
<i>Sub_C</i>	+93%	+41%	-30%	+7%	+47%	+35%	+46%	+2%	+1%
<i>Exp</i>	-10%	-6%	+1%	0%	0%	0%	0%	0%	0%
<i>Sub_T</i>	+88%	+36%	-25%	+6%	+34%	+13%	+34%	+1%	+1%

Table 7.4: Variations in surpluses (C: consumers surpluses; P: producers surpluses) regarding baseline scenario without policy in 2020.

	Total welfare variations compared to baseline (M€) (+ means a net gain, - means a net loss)	Budgetary costs (M€)	Social costs (budgetary costs - Total welfare variations, M€)
<i>Sub_C</i>	+2248	+3000	+752
<i>Exp</i>	-33	0	+33
<i>Sub_T</i>	+1448	+1653	+205

Table 7.5: Total welfare variations, budgetary costs and social costs.

domestic wood flows. It only slightly reduces HRW and SRW production. This is because *Exp* acts via an extra cost on export without modifying domestic prices and domestic agents' behaviors. As a consequence, total roundwood production decreases because of export reduction but this does not lead to a rebound effect on the domestic market. Second, while *Sub_C* and *Sub_T* have almost the same impact on the production of raw products upstream, their impacts on consumption patterns differ. In fact, the impacts of *Sub_C* mostly depend on the price elasticity of the transformed product demand and the price elasticity of the primary product supply. Since the demand of hsw (-0.5) is more elastic than that of ssw (-0.4) and pw (-0.3) and the supply of HRW is more elastic than that of SRW (1.2 vs. 0.9), *Sub_C* has a relatively bigger impact on hsw than ssw. For its acts, *Sub_T* plays via the costs of transformation so that the higher the cost of transformation is, the higher the impact of *Sub_T* will be. This explains the higher impact on plywood (cost of transformation: 534 €/m³) than on hardwood sawnwood (268 €/m³) and on softwood sawnwood (48 €/m³). Third, although *Sub_C* and *Sub_T* are subsidies of the sawnwood and plywood sectors, they also impact fuelwood and, to a lesser extent, the pulp and panel sectors via the increase in production of sawmill residues. This implies a crowding-out effect with IW, which results in a reduction of IW production (-20% and -18%, respectively) that is not observed with *Exp* policy.

Regarding impacts on exports and imports, Table 7.3 shows that *Sub_C* increases imports of hsw, ssw and pw in a proportion depending on the price elasticity of the demand. *Sub_C* therefore creates an important windfall effect. On the other hand, *Sub_T* decreases imports of ssw and pw and does not affect imports of hsw. This is because *Sub_T* only acts on domestic production costs, which makes domestic products more competitive than foreign substitutes.

7.3.2.2 Variation of surpluses and budgetary costs

Table 7.4 shows that while the two subsidies increase all surpluses except the surplus related to IW production *Exp* reduces surplus related to HRW/SRW productions, slightly increases surplus related to IW production and has no significant impact on surpluses related to consumption activities. In the case of *Sub_T*, the driver is the reduction of transformation costs that reduces the consumer price and increases the producer price and, as a consequence, increases both the quantities produced and consumed at the national scale. This results in overall gains in economic agents' surplus. In the *Sub_C* case, the consumer-perceived price is reduced which leads to a higher demand and, therefore, an increase in production upstream. In that case, however, part of the additional demand is fulfilled by imports, as shown in the previous section, which do not increase domestic agents' surplus. Both subsidies have a negative impact over industrial wood activities since they lead to an additional production of sawmill residues, leading to a crowding-out effect with industrial wood upstream.

Table 7.5 shows that while *Sub_C* is the subsidy leading to a higher welfare benefits, it is also the most expensive. When looking at the social costs, *Sub_T* performs better than *Sub_C* since *Sub_T* does not increase imports and does not imply a windfall effect. Budgetary costs of *Exp* are 0 since FFSM does not take transaction costs into account.

7.3.2.3 Discussion about the results

Results show there is no *first best* policy option. From a policy-making perspective, the implementation of a policy to reduce roundwood export must consider the different levels of impacts, namely the welfare variations for each economic segment, the total welfare costs, and the total budgetary costs. *Sub_C* leads to the highest welfare gains for economic agents (except IW suppliers) but is the most costly for the government budget because of the windfall effect. *Sub_T* follows a comparable surplus gains pattern while being half as expensive. *Exp* policy is not beneficial to wood sector surplus but is the least costly if we assume that the transaction and functioning costs are covered by the payment made by roundwood exporters. In addition, it is the only policy in which the IW sector remains unchanged. According to these results, the only possible solution for (1) reducing the crowding out effect between sawmill residues and industrial wood competition with the pulpwood sector, and (2) increasing welfare surplus in the forest sector while (3) preventing a windfall effect would be to combine *Exp* with *Sub_T*. Figure D.7 in the Supplementary Material shows the effect of a range of combinations between these two policies on social cost. However, as outlined before, social cost is not the only criterion to be considered. The choice of a policy mix should imply a debate among all stakeholders impacted by the policy (e.g., including citizens paying for the potential subsidies). We believe that they alone can express which criteria matter the most and which efforts they are willing to make.

In addition, since FFSM has no endogenous growth module, it cannot represent the impacts of subsidies on capital accumulation. Yet, it is very likely that, in reality, when looking at the long term, the net social costs of policies would diminish over time as capital investments increase. At one point, the net social costs may even become negative.

7.4 Conclusion

Our paper fills two important gaps. It is the first in the literature to draw a comprehensive picture of wood flows in the upstream part of the wood sector in France that takes all available data sources into account. To do this, we built an MFA model using a reconciliation process and a homogeneous unit to make the different sources consistent and comparable while quantifying uncertainty. Second, it assesses the economic impacts of three policy alternatives to reduce exports of logs by using FFSM, a partial equilibrium model. Impacts on material flows are evaluated as well. By combining an MFA and an economic modeling framework, our analysis goes beyond diagnosis and proposes insights into policy-makers' recommendations.

We demonstrated the relevance of MFA to reconcile highly heterogeneous datasets. Since no common database exists in the forest-wood sector, these results offer a solid base for analysis and opportunities for development prospects. However, attention must be paid to the temporal aspects of the study. Our MFA provides a snapshot of the situation for a specific reference year and does not capture trends. For instance, concerns on raw wood *leaks* are not only due to current export levels but also, and maybe mostly, to increasing exports trends and sawmill shut-downs. Thus, it would be relevant to repeat the study according to a predetermined time-step (e.g., 5 years), using the same methodology. Comparison across time of wood flow dynamics may be encouraged as a tool to study the wood-forest sector's health and as a powerful monitoring instrument for policy makers. The systematic framework implemented here will hopefully foster this endeavor.

MFA results suggest that while broadleaves dominate conifers in French forests, production of HRW is three times lower than that of SRW. Meanwhile, exports represent 22% of the total HRW production but only 7% of SRW production. This leads to an apparent paradox: the resource is abundant and potentially under-harvested but the sector is unprofitable since part of the value added is created abroad. Nevertheless, the MFA suggests that both hsw production and niche products such as stave wood are a potential commercial outlet for domestic HRW. Yet, as long as the international demand for logs and especially broadleaf products is the driving force behind exports, production of HRW will be oriented toward exportation and investments in the sector will be postponed, exacerbating the trade balance deficit. With this in mind, as the second step of our analysis, we tested three policy options to reduce log exports: a subsidy to consumers, a subsidy to process industries and an additional costs to export due to phytosanitary control, which acts as a ban in the model. The potential effects of these policies help to specify several criteria of interest to aid the decision process: budget costs, welfare variation in the forest-wood sector and redistribution of this welfare among agents. These indicators could also serve to assess potential impacts on local employment given that labor intensiveness differs between sectors. Moreover, a healthier, more dynamic supply chain would arguably make it easier to reach national climate mitigation goals. These last two points would require more in-depth studies but seem crucial if we are to have a holistic view of the sector. While mono-criterion optimization approaches (e.g., optimizing cost-effectiveness) are often used to make policy recommendations, we believe that multi-criteria analysis would be better suited to study possible alternatives. This approach would go hand-in-hand with a decision process involving all of the stakeholders, that is, ideally, anyone affected by the decision, where they are asked what they value most and what compromises they are willing to accept and support.

Finally, we noted in the introduction that the forest-wood sector was an essential part of

many regional economies and cultural identities. Although this was not the purpose of this article, we know that this sector is highly geographically heterogeneous. Therefore, similar studies at regional levels would be beneficial. Rather than a series of individual regional assessments, we would argue for a coherent multi-regional assessment, that is, disaggregating the national MFA and economic model to provide evaluations in all regions. Regional strategies, e.g., specialization strategies, could then be revisited both in terms of their internal effects and consequences on other regions. Interestingly, there is no guarantee that the same policy would be preferred, regardless of whether the focus is put on the national level or on the regional level. We think that a multi-regional approach will therefore be a major direction for future research.

Territorial supply chains from a social sciences' perspective

In Chapter 7, we proposed an example of coupling SC-MFA with economic modeling in order to evaluate potential consequences of policy alternatives. This is one possibility of extending SC-MFA to economic aspects, but there are many others. First, one can make a distinction between establishing a diagnosis and exploring scenarios. Comparing Sankey diagrams of material and monetary flows for instance illuminates present (or possibly past) situations¹. Second, economic aspects can't be reduced to monetary flows. Economic theories are diverse and in some cases, separating economic from social and cultural aspects is simply impossible. For this reason, we wish to explore in this chapter what social sciences (as opposed to environmental sciences) can offer regarding the analysis of territorial supply chains. No case study was conducted on the matter in the course of the thesis, however, we find it useful to reflect on what could be undertaken in the future. Social sciences indeed provide a large set of theories for conducting systemic analyses of supply chains, that is, not only characterizing individual parts of the chain, but also the relationships between them, their links to governance institutions and to the environment. A first section is dedicated to the presentation of such grids of analysis, originating among other fields from management, economics and sociology. Believing that environmental issues are unlikely to be solved separately from social-economic ones, and aware that employment is, even more so in a time of crisis, a top concern for local decision-makers, we put a more practical emphasis on this question in a second section.

8.1 Complementarity of existing frameworks

At the start of our PhD, we participated in a one-week summer school² dedicated to the field of *territorial ecology*³. The group of academic attendees continued the work initiated during the school which eventually lead to the publication of a book (Buclet et al., 2015) dedicated to the formal presentation of methodologies and to their application to the town of Aussois, Savoie. Four aspects are mainly developed: the socio-ecological trajectory of the territory from the

¹In addition to the example provided in the previous chapter (figure D.3 in supplementary material), we illustrate this in the case of Argentinean soy (figure E.1 in appendix). Barles (2007) already used this representation to show how the quantity and valuation of urban waste, and human excreta in particular, changed over the last two centuries, how the roles of actors (households, cities, farmers, waste collectors or fertilizer companies) were consequently redistributed and how these evolutions affected the environment.

²This summer school, entitled "*Territorial ecology, an emerging disciplinary field*", took place in the town of Aussois, in June 2013 and was organized by Nicolas Buclet (CNRS, Université Grenoble Alpes) and Sabine Barles (CNRS, Université Paris 1).

³This field was presented in the introduction (Chapter 1), with the attempt to show in what aspects *territorial ecology* differs from *industrial ecology*.

early 19st century to today (Barles et al., 2015), the systems of wealth creation on the territory and how they respond to people's needs (Buclet et al., 2015), the agri-food system (Bonaudo et al., 2015), and the energetic metabolism of the territory (Courtonne et al., 2015). Although these four chapters aim at balancing quantitative and qualitative descriptions, the first two are more qualitative and the last two more quantitative. In the following, we draw many concepts from this essay, although also relying on alternative sources.

Elinor Ostrom's framework of social-ecological systems (SES), illustrated in figure 8.1, provides a global view of a bio-geo-physical unit and its associated actors and institutions and is therefore a relevant starting point (Ostrom, 2009; McGinnis and Ostrom, 2014). The system is described by four main subsystems: a *resource system* (e.g. forest) contains *resource units* (e.g. trees) that may be used by *actors* (e.g. forest loggers) under certain conditions set by a governance system (e.g. property rights, sustainable management plans). Prominence is attached to the concept of *action situation* in which "*actors in positions make choices among available options in light of information about the likely actions of other participants and the benefits and costs of potential outcomes*" (McGinnis and Ostrom, 2014)⁴. In accordance with this framework, Kébir (2004) shows resources alone do not exist. An object (e.g. a particular material) becomes a resource once its potential has been revealed by a will of using it to a productive end (for instance, uranium ore was of little interest until the development of the nuclear industry). In this sense, resources are both a given and a construct: they are *neutrally* provided by the environment but their fate depends on what people do with it (Kébir and Cremoisier, 2004).

The SES framework would however benefit from an adaptation in order to be more relevant to supply chains. Supply chains are indeed both embedded in territories and a-territorial in the sense that they link different sectors in different territories together. Of course degrees of territoriality may differ for different supply chains, for instance short-circuits have deeper relationships to the territory than export oriented chains. Moreover, chains' functioning is influenced by local, regional, national, continental and international sets of rules and usually impacts both local and global environments. Debusson (2014) proposes a grid of analysis to study local supply chains, and local food chains in particular, in an attempt to identify obstacles and levers of action for territorial sustainable development strategies (table 8.1). The grid is divided in 3 parts. The first part aims at characterizing actors by their situation in the supply chain and their role and motivation (in this perspective, we will develop in a moment the concepts of *power*, *legitimacy* and *interest*). The second part is dedicated to collective action and qualifies modes of interaction (*to what extent do actors share the same goals?*), membership to a type of economic sphere inspired by Polanyi (1944) and Kolm (1984), entity sizes and scopes of influence, and finally type of proximity(ies) between actors: those can be close from a physical distance viewpoint, because they share similar cognitive frameworks (e.g. belong to the same networks, rely on the same technology) or because they share the same values and norms (Pecqueur and Zimmermann, 2004). Finally, the third part of the grid characterizes the environment (context) in which the group of actors operates and how it interacts with it, from a policy, social and ecological viewpoint.

⁴Although the original design of the framework was dedicated to common-pool resources, McGinnis and Ostrom (2014) argue it is also relevant for public goods, and supporting ecosystem services in particular. In economics, both common-pool resources (also called *commons*) and public goods are non-excludable, however, contrary to public goods (e.g. air), common-pool resources are rival (e.g. fisheries).

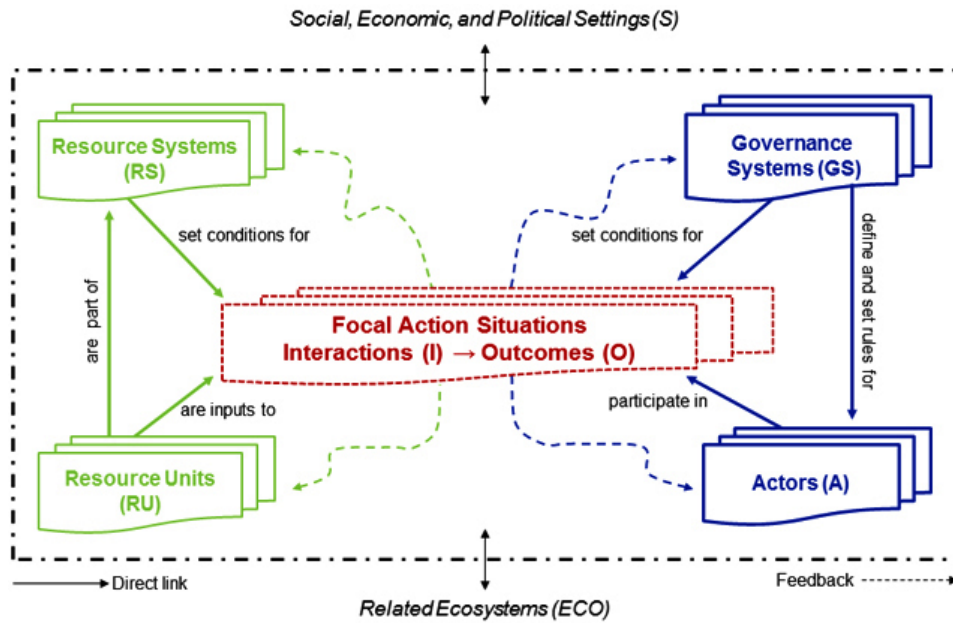


Figure 8.1: A framework for studying social-ecological systems. Source: (McGinnis and Ostrom, 2014). As the layers show, the main categories can be further detailed with “*second-tier variables*”, e.g. economic trends, equilibrium properties of resource systems, number of resource units, actors’ past experiences, government organizations, deliberation processes etc. The full list is proposed in appendix of the chapter (table E.2).

Exploring the dynamics of wealth creation systems, Buclet et al. (2015) additionally refer to the economics of convention (Boltanski and Thévenot, 1987). In this paradigm, interactions between individuals are not purely rational nor purely guided by self-interest: symbolic representations (conventions) also play a role in decision-making and coordination. These *systems of legitimacy* must be analyzed in order to better understand what drives coordination or hold it back. Moreover, the authors attach a lot of importance to the idea of "*territorial capability*" adapted from Amartya Sen's concept (Sen et al., 1999): favorable resources (in the wide meaning of the word) are not sufficient to reach well-being, one requires means to convert these resources into ends.

Actor	Type	Producer, transformer, distributor, consumer, supporting activity
	Role	Initiator, coordinator, participant, funder
Collective action	Interaction mode	Interaction, coordination, coopeation
	Membership	Market, redistributive (public), reciprocity spheres
	Size	Number of people or entities, scope of action or of influence
	Proximity	Geographical, organizational, institutional proximities
Environment	Policy and governance	Stakes and objectives of policies
	Social context	Well-being stakes
	Natural context	Ecological stakes

Table 8.1: Grid of analysis for studying local supply chains and their relationship to sustainability dynamics. Source: translated from Debuissou (2014).

In order to be even more supply chain specific, we now examine the study of Bassene et al. (2014) on two French food chains: organic rice and einkorn (*petit épeautre*). The authors attempt to characterize supply chains' "*systemic sustainability*", which is similar to the concept of resilience introduced in the previous chapter (the ability to absorb shocks while retaining the same functions and identity). After identifying the actors (producers, transformers, packers and distributors) and structure of each chain, they apply network analysis using the governance typology of Vurro et al. (2009)⁵ and the concept of "*survivability*" developed in Thadakamalla et al. (2004)⁶. Because these typologies alone are insufficient to answer their question⁷ they also qualitatively assess a set of economic, social and environmental indicators shown in table 8.2. Although these indicators are dedicated to food chains, they could be adapted to any other sector.

Finally, while the above frameworks refer to *actors*, we believe this notion is worth extend-

⁵This typology is based on two attributes: "*supply chain density*" (defined as the number of links between actors divided by the number of possible links), and "*centrality of the focal organization*" (a star-shaped network will have a centrality index of 100% and a linear network a centrality of 0%).

⁶Four attributes are assessed based on the network's structure: robustness, reactivity, flexibility and adaptability.

⁷The authors for instance wonder: "*Below what density or centrality level is a network's survival threatened?*" (personal translation from Bassene et al. (2014)).

Economic	Social	Environmental
Producers' net margin, Yield level and variability, Dependence to the common agricultural policy, Supply chain's dependence towards external actors, Producers' adaptability	Involvement (motivation for organic farming), Attachment to the farming profession, Quality of life, Products' quality, Contribution to employment, Ability to transfer farms	Producers' protection, By-products' valuation, Toxicity index and treatment frequency index

Table 8.2: Sustainability indicators for agri-food supply chains. Source: translated from Bassene et al. (2014).

ing to that of *stakeholders*. The term was popularized by Freeman (1984) in the context of strategic management and defined as “*any group or individual who can affect or is affected by the achievement of the organization's objectives*”. In this book, Freeman argues that firms' strategic decisions shouldn't only consider *shareholders'* interests but also that of *stakeholders*. The stakeholder model of the corporation proposed by Donaldson and Preston (1995) illustrates this idea (figure 8.2). Donaldson and Preston (1995) further examine justifications for this representation of the firm and distinguish descriptive grounds (the model is describing what a firm really is, i.e. a “*constellation of cooperative and competitive interests possessing intrinsic value*”), instrumental grounds (a mean to achieve a competitive advantage: “*corporations practicing stakeholder management will, other things being equal, be relatively successful in conventional performance terms (profitability, stability, growth, etc.)*”) and normative grounds (“*each group of stakeholders merits consideration for its own sake and not merely because of its ability to further the interests of some other group*”). They ultimately find that this latter ground is fundamental⁸. This being said, organizations cannot take into account all actors of their environment, they need to identify the most relevant ones. Precisely noting that there was no agreement on “*principles of who and what really counts*”, Mitchell et al. (1997) proposed a typology to identify and prioritize stakeholders according to three key attributes: power, legitimacy and urgency. Power is the potential ability of an actor to impose its will to others⁹. Legitimacy is the acknowledgment of a stakeholder by its peers. Urgency corresponds to the degree to which a stakeholder perceives its claims as important and requiring immediate attention. As shown in figure 8.3, a variety of stakeholder's profiles derives from these three attribute and for instance helps to identify pivot (or *definitive*) actors with all three attributes, but also *dominant*, *dependant* and *dangerous* ones. Those who do not possess any attribute should be excluded from concertation processes. In France, this typology was adapted to the study of governance and sustainability of industrial ecology projects (Brullot et al., 2014). The objective being to identify actors that would be suited to actively support a project, the notion of urgency was replaced by interest (e.g. political, economic, environmental interest). Depending on the focus, the two typologies seem well suited to (i) prioritize who should be considered

⁸“*The plain truth is that the most prominent alternative to the stakeholder theory (i.e., the “management serving the shareowners” theory) is morally untenable*” (Donaldson and Preston, 1995).

⁹Etzioni (1964) distinguish *coercive power*, based on physical force, *utilitarian power*, based on financial and material resources and *normative power*, based on symbolic representations.

in the analysis and (ii) provide a first image of motivations, claims and power relationships¹⁰.

More generally, the notion of stakeholder is essential to sustainable development. As Boutaud (2005) shows, sustainable development reshapes the idea of general interest by extending it in space and time. While general interest traditionally refers to present generations in a delimited community, *sustainable general interest* implies to consider the rest of the world as well as future generations, that is two additional groups of stakeholders. Of course finding ways of representing interests of future generation is not easy (Bourg and Whiteside, 2010). We will see in Part 3 that participation can fulfill this role in some situations.

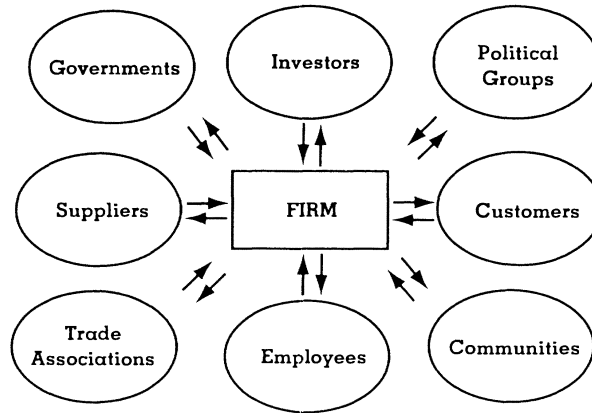


Figure 8.2: A stakeholder model of corporations. This model contrasts with the conventional input-output model which only considers suppliers, clients, employees and investors. Source : Donaldson and Preston (1995).

Going back to territorial issues, we now wish to explore a bit more the question of employment, given supply chains are an essential part of it.

8.2 Characterizing employment

We briefly introduce this section with thoughts on the situation of work in today's societies, then we present an overview of ways to assess the effect of public policy's on employment, on the example of climate policies. Finally, we propose an example of crossing economic, employment and material flow data in three sectors of the forest-wood supply chain in order to show how it can help characterizing the value chain.

Méda (2004, 2010) show that, in western societies, social order is organized around work. Labor is both the main source of subsistence revenues and the main space for social relationships. Both free market advocates and marxists agree on this, the first because they view society as a mean of increasing production and trade and the latter because they view work as the basis

¹⁰Note that the contribution of stakeholder theory to the field of supply chain management has been studied (Wittke, 2014). However, supply chain management is not of direct interest to our work since it mainly studies firms' sourcing strategies (make-or-buy choices), supplier strategies, and contracting decisions.

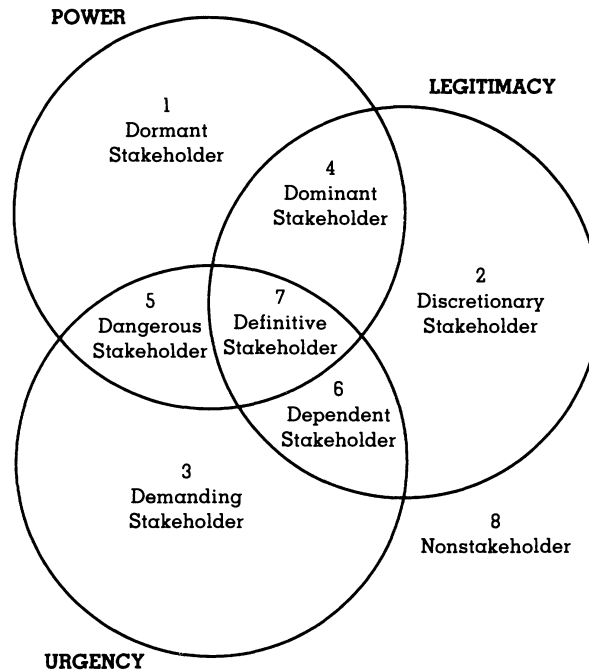


Figure 8.3: A typology of stakeholders. Source : Mitchell et al. (1997).

of social allegiance. The author argues there is no philosophical ground to justify this central space of work other than an utilitarian conception of the world, in which the unemployed are perceived as useless weights. Work certainly produces wealth but forming a society is more than participating in the productive economy. Reducing its importance would leave room for other forms of relationships and involvements, political involvement in particular. These thoughts may be revisited in the perspective of a (wanted or unwanted) transition to post-growth economies.

This being said, employment is currently a key issue for local decision-maker as it represents a large part of a territory's revenues¹¹ and participates in its social dynamic. Policy choices on sustainability issues or therefore unlikely to be made without an assessment of their impacts on job creation. We now propose a description of ways to conduct such assessments, relying on a recent study on the effects of climate policies (Quirion, 2013).

In this paper, Philippe Quirion undertakes the evaluation of the French *négaWatt* scenario of energy transition¹². Here, we only focus on the way he situates it regarding other studies

¹¹In economic geography, the economic base theory introduces a typology of local sources of revenues: the productive (or export) base for instance includes salaries of exporting activities (industry, agriculture, business to business services etc.), the residential base includes retirement pensions and revenues from touristic activities, the public base includes wages of civil servants and the sanitary and social base accounts for health care and other social transfers (Davezies, 2008).

¹²This scenario, built by the *négaWatt* association, is based on a massive development of energy savings (through sobriety and energy efficiency) and renewable energies. By 2050, it aims at a division by 16 of 2010

on the subject. Figure 8.4 illustrates nested scopes (and associated job creation/destruction mechanisms) that can be considered. The most restricted scope (blue frame), only considers direct job creation due to the implementation of a policy. The notion of net job creation appears in the next scope (red frame), by also considering direct jobs destruction (polluting activities that will disappear or at least decrease if the policy is implemented). This is however biased as it leads to favor higher cost technologies or organizational forms¹³. In his study, the author therefore extends the scope (violet frame) to account for the fact that ultimately households or companies have to pay for this extra-cost, therefore decreasing final demand for other activities. We saw in Chapter 5 how Input-Output Analysis makes it possible to estimate production factors (in this case labor) induced by a given level of final demand. Using this methodology, the net effect on job creation has been re-evaluated. Finally, macro-economic models can consider an even wider scope (green frame), for instance estimating the retro-action of a change in wages on labor demand. However, the author argues these models are less transparent and do not allow to have a detailed (sectoral) view on the system.

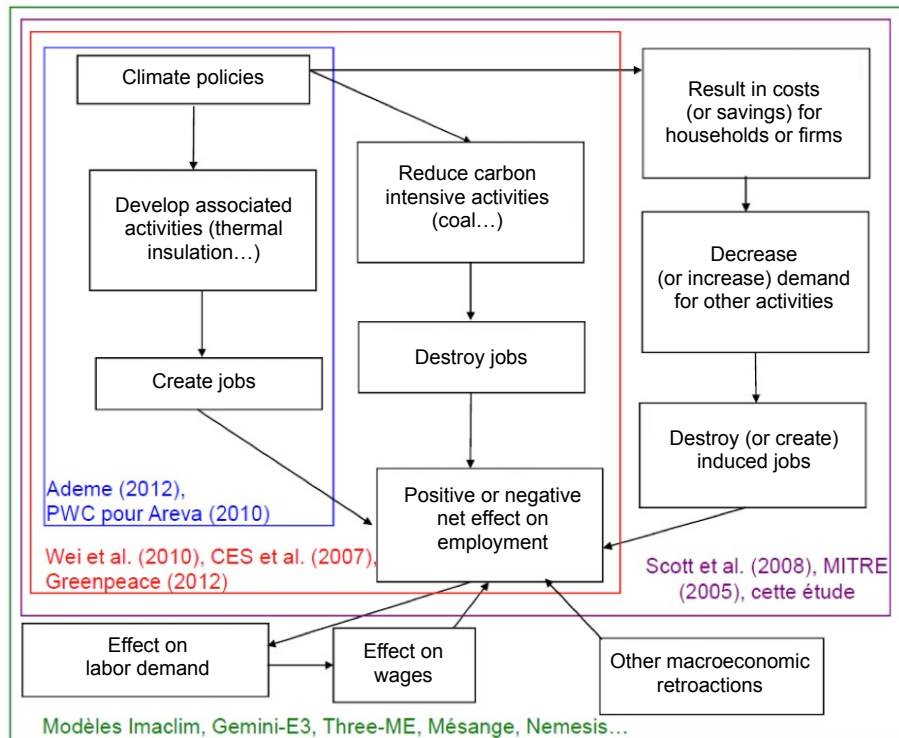


Figure 8.4: Main mechanisms of jobs creations and destructions used to characterize climate policies. Source: translated from Quirion (2013).

French CO₂ emissions, without requiring carbon capture and storage technologies or new nuclear plants.

¹³To produce the same amount of goods and services, in this case energy, more money has to be spent and, given that wages represent the largest part of added value, this is likely to translate into more job creations. Another way to see it is that sectors favored by sustainability policies are in general more labor-intensive than the ones which they substitute.

The main limit of these evaluations is that they use the current *economic recipe* (e.g. matrix of technical coefficient) to forecast future trends. Moreover, the uncertainty is high on the reallocation of households' and companies' final demands for each economic sector, as one could argue such scenarios go along with important changes in modes of consumption. As most forecasting endeavor though, the author points out that it must be considered in terms of comparison with the business-as-usual scenario, and also conducts sensitivity analysis on a few variables to study their effect on results.

Interestingly, Philippe Quirion and colleagues recently used a similar methodology to evaluate the impact on jobs of Solagro's Afterres 2050 scenario for a sustainable agriculture¹⁴. This scenario (as well as its variants), is presented in Chapter 10 as we will use it in a deliberation role-play.

Finally, as we saw in table 8.2, employment should be assessed both in quantitative and qualitative terms. Beyond the number of jobs (which is of course an essential information), relevant evaluations would for instance include work drudgery, exposure to risks, precariousness, continuing training but also less tangible aspects as one's interest in a job and social representations on it.

We now turn to an example of crossing employment, turnover and biophysical data to show how it can help characterizing each sector regarding its material and labor intensiveness. We do so on the example of the French forest-wood chain: Table 8.3 is obtained by crossing economic data from the ministry of agriculture with the MFA presented in Chapter 7.

Although the table does not show it, the proportion of self-employment varies a lot depending on the sector: 57% for wood harvest, 6% for the first transformation, 8% for the second transformation and less than 1% in the pulp and paper industry. Column $\text{k€}/1000 \text{ m}^3(\text{f})$ provides order of magnitude of the economic efficiency of wood in terms of turnover. This conveys a clear idea of the value chain with more and more creation of wealth per unit of material throughput as one moves from harvest to first and then to second transformation. Note that the pulp and paper industry contains in itself first and second transformations and has the highest turnover to material throughput coefficient. The last column, employment per material throughput, is interesting as well. We can see, that although first transformation industries generate nearly 5 times as much value as harvest per material unit, their employment to material ratio is about the same. This can be explained by three factors: harvest also includes forest management that does not directly provide wood to the market, wages in transformation industries are higher than in harvest, and transformation is relying on more capital-intensive investments. The same conclusion can be drawn when comparing the second transformation with the pulp and paper sector: here, capital intensiveness is clearly the main factor explaining that the second transformation is more labor-intensive than the pulp and paper industry per material unit while simultaneously generating less value. Finally, the ratios of the first and second transformation clearly express the fact that the first transformation values the material while the second values work on the material. Note that all ratios presented here only reflect the current situation (degree of horizontal integration in each sector, degree of reliance on imports, available technology etc.) and could not be directly used to provide employment forecasts based on the evolution of physical flows. As we just saw, they can however help better understanding the current functioning of the value chain.

¹⁴This scenario is in fact the biomass part of the négaWatt scenario.

Sector	Employment	Turnover (M€)	Material throughput (Mm ³ (f))	k€/1000 m ³ (f)	Employment / 1000 m ³ (f)
Wood harvest	47900	1600	37	44	1.3
1 st transformation	28200	5000	23	216	1.2
2 nd transformation	112000	9200	19	492	6
Pulp and paper industry	68300	18500	19	995	3.7

Table 8.3: Employment, turnover and material throughput in different sectors of the forest-wood chain. Employment is computed as the addition of self-employment and employees. Ratios of turnover to material throughput and employment to material throughput are computed on this basis. The 1st transformation sector includes sawmills, wood panels and plywood and the 2nd transformation sector includes wooden frames and joineries, wood packaging, furnitures, wooden consumer goods. Numbers related to this sector may be a bit biased because some activities (e.g furniture) encompass other materials as well and are only partially part of the wood chain. The material throughput of each of these four sectors is computed by looking at their inputs (for 1st transformation, 2nd transformation and for the paper industry) or outputs (for harvest). For the pulp and paper industry, we add up pulpwood, residues from sawmills, imported pulp, imported waste paper but not the amount of paper recycled from local waste (which would be double-counting).

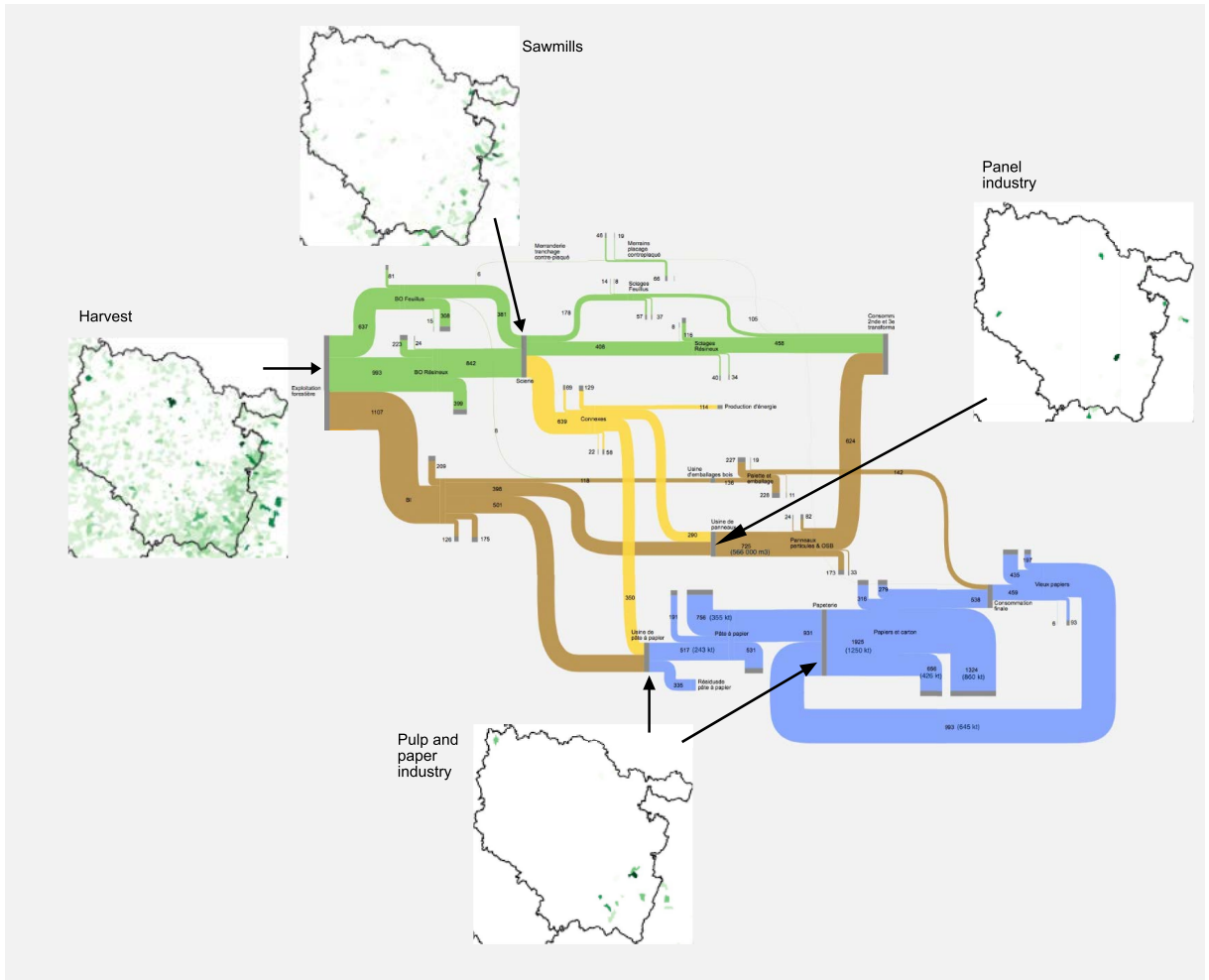


Figure 8.5: Wood flows and spatialization of associated employment in Lorraine.

We finally wish to point out opportunities related to data visualization and geographic information systems (GIS). Most sectors described in SC-MFA can be associated with an official economic classification. Although we mostly exploited regional data, it is noteworthy that data relative to employment is available in France down to the city level in fine sectoral resolution. We therefore think that this spatially-explicit information could be a useful complement to the Sankey diagrams, as illustrated in figure 8.5. Beyond this example, we believe data visualization, and spatialized visualization in particular, is important to transfer research results to stakeholders and decision makers. The MIT urban metabolism group develops interesting visuals on the matter, as figure E.3 (in appendix) shows.

Part two recap

The second part was devoted to extending the supply chain MFA (SC-MFA) model to environmental stakes and exploring possibilities of studying socio-economic aspects. More specifically:

- In Chapter 5, we presented methods aiming at tracing flows, both between regions and between industries. We demonstrated the links between Input-Output Analysis (IOA), Absorbing Markov Chains (AMC), and eventually with the Supply and Use tables (SUT) used to handle data in the SC-MFA model. Using Leontief's minimal example of a 2-sectors economy, we illustrated that while IOA and AMC were equivalent, using the first was more natural for tracing upstream flows (from consumption to production), the latter being more natural for downstream flows.
- In Chapter 6, we extended the MFA study on the French cereal supply chain presented in Chapter 3 to environmental pressures (energy use and greenhouse gases emissions, land use, use of pesticides and blue water footprint). For this purpose, we extended the cereal model to meat, dairy and eggs products and used AMC to trace flows. The main goal was to build environmental footprint accounts from the producer's and consumer's viewpoints but we showed many other questions could be tackled by the model: *What is the fate of a specific product? What are the supply areas of a given region for a given product and along the product's fabrication steps? What life-cycle phases (production, transformation, transport) are the most critical for each pressure? What pressures (e.g. land use) are virtually traded between regions?* We pointed out the limits of this work and possible ways to overcome them; in particular, providing a detailed view of the whole agri-food sector and describing supply chains of other countries seems to be required in order to be more policy relevant.
- In Chapter 7, we developed in collaboration with the Laboratory of Forest Economics (LEF, Nancy), a SC-MFA model of the French forest-wood chain. One important goal was to objectify the importance of raw wood exports and put them in context with flows in the rest of the supply chain. LEF's partial equilibrium model (FFSM) was then applied in order to explore potential consequences of log export reduction policies on both the economy of the sector and material flows. Although the article is only focused on the national level, regional results were obtained as well and an example is given in supplementary material.
- Chapter 8's purpose was to provide an overview of additional socio-economic aspects that could be studied on the basis of the SC-MFA model. To do so, we presented a set of frameworks originating from economics, sociology and management that could be adapted to the supply chain context, including Ostrom's framework of social-ecological systems, concepts applied in *territorial ecology* and stakeholders theory. In a decision-aiding perspective, we then focused on the issue of employment to understand how effects

of public policies could be estimated and provide a first idea of how crossing material flow data with economic and employment data could help to better understand the value chain. In this perspective, Sankey diagrams comparing material and monetary flows offer a powerful representation, all the more so if one is able to spatialize them down to the city level.

Overall, in order to convey more synthetic results and discard information that is considered too uncertain, it would be useful to conduct a "*fuzzification*" process on current outputs from SC-MFA and environmental extensions. In particular, this will require to conduct sensitivity analyses (for instance more systematically testing different distance functions in the data reconciliation process). In turn, this could also provide ideas on how to simplify the model, thus making it more transparent, while retaining essential information.

Transition to part three

The first research objective of this thesis was to complement existing biophysical accounting tools, at subnational scales, with a special attention on assessing both producer's and consumer's responsibilities for environmental pressures. The first two parts were mostly dedicated to this effort: we presented the SC-MFA model, which assesses material flows of a given supply chain at the national and regional levels and an extension to environmental pressures associated with these material flows. Furthermore, we introduced, although in less details, possible ways of coupling this model with socio-economic stakes, for establishing a diagnosis and for exploring scenarios. The basic material for designing qualitative and quantitative environmental, social and economic indicators is therefore identified and could be used to assess supply chains' evolution scenarios.

Our work was oriented towards advancing methodologies rather than towards studying specific issues, although we have discussed some throughout the articles. For this reason, we do not build nor evaluate by ourselves such supply chains' scenarios, but instead examine the second research question of this thesis. *Lots of information are (potentially) available with these tools, however, under what conditions could they best serve decision-making?* As we saw in the introduction, (i) sustainability calls for multicriteria assessments of alternatives (beyond economic optimization strategies) and (ii) uncertainty surrounding scientific knowledge is an additional argument to legitimate various perspectives on an issue, and therefore to involve stakeholders in decision-making processes. Two difficulties then arise:

- How can one make a decision when there is no *first best* option, that is, how to arbitrate between conflicting criteria?
- How can different stakeholders reach a decision? Or at least, how can the deliberation process illuminate the final decision-maker and legitimate a choice?

Part 3 will attempt to address them. Chapter 9 is mainly dedicated to a presentation of decision-aiding processes, deliberation and multicriteria analysis. In Chapter 10, we start by clarifying the scope of decision-making contexts we wish to focus on, then propose a *deliberative multicriteria* procedure, and finally outline a future experiment of the method.

Part III

Structuring public deliberation through multicriteria methods

Principles of multicriteria decision-aiding, participation and deliberation

This chapter (as one can guess from the title) is mainly dedicated to the presentation of *Multicriteria Decision-Aiding* (MCDA), and to the concepts of *participation* and *deliberation*. After outlining the main decision models and theories, we describe each step of MCDA in a participatory context, with a special focus on multicriteria aggregation methods. We then discuss participation and controversies surrounding it before introducing the underlying principles of *deliberative democracy* that will guide us in the next chapter, for the design of a decision-aiding procedure.

9.1 A short introduction to decision theories

Deciding is choosing an action among different possibilities. This choice is based on the values, preferences and objectives of the decision-maker(s). From the 1950's, decision-making has become the subject of an academic discipline, at the crossroads of management, organizations' sociology and political sciences. The *rational model* has been revisited and other decision models have been developed. They underline the fact that decision-making processes are in no way neutral or objective (CEDIP, 2012).

In the *rational model*, the individual (*homo oeconomicus*), is able to rank its preferences transitively, to optimize its resources in order to maximize its satisfaction and to perfectly analyze its environment in order to anticipate the best decisions to make.

In the *bounded rationality model*, individuals cannot find a perfect solution, in the sense of satisfaction maximization, but only a satisfying solution. Indeed, the available information is imperfect (it contains uncertainties that are difficult to handle), the decision-maker has a limited capacity to integrate the information and finally actors may find themselves in situations of strategical interdependence. Only a limited number of actions is studied (Simon, 1957).

In the *political model*, the decision process is a cycle of bargains and negotiations between decision-makers. In order to reach their objectives, the latter can conceal or distort information.

In the *garbage can model*, decisions emerge from random encounters between a flow of problems, a flow of solutions, a flow of participants, and occasions to choose. The interest of this model is not to overestimate the rationality of actors. However, it is ill-suited for planned decision-making processes.

Finally, in the *cognitive hierarchy model*, decision-makers are separated in 3 classes: “*cognitive decision-makers*” who make rational choices depending on objective information available to them, “*affective decision-makers*”, who are more sensible to feelings than to facts, and “*mix decision-makers*”. This model is widely used to study consumer behavior.

As we will see right away, the underlying decision model behind MCDA is the *bounded rationality model*, although all processes described above may also play a role at certain times. Transversely to these models, it is possible to decide alone or in a group. In this last case, one can distinguish between *decision by delegation*, for instance to an expert trusted by the group, *decision by majority*, implying a voting procedure, and finally *decision by apparent consensus*, which is less well know and will be presented in the second section.

9.2 Multicriteria decision-aiding in a multi-stakeholders context

Decision-aiding is defined by Roy and Bouyssou (1993) as an activity serving action (personal translation): “*The purpose of decision aiding is to identify part of an answer to questions asked by stakeholders in a decision process. Decision-aiding acts through the use of explicit but not completely formalized models. These partial answers inform the decision and recommend, or simply foster, a behavior increasing the coherence between the evolution of the process on the one hand and the objectives and systems of values the decision-maker is confronted to on the other hand*”.

In this section, we wish to focus on a particular field of decision-aiding that makes use of multicriteria methods in a participatory context. The implementation of such methods requires several steps: (o) identification of the problem, (i) identification of stakeholders and determination of their involvement, (ii) determination of possible actions to address the problem, (iii) choice of evaluation criteria, (iv) indicators design, (v) evaluation of actions with the selected indicators, and finally, (vi) preference aggregation among criteria and among stakeholders. We will describe these steps shortly, but first, as the involvement of various stakeholders adds a layer of complexity to the process, we present the main grounds for choosing this path for sustainability issues.

9.2.1 Why foster participative processes?

Froger and Oberti (2002) emphasize the incentives of top executives to include sustainable development in their decision processes through the example of the 1992 Rio Declaration on Environment and Development and the Agenda 21 initiatives. Two main reasons are advanced.

The first reason is of epistemic order and is related to problems complexity. Problems are complex because actions (or non-decisions) have delayed or remote consequences, because consequences are uncertain, and because of a network of inter-connections inside ecosystems but also, at all geographical scales, between the economic, social and environmental spheres. This complexity may be managed through the participation of different stakeholders, who address the problem together and justify their points of view based on their experiences and knowledge.

The second reason is of instrumental order. Sustainability issues are characterized by the presence of various stakeholders whose short-term interests diverge. Participation must then

allow to make different judgments explicit; the objective is not necessarily to reconcile them, but to favor the acceptability of decisions. This seems all the more required as the traditional decision model for public projects, organized around the couple State/experts, has been increasingly questioned in recent decades. Part of the population challenges the legitimacy of the decisions taken by their political representatives, as recent confrontations about “*useless imposed mega-projects*” illustrate. While this is not a new issue¹, it becomes more acute in times of crises. Participation is then viewed mostly as a way to reduce the risk of conflict, although under adequate conditions, it can effectively favor the inclusion of various viewpoints, deliberation and transparency.

These reflections are directly linked to the concepts of governance, participatory democracy and deliberative democracy in the field of political science. Note that the definitions of these terms, in particular those of governance, vary in the literature. For example, Scorier (2012) distinguishes them according to a hierarchy of public authorities’ motivations (personal translations). Thus, “*the objective of governance is not to make a legitimate decision, potentially respected by all, but rather to legitimize the actions of public authorities [...]. Governance motivates and empowers actors to achieve its ends*”, while “*participatory democracy is a matter of consolidating the legitimacy of political decisions by involving non-elected citizens in the discussions*”. Finally, participation differs from the deliberative project, as proposed by Habermas (2003). If participation can be a way to anticipate or to defuse conflict, the deliberative project instead seeks to promote a critical activity. It is a matter of “*refining understanding, decoding information, revealing strategies, manipulations and bargains between interest groups, to make room for a communication space where only the best argument prevails*” (personal translation). In this sense, deliberative democracy can be considered as an ideal to strive for. We will come back to this in the second section. Let us now describe the main steps of MCDA.

9.2.2 Identification and involvement of stakeholders

As we saw in Chapter 8, the concept of stakeholder is much broader than that of actor. Future generations, who are directly affected by certain decisions but not involved in problems formulation or solving are a good illustration of the distinction between stakeholders and actors. Banville et al. (1993) propose to classify stakeholders according to two criteria: their relationship to the problem (*are they influenced by the problem, do they influence it, or both?*) and their level of participation (direct or indirect participation in decision-making). Meanwhile, Mitchell et al. (1997) propose an analytical framework based on three criteria: power, legitimacy and urgency².

Participatory decision corresponds to a situation involving several stakeholders: policy makers, experts, interest groups, public etc. It is not a mere consultation nor a negotiation, but a form of intermediate decision. As we have discussed above, the involvement of each stakeholder in the process is essential to achieve some legitimacy. This legitimacy is based on an implicit initial consensus: stakeholders agree to undergo the planned procedure for adopting a solution.

¹Wahnich (2013) shows the permanent tension between the legitimacy of the National Assembly and that of the people during the French Revolution. In particular, she analyzes the *right to resist oppression*, enshrined in the Declaration of the Rights of Man and of the Citizen, and its implementation in the popular uprisings that punctuated the period 1789-1792.

²See Chapter 8 for a description of these attributes.

This is the reason why it is important to clarify the power and mode of intervention of each stakeholder at the beginning. Not all (and usually very few) stakeholders have an ultimate decision-making power and they can play different roles. Keeney (1992) proposes to differentiate between values and facts. Rousseau and Martel (1996) thus indicate that: “*one can ask experts to make judgments based on facts (relations between causes and effects for example), but as experts, they do not bear the responsibility to make value judgments on behalf of the general population. Similarly, one shouldn't ask the public to speculate about complex systems*”. An expert can therefore help feed or animate the decision process but shouldn't act directly on the decision.

9.2.3 Construction of scenarios

Scenario planning emerged in the second half of the 20th century with two main school of thought (Lecourt, 2004)³. The American school emerged mostly under the impulse of the Rand Corporation⁴ and was mainly based on computation, statistics and deductive reasoning. The work undergone in *The Limits to Growth* (Meadows et al., 1972) is related to this branch. The French school of “*la prospective*” on the other hand, for instance represented by the works of Berger (1958), Jouvenel (1999) or DATAR (1975), was more qualitative, multidisciplinary, and aimed at exploring contrasted futures using hypotheses of trend discontinuation. To a large extent, this clear distinction no longer stands as most studies now use a mix of the two approaches.

Kahn and Wiener (1967) define scenarios as “*attempts to describe in some detail a hypothetical sequence of events that could plausibly lead to the situation envisaged*”. Schwartz and Ogilvy (1998) provide a complementary point of view by stating that: “*Scenarios are narratives of alternative environments in which today's decisions may be played out. They are not predictions. Nor are they strategies. Instead they are more like hypotheses of different futures specifically designed to highlight the risks and opportunities involved in specific strategic issues*”. Scenarios can project past trends, leading to a probable future, they can explore possible futures starting from current trends but also from emerging changes, or they can provide a (positive or negative) normative vision of the future and backcast possible trajectories leading to this future.

Among other possibilities, Godet and Durance (2008) propose a method based on the identification of core variables driving the evolution of the system. These can for instance be demography, economic and geopolitic context, technological progress, cultural evolution etc. In a second step, *mini-scenarios* are proposed by participants for each of these variables, for instance the coming of an economic crisis or in contrary of an unexpected technological innovation. Scenarios are then formed by combining the mini-scenarios together and seeing if it is possible to make sense of them (which is of course not the case for all combinations). This methodology, has the advantage of structuring the process and fostering creativity. Of course it is possible to use it only as a starting point of a more thorough reflection.

In this context, participation is valuable as it helps gathering a large variability of knowledge

³This paragraph is for a large extent derived from the courses given by Olivier Mora (INRA) and Thomas Houet (Université Toulouse 2) during the SCEMSITE “*winter school*” on territorial participatory scenario building and modelisation.

⁴The latter designed in particular the Delphi method to forecast the impact of technology on warfare (Linstone et al., 1975).

and viewpoints. One can also point out that debates occurring during this phase can be the base of future collective action. Finally, for the interest of the MCDA process (and of the decision-makers), it is useful to provide contrasted scenarios rather than lighter and darker shades of a central scenario.

9.2.4 Choice of criteria

The choice of criteria and corresponding indicators is a key step in the process and must be conducted in a transparent manner. Criteria determination can be considered in two complementary ways. Keeney and Raifa (1976) assume that certain stakeholders, for instance project promoters, can easily explain their point of views by referring to their objectives, since actions were motivated by these objectives. On the other hand, Roy (1985) stresses that other stakeholders can better explain their perspectives by referring to the consequences of the actions when they are affected by these consequences. It is therefore important to take into account these two methods (objectives and consequences) to ensure that one has properly addressed the interest of each stakeholder.

9.2.5 Design of indicators

OECD (2008a) proposes a practical manual for the design of composite indicators in which important factors that must be taken into account when selecting indicators are listed. These are *relevance*, *simplicity*, *reliability (and sensitivity to change)*, *political bias*⁵, *feasibility* in terms of timeliness and data collection, and *contribution to a coherent and comprehensive view*. Regarding this last factor (global contribution), the European Environment Agency suggests to classify indicators according to the DPSIR framework (Drivers, Pressures, State, Impacts, and Responses). Under this framework, adapted to the environmental issues, drivers (e.g. economic activities) produce pressures (e.g. greenhouse gas emissions) that change the state of the system (e.g. the chemical composition of the atmosphere). This produces a series of cascading effects, often undesirable (e.g. climate change will cause a rise in sea level and population migration). Policymakers must then take measures (responses) in order to target each of the previous steps (develop plans to adapt to climate change impacts, encourage businesses and households to emit less carbon etc.). Starting from the DPSIR framework, one can build efficiency indicators. for instance, the energy efficiency of the economy can be measured by dividing the quantity of goods and services (driver indicator) by energy consumption (pressure indicator). Figures 9.1 and 9.2 illustrate respectively DPSIR indicators and a few efficiency indicators one can build with them. This framework however has blind-spots. The European Environment Agency therefore proposes a complementary organization grid, that structures indicators into: (a) descriptive indicators (*what is happening?*), (b) performance indicators (*does it matter?*), (c) efficiency indicators (*are we improving?*), (d) policy effectiveness indicators (*are the measures working?*) and (e) total welfare indicators (*are we on the whole better off?*).

Other critical points concern the normalization of indicators and the possible aggregation strategies to form composite indicators. This last step is often essential to maintain a manageable number of indicators in a decision process (for one to understand a specific problem, it is recommended not to exceed ten indicators). In return, it is critical to pay attention to

⁵Of course one can argue an indicator is never completely neutral, on the other hand limiting bias is possible.

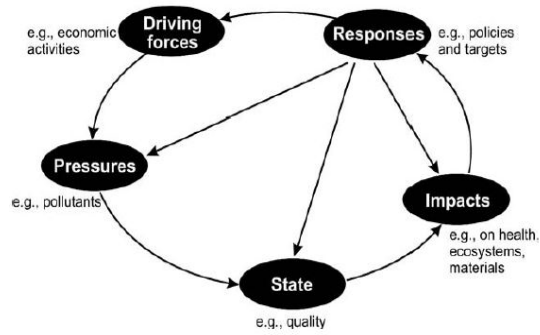


Figure 9.1: Driver (D), Pressure (P), State (S), Impact (I) and Response (R) indicators. Source: European Environment Agency.

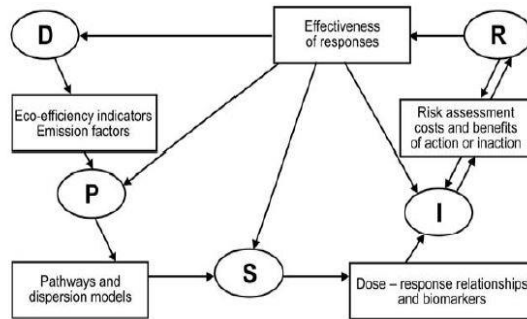


Figure 9.2: Efficiency indicators using the DSPiR framework. Source: European Environment Agency.

possible compensation phenomena between incomparable issues. This leads us to address the multi criteria aggregation methods in the following paragraph.

9.2.6 Multicriteria aggregation

9.2.6.1 Overview of multicriteria analysis

The two major multi-criteria approaches, compensatory and non-compensatory, directly derive from the work of Condorcet and Borda on electoral processes. The latter are besides considered to be the founders of social choice and rational choice theories (Gaertner, 2009). Before presenting these branches, two conclusions are worth noting. On the one hand, the final decision is partly conditioned by the voting system chosen. On the other, Arrow (1951) demonstrates that it is impossible to aggregate multiple preferences into a single collective preference endowed with all desirable characteristics (universality, unanimity, independence of irrelevant alternatives) without using the dictatorship of one viewpoint⁶. Therefore, there is no universal procedure. A voting or multi-criteria decision procedure must be formulated considering the context and the objectives, and focus on certain features at the expense of others. There is a direct link between a voting procedure and a multi-criteria decision: alternatives to assess in a multi-criteria procedure can be likened to candidates and the criteria to voters.

Compensation refers to the existence of trade-offs, that is, the possibility of offsetting a disadvantage on some criteria by a sufficiently large advantage on another criterion. Compensatory methods commonly begin by aggregating and then compare. The most widely used one is the weighted arithmetic average. However, this technique tends to favor extreme alternatives at the expense of balanced alternatives (in terms of their performance on each criterion). In this regard, the geometric mean is less compensatory than the arithmetic mean as it tends to favor balanced alternatives. Utility functions such as the Multi Attribute Utility Theory (MAUT) are a generalization of these compensatory methods.

In certain circumstances, allowing compensation between criteria may not be wanted because criteria are incomparable. For example, in the family of environmental criteria, local and global pollution can be considered incomparable. Similarly, in a perspective of strong sustainability, one cannot compensate weak environmental performance with good economic performance. The non-compensatory methods begin by comparing and then aggregate. Most often, the comparison step is characterized by a pairwise comparison of alternatives, as in the PROMETHEE and ELECTRE methods. Some methods authorize vetoes (acceptability thresholds). Non-compensation is eventually based on two scales of distinct values: a scale of preference and a scale of rejection. These methods enable a clearer analysis of possible choices, eliminate certain alternatives, but generally do not generate a transitive preference relation among the different alternatives: some can be considered incomparable. The decision then has to be justified by the greater attachment to a system of values over another.

⁶This point however needs to be qualified as the theorem is demonstrated for ordinal preferences only (in opposition to cardinal preferences): one can rank candidates but cannot express its preference intensities. Taking into account cardinal preferences is proposed by some voting procedures, which can then respect reformulated versions of Arrow's conditions (Sen, 2014).

9.2.6.2 A didactic example with Lara, Pablo and Juan: Weighted average, AHP and Promethee

The goal here is not to present all existing multi-criteria methods, nor to study them from a mathematical point of view. In order to do that, the reader can for instance refer to Ishizaka and Nemery (2013). Rather, we want to apply three different methods on a single example stripped down to the bare minimum in order to show the importance of the choice of the method and of its parameters. By doing so, we point out the distinction between methods that allow compensation between criteria and methods that don't.

The problem

A school wants to select the best student between Pablo, Lara and Juan (3 alternatives) given their grades in French and Maths (2 criteria). The following table summarizes their performance in those subjects:

	Pablo	Lara	Juan
French	10	3	6
Maths	3	10	6

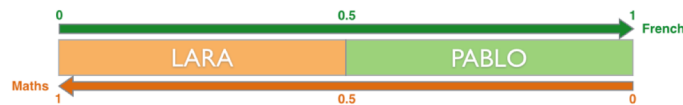
Zero would be the worst possible grade and 10 the best possible grade.

Methods with compensation

Weighted average

The weighted average is the most common/natural method to solve this kind of problem. Coefficients (weights) are chosen for French and Maths (i.e., for each criteria), a weighted average is computed for each student (i.e., for each alternative) and the students are ranked based on this single indicator. Each coefficient can take all the values from 0 to 1, under the constraint that the sum of all coefficients must be equal to 1.

The figure below shows that whatever the coefficients chosen, Juan will never be selected as the best student (arrows represent the coefficients in French and Maths).

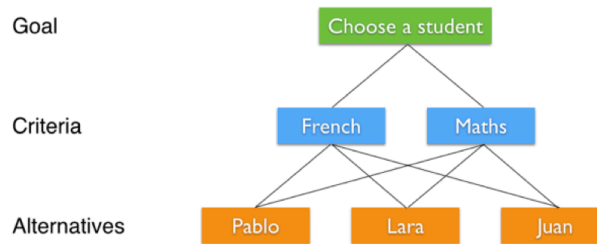


The weighted average penalizes balanced profiles because it allows full compensation between criteria: poor Maths skills can be compensated by excellent French skills. In many cases, this is not a desired property, so decision-makers should be aware of it. For instance, here, the school may want to select someone that has (at least) an average level in French and Maths. Of course, the weighted average does not always eliminate balanced profile; for example, if Juan has 7 in both Maths and French, Juan dominates both Lara and Pablo for equal weights. However, the weighted average method has a strong tendency to do so as can be seen from the fact that 7 is already a high grade.

AHP (Analytical Hierarchy Process)

AHP is well adapted to human thinking. Therefore its results are more likely to reflect the judgments of the decision-makers. Indeed, it uses pairwise comparisons to assess:

- How well each alternative performs against each criterion. In this step, the available information on alternatives (qualitative or quantitative, in our case, the grades in French and Maths) are used to produce a relative scoring of alternatives for each criteria. The score is relative to the other alternatives it is compared with.
- How important is each criteria; this step leads to the choice of the relative weight of each criteria.



The scale used for pairwise comparisons is the one below:

Pairwise comparison score	Explanation
1	No preference
3	Moderate preference
5	Strong preference
7	Very strong preference
9	Extreme preference

If the school really wants to select someone with sufficient French and Maths proficiency, but does not really seek excellent skills in these subject matters, the scores of pairwise comparisons could look like this:

FRENCH		MATHS	
Pablo vs. Lara	9	Lara vs. Pablo	9
Pablo vs. Juan	2	Lara vs. Juan	2
Juan vs. Lara	8	Juan vs. Pablo	8

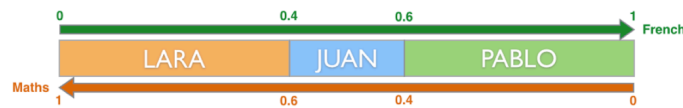
It is worth noting that those comparisons are not necessarily fully consistent from a purely rational point of view (no transitivity property) because each comparison is conducted independently. For instance, it is not impossible to have the following judgment for alternatives A, B, C: $A > B$, $B > C$ and $C > A$. An index of consistency has to be computed (Saaty, 1987), and it may not be a good choice to keep using AHP if this index is too low. The comparison scores are then put in a matrix form.

FRENCH	Pablo	Lara	Juan	Score	MATHS	Pablo	Lara	Juan	Score
Pablo	1	9	2	0.59	Pablo	1	1/9	1/8	0.05
Lara	1/9	1	1/8	0.05	Lara	9	1	2	0.59
Juan	1/2	8	1	0.36	Juan	8	1/2	1	0.36

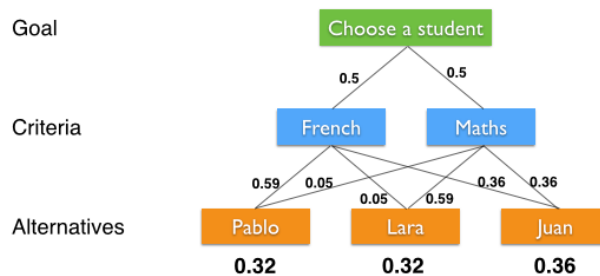
Final (relative) scores are computed (blue column) as the principal right eigenvector of the matrices. Those scores can be interpreted as relative preference intensities: for instance, here we can conclude that, regarding French, Pablo is preferred $0.59/0.36 = 1,64$ times over Juan and $0.59/0.05 = 11.8$ times over Lara.

The second step consists of choosing weights for each criteria. With only two criteria (French and Maths), there is little interest in using AHP for defining weights. AHP becomes very useful, however, when there are 3 or more criteria. In this case, similarly to what is presented above, pairwise comparisons have to be conducted on the criteria (for instance, *What is the decision maker's preference between French and Maths, French and History, Maths and History?*), using the same scoring scale (from 1 to 9). The final weights are obtained by the principal right eigenvector of the new matrix.

The figure below shows the intervals of coefficients where each candidate can be selected (numbers are rounded for simplification): we can see that if the school is seeking a balanced profile, it will choose balanced coefficients in French and Maths, i.e. close to 0.5. This corresponds to the domain of value where Juan is ranked first.



In the case of coefficients 0.5 in French and Maths, the following representations can be used:



Using AHP allowed the decision-maker to better express his preferences, comparatively to the weighted average method. However the method still has a few drawbacks:

- Even in the most favorable case (coefficients of 0.5 in French and Maths), Juan is not selected with a strong preference intensity: $0.36/0.32 =$ only 1.1 times as much as Pablo or Lara. The table below gives the final (weighted) relative scores of the students with these coefficients.

Pablo	Lara	Juan
0.32	0.32	0.36

This is explained by the fact that AHP still allows compensation between criteria.

- The final ranking provided by AHP is sensitive to the alternatives originally considered. For instance, in the last example, Juan is preferred to Pablo but it may happen that starting the procedure again with another new candidate, Ines, will lead to an inversion of this ranking: Pablo being preferred to Juan. This property is of course not intuitive and not desirable. Consequently, if one uses AHP, we would advise to first consider all possible alternatives, and then restart the process with a reduced number of alternatives (the ones which scored the highest) to see if their relative ranking is modified or not.

Methods without compensation (outranking): the example of Prométhée

Outranking methods do not lead to the same type of results as compensation methods. The main advantage is that they don't reduce the problem to the comparison of a single indicator. For instance, Prométhée leads to two different rankings of alternatives: one ranking according to preference intensities and a second ranking for rejection intensities. This is a way of simplifying the problem while still reflecting the preferences and values of decision-makers. The main drawback however is that some options can appear at the end of the process as incomparable: in the general case, outranking methods will not produce a complete ranking of alternatives. In the following, we illustrate this by using the Prométhée method on our basic example.

Similarly to AHP, Prométhée uses pairwise comparisons, to compare alternatives relatively to each criteria. The scale is the following:

Pairwise comparison score	Explanation
0	No preference
1	Extreme preference

If we still take the example of a school looking for balanced profiles, the following scores may follow from the pairwise comparison process:

FRENCH		Maths	
Pablo vs. Lara	1	Pablo vs. Lara	0
Pablo vs. Juan	0.2	Pablo vs. Juan	0
Juan vs. Lara	0.8	Juan vs. Lara	0
Juan vs. Pablo	0	Juan vs. Pablo	0.8
Lara vs. Pablo	0	Lara vs. Pablo	1
Lara vs. Juan	0	Lara vs. Juan	0.2

From this, we can compute average preference and rejection intensities for each alternative and criteria as shown in the next figure:

FRENCH	Pablo	Lara	Juan
Positive flow (preference intensity)	0.6	0	0.4
Negative flow (rejection intensity)	0	0.9	0.1

$(1 + 0.2) / 2$ $(0.8 + 0) / 2$
 $(1 + 0.8) / 2$ $(0.2 + 0) / 2$

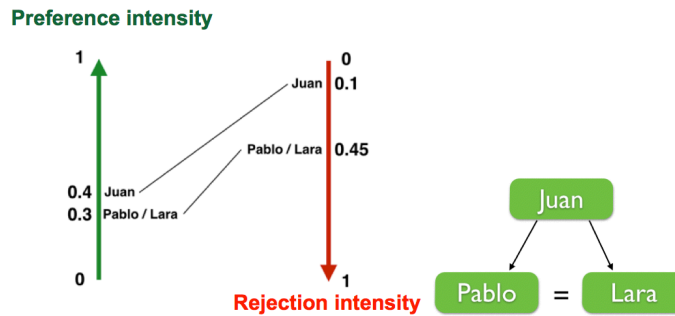
For instance, Juan has an average preference intensity of 0.4 in French because he scores 0.8 against Lara and 0 against Pablo. We repeat this for each criteria, in our case for Maths:

MATHS	Pablo	Lara	Juan
Positive flow (preference intensity)	0	0.6	0.4
Negative flow (rejection intensity)	0.9	0	0.1

The last step consists in attributing weights to each criteria. As discussed in the AHP section, this is rather simple to do with only 2 criteria but can become more subtle in the presence of 3 or more criteria. In the latter case, AHP could be used to define weights that correctly reflect the decision-maker’s opinion. Below we use two different sets of weights to illustrate the type of output provided by Prométhée.

CASE ONE. Weights of 0.5 for French and Maths.

We compute a weighted average of preference and rejection intensities of each alternative and then display them on the following graph:

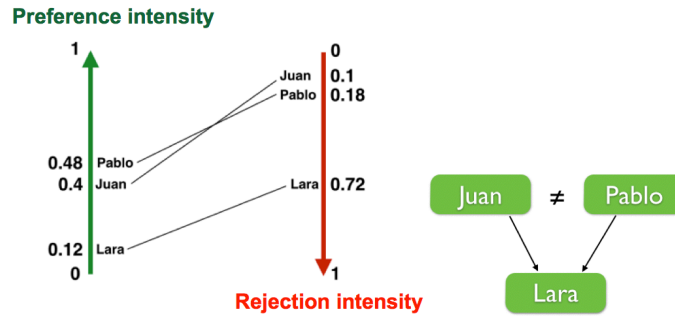


The higher the alternative is located, the best it is (it is more strongly preferred and less strongly rejected). In this case, we can conclude that Juan is preferred over Pablo and Lara and the decision is easy to take for the decision-maker.

It is interesting to see that Juan is not strongly preferred but rather substantially less rejected than the other two options.

CASE TWO. Weights of 0.8 in French and 0.2 in Maths.

The choice of this coefficients means that the school attaches more importance to French than to Maths. This question is independent from defining a scale of values for each criteria (e.g. saying that the difference between grades 10 and 6 is less important than the difference between 6 and 2). In this case, the output will look like this:



Pablo and Juan are both better choices than Lara (in the case of this particular choice of coefficients of course), however they are incomparable: Pablo is preferred to Juan but Juan is less rejected than Pablo. The interest of such a result for decision-making may not be obvious in this simple example but it gets clearer when the complexity increases:

- It makes it possible to reduce the number of considered alternatives (for instance, Lara would be rejected here),
- It summarizes all the criteria in only two rankings which are easy to interpret (preference and rejection intensities); note that it is possible to subtract rejection from preference to end up with a single indicator (here, Pablo and Juan would score 0.3 and Lara -0.6), but in this case, the interest of non-compensation methods is lost,
- It is possible to study further incomparable alternatives by for instance adding new criteria or applying another method to them.

One shouldn't lose sight of the fact that the main goal of multi-criteria methods is not to so much to select the best alternative as to organize the discussions and to help the decision-maker to formalize his/her values. Many other methods exist and none is ideal. What matters is to be aware of the consequences of the choice of methods and parameters, and to conduct the process in a transparent way.

9.2.6.3 MCDA on environmental issues and a few empirical lessons

Huang et al. (2011) conducted a scientific literature review of multi-criteria methods applied to environmental issues, analyzing over 300 papers published between 2000 and 2009. They emphasize that there has been a significant growth in environmental applications of MCDA over the last decade.

In particular, the graph on figure 9.3 shows which methods were most commonly used depending on the environmental stake under study. Interestingly, the authors also point out that a large majority of Asian and North American papers use the AHP method whereas the method mix is a lot more balanced in Europe. This is consistent with the influence of the *French school* of multicriteria analysis, in particular regarding the promotion of outranking methods.

Continuing with empirical lessons, CLG (2009) highlight some good-practices in MCDA:

- The objective of the process should be explicitly stated at the beginning: does one want to select the best option, to select a short list of alternatives, to rank all alternatives? Indeed, depending on the objective, judgments from stakeholders may vary,

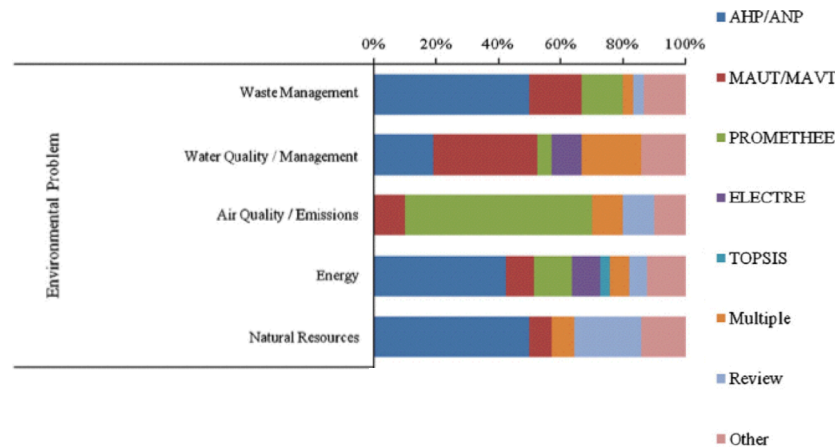


Figure 9.3: Percentage distribution of MCDA methods by application areas. Source: Huang et al. (2011).

- It can be useful to start the MCDA process from the beginning of the project, because the first discussions may point to missing data for decision-making,
- MCDA is meant to be an iterative process: the result should not be expected in the first go. One should leave time to explore the model fully. The authors specify that: *“MCDA is a divide and conquer strategy in the sense that a complex issue is subdivided into parts that are easier to deal with separately, and the theory is used to reassemble the parts. The resulting high-level view typically reveals new features that were not observed in the individual parts. [...] If the results of the modeling don't feel right, explore the discrepancies. [...] Create different displays, conduct sensitivity analysis on weights to help participants to gain a better qualitative feel for the issues and to increase their confidence in the decision”*,
- The MCDA model should not be over-complicated,
- MCDA does not give *the answer* to a problem, subjective judgments are necessary inputs to the modeling. Making decisions is necessarily a human function,
- Time should be devoted to the design of the final output of the process. Graphs can be useful but words should not be neglected in order to convey the subtlety of the results. Sensitivity analysis enables the results to be couched as conditional conclusions: *“If you believe this, this and this, then [A] is best, but if you believe that, that and that, then [B] is best”*. They conclude that: *“This approach highlights the key value judgments, providing realistic freedom of choice, within bounds, for the decision-maker”*.

9.3 Participation and Deliberation

9.3.1 Participation and its controversies

Participation refers to the involvement of non-decision makers and non-experts in a decision process, most frequently, members of the civil society. The incentives to implement participatory processes clearly increased in the context of sustainability issues, but participation was already put forward in other contexts long before the Rio conference. The controversies it generates haven't changed much as one can notice in an article by Arnstein (1969). As Arnstein provocatively puts it: "*The idea of citizen participation is a little like eating spinach: no one is against it in principle because it is good for you. Participation of the governed in their government is, in theory, the cornerstone of democracy - a revered idea that is vigorously applauded by virtually everyone. The applause is reduced to polite handclaps, however, when this principle is advocated by the have-not blacks, Mexican-Americans, Puerto Ricans, Indians, Eskimos and whites. And when the have-not define participation as a redistribution of power, the American consensus on the fundamental principle explodes [...]*". Considering that a typology was needed to differentiate *empty rituals of participation* from real citizen power, he proposed a "*Ladder for Citizen Participation*" displayed in figure 9.4, and used it to characterize examples of federal social programs in the late 60's USA: urban renewal, anti-poverty, and Model Cities. He distinguishes eight levels of increasing participation. Manipulation (1) as well as Therapy (2) refer to uses of participation as pretexts for power-holders to "*educate or cure the participants*" and strengthen their authority. Informing (3), Consultation (4) and Placation (5) are referred to as degrees of "*tokenism*" (i.e. the practice of making no more than a minimal gesture): citizens can express their opinion, be heard or even advise but they don't have any decision power. Upper in the ladder, citizens gain power on some aspects of the decisions: in Partnership (6), they can negotiate with powerholders and in Delegated power (7) and Citizen control (8), "*have-not citizen obtain the majority of decision-making seats, or full managerial power*".

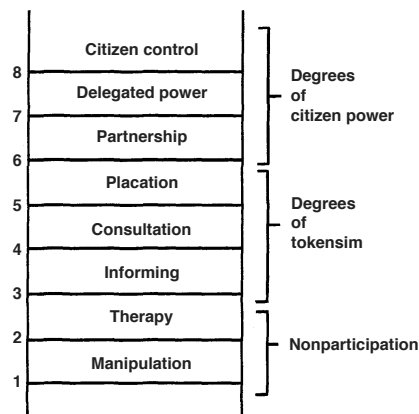


Figure 9.4: Eight rungs on a Ladder of Citizen Participation. Source: Arnstein (1969).

Of course, participation can arise disbelief and hostility in people that have felt *manipulated*. This is all the more true in a context where citizens increasingly question the legitimacy of their

representatives, while at the same time losing interest in politics (Van Reybrouck, 2014). Giving up on participation is however not a real option for anyone who believes in democracy. The question is then to be able to spot and expose *nonparticipation* and to imagine conditions that could be favorable for both participants and decision-makers. As we already highlighted, engaging in transparent processes is a start for people to regain confidence.

At the beginning of the chapter, we provided insights on the differences between participatory and deliberative democracy. The first can be seen as concrete and instrumental. The latter first and foremost has normative grounds, that we will now present.

9.3.2 Deliberative democracy

9.3.2.1 A procedural legitimacy

What is it that makes a political decision legitimate? This is the question tackled by Bernard Manin in his 1985 article *Volonté générale ou délibération ?* (Manin, 1985)⁷. Reflecting on the notion of justice and on the possibility to define universal social rules, he begins by examining what he considers the most commonly accepted source of legitimacy: unanimity. A decision is legitimate in so far as all individuals support it.

In this view, for radical liberals, “*security is the only acceptable political principle*” as individuals seek to pursue their own interests “*in peace*” with the least possible constraints. The State shouldn’t set rules influencing material conditions since definitions of well-being vary from one individual to the other. However, Manin points out that “*for individuals whose incomes and actual circumstances are below a certain threshold, [the right to pursue one’s objectives without constraints], simply loses its meaning.*”, which disqualifies liberal theories’ claim of universality.

Democratic theories in fact do not only think in terms of *legitimacy* but also in terms of *efficiency*. The majority principle is precisely introduced as a way to reach decisions. However, one must keep in mind that: “*The majority will is not intrinsically legitimate, it is legitimized because one decides to confer upon it all attributes of unanimous will*”. Only utilitarian theories can consistently justify it as they seek to maximize happiness for a majority of people, be it at the detriment of a minority. These views however seem morally unacceptable to Manin.

Universalistic theories, notably that of Rousseau and Rawls seek to prove universal principles exist such that unanimity and justice can be reached. In Rousseau’s writing, individuals abiding by the general will are only obeying themselves (even if they are not aware of it), since their predetermined will is by nature congruent with the general will. In this view, debate can only distort individual wills, for instance because of rhetorical abilities of certain speakers, and twist the general will (which is then referred to as *the will of all*). Rawls puts the underlying intuition of Rousseau’s social contract in a different perspective. His *Theory of Justice* (Rawls, 2009) states that under circumstances where individuals wouldn’t know their position in society (the “*veil of ignorance*”), they would naturally advocate that (i) “*each person [should have] an equal right to a fully adequate scheme of equal basic liberties which is compatible with a similar scheme of liberties for all*” and (ii) that “*Social and economic inequalities are to satisfy two conditions. First, they must be attached to offices and positions open to all under conditions*

⁷This article was published in English under the title *On legitimacy and deliberation* (Manin et al., 1987), however the citations provided here are personal translations since we couldn’t access the English version when writing this synthesis.

of fair equality of opportunity; and second, they must be to the greatest benefit of the least advantaged members of society." According to Manin, however, this second principle cannot be recognized as universal as it implies a dissymmetry between two groups of individuals.

More deeply, in agreement with Simon's bounded rationality model, he argues that people do not have *a priori* predetermined preferences on all subjects: "*When individuals have to make a decision about society, it is absolutely unreasonable to assume they possess all necessary information. [...] It is through collective deliberation and individual pondering that incomplete information [...] are clarified without however reaching completeness.*". Moreover, "*it is unrealistic and illegitimate to assume individuals have from the start a coherent set of preferences [...]. Through deliberation and the exchange of arguments, individuals become aware of internal conflicts related to their own desires*".

It is in fact a preconceived idea that the only source of political legitimacy is the will of individuals. Manin's central thesis is that: "*The legitimate decision is not the will of all, but the one resulting from the deliberation of all; it is the process of will formation which confers legitimacy to the result, not the predetermined wills. Such a principle is both individualistic and democratic.*". It is democratic in the sense that one assumes all can participate in the deliberation process, and individualistic because everyone freely makes up his mind on one option or another.

Deliberation is a rational argumentative process where opposing visions attempt to convince one another. However, setting out arguments does not mean demonstrating a *truth* and people are free to accept or reject them. Therefore deliberation cannot lead to "*necessary and universally accepted truths*". However it helps reassess one's preconceived ideas, for instance, in view of new information on potential consequences of actions.

He suggests that the deliberative process ends with a vote, when wills have formed. Only at this moment is the majority principle justified because "*the support of the greater number of people reflects the superior strength of one argumentation relatively to others*". However, one must also acknowledge that reasons for supporting other options exist, even though minorities defending them were less convincing this time. This is an important point as it contributes to a balance of power: "*A will that faces no obstacle deliberates less on what it decides and justifies its decisions less*".

In conclusion, Manin clarifies that fundamental values such as human rights, or the ability for all to participate in political life, retain superior legitimacy and could not be questioned by deliberation results. A more recent article of Habermas (2003), precisely dedicated to the issue of conflict between human rights and popular sovereignty, advocates that deliberative democracy overcomes this contradiction. In this context, rights would not be constraints, but on the contrary, the expression of democratic self-governance.

Manin described one possible way to reach a decision, voting; we will now describe the other, *apparent consensus*, which we also find relevant to our analysis.

9.3.2.2 Apparent consensus

The various aggregation methods used in multi-criteria/multi-stakeholders analysis all amount to a particular choice of voting procedure. They are legitimate in as much as voting procedures are; and once one has noticed that election results depend on the procedure, one usually looks at them with some reasonable suspicion. This being said, it is important to note that voting

is but one of two ways to reach a decision, the other being what has been dubbed “*apparent consensus*” by the French political scientist that pointed out its relevance in modern democratic deliberation processes (Urfalino, 2007). Apparent consensus refers to a decision reached by a political body (e.g., a village assembly, or a shareholders’ meeting), when nobody finds it useful, constructive or profitable to further argue for or against the said decision. It does not mean that unanimity has been reached. And it is not either a majority rule: there is no denying of the rights or opinions of a minority in this process, and usually no oppression of the minority by the majority; furthermore, it may happen that the decision actually reflects the preferred choice of a minority, if it is also the least rejected option of the majority or of the largest but conflicting groups of influence. Apparent consensus also implies that good arguments may win, not simply the most authoritative ones, which does not imply that some people in the assembly are not more influential than others, only that their influence is perceived as legitimate. Of course, this also implies a level of honesty in at least a majority of participants, and at least some willingness to make one’s opinion evolve in the discussion process at the light of important/relevant arguments. Apparent consensus is reached in several steps. A first round of discussion on the issue at stake is organized by the discussion leader, who also at some point summarizes the options and opinions expressed thus far and sketches a possible decision or line of action. A second round follows if participants are not satisfied with the first sketch, leading to another summary and proposed option, and so on until apparent consensus as defined above is reached. Several remarks are important here:

- The role of the discussion leader is critical, both in the way he fosters discussions and opinions, and in the way he is able to recast what has been said in summarized form, or in different forms etc.
- Multi-criteria and multi-stakeholder decision analysis methods provide a powerful way to help achieving this purpose, and in organizing debates towards reaching apparent consensus, if feasible.
- Scientists do not only act here as experts of the Multi-Criteria Analysis (MCA) methods used in the process, but also ideally must provide alternative ways of enlarging or focusing the debate, present alternative options, etc; they should also be able to recast the problem in different forms for MCA analysis, either by capturing from the discussion forgotten criteria or forgotten options, or by pointing them out from their somewhat external point of view. This may be used either as a substitute for the discussion leader if the scientists are experienced enough in leading this type of discussion and can maintain a neutral stand with respect to all options, or instead, as an important expert help to the discussion leader, who should in any case be proficient in negotiation/mediation/deliberation techniques.
- If apparent consensus cannot be reached, then one needs to resort to a final voting procedure; the procedure is usually chosen by apparent consensus. Note also that *indicative votes* can also be made at various points in the course of the discussion in order to make further progress towards apparent consensus.

The widespread use of voting procedures in democratic countries is motivated by the huge amount of people involved in the decision process, and by the large geographic extent of modern countries with respect to, e.g., the original democracy of the Greek polis (Athens in particular, whose constitution we know thanks to Aristotle). However, the second method (apparent

consensus) is the method of choice in quite a number of traditional societies on the one hand, and quite a number of associations or political bodies in the modern world on the other. In public decision-making, the number of stakeholders rarely exceeds a dozen or so; therefore apparent consensus should be aimed at first, and formal votes used only as a last resort and with proper preliminary discussion of the voting procedure to be applied. When apparent consensus is reached, participants feel much more implicated in the decision process, and as a consequence are usually much more committed to the decision reached as it is perceived as the best outcome considering all constraints, even if it is not their preferred option, except for those stakeholders whose agenda is not to reach a common decision, of course.

Proposition of a multicriteria deliberation-aiding procedure

Now that underlying principles (and controversies) of participation, deliberation, decision-aiding and multicriteria analysis have been presented, we will reflect on the way they could be assembled in a *deliberative decision-aiding procedure*. Starting from thoughts on science in policy and from different typologies of decision-making contexts, we clarify the scope of our research question by defining *deliberative multicriteria* procedures in contrast with *optimization* and *technical multicriteria* strategies. We analyze several outranking methods to understand their essence and see how they could be adapted to our needs. We then propose a decision-aiding procedure built around a deliberative multicriteria framework, called Satisfaction-Regret III. Finally, the soon-to-come experiment of the method on the case of the Afterres 2050 agricultural scenarios is outlined.

10.1 A typology of decision-making contexts and possible decision-support tools

The following reflections attach much importance to analyzing decision-making contexts. Whether they attempt to characterize possible roles of scientists in society, to describe decision-making styles or classify decision-support tools, they make use of the same two attributes: the level of consensus among stakeholders and the degree of uncertainty.

10.1.1 Science in policy

Pielke (2007) analyses four *idealized* roles scientists can play in society:

- The *pure scientist* focuses on his research with no consideration for its use and no connection with decision-makers,
- The *science-arbiter* seeks to focus on issues that can be resolved by science (positive issues in opposition to normative issues) and accepts the role of expert to answer specific questions raised by decision-makers,
- The *issue advocate* seeks to participate in the decision-making process and aligns himself with specific interest groups,
- The *honest broker of policy alternatives* participates in decision-making by “*clarifying and, at times, seeking to expand the scope of choice available to decision-makers*”. In other words, its role is not to decide what choices should be taken but to indicate possible choices and constraints associated to them.

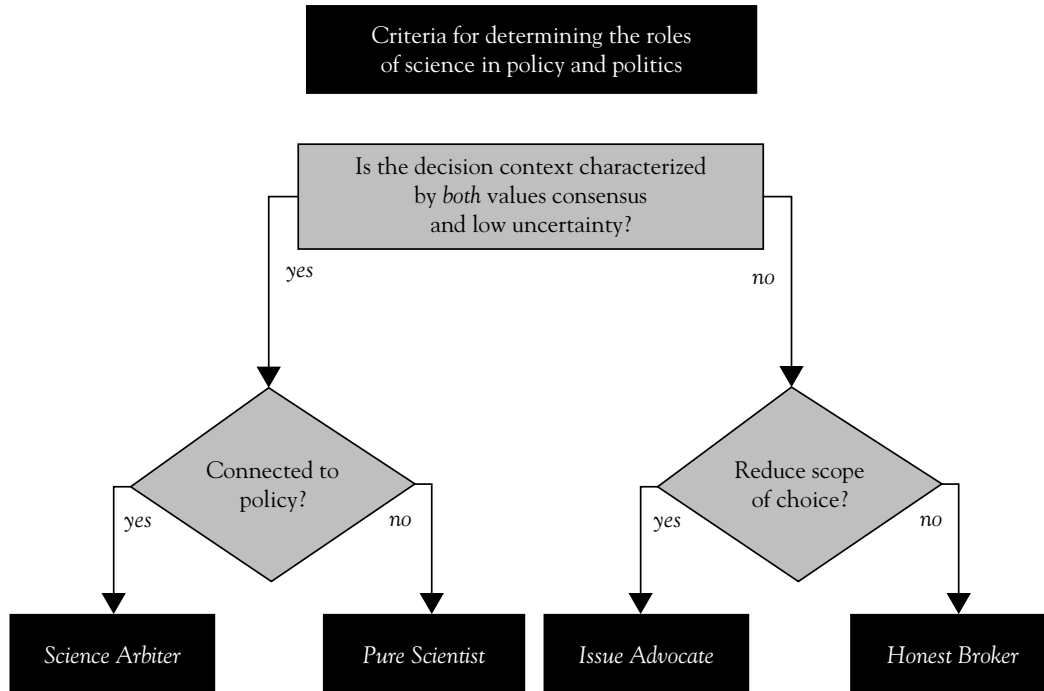


Figure 10.1: Flowchart illustrating the logic of roles for scientists in policy and politics. Source: Pielke (2007).

Of course, these roles are idealized, in the sense that one is unlikely to be found all the time in the same role. The author for instance often uses the expression *stealth advocacy* to refer to scientists who present themselves as neutral but are in fact, consciously or unconsciously, using science to promote their political views. Moreover, there is no *good* or *bad* role in absolute, for instance, *issue advocacy* can be useful in democratic functioning as far as it is recognized as such. Roles are however more or less suited to decision-making contexts defined by the degree of consensus and uncertainties, by the connection to policy and by the will to widen or reduce the scope of choices. This is what is illustrated in figure 10.1.

In the continuity of the *Honest broker of policy alternatives*, Edenhofer and Kowarsch (2015) propose a model for solution-oriented assessments called “*the pragmatic-enlightened model*” (PEM). Starting from the question “*How can assessments of environmental policy issues be policy-relevant without being policy-prescriptive?*”, they propose to overcome the dichotomy between technocratic responses, which suppose science can be value-free, and democratic participatory models, where the role of researchers is often unclear. The PEM model “*suggests that after researchers and stakeholders have jointly framed the problem, they explore the objectives, means and consequences. [...] The public debate on alternative policy pathways, as well as policy decisions and implementation by policymakers are outside the assessment-process per se. Next, there is a scientific ex-post evaluation of the actual means-consequences, which is also the starting point for a new assessment cycle*”.

10.1. A typology of decision-making contexts and possible decision-support tools

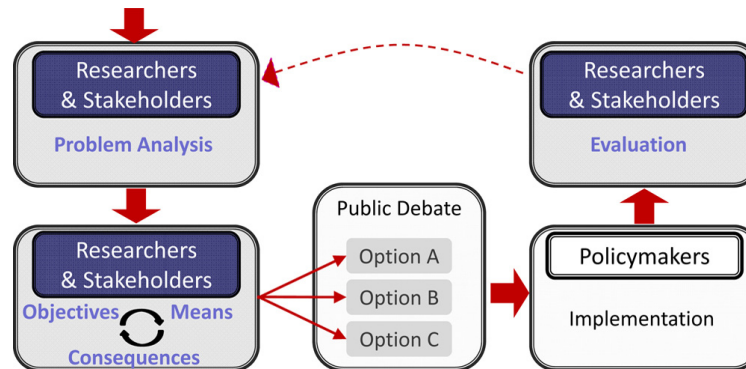


Figure 10.2: The *Pragmatic-Enlightened Model*. Source: Edenhofer and Kowarsch (2015).

While the first two parts of the thesis aimed at problem analysis (and to a lesser extent at envisioning potential consequences of actions), this chapter is dedicated to the public debate phase, and more specifically aims at providing tools to structure it.

At this point it is useful to highlight that the underlying conviction of our research team¹ is that scientists should be more involved in political debates on the sustainability issues that they otherwise analyze, not to act as decision-makers, but rather as *honest brokers of policy alternatives* helping to structure research questions with a double objective in mind:

- Research questions, although retaining their own justified logic, should not ignore real-world problems and the way to manage them,
- Conversely, helping decision-makers to become more aware of the depth of the issues they handle.

10.1.2 Governance

In an article on "*innovation*" and "*powerlessness*" of environmental governance, Theys (2002) introduces the concept of "*governability*" that "*emphasizes the specificity of situations and the probability, in the face of these more or less complex specific situations, of finding both efficient and acceptable solutions*". He adds: "*Certain situations are both intrinsically and politically manageable. Others are not, or cannot be except at the price of considerable difficulty and effort.*". There is therefore no universal governance tool and one should recognize difficult situations, for instance characterized by an ill-structured problem, lack of immediate practical solutions or of mobilizing project, or lock-in of a major actor: in such cases conditions for "*good governance*" are not fulfilled and need to be built. In the same spirit, Godard (1993) distinguishes decision-making in a *stabilized* and in a *controversial* world. In the first case agents are informed by scientific knowledge relevant to action (e.g. causality chains are understood) and what is at stake is rather economic effectiveness and equity. On the contrary, in the second case, some key stakeholders are missing, scientific knowledge is more controversial and visions of the world and of the future compete. Similarly, Mény and Thoenig (1989) propose a typology of

¹STEEP team, Inria Grenoble, France.

programmed, negotiated, pragmatic and chaotic processes depending on the degree of certainty and the degree of agreement on values between actors (chaotic processes corresponding to high uncertainty and value conflict). These are presented in more details in appendix in figures F.1, F.2 and F.3. According to Jacques Theys, four conditions are needed in order to overcome the previously stated difficulties and reach a good environmental governance: a methodological condition (making governance procedures more transparent and efficient), a political condition (restore the balance of power between actors), an institutional condition (redistribute the power between the representative government and participatory governance) and a cultural condition (promoting “*cognitive democracy*”).

Our work precisely focuses on the first (methodological) condition. Before going further an important point should be highlighted. As Faucheux and O’Connor (2012) put it, “*democratic debates and stakeholders dialogs cannot eliminate complexity, uncertainty or conflict [...]. Disagreements will always appear regarding inappropriate or unbalanced representations and abuse of power. Nevertheless deliberative processes can be used to facilitate the construction of a clear image of merits and drawbacks of alternatives.*”. We adopt a similar view, considering that the primary goal of deliberation shouldn’t be to reach (or expect) consensus but to structure controversies. This is not to say that consensus is not desirable, just that it may not occur even under favorable conditions.

10.1.3 Decision-support tools

We now wish to study the constraints brought by the decision contexts to the relevance of tools used to support decision-making. We underlined in the previous chapter that multicriteria analysis seemed well suited to tackle the challenges of *strong sustainability*, that is highlighting trade-offs between non-compensatory effects. However, given the numerous case studies on the subject, we felt the need for making explicit what approaches seemed the closest to our concerns.

To do so, we rely on the definitions of *finality, goal, objective* and *means* provided by Maystre and Bollinger (1999) in their book *Aide à la négociation multicritère* (Multicriteria negotiation-aiding). According to them, *finality* refers to a fundamental idea, stated generally enough for everyone to make sense of it (e.g. *preserving the environment*). A *goal* is also a general statement, but more concrete, that contributes to this finality (e.g. *preserving water bodies from pollution*). An *objective* has an operational meaning, refers to an action defined in space and time (e.g. creating a waste landfill facility in a given region). *Means* are what are needed in order to implement the objective². They underline that in their case studies, they assume people share the same finality and goal (which explains why they meet). They may have different opinions on objectives, and most certainly diverge on the means (which is why they call it a negotiation)³. We translate these concepts on a scale of *technicality* and *values* displayed in figure 10.3, mean being the closest to technicality and finality the closest to values. Based on these possible *levels of value conflict*, we propose a flowchart on figure 10.4 that distinguishes

²The authors note that these definitions are relative and *sliding*: for instance a given objective can be a mean to an objective of higher level (creating one facility is a mean to reach the regional objective of volume of waste treatment capacity).

³They finally point out that starting a meeting by explaining this terminology may foster the group’s dynamic and facilitate the work on scenarios and criteria design.

10.1. A typology of decision-making contexts and possible decision-support tools

optimization, technical multicriteria, deliberative multicriteria and other decision-support tools.

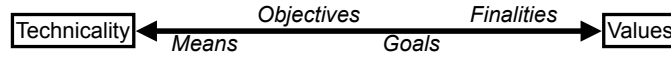


Figure 10.3: Scale of technicality and scale of values: positions of the concepts of *Means*, *Objectives*, *Goals*, *Finalities* defined by Maystre and Bollinger (1999).

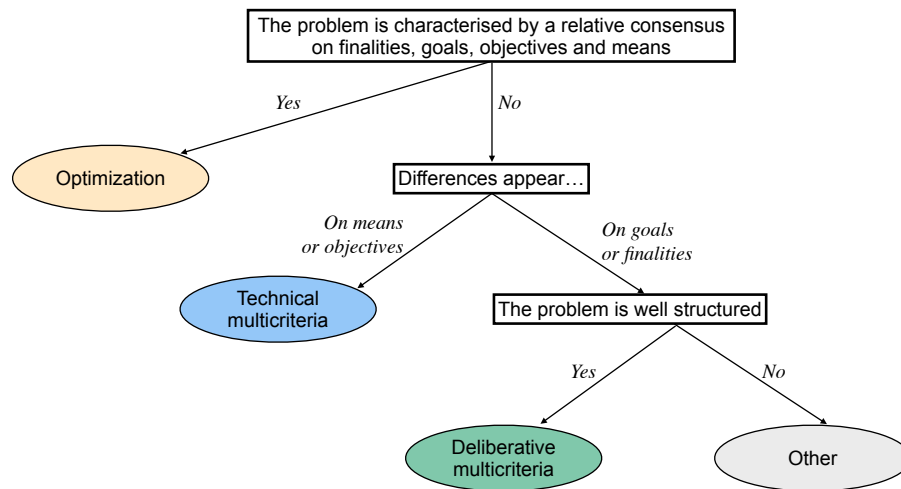


Figure 10.4: Flowchart for choosing decision-aiding tools.

Optimization. When there is a relative consensus on values, the question is rather to optimize a criterion under a set of constraints. In mathematics, the area studying the evolution of dynamic systems under constraints is known as viability theory (?). Taking the example of fisheries, one can for instance look for trajectories satisfying both revenue and fish stock constraints. Cost-efficiency analysis, for instance assessing climate mitigation and adaptation plans, also falls in this category of relative consensus. Here the engineering tool is at the core of the decision-making process.

Technical multicriteria. As pointed out by Maystre and Bollinger (1999), other situations are characterized by a consensus on a general objective but possible disagreement on the priorities to set. This case is the most often encountered in multicriteria analysis studies. Typically, multicriteria methods are applied in three main fields (Behzadian et al., 2010):

- Choosing a technical solution (e.g. between different waste treatment alternatives, soil remediation techniques, construction materials...),
- Choosing the location of an infrastructure (e.g. a wind park, a high speed railroad...),
- Choosing a policy mix to tackle a particular environmental issue (e.g. regarding air quality, mixes of taxes, subsidies, norms, urban planning etc.).

This of course requires a consensus on finalities and goals among stakeholders. For instance, citizen opposing the construction of a highway or railroad because they deny its public utility⁴, won't agree to participate in a process where the scope of alternatives is reduced to the choice of a location. Of course, technical multicriteria strategies are also designed to favor discussions among stakeholders (and some authors suggest this is their main objective⁵) but they always give a large place to the tool itself. Indeed most tools are complex and stakeholders require time to apprehend them.

Deliberative multicriteria. The more the decision is complex to make, either because of high uncertainties or because the stakes are high and generate conflicts, the more technical tools must give way to other animation techniques. We define *deliberative multicriteria* tools as *artefacts* aiming at reproducing the principles of multicriteria methods but keeping technicality to a minimum in order to leave more space for other forms of discussion. Taking too much time to fill a tool's parameters may indeed be perceived as inappropriate. Also, in this view, using qualitative assessments may be encouraged. Typically, one could imagine a confrontation of views on an infrastructure project based on the evaluation of economic, social, local and global environmental impacts.

Other tools and strategies. Finally, we are only stating the obvious by saying that multicriteria methods are not adapted to any kind of debate. On figure 10.4, we use a criterion relative to the problem's structuring to make this distinction. Indeed, a lot of questions couldn't (reasonably) be structured in the form of criteria assessment and any attempt to do so would certainly sound trivial (examples of this include most societal debates such as death penalty, euthanasia, gay marriage etc.).

Transversely to this scale of value conflicts, we find it useful to integrate a scale of uncertainty. Indeed, as uncertainties increase *facts* tend to give way to *values* and technical tools arguably become less appropriate and accepted by stakeholders. We summarize these thoughts in figure 10.5.

In the course of this section, we may have given a false impression that one strategy is *better* than another, that *deliberative multicriteria* should be preferred to *technical multicriteria*, but this isn't what is meant here. We merely wish to highlight the fact that tools need be adapted to contexts. In the following we explore possibilities for deliberative multicriteria tools and start by presenting what we consider an existing example of it.

10.2 Deliberative multicriteria tools

The REEDS lab⁶ has developed a tool called KerDST (KerBabelTM online Deliberation Support tool), which is usually used as part of a meta-model (called *Integraal*) which consists of

⁴In his book about the Lyon-Turin railroad project, Ibanez (2014) insists on the fact that the opposition to *useless imposed mega-projects* relies a lot more on the questioning of their public utility than on the NIMBY (*not in my backyard*) effect.

⁵The term *deliberative multicriteria* is used in some articles as a synonym of participatory multicriteria, that is involving several stakeholders (e.g. in Proctor and Drechsler (2006)).

⁶Université Versailles Saint-Quentin, France.

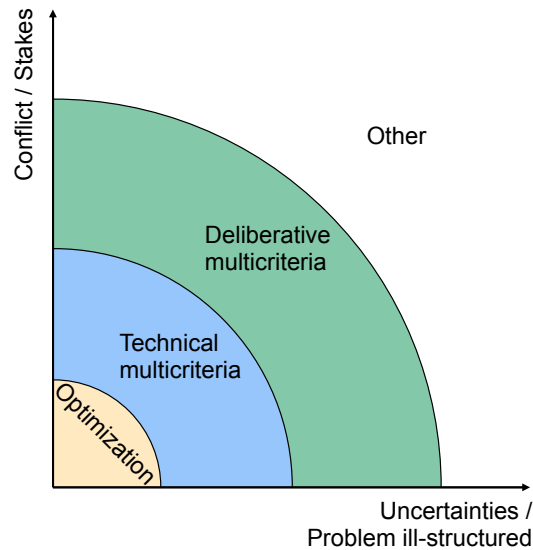


Figure 10.5: Decision-aiding tools depending on systems uncertainties and conflict on values: optimization, technical and deliberative multicriteria methods. The x-axis can also be interpreted as the degree of the problem's structuring and the y-axis as the level of stakes. This representation is directly inspired by the one used by Funtowicz and Ravetz (1993) to situate *post-normal* science relatively to other problem-solving strategies.

the following five steps (Chamaret et al., 2009):

1. Identify the problem,
2. Organize the problem: identify actors, options and quality/performance issues (criteria),
3. Mobilize tools for representation (indicators, maps, models),
4. Multi-criteria and multi-actor deliberation about actions to undertake,
5. Discussion, validation, communication of results,
6. Back to step 1.

During step 4, stakeholders express individually how they think scenarios perform relatively to each criterion. They can either use a three-color code (green for good performance, yellow for mediocre, red for unacceptable), use a color and add a comment to explain it or attribute a color to each indicator relevant to the criterion (when these indicators are available) and weigh them. Each cell of the deliberation matrix is therefore partly or entirely colored in green, yellow or red, reflecting the judgment of actor y on scenario z relatively to criterion x , as figure 10.6 shows.

In practice, this leads to representation such as figure 10.7a. Then, criteria, actors or scenarios can be aggregated using a weighted average to lead to a more synthetic representation 10.7b and the facilitator can iteratively show aggregated and disaggregated results to outline

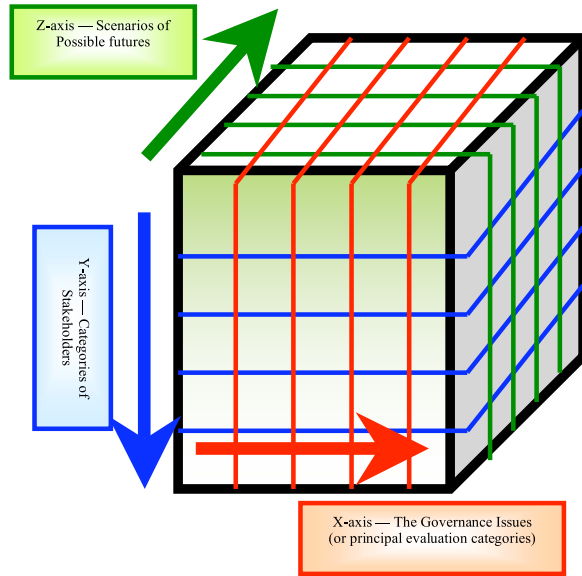
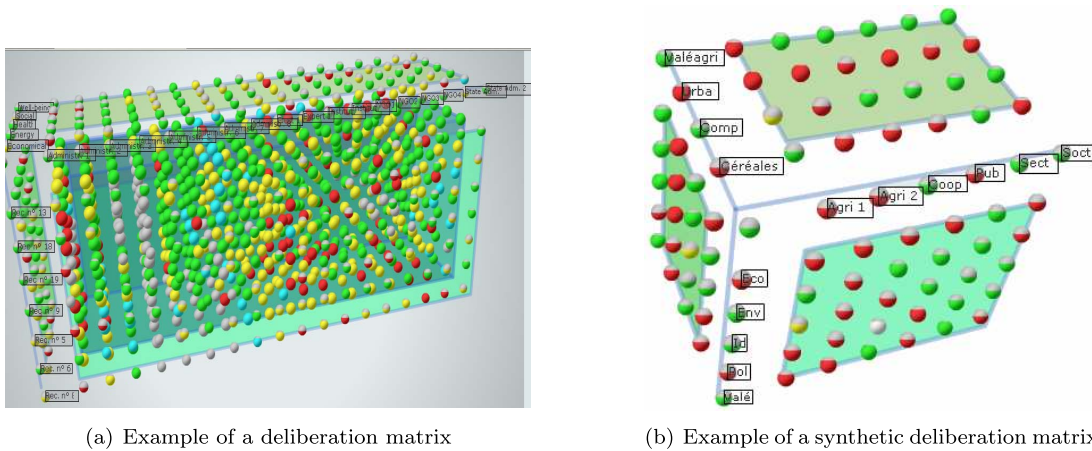


Figure 10.6: The deliberation matrix in KerDST. Source: Chamaret et al. (2009).



(a) Example of a deliberation matrix

(b) Example of a synthetic deliberation matrix

Figure 10.7: Visualization of deliberation matrices with KerDST. Sources: Remvikos et al. (2010), Da Cunha (2010).

the view of each actor. Other options can of course emerge during the deliberation in which case it is possible to add it to the matrix.

This tool has been used in many studies in the past decade. In particular, Remvikos et al. (2010) evaluated different air quality strategies for the Parisian region, Da Cunha (2010) studied alternative agricultural futures (in the Parisian region as well), and Brou (2012) analyzed possible natural resources management plans, more specifically for mine and forestry projects in Africa.

We share with this approach the goal to use multicriteria as a deliberation tool. This method is simple enough to be transparent for actors. However, this simplicity is achieved through the use of weighted average aggregation which we wish to avoid for reasons stated in the previous chapter. Simply put, we wish to propose a synthetic view on the problem using properties of outranking methods. Their underlying principles seem well-adapted to sustainable development issues. For instance, it is important to account for non (or partial) compensation and to be able to pinpoint incomparable scenarios and associated trade-offs. Additionally, both the *majority principle* and the *respect of minorities principle* are usually implemented in the methods. Electre and Promethee, the two most widely used outranking methods, have robust foundations, however we judge them too technical for our purpose. The choice of an *artefact* is important (e.g. the deliberation matrix in the case of KerDST) and we believe the quadrant displayed in figure 10.8, based on the measure of satisfaction and regret intensities, could be adapted to facilitate the debate. It is in particular inspired by Promethee's positive and negative flows⁷. In a nutshell, the method proposed transforms multiple criteria into a couple of criteria (satisfaction and regret), that carry important information for reaching a decision. Indeed, apparent consensus implies that a solution rejected by a stakeholder is rejected by the whole group. As we will see, satisfaction can be related to the majority principle and regret to the respect of minorities.

Interestingly, cognitive psychology shows human beings are generally more sensitive to losses than to gains. Kahneman (2011) for instance illustrates it with this simple example: "*You are offered a gamble on the toss of a coin. If the coin shows tails, you lose \$100. If the coin shows heads, you win \$150. Is this gamble attractive? Would you accept it?*". Experiments show that most people refuse such proposition because they fear losses more than they value gains. We believe we can extend this observation to satisfaction and regret, that is to say, most people are more sensitive to regret than to satisfaction. In practice, this means that in a weighted average, scenarios that perform very bad on one or more criteria are not penalized enough compared to what people think of them.

In the next, section, we will therefore examine how Promethee and Electre (versions I and III) capture the concepts of satisfaction and regret. In the course of our research we also found a less well-known method precisely called Satisfaction-Regret (André and Oberti, 2002). We will therefore also study its properties and see how it can be adapted.

Keep in mind that the decision-aiding procedure we envision is structured in two main steps: (i) each individual stakeholder evaluates scenarios using a multicriteria method (the purpose of section 10.13 is to select this method) and (ii) these evaluations are shared between

⁷Didactic examples were presented in Chapter 9

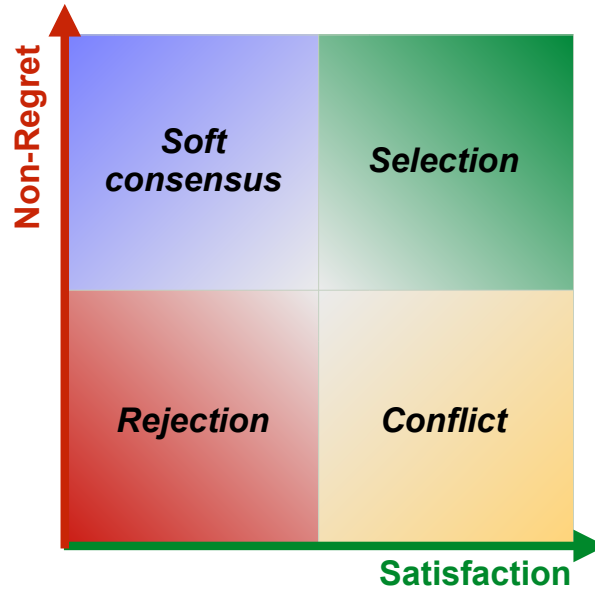


Figure 10.8: The satisfaction-regret matrix with rejection, selection, conflict of soft consensus quadrants. Conflict is characterized by both high satisfaction and high regret.

all participant and are used to structure the deliberation process (this point will be tackled in section 10.4).

10.3 Satisfaction and Regret

10.3.1 Satisfaction and Regret in four outranking methods

The flowcharts presented here are based on methods description by numerous sources, including Figueira et al. (2005), Lenca (2004), André and Oberti (2002). Before analyzing the methods, we provide a quick definition of the outranking principle. Option a outranks option b (aSb) if it is judged at least as good as b and if there is no important reason to think otherwise. From there:

- if aSb and $b\bar{S}a$, then a is preferred to b (aPb),
- if aSb and bSa , then a and b are indifferent (aIb),
- if $a\bar{S}b$ and bSa , then b is preferred to a (bPa),
- if $a\bar{S}b$ and $b\bar{S}a$, then a and b are incomparable (aRb).

Figure 10.9 contains a table summarizing these relations.

In Electre I (figure 10.9), the notion of satisfaction appears in the concordance index for pairwise comparison of alternatives. The majority principle is applied (sum of weights of criteria

where a is better than b). This relation is binary: a criterion gives all its weight or none of it to the index. The notion of regret appears in the discordance index of pairwise comparison of alternatives. The respect of minority principle is applied: final discordance corresponds to the worst under-performance of a compared to b , even if it occurs on a criterion of low weight. However, regret does not increase even if a similar under-performance is found on another criterion.

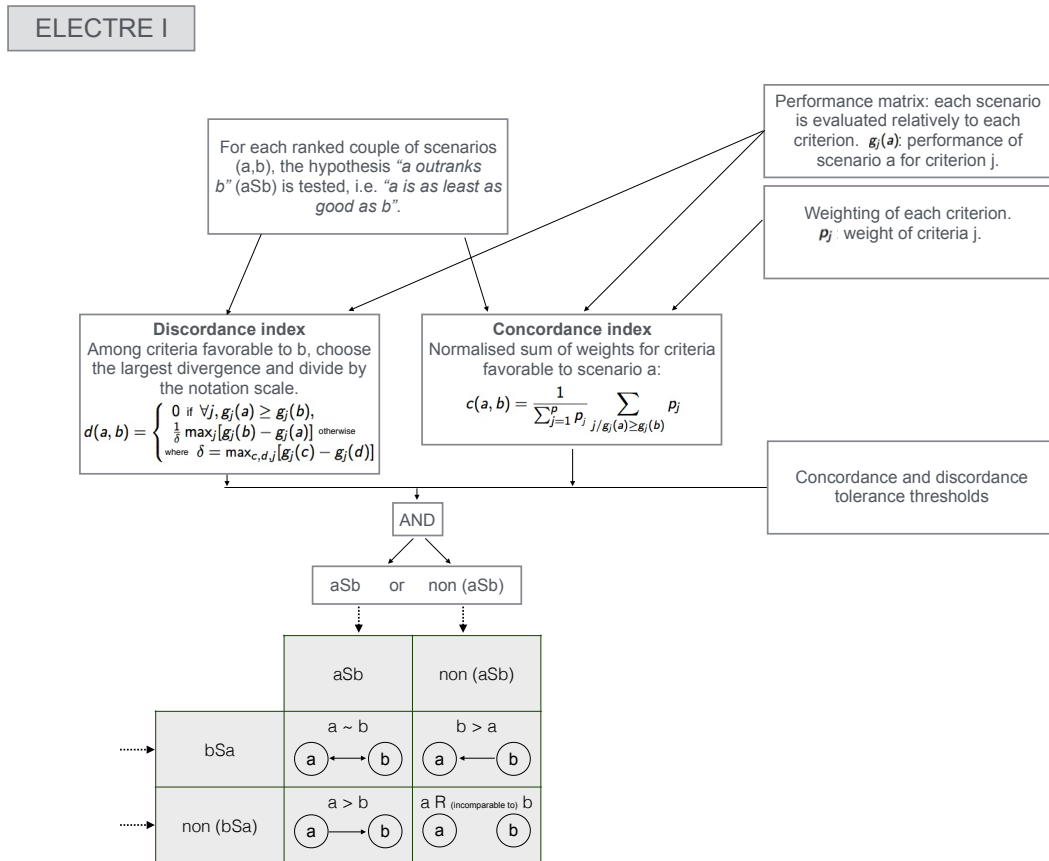


Figure 10.9: Flowchart of the ELECTRE I method.

In Electre III (figure 10.10), satisfaction is found as in Electre I in the concordance index. In this case however, the criterion-specific preference intensity is no longer binary but can take values between 0 and 1. Regret appears in the term penalizing concordance, thus forming the outranking credibility index: several criteria can contribute to it, although their number is necessarily limited (as described by set V). Notions of satisfaction and regret are also present in the production of two distinct rankings at the end of the process: a ranking by weakness and one by strength. These are absolute intensities and no longer refer to other alternative. In its principles, this approach is close to Promethee’s positive and negative flows.

Schärlig (1996) considers Promethee (presented in figure 10.11) as a simplification of Electre III. A notable difference however is that it does not implement a discordance index: the

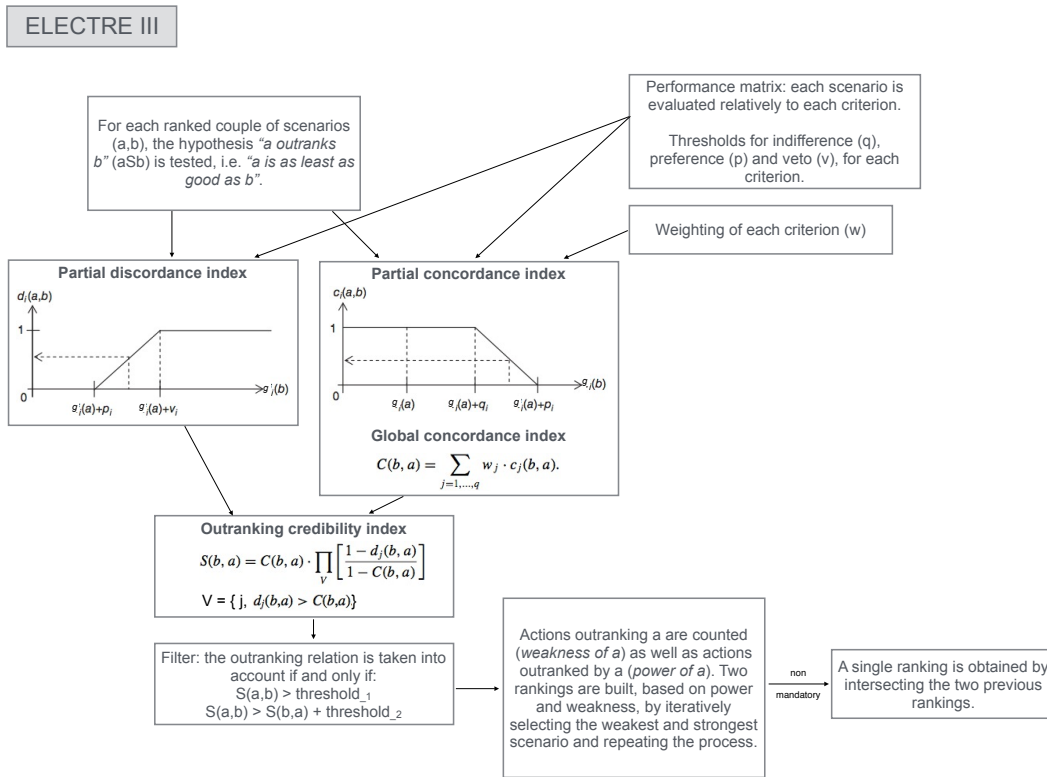


Figure 10.10: Flowchart of the ELECTRE III method.

outranking index is only based on concordance. This simplification is (partially) justified by the fact that concordance computed with Promethee is more strict since one asks the question ‘*To what extent is a better than b?*’, instead of ‘*To what extent is a at least as good as b?*’. Figure 10.12 summarizes this difference by presenting the concordance index $c(a, b)$ in dotted line for Electre III and in solid line for Promethee. Note that due to the absence of discordance in Promethee, it is not possible for two scenarios to be incomparable if they are the only two scenarios compared. Indeed, one can easily show that in this case $\Phi^+(a) = \Phi^-(b)$ (NB: the notations are defined in figure 10.11):

$$\Phi^+(a) = \frac{1}{n-1} \sum_x \sum_k P_k(a, x) \cdot w_k = \frac{1}{n-1} \sum_k P_k(a, b) \cdot w_k = \frac{1}{n-1} \sum_x \sum_k P_k(x, b) \cdot w_k = \Phi^-(b)$$

This means that the positive flow is always identical to the negative flow (i.e. a and b are always comparable):

$$\Phi^+(a) > \Phi^+(b) \Rightarrow \Phi^-(b) > \Phi^-(a)$$

$$\Phi^+(b) > \Phi^+(a) \Rightarrow \Phi^-(a) > \Phi^-(b)$$

$$\Phi^+(a) = \Phi^+(b) \Rightarrow \Phi^-(b) = \Phi^-(a)$$

This is rather a counter-intuitive result as the fact that two scenarios are incomparable shouldn’t depend on other alternatives.

Coming back to our main focus, the notion of satisfaction is present both in the pairwise comparison of alternatives in the $\pi(a, b)$ term and in absolute in the positive flow $\Phi^+(a)$. Weights of criteria are considered in both cases. It is worth noting that for the computation of $\pi(a, b)$, there is no distinction between criteria where b largely outperforms a and criteria where b is only a little better than a (this will be however accounted for in $\pi(b, a)$). Regret is found in the term $\Phi^-(a)$. Note that Promethee also proposes (but it isn’t mandatory) to aggregate $\Phi^+(a)$ and $\Phi^-(a)$ using an arithmetic mean, suggesting satisfaction and regret have equal importance and can be mutually compensative.

As explained earlier, a method called Satisfaction-Regret (S-R) already exists, although it has been very little used to our knowledge. It is presented in Oberti (1995) and André and Oberti (2002) and we propose a flowchart description of it on figure 10.13. It is usually based on a discrete, qualitative evaluation scale, although it is not a requirement. This method does not do pairwise comparisons in order to compute satisfaction and regret. Rather, each action is compared to an ideal scenario. This ideal scenario is defined by performances equal to criteria weights. For instance if a participant responds *True* to the assertion *Criterion x matters* then the ideal scenario will have to perform well on this criteria. For the satisfaction index, the authors propose to use a *Maximum* (S-R version I) or a *Median* (S-R version II) operator. However this goes against the majority principle which implies to take criteria weights into account (as in Electre or Promethee). For the regret index, the distance to the ideal is measured on each criterion, then partial regrets are aggregated in a global regret index using the operator *Maximum* (S-R version I) or *Median* (S-R version II, in which case the respect of minority principle no longer stands). Satisfaction and Regret can be aggregated (the authors suggest using *Min(satisfaction, non-regret)*), however the interest of the methods is precisely to put the emphasis on this distinction.

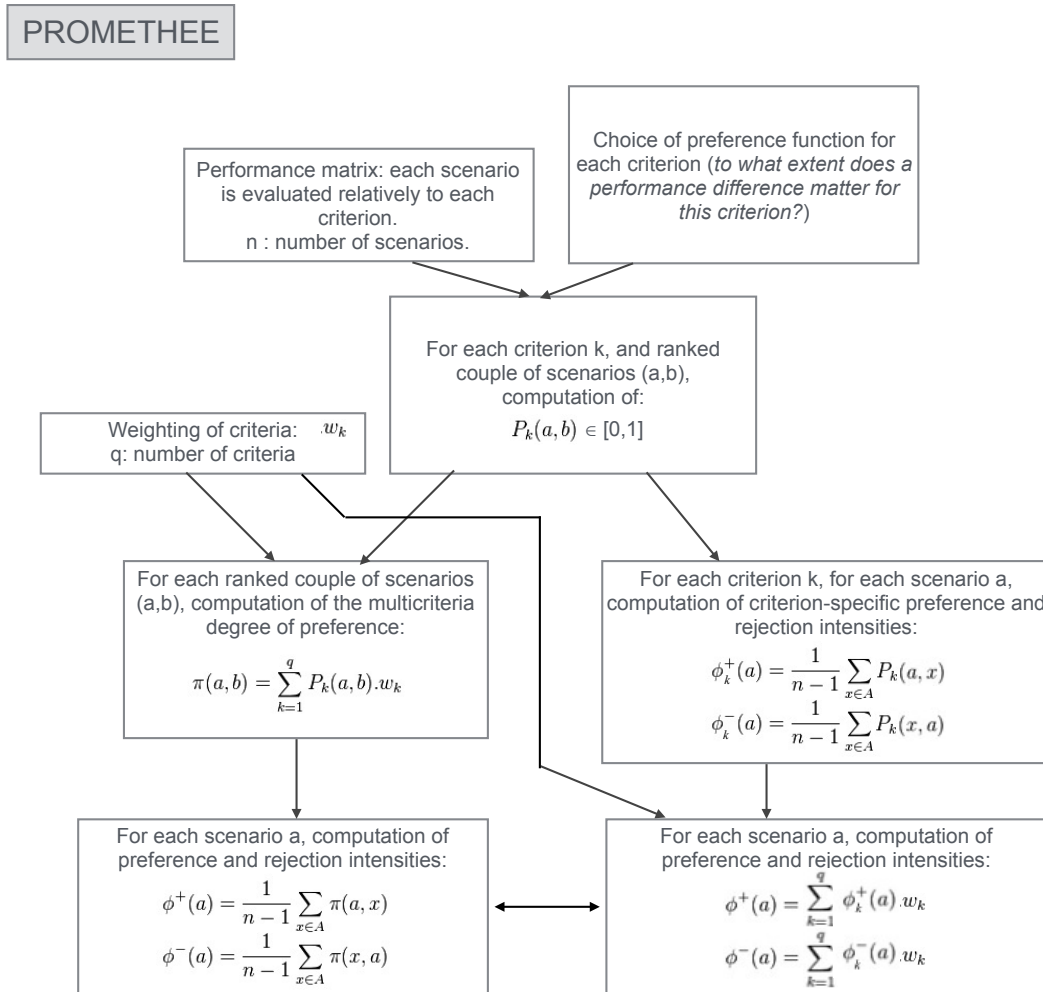


Figure 10.11: Flowchart of the Promethee method. The two branches at the bottom correspond to two equivalent ways of expressing the positive and negative flows (Φ^+ and Φ^-). Note that the Promethee method was informally used (without explicit preference functions) in Chapter 9 on a minimal example.

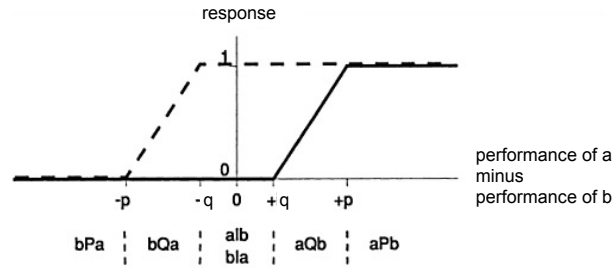


Figure 10.12: Comparison of Electre (dotted line) and Promethee (solid line) concordance indexes. The x-axis is the difference of performance between options a and b and the criterion considered. p and q refer to preference and indifference thresholds. aQb means there is a weak preference for a over b . We can see that in Electre, concordance index $c(a,b)$ (called response on the graph) is equal to 1 as soon as a is indifferent to b , whereas Promethee requires a to be strictly preferred to b . Source: adapted from Schärliig (1996).

10.3.2 Satisfaction-Regret III

The S-R methods have many strengths : they keep things simple while retaining the essential idea of regret, they do not necessitate pairwise comparisons and are therefore less time-consuming, and finally they use a qualitative scale. We find this last property interesting because it is both a way of handling uncertainties, and a way of putting the focus on judgment values rather than on numbers.

Following our remarks on S-R I and S-R II regarding principles we wish to respect, we propose to implement the following modification, therefore leading to... a SR-III method:

- Regret is computed with the *Maximum* index (as in SR-I), in order to implement the respect of minorities principle,
- Satisfaction is computed as the *Weighted Median* of partial (criterion-specific) satisfactions, in order to satisfy the majority principle.

The small example below illustrates this in the case of 3 scenarios (a, b, c) and 3 criteria (x, y, z). As shown in figure 10.13, the first step is to define a qualitative evaluation scale from *False* to *Right*. It is possible to choose coarser or finer subdivisions and here we use a limited scale: *False (F)* - *Rather False (RF)* - *As True As False (ATF)* - *Rather True (RT)* - *True (T)*. Then we have to fill a qualitative performance matrix. Remember that the ij th term of this matrix corresponds to the evaluation of scenario i performance on criterion j and that the assertion made is: "*Performance of scenario i is good on criterion j* ". As discussed in Chapter 9, in order to answer this question, one can make use of quantitative or qualitative indicators otherwise available (for instance, one can choose to assess the overall social performance of a scenario based on the number of job creations only, or on a composite indicator taking into account other variables). Here, we make the hypothesis that quantitative indicators are available for each scenario and already organized in criteria (x, y, z). This is what is shown in table 10.1, assuming all indicators take values from 0 to 10. Note that table 10.1 corresponds in principle to that of the real case study presented at the end of this chapter (table 10.16)⁸

⁸Except lines and columns are transposed.

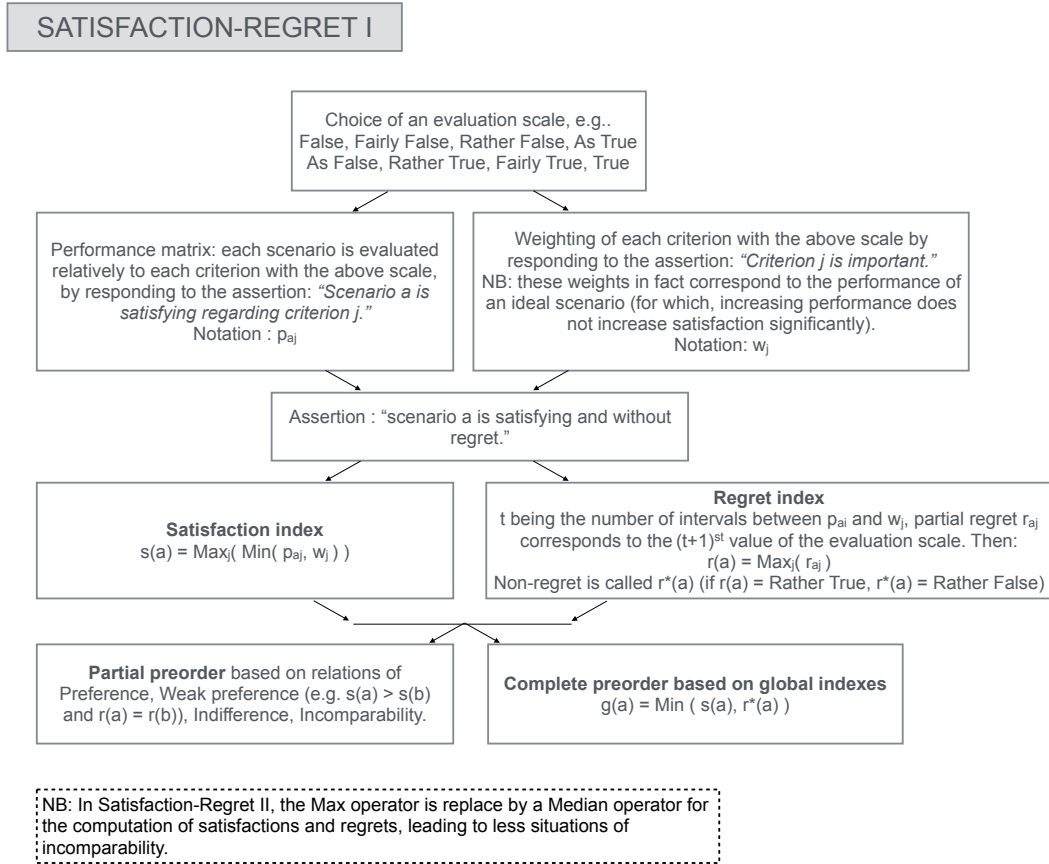


Figure 10.13: Flowchart of the Satisfaction-Regret I (S-R I) methods. The variant of S-R II is made explicit in the dotted rectangle. Note that the two rectangles at the bottom (partial preorder and complete preorder) correspond to two possible alternatives to rank scenarios: one partial ranking and one complete ranking. Of course, the interest of the method lies in the fact that one can differentiate satisfaction from regret, so a complete aggregation is not advised.

	x	y	z
a	10	9	2
b	7	7	5
c	9	5	4

Table 10.1: Quantitative indicators available for the evaluation of each scenario.

One can then translate those quantitative information into qualitative judgments by answering the assertion, which results in table 10.2:

	x	y	z
a	T	T	F
b	RT	RT	ATF
c	T	ATF	RF

Table 10.2: Performance matrix expressed in qualitative terms.

Then, qualitative weights need to be chosen by responding to the assertion: *Criteria i is important*. One has to use the same qualitative set as in table 10.2, which gives:

x	y	z
T	RT	ATF

Table 10.3: Criteria weights.

At this stage, all the information needed for the computation of the satisfaction and regret indices has been gathered. Partial regrets, global regrets and global non-regrets are shown in table 10.4. If on criterion j , scenario i performs better or as good as the ideal scenario (which performances are defined by criteria weights), then the partial regret r_{ij} is worth *False*. Otherwise partial regret corresponds to the distance between the two.⁹

Partial and global satisfactions are shown in table 10.5. For each scenario and each criterion, partial satisfaction refers to the minimum between the weight of the criterion and the scenario's performance on this criterion. For computing the global satisfaction (weighted median of partial satisfactions), we start by writing the worst partial satisfaction a number of times equal to the weight of the corresponding criterion, then the second worst and so on. We use the following convention linking qualitative criterion weight and number of repetition: *False=0*, *Rather False=1*, *As True As False=2*, *Rather True=3*, *True=4*.

We can finally position actions (a, b, c) on the Satisfaction - Regret diagram as shown in figure 10.14. As in any multicriteria method, conducting sensitivity analysis can help assess the results' robustness. For instance, the satisfaction indexes of a and c could probably be evaluated as *True* with little change in the parameters.

⁹E.g., if criterion weight is *Rather True* and scenario performance is *Rather False*, the distance is of two steps and partial regret is *As True as False*.

	Partial regrets			Global regret	Global non-regret
	x	y	z	Max()	
a	F	F	ATF	ATF	ATF
b	RF	F	F	RF	RT
c	F	RF	RF	RF	RT

Table 10.4: Matrix of partial and global regrets.

	Partial satisfactions			Ranked and weighted partial satisfactions	Global satisfaction
	x	y	z		Median()
a	T	RT	F	F-F-RT-RT-RT-T-T-T-T	RT
b	RT	RT	ATF	ATF-ATF-RT-RT-RT-RT-RT-RT-RT-RT	RT
c	T	ATF	RF	RF-RF-ATF-ATF-ATF-T-T-T-T	ATF

Table 10.5: Matrix of partial and global satisfactions.

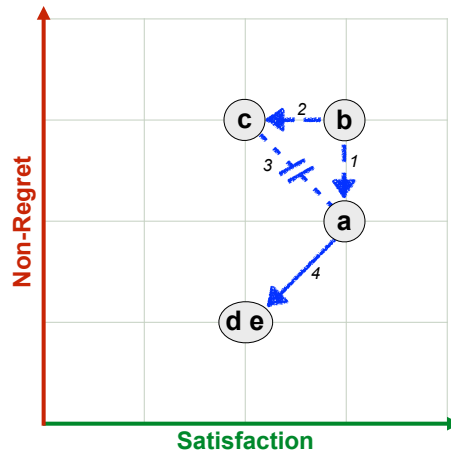


Figure 10.14: Result of the S-R III method. The graph of preference is bQa , bQc and aRc meaning there is a weak preference for b over a and c , and a and c are incomparable (c provides less regret but also less satisfaction than a). Weak preference (noted Q) refers to the fact that b outperforms a and c on only one criterion (satisfaction or regret) and not on both. Visually, weak preferences are represented by dotted arrows 1 and 2 and incomparability by the broken dotted line 3. For the sake of comprehensiveness, we added two other scenarios, d and e . dIe which means that d and e are indifferent (same satisfaction and same regret). They are therefore situated on the same position on the diagram. Preference relation aPd (or aPe) is visualized with solid arrow 4.

10.4 A procedure for deliberation-aiding

There are three ways of envisioning multi-stakeholders multicriteria processes:

- *Option 1:* One can start by aggregating individual preferences and then deliberate in group (multicriteria then multi-stakeholders),
- *Option 2:* Each stakeholder chooses the parameters for the multicriteria method, then the deliberation is organized around the average result, also analyzing dispersion of viewpoints,
- *Option 3:* Stakeholders deliberate on the parameters of the multicriteria method (simultaneous multicriteria and multi-stakeholders).

Option 3 is not desirable in our context as there would be a risk to confiscate the debate on value at the profit of a technical debate. Moreover, it would be difficult for stakeholders to apprehend the true consequences of a choice of parameter on the final decision. *Option 2* is for instance what is proposed by André and Oberti (2002), using the most severe and the most favorable evaluations to present results, and Proctor and Drechsler (2006), that use the mean and standard diversion to convey the idea of agreement or disagreement. We are rather interested in each individual stakeholder expressing its viewpoint and making his/her values explicit, which is why we choose *Option 1*.

Following Proctor and Drechsler (2006), we propose a decision-aiding procedure going from problem identification to the implementation of the multi-stakeholder multicriteria method. As we will see we propose two possible outcomes: either apparent consensus is reached or we use a voting procedure. Note that our starting hypothesis is that we are in a situation of *concertation*, meaning stakeholders are encouraged to express their viewpoints and propose an agenda but don't have the final say. Such situations are common in real life, for instance when a group is asked to write a *White Paper*. Even if decision-makers are not forced to follow instructions, they have incentives to do so, especially if the group deliberation process was conducted transparently. As figure 10.15 shows, this is a 10 steps procedure, that we will now describe.

The first 6 steps are classical and were already discussed in the previous chapter: problem identification, identification of stakeholders, presentation of the process and agreement on collective rules of participation¹⁰, co-elaboration of scenarios and of criteria to assess those scenarios, choice or design of indicators to feed the criteria and eventually construction of a performance matrix. Of course, these steps already imply a form of deliberation in order to agree on what aspects should be considered. At this point, we propose to use the Satisfaction-Regret III method to structure the debate. Step 7 (elicitation of satisfactions and regrets) is performed with each stakeholder individually, before the deliberation stage itself. The deliberation really occurs at Step 8 and is built around the Satisfaction - Non-regret diagram.

¹⁰Rousseau and Martel (1996) insist on the fact that the agreement on the decision-making procedure is: "*the foundation that will confer legitimacy to the decision*". One can extend this notion and apply it to any rule used during the deliberation preparation workshops: speaking time, respect of others etc. For instance, the PAT Miroir© method can be used where participants are first asked to express their concerns about the process, their incentives for participating and the temptations they know will happen. Proposals are then formulated in the form of precautions, strategies and instruments and code of behavior. Initial formal discussions of this type usually help achieving more confidence in the group.

In this step, stakeholders successively present their views to other participants and situate scenarios on the S-R diagram. They explain the weights given to criteria by making their values explicit. They can formulate their points of hesitation. Once everyone has spoken, the facilitator can propose to remove some scenarios that are clearly outperformed and synthesize conflicting positions. At this point, we propose to use the *Six Thinking Hats* methods developed by De Bono (1999) in the field of creative thinking. Indeed this method can be used to evaluate a concept in group, improve an idea and prevent confusion and non-constructive arguing. Many variants exist and we only present one here. All participants must adopt the same perspective (*hat*) on a scenario and formulate ideas in this direction. They successively focus on:

- Positive aspects and advantages,
- Negative aspects and risks,
- Ways of improving, optimizing, overcoming risks,
- Emotional reactions (*I am convinced that..., That arouses in me a feeling of...*),
- *Neutral* facts (numbers, pointing to lack of information etc.).

The last hat is that of organization which consists in synthesizing what has been expressed. Of course some *hats* may be left out.

Deliberation can consist in moving from zone to zone, for instance starting by soft consensus and trying to discuss more ambitious outcomes or instead starting from conflicting scenarios and analyze how to decrease regret. If needed, one can come back to the initial performance matrix at any time and criticize it, modify the weights of the criteria or propose new alternatives. The best case scenario for the process is to make positions evolve: a stakeholder accepts a solution that is not optimal in view of agreed efforts of other parties. This case corresponds to Step 9a of the diagram: apparent consensus is reached and one can also trace back initial positions of stakeholders. In many situations however, this may not be reached. Rather than stopping there, we propose a voting procedure before closing the debate, as a way of synthesizing views. *Majority judgment*¹¹ fulfills many satisfactory criteria; for instance it is claimed to be quite resistant to *tactical voting* and satisfies the criterion of *independence of irrelevant alternatives*. Anyway, the choice of the voting procedure could be made by apparent consensus.

Finally in Step 10, the decision-maker makes the final choice in light of deliberation outcomes and justifies it. Feedbacks can then lead to reformulate the issue or to identify another one. If participants were decision-makers, one would stop at Step 9. However, then the questions of stakeholders' selection (and of a potential voting procedure) should be discussed more thoroughly as they would be fundamental for legitimating the process. As we saw in the previous chapter, thinkers of deliberative democracy invented a variety of procedures for this purpose.

Van Asselt Marjolein and Rijkens-Klomp (2002) propose to situate participative procedures relatively to 2 attributes: on the one hand, is it aiming at "*mapping out diversity*"?, or rather at "*reaching consensus*"? and on the other hand, is the process viewed as a goal ("*a way to organize decision-making*")? or as a means ("*a method to enrich the assessment and decision-making*")?

¹¹This voting procedure is suggested by Balinski and Laraki (2010): voters freely grade each candidate in one of several named ranks, for instance from "excellent" to "bad", and the candidate with the highest median grade is the winner.

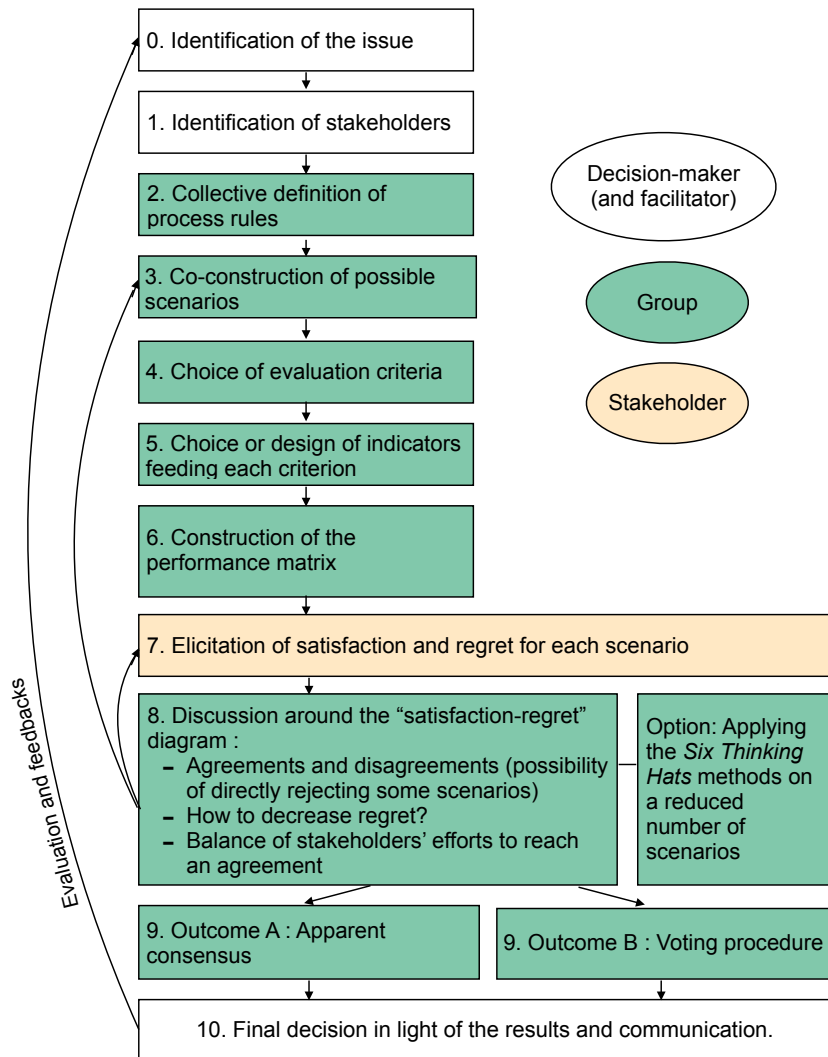


Figure 10.15: Flowchart of the procedure.

as a part of a decision-support process.")? As we just pointed out, the procedure is designed under the hypothesis of *concertation*, i.e. participants are not decision-makers (or at least the majority of them isn't), therefore, we would rather situate ourselves in the *Process as a means* category. Positioning ourselves on the other axis is more problematic. Indeed, the beginning of the process aims at highlighting conflicting positions but the goal of the deliberation phase is to analyze whether or not stakeholders wish to solve this conflict, and in the best case reach apparent consensus. The procedure could therefore be seen in a dynamic way starting from *mapping out diversity* and then attempting to *reach consensus*. Moreover, we aim at a certain balance of power throughout the process: each stakeholder has dedicated time to express its views.

10.5 Application on Afterres 2050 scenarios

Solagro's Afterres 2050 scenario was already mentioned twice in this thesis. In the conclusion of Chapter 6, we outlined some of its features related to the cereals chain¹². In Chapter 8, we mentioned a recent evaluation of the scenario's effect on employment¹³.

The main characteristics of the central scenario are described in table F.1 in this chapter's appendix. It is noteworthy that it acts upon modes of production and modes of consumption. Two variants of this scenario are also proposed. The *REP* version (*Résilience et Production*, i.e. resilience and production) is more export-oriented and consumes more inputs (mineral nitrogen, pesticides and irrigation). The *SAB* version (*Santé, Alimentation, Biodiversité*, i.e. health, food and biodiversity) is rather oriented towards less productivity (especially for non-food products), less exports but also less inputs and emissions to the environment (nitrogen consumption, ammonia emission, pesticides, irrigation). We show the performance of these scenarios relatively to a set of environmental indicators in table 10.16.

In collaboration with Solagro¹⁴ we planned an experiment of group deliberation, using the Satisfaction-Regret method on these scenarios. Although the set of indicators is incomplete (for instance, no economic indicators are available¹⁵), we believe this example corresponds to our scope of study. Indeed, they do not only imply trade-offs between technical criteria but between more fundamental values. Normative questions could for instance be formulated as follows: *Should France keep its role of exporter, not to endanger populations of importing countries? Should we rather use this production capacity for energy production and thereby contribute to the objectives of energy transition and climate mitigation? Or, should agriculture focus on local food provision and on preserving soils and the environment?*

¹²In particular, a reduction of cereals exports, and a reduction of animal proteins in diets leading to less cereals for food purposes (even if direct intake increases).

¹³The study lead by Philippe Quirion (CIRED) estimates that, compared to the business as usual scenario, Afterres would generate about 73,000 additional jobs in agriculture, but 78,000 less in the agro-industry. Additionally, considering change in diets, households would gain purchasing power, leading to increasing final demand in other activities, estimated to 144,000 jobs. The net effect would therefore be positive (noting the limits of such evaluations that we discussed in Chapter 8). Source: <http://afterres2050.solagro.org/2016/02/afterres2050-unsolde-net-de-148-000-emplois>.

¹⁴Christian Couturier and Sylvain Doublet in particular.

¹⁵Except for the impact on employment which was computed for the central scenario.

Scenario	Unit	Current situation (2010)	Business as usual (2050)	Afterres 2050 v. Oct. 2015 (2050)	SAB (2050)	REP (2050)
Primary production (+)	PJ	4 202	4 200	4 300	4 000	4 300
Net exports (+)	PJ	530	568	474	254	624
Non-food production (+)	PJ	41	192	787	665	762
Greenhouse gases (-)	MteqCO2	114	89	46	44	51
Carbon footprint (except materials and energy) (-)	MteqCO2	102	79	32	33	34
Mineral nitrogen consumption (-)	Mt	2,1	1,9	0,7	0,1	1,3
Emissions of ammonia (-)	kt	749	388	221	185	214
Pesticides index (-)	M NODU doses	86	57	23	4	44
Irrigation (-)	Mds m3	2,8	3,7	2,4	2,2	2,9
Agroecological infrastructures (hedges, agroforestry, ...) (+)	kha	526	326	1 110	890	1 043

Figure 10.16: Environmental performance matrix of business as usual and Afterres 2050 scenarios. Source: translated from Solagro (2015).

Beyond the interest of these questions, which are intimately related to the biomass topics we studied in this thesis, the main goal was to test the deliberation procedure previously described to check whether it can easily be implemented, if it effectively facilitates a comprehensive expression of viewpoints and if it can facilitate the reaching of apparent consensus. The workshop was part of a day of scenario presentation organized by Solagro and lasted about one hour. Due to the time constraint, it was limited to a maximum of 10 participants (volunteers from conference attendees). It was originally planned as follows:

1. Quick presentation of the goal of the workshop and of main steps,
2. Deeper presentation of the scenarios under study and of table 10.16,
3. Going around the table, each participant in turn expresses what criteria matter to him/her in order to make a choice, and why.
4. The group agrees on a limited set of criteria (e.g. no more than 8) and participants evaluate scenarios individually using a qualitative scale (0 to 6 corresponding to the *False - Rather False - ... - True* scale presented before)¹⁶,
5. Each participant defines the importance of each criterion using the same qualitative scale (*This criterion really matters for you*),
6. Loading of performances and weights in an excel sheet to quickly compute Satisfaction and Regret indexes for each participant,
7. Participants successively position their indices on a dashboard and express the values justifying their choices,
8. Analysis of each participant's position and open discussion: *Is there a form of consensus? If not, what is the main source of regret and could it be overcome? What information are lacking to make the decision?*,
9. Gathering of impressions of participants. *What steps were unclear? What could have helped? Suggestions for future implementations....* If enough time, voting procedure

¹⁶The method does not require that every participant has the same criteria or even the same number of criteria. It may however facilitate the comparison process afterwards.

based on *majority judgment* (votes could then be compared the more comprehensive understanding resulting from the deliberation procedure).

We unfortunately only had time to go through the first 7 steps, therefore not engaging in the true debating phase (step 8). Regarding our testing objectives, the experiment however showed that:

- The methodology is simple enough to be quickly understood by everyone,
- Participants are able to express the criteria that matter to them, to evaluate the performance of the scenarios, and to weigh the criteria,
- Unsurprisingly, the procedure is viewed as unusual and a bit puzzling. This feeling would have likely be weaker had we had the time to go through the whole procedure described in figure 10.15 (especially co-construction of scenarios with the same group of participants).

10.6 On the use of tools to improve the efficiency of public debates

To conclude this part, it is worth recalling some intrinsic limitations of *tools*¹⁷ when it comes to public debate or more generally to group animation:

- In order to be efficient, they need to be chosen or at least understood and accepted by participants. For this purpose, they need to be simple and transparent,
- A skilled and trained discussion leader is paramount to be able to make the best of the tools, to change plans to adapt to the form of the debate etc.
- Finally, tools will never replace simple forms of discussion between stakeholders, nor possible trust relationships established over years of working together.

Having these limitations in mind, we also believe animation *tools* should be more studied and tried out. As emphasized by many authors (e.g. Benasayag and del Rey (2014)), a well-functioning democracy is able to expose conflict and deal with it, as much as possible in a non-violent manner. We can only observe, however, that our education and cultural background most of the time does not favor nonviolent communication (NVC, Rosenberg (1995)). Basic NVC principles are very much like the ones we presented in this part: expression of personal opinions and feelings, listening to others, etc. While these are rather obvious rules, they are much less obvious to put into practice. Because these communication methods and behaviors are not natural for most of us, we believe one has to practice to get familiar with them even though some may sound *puzzling* at first.

Finally, although only participative multicriteria methods were studied in the course of this thesis, many other group animation and deliberation methods (e.g. serious games, creative thinking...) have been developed in the past decades already providing positive results. Learning more about them will be the next step to advance towards improved public deliberation environments.

¹⁷Other words could be used indifferently here: *methods, approaches, behaviors* etc.

Part three recap

The third part was designed around the observation that scientific knowledge is insufficiently translated into policy making. Its underlying conviction is that scientists should be more involved in political debates on the sustainability issues that they otherwise analyze, not to act as decision-makers, but rather as *honest brokers of policy alternatives* helping to structure research questions with a double objective in mind: (i) research questions, although retaining their own justified logic, should not ignore real-world problems and the way to manage them, and (ii) conversely, helping decision-makers to become more aware of the depth of the issues they handle. In the context of this thesis, we therefore reflected on ways the environmental assessment tools presented in the first two parts could be used as supporting information in the context of deliberation and decision-making:

- Sustainability issues being characterized by the inter-connection between environmental, social and economic issues, we first described in Chapter 9 the main steps of *multicriteria decision-aiding*, with a didactic focus on three multicriteria methods (the weighted average, AHP and Promethee). We then discussed the notion of *participation*, and presented the normative grounds of *deliberative democracy*: a decision is legitimate not because it is unanimous, but in so far as the deliberation process that leads to it is. The principle of *apparent consensus*, a way of reaching decisions alternative to voting procedures, was eventually outlined.
 - In Chapter 10, we first clarified the scope of our research question by proposing a typology of decision-making contexts and associated decision-support tools. We made the hypothesis that, contrary to *optimization*, or *technical multicriteria* strategies, *deliberative multicriteria* is adapted to contexts where both uncertainties and value conflicts are high. We defined deliberative multicriteria tools as *artefacts aiming at reproducing the principles of multicriteria methods but keeping technicality to a minimum in order to leave more space for other forms of discussion*. Keeping this in mind, we adapted an existing method, based on the elicitation of satisfactions and regrets of stakeholders regarding possible futures, with the idea that conflicts emerge for alternatives combining both high satisfaction and high regret (be it internal conflicts or conflicts between stakeholders). We situated this method in a global decision and deliberation-aiding procedure (starting from the identification of a sustainability issue), outlined an experiment of the method on the case of the Afterres 2050 scenarios for a sustainable agriculture, and finally proposed a discussion on the role of tools in public debates.
-

Conclusion and outlook

Conclusion and outlook

Arriving at the end of this study, we first would like to step back and take a look at the big picture: *What was the original motivation of the research? How did it evolve over time? What are the contributions of the thesis both to research fields and practical management? What are its limits?* Secondly, we propose a summary of the perspectives for further quantitative and qualitative developments that were presented over the chapters and try to envision what these joint developments could lead to. Promoting biophysical accounting without questioning its effectiveness and potential pitfalls would be an incomplete endeavor. We therefore attempt in a final section to put together thoughts on the subject and to imagine what could be guidelines to *count wisely*.

11.1 Contributions and limits of the thesis

11.1.1 Original motivation of the research

It is somehow difficult to precisely trace back how we first got interested in *sustainable development*. Rather than a linear path, it could be described as a mind-map where knowledge on apparently different topics over time becomes connected and ends up forming a consistent view of the world. This being said, with the joint discovery of *The limits to growth* (Meadows et al., 1972), Jean-Marc Jancovici's analyses of carbon and energy issues (Jancovici and Grandjean, 2006) and Aurélien Boutaud's PhD thesis (Boutaud, 2005) on the history of the concept of sustainable development and on the Ecological Footprint (Boutaud and Gondran, 2009), we clearly engaged in the topic with a biophysical, consumer-oriented accounting perspective. To express it shortly, the concern was: *How to measure environmental sustainability in order to complement welfare indicators and prevent collapse?* A trifling matter for sure.

11.1.2 Evolution of the research focus

After digging on the National Footprint Accounts thanks to an internship at Global Footprint Network and exchanging with the members of INRIA's STEEP team, it became clear that focusing on regional (subnational scale), would be relevant for numerous reasons, including locks at the international scale, the progressive decentralization of France, and the multiplication of local initiatives building alternatives. The research question therefore became: *How to measure the environmental sustainability of a territory from a producer and consumer perspective?* We studied existing approaches, in particular environmentally-extended input-output analysis (EEIOA), life-cycle analysis (LCA), economy-wide material flow analysis (EW-MFA). The choice to focus on supply-chain material flow analysis (SC-MFA) was motivated by the relative lack of literature in France compared to other approaches, but also by the desire to highlight the material basis of the economy. To choose means to renounce: here, we (temporarily) gave up

the idea of providing a comprehensive environmental assessment of a territory, in exchange of providing a detailed understanding of the fate of specific materials in all French regions. With an Ecological Footprint background, the focus on biomass supply chains naturally stood out, also in line with the will to be relevant to all (or at least, to the majority of) local territories. The emphasis on environmental stakes was present at the starting point and remained throughout time. As work advanced, it however appeared that providing analysis on economic and social stakes would also be critical in a decision-aiding point of view. Regarding these issues, we relied on existing models and methodologies and did not develop new lines of thought (Chapters 7 and 8).

This *triple-bottom-line* approach (Elkington, 1997) is of course intimately related to the decision-aiding part of the thesis developed in parallel of the work on accounting. The initial goal was to reflect on the conditions for our research to best serve decision-making. Because of the specificity of sustainability issues, most of the analysis was targeted towards multi-criteria and multi-stakeholders deliberation, and towards outranking (non-compensatory) methods in particular. We over time became aware that the complexity of these tools was an obstacle to their widespread use. More specifically, sophisticated multicriteria methods are very well adapted to certain decision-making contexts but not for those characterized by high uncertainty and/or value conflicts. Starting from this observation, we asked ourselves how they could be simplified while still retaining their essential strengths.

11.1.3 Contributions to research and management and limits of the thesis

This thesis has made incremental contributions to the fields of Industrial Ecology and Ecological Economics with a proposition of framework for multi-regional SC-MFA (Chapter 3). In addition, coupling MFA with AMC on a practical case hopefully helped clarify the mathematical relationships between MFA, IOA and AMC (Chapters 5 and 6). The uncertainty analysis of the French domestic road freight survey (Chapter 4) will be useful for other research studies, in France and potentially in other European countries. On the practical side, we already had the opportunity to use these results to assess the uncertainties of the EW-MFA of the Lorraine region, and it will probably interest all agents using the SitraM database, first of which are the regional observatories on transport. The work on the forest-wood supply chain (Chapter 7) was presented to different public agencies and could be used to inform the future Regional Scheme on Biomass, Regional Forest-Wood Plans and National Bioeconomy strategy. It seems on the contrary premature to find a direct application to the work on cereals since agri-food issues need a multi-supply-chain perspective. Therefore our case studies on material flows and pressures are rather a proof of feasibility and a step toward this goal. Overall, we can only acknowledge that the tools developed have failed to combine efficiency with sobriety. They still lack transparency and synthesis strength to be really useful to decision-aiding. This is in particular due to the fact that our research was oriented towards broad methodological developments rather than focused on a particular environmental issue. Eventually, as stated at the beginning of the introduction, we experienced that technical developments are partly self-propelled and that acknowledging it is time to stop *counting more* is not a natural thing. In fact, this observation partly motivated the orientation of this conclusion towards the analysis of the pitfalls of quantification.

Regarding the decision-aiding part of the thesis, we believe our attempt to clarify which multicriteria methods should be used depending on the decision-making context was useful.

The study of existing multi-criteria methods from a satisfaction-regret perspective as well. We adopted a bias of transitioning from quantitative to qualitative assessments to put the emphasis on the expression of each stakeholder's values. The goal was not to erase conflicting positions but rather to structure the debate in a more efficient way. The suggested deliberation process (Chapter 10) is of course very modest and would benefit from role-plays and real-life applications since theory can only do so much. The study of other deliberation and group animation tools would also be important on that matter.

11.2 Perspectives for future work

We detail in this section what we identified as relevant perspectives for future work.

11.2.1 Quantitative developments

A first axis of development concerns the application of the models to other supply chains. This would be especially useful for the other supply chains of the agricultural sector since it will then be possible to have a comprehensive view on the agri-food issues. Typically, the supply chain analysis could be bridged to the regional Afterres 2050 scenarios (or more generally to any scenario). The methods developed are also probably suited for the analysis of construction materials. These materials indeed share with biomass the "local stake" property as the majority of construction minerals used in a region is usually extracted from the region itself¹.

A second axis would be modeling domestic supply chains of other countries, using international statistics data (e.g. FAO data, as suggested in the discussion of chapter 6) or more precise local information when available. The model is well suited to encompass different levels of precision among geographic areas. Therefore, having a rough view of the worldwide agri-food supply-chain while providing a more detailed analysis of inter-regional linkage between French and Spanish regions (for instance) would be an achievable goal.

As figure 11.1 shows, the supply-chain approach developed in this thesis would however be insufficient to assess all sustainability aspects, or even environmental aspects of a territory. The SC-MFA methodology is better suited in cases where the considered raw material is eventually embodied in a limited number of products. To illustrate this, we saw in Chapter 3 that tracing the fate of starch and glucose was a task in itself and did not study it. Similarly, we did not study second and third transformation lumber products (Chapter 7). Given the scarcity of the data, there is a risk that modeling these flows would have resulted in a false impression of precision. In these cases, we believe providing order of magnitudes² to complement the SC-MFA study is a way to handle the issue. While the SC-MFA methodology would probably still be achievable in the case of metals³, chemical components would most certainly be impossible to trace after the first transformation. Generally speaking, other tools, probably less detailed but more comprehensive such as IOA) are required to tackle the issue of environmental pressures embodied in consumer goods. In this perspective SC-MFA could for instance be coupled with the territorial LCA methodology proposed by Loiseau (2014).

¹This is in particular showed by the regional EW-MFA conducted in France in Ile-de-France (Barles, 2009), Bourgogne (?), Midi-Pyrénées, Alsace (?) and Lorraine.

²For instance, in the case of wood, an order of magnitude of the territorial trade balance for furnitures.

³See for instance the work of Bonnin et al. (2012) for the analysis of the French copper cycle.

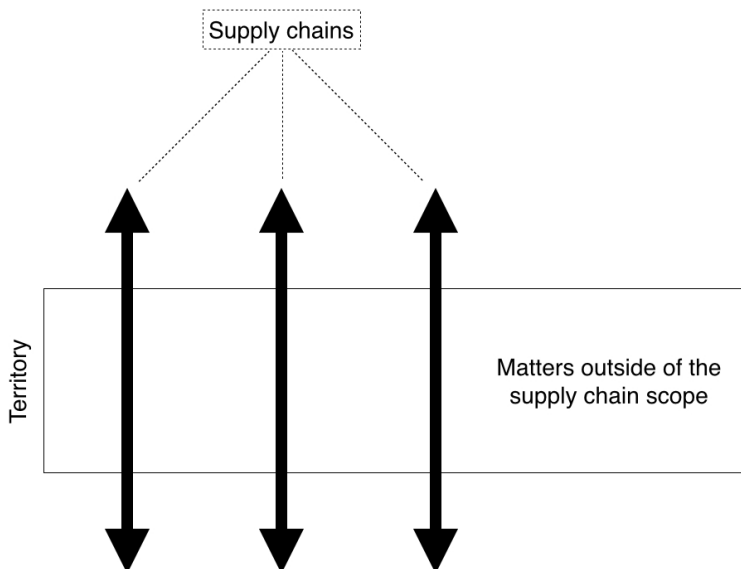


Figure 11.1: Schematic representation of complementarity between supply chain analysis and territorial analysis.

A fourth axis of development is related to the step from environmental pressures to environmental impacts, using the DPSIR terminology (Driver, Pressure, State, Impact, Response) presented in Chapter 9. This will probably necessitate other skills than the one used in the course of our study, the most obvious being knowledge in ecology and biogeochemistry. While pressures are independent of the local environment they arise from, states and impacts are intimately related to it. To take only one example, the state of waterways will not only depend on the quantities of fertilizers used but also on the local water regime (precipitations, flows of surface and underground water), on the type of soil (e.g. rather clay soil or limestone soil) and on local agricultural practices (crop rotation, period of use etc.). This of course complicates the simultaneous study of all territories: it would probably be preferable to be more accurate from an impact assessment point of view and less comprehensive in terms of geographic coverage. Typically, the agri-food and forest-wood supply chain analyses could be linked to the work on ecosystem services networks underway in the Grenoble area⁴. The STEEP team of INRIA is as a matter of fact already involved in this project.

11.2.2 Qualitative developments

Although any increment of knowledge is of course worthwhile in absolute, in a decision-aiding perspective, quantitative developments should be guided by a precise enough *qualitative* objective. Applying this critical lens to our work, the study of the forest-wood supply chain seem

⁴See the ESNET project (<http://www.projet-esnet.org>): future of ecosystem services networks in the Grenoble urban region.

11.3. How to count wisely? Biophysical accounting and democratic challenges²³⁵

more relevant than the cereals' one, since it provides new information to stakeholders on management questions such as: *Given the current harvest and the local forest resource, could we exploit more wood? Is the local production enough to satisfy today or future needs or are we dependent from imports? Is there a risk of over-fostering the energy wood sector, in particular for the lumber industry?* Again, in the case of cereals, a comprehensive view on the food issue would be needed in order to be policy relevant.

A first axis of qualitative development would be to apply the different frameworks of stakeholders analysis described in Chapter 8 on a given regional supply chain. Confronting model results with stakeholders would also allow to improve them (in the studied region and in other regions as well since they are all connected). Going one step further, it would be interesting to evaluate in collaboration with stakeholders the possibilities of promotion of more sustainable supply chains. Related to this issue is the *sustainable job* issue to which we dedicated a few words in Chapter 8. This research would of course involve many disciplines, including geography, sociology and economics.

Finally, multiplying opportunities of testing new deliberation tools would help to advance towards more efficient deliberation procedures. Beyond multicriteria methods, this would include analyses developed in group psychology, creative thinking or negotiation theory, to name only a few.

11.3 How to count wisely? Biophysical accounting and democratic challenges

Whilst not claiming to provide a comprehensive view on them, we successively investigate the following questions:

- *What are the criticisms addressed to quantification?*
- *What is quantification useful for?*
- *Taking these issues into account, what could be the guidelines to count wisely and what democratic challenges go along with them?*

11.3.1 The criticisms of quantification

We identified two major lines of criticism of quantification: the criticism of indicators and statistics and the criticism of data hyperinflation.

11.3.1.1 The criticism of indicators and statistics

As Florence Jany-Catrice points out, regarding statistics, the main point raised by critics is well summarized in the three-word title of Marilyn Waring's documentary: *who is counting?* (Waring, 1995). This question indeed conveys a double meaning: on the one hand what institutions are producing the statistics and on the other hand, *who*, and in wider meaning *what*, is judged to be worth counting. Another way of expressing these ideas would be that quantification is generally serving dominant forces and is simultaneously a reductive representation of the world. There is no denying that statistics are intimately linked with power, the word itself

coming from the German *Staat* (State). In this perspective, Desrosières (2008) interestingly analyzed the various forms of statistics States have chosen to focus on throughout history:

- The engineer State focuses on demography, physical production and inter-industries trade,
- The liberal State focuses on market transparency and market shares (making it possible to identify dominant positions),
- The Welfare State focuses on work statistics (salaries, employment), social inequalities and purchasing power,
- The Keynesian State focuses on national accounting and on analyses of economic situations,
- The neoliberal State designs and uses indicators to evaluate and rank performances (benchmark is promoted in addition to, or in place of, directives and rules).

As Bruno et al. (2014) note, the radical and reformist criticisms of statistics really emerged as a response to the development of benchmark, congruent with this latter form of state. Jany-Catrice (2012) insists on the fact that once an indicator has gained legitimacy and becomes official, there is a risk that it becomes an end in itself rather than a mean of knowledge. In such a case, accounting rules become comparable to rules of law and the indicator “*creates its own reality*” by progressively shaping the world. As we saw in the introduction, this situation is perfectly illustrated by the Growth Domestic Product (GDP), around which most public policies are built. Finally, while it is widely recognized that indicators always depend on choices and on practical possibilities of measurement, their use is almost always decontextualized and their subjective component forgotten. For instance, OECD commonly compares unemployment rates between countries whereas the different definitions given to unemployment should prevent such a direct comparison.

11.3.1.2 The criticism of data hyperinflation

The second line of quantification criticism, which we refer to as the criticism of data hyperinflation, is more global and philosophical. Cukier and Mayer-Schönberger (2013) define the big data phenomenon and put it in a historical perspective (personal translation): “*Hyperinflation of data is a relatively new phenomenon. In 2000, one quarter only of worldwide existing information was available in digital format. Paper, film and other analogical support shared all the rest. Because of the explosive growth of files - whose volume doubles every three years - the situation has undergone a complete reversal. In 2013, digital format represents about 98% of the total. The Anglophone world forged a term to designate this gigantic mass that threatens to escape government and citizen control: big data. [...] Big data constitutes the last manifestation of the irrepressible human desire to understand and quantify the world. [...] Data creation is not digitalization, that designates the process of translating analogical content to a series of machine-readable zeros and ones. It refers to a much wider action, many implications of which still remain unsuspected: digitalizing not only documents, but all aspects of life*”. After pointing to the uncertainty surrounding future uses of collected data, and to the necessity to protect citizens against their abusive utilization by governments and private actors, the authors raise concerns about losing sight of core components of the human essence through the sole reliance on numbers. In this context, they also question the space left to imagine alternative futures:

11.3. How to count wisely? Biophysical accounting and democratic challenges 237

*“We can only be glad if data interpretation leads to improve conditions of living, but this should not make us forget basic common sense. [...] Humankind may rediscover the virtues of unpredictability: instinct, risk taking, accident and even mistake. It may then appear necessary to preserve a space where intuition, common sense, challenge to logic, serendipity and all that composes the human substance will stand up to computers. [...] If Henri Ford had asked algorithms to evaluate customers expectations, they would have probably answered: “Faster horses””. A practical example of such threats is analyzed in Grégoire Chamayou’s *Drone theory* (Chamayou, 2013), which puts the emphasis on the dehumanization of war (on one side at least), soldiers’ bodies being replaced by drones with more and more decision autonomy⁵.*

In the same vein, in her book *Addiction générale* (global addiction), Isabelle Sorente uses the metaphor of addiction to explore our dependence to numbers as well as the deception of numbers (Sorente, 2011). Far from being the expression of a superior human rationality, she argues numbers often form a screen between us and reality. Not a single day goes by without us consuming and producing numbers. In this digital era, the body is reduced to a weight, intelligence to an IQ, security to a number of police arrests, a war or natural disaster to a number of casualties. While one could think these information are effective to raise awareness, their accumulation rather produces an anesthetic effect⁶. Sorente goes on arguing that this coldness of numbers in our daily lives explains for a large part the need for intense collective emotions, summoning the examples of Michael Jackson’s funerals followed by tens of millions as well as famous sport events. Clearly, the belief that human rationality lies in calculus is a major misunderstanding of our time: if the human mind is no more than a linear sequence of algorithms, then computers are only better versions of us. The author therefore uses the notion of compassion to explain how she thinks our specific rationality can be saved. She defines it as an elementary shift of the human spirit making it possible to imagine oneself in someone else’s position. Compassion, thus defined, is the recognition of the multiplicity of points of view on the world and an invitation to leave, at least for a moment, our management/optimization perspective. Numbers are addictive because they provide the illusion of mastering the world and managing uncertainty. They are somehow a reassuring belief. Rather than giving up on numbers, the argument is to acknowledge them for what they are and making space for other perspectives.

Finally, we believe massive quantification, in particular through performance benchmark, is intimately linked to the way people deal with time, and often leads to favor short-term over longer-term issues. In his book *Social acceleration*, Hartmut Rosa for instance delivers a powerful analysis of the *deadline* concept (Rosa, 2013):

“Activities that are held to be valuable or choiceworthy for their own sake disappear from view. No time is left over for “genuinely” valuable activities. This is at least as true of work as it is of free time. Everywhere it seems like there is no time

⁵A recent article by cybersecurity experts (Grothoff and Poru, 2016) follows the same ideas and opens up on this: *“In 2014, the former director of both CIA and NSA proclaimed that “we kill people based on metadata.” Now, a new examination of previously published Snowden documents suggests that many of those people may have been innocent”*.

⁶For instance, learning 22,000 migrants died on their way to Europe since year 2000 (Bordenet and Zerrouky, 2015) has less impact on public opinion than the publication of a photograph of Aylan, a three-year-old Syrian boy who drowned in Mediterranean sea in September 2015.

available for long-term goals - in the example of the scholar, for instance, writing her new book - because of the constant pressure of small demands in the meantime, things which are very often directly related to keeping open opportunities. [...] Sequencing represents an almost natural means of weighting and ordering activities in accordance with their value. Do the most important or valuable thing first, then the second most important, etc., and the less important things will get done if afterward there are still time resources available. In a functionally differentiated society with widely linked interaction chains, however, this ordering principle is replaced more and more by deadlines and appointments for coordinating and synchronizing action. [...] The power of the deadline now determines the serial order of activities and, under conditions of scarce time resources, brings it about that goals that are not bound to deadlines or appointments are lost from view because the burden of what "has to get done (before)" smothers them, as it were - they leave behind only a vague feeling that one does not have time to do "anything" anymore. We are constantly "putting out the fires" that flare up again and again in the wake of the many-layered coordination imperatives of our activities and no longer get around to making, let alone pursuing, long-term objectives."

11.3.2 Quantification retains critical contributions

Keeping these arguments in mind, it also seems necessary to remember the contributions of quantification, not to throw out the baby with the bath water.

The most obvious point is that without quantification, we would have to rely entirely on our experiences and perceptions to take decisions and this would of course be an important source of bias. That is all the more true as cognitive psychology showed that we can be deeply convinced by an opinion even when we know we are lacking of crucial elements to decide: what matters is the coherence of the story we can tell. As Kahneman (2011) puts it: "*The confidence that individuals have in their beliefs depends mostly on the quality of the story they can tell about what they see, even if they see little. We often fail to allow for the possibility that evidence that should be critical to our judgment is missing: what we see is all there is. Furthermore, our associative system tends to settle on a coherent pattern of activation and suppresses doubt and ambiguity*".

Secondly, following Bruno et al. (2014), we believe giving up on numbers would be a tactical mistake in the struggle for sustainability. In this essay, researchers, artists and activists elaborate on the concept of *statactivism* which can be defined as both subverting mainstream statistics and using quantification for emancipation. Among the numerous examples taken, they explain the major influences of Bourdieu's and more recently Piketty's statistical works on public debate. By analyzing the correlation between simple socio-economic variables, *Les Héritiers* (Bourdieu and Passeron, 1964) indeed provided ground to contest the concept of meritocracy, arguing that rather than rectifying cultural inequalities, school was a means of legitimizing them. According to Luc Boltanski, this book, which was "*totalizing a series of individual experiences that it objectified statistically*" played a significant role in the preparation of 1968. Along with other economists, Thomas Piketty decided to study economic inequalities by zooming on the top 1%, 0.1% and even 0.01% rather than on the top 10%. This work, which

11.3. How to count wisely? Biophysical accounting and democratic challenges 239

received worldwide attention, put the issue of inequalities back to the center of concerns and can be related to social movements claiming “*we are the 99%*”. A last and different example concerns the initiative of building alternatives to GDP. Indeed, showing the paradox between the major shortcomings of GDP and its continuing supremacy in policy-making is necessary but insufficient if no alternative is built. This is precisely the purpose of FAIR (the forum for other welfare indicators) whose efforts lead to concrete results: the ARF (association of French regions) adopted in 2012 a set of 22 technical indicators, half of which are biophysical indicators, and 3 headline indicators, the Human Development Index, the Social Health Index, and the Ecological Footprint. A convention recently signed with Insee, the French national institute of economic statistics, will ensure the availability and update of those indicators at regional levels.

A third aspect worth mentioning is that confronting quantitative models with beliefs initiates a learning process for both stakeholders and scientists. Results can either be in line with people’s preconceived ideas, in which case numbers confer objectivity to them and provide orders of magnitude allowing comparison⁷, or on the contrary bring about unexpected knowledge⁸. More generally, quantified modeling is in itself a tool for understanding underlying mechanisms in complex systems, in particular through the use of sensitivity analysis. The World 3 model at the core of *The Limits to Growth* (Meadows et al., 1972) is still remembered because it helped formalizing the mechanisms of collapse and it was convincing because a large number of scenarios, including optimistic ones, were tested and lead to the same conclusion in the long-run.

A fourth remark concerns the coldness of numbers and their anesthetic effect described by Isabelle Sorente. While we agree with the observation itself, it can simultaneously be argued that cold numbers could sometimes help to take more reasonable decisions. For instance, while decisions should not be made based on the sole comparison of casualties, each situation being complex and set in a different context, the cold comparison of number cannot be simply discarded: it has the power to set into motion reflections on our values. Although numbers must be taken with caution, they can be helpful to distance ourselves from the immediate reality, and therefore, to undertake more reasonable actions based on a clear expression of these values.

11.3.3 Biophysical accounting and democratic challenges

Throughout our study, we exclusively focused on the decision-aiding role of biophysical accounting; it was in particular one of the purposes of the third part to see how it could be incorporated in decision-aiding processes. We now wish to widen this horizon, decision-aiding not being its only role nor possibly the most important one. In the long-run, the central contribution of biophysical accounting may very well consist in shifting social imagination, which one could argue is a prerequisite for a large-scale radical change. In other words, won’t spreading the use

⁷For instance, while large exports of raw hardwood was already identified as an issue by stakeholders, our study allowed to quantify it at various scales: in France, about 22% of raw hardwood production is exported whereas in the Grand-Est, this rate increases to about 35%, and even reaches about 50% in Lorraine.

⁸The *food miles* studies performed in the last 20 years showed for instance that large quantities transported on long distances can result in less emissions than small quantities transported on short distances because of higher logistic optimization: regarding climate mitigation issues, modes of production and modes of distribution to customers seem to be the key factors (?). Of course, in both cases, one should also take into account the refrigeration energy consumed by households afterwards.

of biophysical accounting in daily lives, that is progressively thinking more in *tonnes* and less in *euros*, bring about a different relationship to the world? Paul Valéry wrote in 1931 that “*the time of the finite world [had] come*”. Ironically, national (monetary) accounting would thrive at about the same period and dominate imaginations for decades. *Euros* have intrinsically no limits; contrary to the saying, trees can, and do, grow to the sky as the amount of world debt or that of financial derivative products show⁹. As money can be printed without limit, people may get the false impression that *problems are solved*. Quite the contrary, biophysical accounting carries by itself a finite image of the environment, one cannot consume resources that no longer exist, and can therefore set limits to *hybris*. In a sense, the evolution we are describing here has already started. For instance carbon accounting has now spread beyond the domain of experts to the general public. Whereas it would probably be naive to think that this is sufficient to trigger change, it can certainly contribute to this objective.

We eventually wish to propose the following guidelines for biophysical accounting: sobriety, transparency, integration in decision-chains involving diverse stakeholders, systematic use of complementary qualitative analysis.

Sobriety

We strongly believe quantitative methods, and sometimes relatively heavy ones such as sensitivity analysis, can bring important information to the table and even be a prerequisite to deeper qualitative analysis. We believe at the same time that pros and cons of *counting more* should be continuously questioned in a cost-benefit perspective: *Does the greatest contribution to the research question lies in a more precise quantification? Will the increment of knowledge be worth the additional complexity of the model (and the difficulty to explain it to end-users)?*. Clearly, the question of engaging in the big data race is open to industrial ecologists and ecological economists and there is no unique answer to it.

Transparency

This is merely a criterion for any scientific endeavor. Two aspects are worth differentiating here:

- The design of models and indicators should be transparent: what hypotheses are used, what are the data sources, how selection, normalization, aggregation choices have been made and so on,
- One should, as much as possible, evaluate results uncertainties and their sensitivity to hypotheses and input parameters.

Of course transparency goes hand in hand with the possibility of independent control and counter-expertise. Moreover, combining sobriety and transparency is critical if one wants to promote individual autonomy: citizens should be able to read accounts (at least to some extent) in order to fulfill their democratic duty.

Integration in a multi-stakeholders decision-aiding chain

When biophysical accounting is used to help decision-making, we argue involvement of re-

⁹In a blog post, Jean Gadrey tries to summarize different approaches to measure the disproportion between finance and real economy (Gadrey, 2014).

11.3. How to count wisely? Biophysical accounting and democratic challenges241

searchers should be extended. Upstream, it implies to start by asking citizens, stakeholders and decision-makers what their concerns are, what questions or scenarios they wish to investigate and to build tools accordingly, as much as possible in interaction with them. Downstream, it implies to think of the ways information will be used and of efficient¹⁰ forms of deliberation. Didactic open source software tools could potentially play a role in stakeholders workshops.

Use of complementary qualitative analysis

In a time-constrained project, taking the time to conduct qualitative analysis, for instance relying partly on interviews with a large-enough panel of stakeholders, is not always easy if it hasn't been planned from the start. We showed in Chapter 8 that this complementarity was in particular at the essence of *territorial ecology*. Beyond that, qualitative analysis, for instance under the form of monographs, is paramount if one seeks to reflect the diversity and subtlety of phenomena.

The necessary extension of the domain of democracy

Of course, this situation will remain an ideal as long as locks of the current institutions will stand: in deliberative democracies, people should be able to discuss and re-discuss any subject and to implement a decision once it has been made. They should be able to equally express what subjects matter to them (what economic, social and environmental aspects are worth counting), deliberate on what collective goods should be pursued and on the research priorities to set in consequence.

Currently, one can only recognize that decision-makers lack of (or some will say, do not wish to use) key levers of actions to make radical shifts happen. Some critical issues are indeed in practice confiscated from public debate and people are merely left the possibility to adapt to the *faits accomplis*. If subjects that matter for citizens are left out of the space of possible decisions, then one will fall low in Arnstein's ladder of participation and people may increasingly lose interest in local politics. On the other hand, one should also acknowledge, and take advantage of, the degrees of freedom in existing constraints. As Manin (2002) emphasizes, participation can be both an instrument for power, to increase the efficiency of decisions and limit conflict, and for citizens and social forces, to redraw the lines of what can be done (personnal translation): *"Institutions or practices established with a given purpose, [can quite easily serve] other purposes subsequently or even simultaneously. In fact, generally speaking, robust institutions serve many purposes and satisfy many forces at a time"*.

¹⁰Efficient meaning in this context achieving the goals of making everyone's positions clear, including conflicting ones, and understanding what is and what is not negotiable.

Bibliography

Bibliography

- Alexandre, S. (2014). Le bois, un matériau rare ? Vers une hiérarchie des usages du bois. *Revue Forestière Française* 66, 325–336.
- Allenby, B. R. (1992). Achieving sustainable development through industrial ecology. *International Environmental Affairs* 4, 56–68.
- Alterre-Bourgogne (2013). La bourgogne comptabilise ses flux de matières. *Repères* 64, 1–12.
- André, S. and P. Oberti (2002). L’analyse multicritère de projets d’éducation à l’environnement: un outil de gouvernance participative en région Corse. In *Actes de la 7ème Conférence biennale de la Société Internationale pour l’Économie Ecologique, Université du Centre, Sousse*, pp. 6–9.
- Arnstein, S. R. (1969). A ladder of citizen participation. *Journal of the American Institute of planners* 35, 216–224.
- Arrow, K. (1951). *Social choice and individual values*. John Wiley and Sons.
- Babayou, P., J.-L. Volatier, and M. Chambolle (1996). *Les disparités régionales de la consommation alimentaire des ménages français*. Paris: CREDOC.
- Baccini, P. and P. H. Brunner (2012). *Metabolism of the Anthroposphere - Analysis, Evaluation, Design 2e*. Cambridge, Mass: MIT Press.
- Bais, A., C. Lauk, T. Kastner, and K. Erb (2015). Global patterns and trends of wood harvest and use between 1990 and 2010. *Ecological Economics* 119, 326–337.
- Balinski, M. L. and R. Laraki (2010). *Majority judgment: measuring, ranking, and electing*. MIT press.
- Banville, C., M. Landry, J.-M. Martel, and C. Boulaire (1993). A stakeholder’s approach to MCDA - Document de travail.
- Barles, S. (2007). Urban metabolism and river systems: an historical perspective - paris and the seine, 1790-1970. *Hydrology and Earth System Sciences* 11, 1757–1769.
- Barles, S. (2009). Urban metabolism of paris and its region. *Journal of Industrial Ecology* 13, 898–913.
- Barles, S., J. Cerceau, and M. Debuissou (2015). Aussois et la Maurienne, une approche par les trajectoires socio-écologiques, XIXe-XXIe siècle. In N. Buclet (Ed.), *Essai d’écologie territoriale: L’exemple d’Aussois en Savoie*, pp. 13–45.
- Bassene, J.-B., S. Quideville, D. Chabrol, F. Lançon, and P. Moustier (2014). Organisation en réseau et durabilité systémique de deux filières alimentaires (riz biologique et petit épeautre en France). *INRA, SFER, CIRAD. 8èmes Journées de recherches en sciences sociales, Grenoble, France*, 11–12.

- Behzadian, M., R. B. Kazemzadeh, A. Albadvi, and M. Aghdasi (2010). Promethee: A comprehensive literature review on methodologies and applications. *European journal of Operational research* 200, 198–215.
- Bellassen, V. and S. Luyssaert (2014). Carbon sequestration: managing forests in uncertain times. *Nature* 506, 153–155.
- Benasayag, M. and A. del Rey (2014). *Éloge du conflit*. La découverte.
- Berger, G. (1958). L'attitude prospective. *Revue Prospective* 1.
- Berger, M. and M. Finkbeiner (2013). Methodological challenges in volumetric and impact-oriented water footprints. *Journal of Industrial Ecology* 17, 79–89.
- Berger, Y. G. (1998). Rate of convergence for asymptotic variance of the Horvitz-Thompson estimator. *Journal of Statistical Planning and Inference* 74, 149–168.
- Berger, Y. G. (2003). A modified Hájek variance estimator for systematic sampling. *Statistics in Transition* 6, 5–21.
- Billen, G. (2010). Calcul des aires d'approvisionnement à partir de la base de données SitraM du transport de marchandises.
- Billen, G., S. Barles, J. Garnier, J. Rouillard, and P. Benoit (2009). The food-print of paris: long-term reconstruction of the nitrogen flows imported into the city from its rural hinterland. *Regional Environmental Change* 9, 13–24.
- Billen, G., F. Toussaint, P. Peeters, M. Sapir, A. Steenhout, and J.-P. Vanderborght (1983). *L'écosystème Belgique: essai d'écologie industrielle*. Centre de recherche et d'information socio-politiques.
- Binder, C. R. (2007). From material flow analysis to material flow management Part I: social sciences modeling approaches coupled to mfa. *Journal of Cleaner Production* 15, 1596–1604.
- Binder, C. R., C. Hofer, A. Wiek, and R. W. Scholz (2004). Transition towards improved regional wood flows by integrating material flux analysis and agent analysis: the case of Appenzell Ausserrhoden, Switzerland. *Ecological Economics* 49, 1–17.
- Binder, C. R., E. Van Der Voet, and K. S. Rosselot (2009). Implementing the results of material flow analysis. *Journal of Industrial Ecology* 13, 643–649.
- Blezat-Consulting (2010). Etude sur la logistique alimentaire en Rhône-Alpes et ses flux de matières.
- Boltanski, L. and L. Thévenot (1987). *Les économies de la grandeur*. Presses universitaires de France.
- Bonaudo, T., G. Billen, J. Garnier, F. Barataud, S. Bognon, P. Marty, and D. Dupré (2015). Le système agro-alimentaire, un découplage progressif de la production et de la consommation. In N. Buclet (Ed.), *Essai d'écologie territoriale: L'exemple d'Aussois en Savoie*, pp. 13–45.

- Bonnin, M., C. Azzaro-Pantel, L. Pibouleau, S. Domenech, and J. Villeneuve (2012). Development of a dynamic material flow analysis model for French copper cycle. In *Computer Aided Chemical Engineering*, Volume 30, pp. 122–126. Elsevier.
- Bordenet, C. and M. Zerrouky (2015). Méditerranée : chiffres et carte pour comprendre la tragédie. *Le Monde*.
- Bouman, M., R. Heijungs, E. van der Voet, J. C. J. M. van den Bergh, and G. Huppes (2000). Material flows and economic models: an analytical comparison of SFA, LCA and partial equilibrium models. *Ecological Economics* 32, 195–216.
- Bourdieu, P. and J.-P. Passeron (1964). *Les Héritiers : les étudiants et la culture*. Les Editions de Minuit.
- Bourg, D. and K. Whiteside (2010). *Vers une démocratie écologique*. Seuil/La République des Idées.
- Boutaud, A. (2005). *Le développement durable : penser le changement ou changer le pansement ?* Ph. D. thesis, Ecole des Mines de Saint-Etienne - Université Jean Monnet, Saint-Etienne.
- Boutaud, A. and N. Gondran (2009). *L’empreinte écologique*. La découverte, Paris.
- Bringezu, S. and Y. Moriguchi (2002). Material flow analysis. In R. Ayres and A. Leslie (Eds.), *Handbook of industrial ecology*, pp. 79–90. Cheltenham: Edward Elgard Publishing.
- Brou, E. (2012). Potentialités et perspectives d’un outil d’évaluation multi-acteur et multi-critère des projets d’exploitation des ressources naturelles. In *17e colloque international en évaluation environnementale, Montréal*.
- Brown, L. (2011). *World on the edge: how to prevent environmental and economic collapse*. W.W. Norton & Company.
- Bruckner, M., S. Giljum, C. Lutz, and K. Svenja Wiebe (2012). Materials embodied in international trade: Global material extraction and consumption between 1995 and 2005. *Global Environmental Change* 22, 568 – 576.
- Brulot, S., M. Maillfert, and J. Joubert (2014). Stratégies d’acteurs et gouvernance des démarches d’écologie industrielle et territoriale. *Développement durable et territoires* 5.
- Brundtland, G. H. (1987). *Report of the World Commission on environment and development: our common future*. UN.
- Brunner, P. H. and H. Rechberger (2003). *Practical Handbook of Material Flow Analysis* (1 edition ed.). Boca Raton, FL: CRC Press.
- Bruno, I., E. Didier, and J. Prévieux (2014). *Statactivism, Comment lutter avec des nombres*. Editions Zones.
- Buclet, N., F. Barataud, S. Barles, G. Billen, M. Bloin, S. Bognon, T. Bonaudo, P. Chatzimpiros, J. Cerceau, J.-Y. Courtonne, M. Debuisson, D. Dupré, J. Garnier, A. Herbelin, M. Maillfert, P. Marty, R. Metereau, P. Pech, D. Perrotti, M. Talandier, and A.-L. Vernay (2015). *Essai d’écologie territoriale: L’exemple d’Aussois en Savoie*. CNRS Editions.

- Buclet, N., S. Barles, J. Cerceau, and A. Herbelin (2015). L'écologie territoriale entre analyse de métabolisme et jeux d'acteurs. In N. Buclet (Ed.), *Essai d'écologie territoriale: L'exemple d'Aussois en Savoie*, pp. 13–45.
- Buclet, N., J. Cerceau, M. Debuisson, M. Maillefert, R. Météreau, P. Pech, and M. Talandier (2015). Création de richesses et réponses aux besoins de la population d'aussois. In N. Buclet (Ed.), *Essai d'écologie territoriale: L'exemple d'Aussois en Savoie*, pp. 105–160.
- Bösch, M., D. Jochem, H. Weimar, and M. Dieter (2015). Physical input-output accounting of the wood and paper flow in Germany. *Resources, Conservation and Recycling* 64, 99–109.
- Calame, P. and A. Lalucq (2009). *Essai sur l'æconomie*. Charles Léopold Mayer.
- Capellán-Pérez, I., M. Mediavilla, C. de Castro, O. Carpintero, and L. Javier Miguel (2014). Fossil fuel depletion and socio-economic scenarios: An integrated approach. *Energy* 77, 641–666.
- Caurla, S., P. Delacote, F. Lecocq, and A. Barkaoui (2013). Combining an inter-sectoral carbon tax with sectoral mitigation policies: Impacts on the French forest sector. *Journal of Forest Economics* 19(4), 450–461.
- Caurla, S., F. Lecocq, P. Delacote, and A. Barkaoui (2013). Stimulating fuelwood consumption through public policies: An assessment of economic and resource impacts based on the French forest sector model. *Energy Policy* 63, 338–347.
- Cazcarro, I., R. Duarte, and J. S. Chóliz (2013). Multiregional input-output model for the evaluation of Spanish water flows. *Environmental Science & Technology* 47, 12275–12283.
- Cazcarro, I., R. Duarte, J. Sánchez-Chóliz, C. Sarasa, and A. Serrano (2014). Environmental footprints and scenario analysis for assessing the impacts of the agri-food industry on a regional economy. *Journal of Industrial Ecology*.
- CEDIP (2012). La prise de décision.
- Cencic, O. and H. Rechberger (2008). Material flow analysis with software STAN. *Journal of Environmental Engineering Management* 18, 3–7.
- CGDD (2014). Comptabilité des flux de matières dans les régions et les départements: Guide méthodologique.
- CGDD-SOeS (2011). Fiche qualité de l'enquête transport routier de marchandises 2010.
- Chamaret, A., M. O'Connor, and J.-M. Douguet (2009). KerDST: The kerbanel on-line deliberation support tool. *Centre of economics and ethics for environment and development. University of Versailles Saint-Quentin-en-Yvelines: France*.
- Chamayou, G. (2013). *Théorie du drone*. La fabrique éditions.
- Cheng, S., Z. Xu, Y. Su, and L. Zhen (2010). Spatial and temporal flows of China's forest resources: Development of a framework for evaluating resource efficiency. *Ecological Economics* 69, 1405–1415.

- Chevallier, L., V. Forot, and A. Rouillon (2014). Etude de faisabilité pour l'évaluation des flux de matière de biomasse. Technical report, ADEME, FranceAgrimer.
- Ciacci, L., W. Chen, F. Passarini, M. Eckelman, I. Vassura, and L. Morselli (2013). Historical evolution of anthropogenic aluminum stocks and flows in Italy. *Resources, Conservation and Recycling* 72, 1–8.
- CLG (2009). Multi-criteria analysis: a manual.
- Cochran, W. G. (1977). *Sampling Techniques, third edition*. Wiley.
- Colin, A. and H. Chevalier (2009). Rapport technique module biologique LEF. Technical report, Inventaire Forestier National.
- Colin, A. and A. Thivolle-Cazat (2016). Disponibilités forestières pour l'énergie et les matériaux à l'horizon 2035. Technical report, IGN, FCBA, ADEME.
- Cooke, B. and U. Kotiiari (2001). *Participation: The New Tyranny*. London: Zed Books.
- Cordier, M. (2011). *Ecosystème estuarien et système économique régional : faisabilité d'une intégration par modélisation Input-Output. Application au cas de l'habitat halieutique dans l'estuaire de la Seine*. Ph. D. thesis, Université de Versailles-St-Quentin-En-Yvelines - Université Libre de Bruxelles.
- Courtonne, J.-Y., J. Alapetite, P.-Y. Longaretti, and D. Dupré (2016). Environmental pressures embodied in the french cereal supply chain. *Journal of Industrial Ecology* 20, 423–434.
- Courtonne, J.-Y., J. Alapetite, P.-Y. Longaretti, D. Dupré, and E. Prados (2015). Down-scaling material flow analysis: The case of the cereal supply chain in france. *Ecological Economics* 118, 67 – 80.
- Courtonne, J.-Y., P. Chatzimpiros, D. Perroti, A.-L. Vernay, and M. Blouin (2015). Le métabolisme énergétique d'un territoire. In N. Buclet (Ed.), *Essai d'écologie territoriale: L'exemple d'Aussois en Savoie*, pp. 183–208.
- Cukier, K. and V. Mayer-Schönberger (2013). Mise en données du monde, le déluge numérique. *Le Monde diplomatique*.
- Da Cunha, C. (2010). *Quelle prise en compte de la diversité dans les enjeux de performances de l'activité agricole en Ile de France? Expérimentation d'une démarche d'évaluation participative multicritère*. Ph. D. thesis, Versailles-St Quentin en Yvelines.
- Dahlström, K. and P. Ekins (2006). Combining economic and environmental dimensions: Value chain analysis of UK iron and steel flows. *Ecological Economics* 58, 507–519.
- Daly, H. E. and J. Farley (2011). *Ecological economics: principles and applications*. Island press.
- Danius, L. (2002). Data uncertainties in material flow analysis. *KTH, Royal Institute of Technology, Sweden*.

- DATAR (1975). *Méthode des scénarios. Une réflexion sur la démarche et la théorie de la prospective*. La Documentation Française, Paris.
- Davezies, L. (2008). *La République et ses territoires: la circulation invisible des richesses*. Seuil Paris.
- De Bono, E. (1999). *Six thinking hats*. New York Boston: Back Bay Books.
- Debuisson, M. (2014). *Les modes d'interaction pour une dynamique territoriale soutenable : un apport à l'écologie territoriale*. Ph. D. thesis, Université de Technologie de Troyes.
- Desrosières, A. (2008). *Pour une sociologie historique de la quantification, l'argument statistique*. Presses des Mines.
- Diamond, J. (2005). *Collapse: How societies choose to fail or succeed*. Penguin.
- Donaldson, T. and L. E. Preston (1995). The stakeholder theory of the corporation: Concepts, evidence, and implications. *Academy of management Review* 20, 65–91.
- Dornburg, V. and A. Faaij (2005). Cost and co2-emission reduction of biomass cascading: Methodological aspects and case study of srf poplar. *Climatic Change* 71, 373–408.
- Drogoul, C., R. Gadoud, M.-M. Joseph, and R. Jussiau (2004). *Nutrition et alimentation des animaux d'élevage : Tome 2* (Édition : 2e édition ed.). Dijon: Educagri.
- Dubois, D., H. Fargier, M. Ababou, and D. Guyonnet (2014). A fuzzy constraint-based approach to data reconciliation in material flow analysis. *International Journal of General Systems* 43, 787–809.
- Duchin, F. (2009). Input-output economics and material flows. In *Handbook of Input-Output Economics in Industrial Ecology*, pp. 23–41. Springer.
- Duchin, F. and S. H. Levine (2010). Embodied resource flows and product flows. *Journal of Industrial Ecology* 14, 586–597.
- Duchin, F. and S. H. Levine (2013). Embodied resource flows in a global economy. *Journal of Industrial Ecology* 17, 65–78.
- Eckelman, M. J. and I. Daigo (2008). Markov chain modeling of the global technological lifetime of copper. *Ecological Economics* 67, 265–273.
- Eckelman, M. J., B. K. Reck, and T. E. Graedel (2012, June). Exploring the global journey of nickel with markov chain models. *Journal of Industrial Ecology* 16, 334–342.
- Edenhofer, O. and M. Kowarsch (2015). Cartography of pathways: A new model for environmental policy assessments. *Environmental Science & Policy* 51, 56–64.
- Elkington, J. (1997). *Cannibals with Forks: The Triple Bottom Line of 21st Century Business*. Capstone/John Wiley.
- Ercin, A. E., M. M. Mekonnen, and A. Y. Hoekstra (2012). The water footprint of france. <http://www.waterfootprint.org/Reports/Report56-WaterFootprintFrance.pdf>.

- Etzioni, A. (1964). *Modern organization*. Englewood Cliffs: Prentice Hall.
- Eurostat (2001). Economy-wide material flow accounts and derived indicators: a methodological guide.
- Faucheux, S. and M. O'Connor (2012). Au-delà de la prospective technologique-une gestion démocratique des déchets est-elle possible ?
- FCBA (2013). *Mémento*.
- Figueira, J., V. Mousseau, and B. Roy (2005). Electre methods. In *Multiple criteria decision analysis: State of the art surveys*, pp. 133–153. Springer.
- Fortin, M., F. Ningre, N. Robert, and F. Mothe (2012). Quantifying the impact of forest management on the carbon balance of the forest-wood product chain: A case study applied to even-aged oak stands in France. *Forest Ecology and Management* 279, 176–188.
- FranceAgriMer (2012). Panorama des échanges extérieurs du secteur agroalimentaire en 2011. <http://www.franceagrimer.fr/content/download/13153/94179/file/2012echanges-exterieursweb.pdf>.
- Freeman, E. (1984). *Strategic management: a stakeholder approach*. Pitman.
- Froger and Oberti (2002). L'aide multicritère à la décision participative : une démarche originale de gouvernance en matière de développement durable. In editor (Ed.), *Eurocongrès Développement local, développement régional, développement durable : quelles gouvernances ?*
- Frosch, R. A. and N. E. Gallopoulos (1989). Strategies for manufacturing. *Scientific American* 261, 144–152.
- Fuller, W. (2009). *Sampling Statistics*. Wiley.
- Funtowicz, S. O. and J. R. Ravetz (1993). Science for the post-normal age. *Futures* 25, 739–755.
- Gadrey, J. (2014). La finance pèse-t-elle 100 fois plus que l'économie réelle ? 10 fois plus ? bien moins ?
- Gaertner, W. (2009). *A Primer in Social Choice Theory: Revised Edition*. Oup Oxford.
- Gereffi, G. (1994). The organization of buyer-driven global commodity chains: How us retailers shape overseas production networks. *Commodity chains and global capitalism*.
- Giljum, Hubacek, S. (2004). Beyond the simple material balance: a reply to Sangwon Suh's note on physical input-output analysis. *Ecological Economics* 48, 19–22.
- Godar, J., U. M. Persson, E. J. Tizado, and P. Meyfroidt (2015). Towards more accurate and policy relevant footprint analyses: Tracing fine-scale socio-environmental impacts of production to consumption. *Ecological Economics* 112, 25 – 35.
- Godard, O. (1993). Stratégies industrielles et conventions d'environnement: de l'univers stabilisé aux univers controversés. *Insee Méthodes* 39, 145–174.

- Godet, M. and P. Durance (2008). *La prospective stratégique pour les entreprises et les territoires*. Dunod.
- Goodland, R. and H. Daly (1996). If tropical log export bans are so perverse, why are there so many? *Ecological Economics* 18, 189–196.
- Graedel, T., D. van Beers, M. Bertram, K. Fuse, R. B. Gordon, A. Gritsinin, A. Kapur, R. J. Klee, R. J. Lifset, L. Memon, H. Rechberger, S. Spatari, and D. Vexler (2004). Multilevel cycle of anthropogenic copper. *Environmental Science & Technology* 38, 1242–1252.
- Grothoff, C. and J. Poru (2016). The NSA’s SKYNET program may be killing thousands of innocent people.
- Guan, D. and K. Hubacek (2007). Assessment of regional trade and virtual water flows in china. *Ecological Economics* 61, 159 – 170.
- Habermas, H. (2003). Au-delà du libéralisme et du républicanisme, la démocratie délibérative. *Raison publique* 1, 40–57.
- Hansen, E., R. Panwar, and R. Vlosky (2013). The global forest sector: Changes, practices, and prospects. Technical report, CRC Press.
- Hashimoto, S. and Y. Moriguchi (2004). *Data book: material and carbon flow of harvested wood in Japan*. Center for Global Environmental Research, National Institute for Environmental Studies, Tsukuba.
- Hedbrant, J. and L. Sörme (2001). Data vagueness and uncertainties in urban heavy-metal data collection. *Water, Air and Soil Pollution: Focus* 1, 43–53.
- Hekkert, M. P., L. A. J. Joosten, and E. Worrell (2000). Analysis of the paper and wood flow in the Netherlands. *Resources, Conservation and Recycling* 30(1), 29–48.
- Holling, C. (1973). Resilience and stability of ecological systems. *Annual Review of Ecology and Systematics* 4, 1–23.
- Hopkins, T. K. and I. Wallerstein (1994). Commodity chains: construct and research. *Contributions in economics and economic history*, 17–17.
- Huang, Keisler, and Linkov (2011). Multi-criteria decision analysis in environmental sciences: 10 years of applications and trends. *Science of the total environment* 409, 3578–3594.
- Hubacek, K. and S. Giljum (2003). Applying physical input-output analysis to estimate land appropriation (ecological footprints) of international trade activities. *Ecological Economics* 44, 137 – 151.
- Ibanez, D. (2014). *Trafics en tous genres, Le projet Lyon-Turin*. Timbuctu Editions.
- IMA (1996). Value chain analysis for assessing competitive advantage.
- INSEE (2014). La filière forêt-bois en Franche-Comté Edition 2013. Technical report, Les dossiers de l’INSEE Franche-Comté, 30 p.
- Ishizaka and Nemery (2013). *Multi-Criteria Decision Analysis, Methods and Software*. Wiley.

- Jancovici, J.-M. and A. Grandjean (2006). *Le plein s'il vous plaît, la solution au problème de l'énergie*. Seuil.
- Jany-Catrice, F. (2012). *La performance totale, nouvel esprit du capitalisme ?* DARES.
- Jensen, M. C. (2009). Value maximization, stakeholder theory, and the corporate objective function. *Business Ethics Quarterly* 12, 235–256.
- Johnson, R., R. Rucker, and H. Lippke (1995). Expanding U.S. log export restrictions: impacts on state revenue and policy implications. *Journal of Environmental Economics and Management* 29, 197–213.
- Jouvenel, d. H. (1999). La démarche prospective. un bref guide méthodologique. *Futuribles* 247, 47–68.
- Kahn, H. and A. J. Wiener (1967). *Year 2000, A framework for speculation on the next thirty-three years*. Macmillan.
- Kahneman, D. (2011). *Thinking fast and slow*. Farrar, Straus and Giroux.
- Kastner, T., M. Kastner, and S. Nonhebel (2011). Tracing distant environmental impacts of agricultural products from a consumer perspective. *Ecological Economics* 70, 1032 – 1040.
- Kastner, T., A. Schaffartzik, N. Eisenmenger, K.-H. Erb, H. Haberl, and F. Krausmann (2014). Cropland area embodied in international trade: Contradictory results from different approaches. *Ecological Economics* 104, 140 – 144.
- Keeney (1992). *Value focused thinking: a path to creative decision making*. Harvard University Press, Cambridge.
- Keeney and Raifa (1976). *Decisions with multiple objectives: preferences and value tradeoff*. Wiley and Sons.
- Kemeny, J. and J. Snell (1976). *Finite Markov chains*. New-York, NY, USA: Springer-Verlag.
- Knaggs, G. and E. O Driscoll (2008). Estimated woodflow for the Republic of Ireland in 2007. Technical report, COFORD Processing / Products No 18.
- Koebel, B., A.-L. Levet, P. Nguyen-Van, I. Purohoo, and L. Guinard (2016). Productivity, resource endowment and trade performance of the wood product sector. *Journal of Forest Economics* 22, 24–35.
- Kolm, S.-C. (1984). *La bonne économie: la réciprocité générale*, Volume 33. Presses universitaires de France.
- Kovanda, J., J. Weinzettel, and T. Hak (2009). Analysis of regional material flows: The case of the Czech republic. *Resources, Conservation and Recycling* 53, 243–254.
- Kytzia, S., M. Faist, and P. Baccini (2004). Economically extended-MFA: a material flow approach for a better understanding of food production chain. *Journal of Cleaner Production* 12, 877–889.

- Kébir, L. (2004). *Ressource et développement : une approche institutionnelle et territoriale*. Ph. D. thesis, Université de Neuchâtel.
- Kébir, L. and O. Cremoisier (2004). Dynamique des ressources et milieux innovateurs. In D. Maillat, R. Camagni, and A. Mattéaccioli (Eds.), *Ressources naturelles et culturelles, milieux et développement local*, pp. 261–290.
- Laner, D., H. Rechberger, and T. Astrup (2014). Systematic evaluation of uncertainty in material flow analysis. *Journal of Industrial Ecology* 18, 859–870.
- Le Noë, J., G. Billen, L. Lassaletta, M. Silvestre, and J. Garnier (2016). La place du transport de denrées agricoles dans le cycle biogéochimique de l’azote en France: un aspect de la spécialisation des territoires. *Cahiers Agricultures* 25, 15004.
- Lecocq, F., S. Caurla, P. Delacote, A. Barkaoui, and A. Sauquet (2011). Paying for forest carbon or stimulating fuelwood demand? Insights from the French forest sector model. *Journal of Forest Economics* 17(2), 157–168.
- Lecourt, D. (2004). Philosophie prospective. *Les Docs d’Aleph* 23.
- Leigh, M. and X. Li (2014). Industrial ecology, industrial symbiosis and supply chain environmental sustainability: a case study of a large UK distributor. *Journal of Cleaner Production*.
- Leip, A., G. Marchi, R. Koeble, M. Kempen, W. Britz, and C. Li (2008). Linking an economic model for European agriculture with a mechanistic model to estimate nitrogen and carbon losses from arable soils in europe. *Biogeosciences* 5, 73–94.
- Lenca, P. (2004). Aide multicritère à la décision - méthodes de surclassement.
- Lenzen, M. and C. Dey (2000). Truncation error in embodied energy analyses of basic iron and steel products. *Energy* 25, 577–585.
- Lenzen, M., J. Murray, F. Sack, and T. Wiedmann (2007). Shared producer and consumer responsibility ? Theory and practice. *Ecological Economics* 61, 27 – 42.
- Leontief, W. (1970, August). Environmental Repercussions and the Economic Structure: An Input-Output Approach. *The Review of Economics and Statistics* 52, 262–71.
- Levet, A.-L., L. Guinard, and I. Purhoo (2014). Le commerce extérieur des produits bois : existe-t-il réellement un paradoxe français ? *Revue Forestière Française* 66(1), 51–66.
- Linstone, H., M. Turoff, et al. (1975). *The Delphi method: Techniques and applications*. Addison-Wesley Reading, MA.
- Liski, J., A. Pussinen, K. Pingoud, R. Mäkipää, and T. Karjalainen (2001). Which rotation length is favourable to carbon sequestration? *Canadian Journal of Forest Research* 31, 2004–2013.
- Liu, G. and D. B. Müller (2013). Mapping the global journey of anthropogenic aluminum: A trade-linked multilevel material flow analysis. *Environmental Science & Technology* 47, 11873–11881.

- Liu, J. (2014). Forest sustainability in China and implications for a telecoupled world. *Asia & the Pacific Policy Studies* 1, 230–250.
- Lobianco, A., P. Delacote, S. Caurla, and A. Barkaoui (2015). The importance of introducing spatial heterogeneity in bio-economic forest models: Insights gleaned from FFSM++. *Ecological Modelling* 309-310, 82–92.
- Lobianco, A., P. Delacote, S. Caurla, and A. Barkaoui (2016). Accounting for active management and risk attitude in forest sector models. an impact study on French forests. *Environmental Modeling and Assessment* 21(3), 391–405.
- Loiseau, E. (2014). *Methodological proposals for performing an environmental assessment of territories based on the Life Cycle Assessment (LCA) framework*. Ph. D. thesis, Montpellier SupAgro - IRSTEA.
- Loiseau, E., G. Junqua, P. Roux, and V. Bellon-Maurel (2012). Environmental assessment of a territory: an overview of existing tools and methods. *Journal of Environmental Management* 112, 213–225.
- Lorius, C. and L. Carpentier (2011). *Voyage dans l'Anthropocène, cette nouvelle ère dont nous sommes les héros*. Actes Sud.
- Manin, B. (1985). Volonté générale ou délibération ? *Le Débat* 33, 72–93.
- Manin, B. (2002). L'idée de démocratie délibérative dans la science politique contemporaine. introduction, généalogie et éléments critiques. *Politix* 15, 37–55.
- Manin, B., E. Stein, and J. Mansbridge (1987). On legitimacy and political deliberation. *Political theory* 15, 338–368.
- Mantau, U. (2012). Wood flows in Europe (EU27). Technical report, Project report. celle 2012.
- Mantau, U. (2015). Wood flow analysis: quantification of resource potentials, cascades and carbon effects. *Biomass and Bioenergy* 73, 28–38.
- Maystre, L. Y. and D. Bollinger (1999). *Aide à la négociation multicritère: pratique et conseils*, Volume 15. PPUR presses polytechniques.
- McGinnis, M. D. and E. Ostrom (2014). Social-ecological system framework: initial changes and continuing challenges. *Ecology and Society* 19, 30.
- Meadows, D., D. Meadows, J. Randers, and W. Behrens (1972). *The limits to Growth*. Universe Books, New-York.
- Meadows, D., J. Randers, and D. Meadows (2004). *Limits to growth: the 30-year update*. Chelsea Green Publishing.
- MECON (2011). Complejo oleaginoso - producción regional por complejos productivos.
- Mekonnen, M. M. and A. Y. Hoekstra (2011, May). The green, blue and grey water footprint of crops and derived crop products. *Hydrol. Earth Syst. Sci.* 15, 1577–1600.
- Mény, Y. and J.-C. Thoenig (1989). *Politiques publiques*. Presses Universitaires de France-PUF.

- METLA (2011). Wood flows in Finland 2010. Finnish statistical yearbook of forestry. Technical report, METLA.
- Miller, R. E. and P. D. Blair (2009). *Input-output analysis: foundations and extensions*. Cambridge University Press.
- Mintcheva, V. (2005). Indicators for environmental policy integration in the food supply chain (the case of the tomato ketchup supply chain and the integrated product policy). *Journal of Cleaner Production* 13, 717–731.
- Mitchell, Agle, and Wood (1997). Toward a theory of stakeholder identification and salience: Defining the principle of who or what really counts. *Academy of Management Review* 22, 853–886.
- Moll, S., J. Acosta, and H. Schütz (2005). Iron and steel, a materials system analysis - pilot study examining the material flows related to the production and consumption of steel in the European Union.
- Méda, D. (2004). *Le travail*. Presses universitaires de France.
- Méda, D. (2010). *Le travail, une valeur en voie de disparition ?* Editions Flammarion.
- Nakamura, Kondo, Matsubae, Nakajima, and Nagasaka (2011). Upiom: a new tool of mfa and its application to the flows of iron and steel associated with car production. *Environmental Science and Technology* 45, 1114–1120.
- Nakamura, Nakajima, Kondo, and Nagasaka (2007). The waste input-output approach to material flow analysis. *Journal of Industrial Ecology* 11, 50–63.
- Nakamura, S. and Y. Kondo (2009). *Waste Input-Output Analysis: Concepts and Application to Industrial Ecology*. Springer Science & Business Media.
- Narayanaswamy, V., J. A. Scott, J. N. Ness, and M. Lochhead (2003). Resource flow and product chain analysis as practical tools to promote cleaner production initiatives. *Journal of Cleaner Production* 11, 375–387.
- Niza, S., L. Rosado, and P. Ferrão (2009). Urban metabolism. *Journal of Industrial Ecology* 13, 384–405.
- Négawatt (2013). Scénario négaWatt 2011 - dossier de synthèse.
- Oberti, P. (1995). Extension des modèles Satisfaction - Regret par la définition d'une structure de quasi-ordre valué.
- OECD (2008a). Handbook on constructing composite indicators - methodology and user guide.
- OECD (2008b). Measuring material flows and resource productivity - synthesis report.
- Ostrom, E. (2009). A general framework for analyzing sustainability of socio-ecological systems. *Science* 325.
- Parobek, J., H. Palus, V. Kaputa, and M. Supin (2014). Analysis of wood flows in Slovakia. *BioResources* 9(4), 6453–6462.

- Passion-Céréales (2013). Des chiffres et des céréales, l'essentiel de la filière.
- Patricio, J., Y. Kalmykova, L. Rosado, and V. Lisovskaja (2015). Uncertainty in material flow analysis indicators at different spatial levels. *Journal of Industrial Ecology* 19, 837–852.
- Pecqueur, B. and J.-B. Zimmermann (2004). *Economie de proximités*. Hermes-Lavoisier.
- Perez-Garcia, J., B. Lippke, J. Comnick, and C. Manriquez (2005). An assessment of carbon pools, storage, and wood product market substitution using life-cycle analysis results. *Wood and Fiber Science* 37, 140–148.
- Peters, G. P. and E. G. Hertwich (2006a). Pollution embodied in trade: The Norwegian case. *Global Environmental Change* 16, 379–387.
- Peters, G. P. and E. G. Hertwich (2006b). Structural analysis of international trade: Environmental impacts of Norway. *Economic Systems Research* 18, 155–181.
- Petersen, A. (2006). A comparison of avoided greenhouse gas emissions when using different kinds of wood energy. *Biomass and Bioenergy* 30, 605–617.
- Petersen, A. K. and B. Solberg (2005). Environmental and economic impacts of substitution between wood products and alternative materials: a review of micro-level analyses from Norway and Sweden. *Forest Policy and Economics* 7(3), 249–259.
- Pielke, R. (2007). *The honest broker: making sense of science in policy and politics*. Cambridge University Press.
- Pingoud, K., A.-L. Perälä, and A. Pussinen (2001). Carbon dynamics in wood products. *Mitigation and Adaptation Strategies for Global Change* 6, 91–111.
- Piskur, M. and N. Krajnc (2007). Roundwood flow analysis in Slovenia. *Croatian Journal of Forest Engineering* 28(1), 39–46.
- Polanyi, K. (1944). *The great transformation: The political and economic origins of our time*. Beacon Press.
- Porter, M. E. (2011). *Competitive advantage of nations: creating and sustaining superior performance*. Simon and Schuster.
- Pouet, J.-C. and A. Gauthier (2013). Etude sur le chauffage domestique au bois : marché et approvisionnement. Technical report, ADEME.
- Proctor, W. and M. Drechsler (2006). Deliberative multicriteria evaluation. *Environment and Planning C: Government and Policy* 24, 169–190.
- Profft, I., M. Mund, G.-E. Weber, E. Weller, and E.-D. Schulze (2009). Forest management and carbon sequestration in wood products. *European Journal of Forest Research* 128, 399–413.
- Quirion, P. (2013). L'effet net sur l'emploi de la transition énergétique en France : Une analyse input-output du scénario négaWatt. Working paper.
- Raikes, P., M. Friis Jensen, and S. Ponte (2000). Global commodity chain analysis and the French filière approach: comparison and critique. *Economy and Society* 29, 390–417.

- Rawls, J. (2009). *A theory of justice*. Harvard university press.
- Read, C. (1920). *Logic: Deductive and Inductive*. Public Domain.
- Rechberger, H., O. Cencic, and R. Frühwirth (2014). Uncertainty in material flow analysis. *Journal of Industrial Ecology* 18, 159–160.
- Remvikos, Y., A. Mahamat, and V. Reichel (2010). L'interface science/décision au travers d'une évaluation multicritères et multi-acteurs du plan régional pour la qualité de l'air en Ile-de-France.
- Rochat, D., C. R. Binder, J. Diaz, and O. Jolliet (2013). Combining material flow analysis, life cycle assessment, and multiattribute utility theory. *Journal of Industrial Ecology* 17, 642–655.
- Rockström, J., W. Steffen, K. Noone, Å. Persson, F. S. Chapin, E. F. Lambin, T. M. Lenton, M. Scheffer, C. Folke, H. J. Schellnhuber, et al. (2009). A safe operating space for humanity. *Nature* 461, 472–475.
- Rosa, H. (2013). *Social acceleration, a new theory of modernity*. Columbia University Press.
- Rosenberg, M. (1995). *Words Are Windows or They're Walls. - Nonviolent Communication*. Create Your Life - Productions.
- Rousseau and Martel (1996). La décision participative : une démarche pour gérer efficacement les conflits environnementaux - document de travail 96-24. *Centre de recherche sur l'aide à l'évaluation et à la décision dans les organisations, Faculté des sciences de l'administration de l'Université Laval, Québec*.
- Roy, B. (1985). *Méthodologie multicritère d'aide à la décision*. Economica, Paris.
- Roy, B. and D. Bouyssou (1993). *Aide multicritère à la décision : méthodes et cas*. Economica.
- Réseau-Action-Climat (2013). Les émissions importées, le passager clandestin du commerce mondial.
- Samuelson, P. (1952). Spatial price equilibrium and linear programming. *American Economic Review* 42, 283–303.
- Sathre, R. and L. Gustavsson (2006). Energy and carbon balances of wood cascade chains. *Resources, Conservation and Recycling* 47(4), 332–355.
- Sauquet, A., S. Caurla, F. Lecocq, P. Delacote, A. Barkaoui, and G. S. (2011). Estimating armington elasticities for sawnwood and application to the French forest sector model. *Resource and Energy Economics* 33(4), 771–781.
- Schmidt, Weidema, and Suh (2010). Forcast 6.4 - documentation of the final model used for the scenario analysis.
- Schmidt, M. (2008). The sankey diagram in energy and material flow management. *Journal of Industrial Ecology* 12, 173–185.

- Schwartz, P. and J. Ogilvy (1998). *Plotting your scenarios*, pp. 57–80. John Wiley and Sons, New York.
- Schärli, A. (1996). *Pratiquer Electre et Prométhée, un complément à Décider sur plusieurs critères*.
- Scorier, P.-E. (2012). *Démocratie managériale, démocratie délibérative et écologie politique*.
- Sen, A. et al. (1999). *Commodities and capabilities. OUP Catalogue*.
- Sen, A. K. (2014). *Collective choice and social welfare*, Volume 11. Elsevier.
- Sikkema, R., M. Junginger, P. McFarlane, and A. Faaij (2013). The GHG contribution of the cascaded use of harvested wood products in comparison with the use of wood for energy. A case study on available forest resources in Canada. *Environmental Science & Policy* 31, 96–108.
- Simas, M., R. Wood, and E. Hertwich (2014). Labor embodied in trade. *Journal of Industrial Ecology*.
- Simon, H. (1957). *Models of Man*. John Wiley.
- Skelton, A., D. Guan, G. P. Peters, and D. Crawford-Brown (2011). Mapping flows of embodied emissions in the global production system. *Environmental Science & Technology* 45, 10516–10523.
- Smaranda, B. (2013). Data mining for material flow analysis: application in the territorial breakdown of French regions. *Hal*.
- Smith, R. A., P. I. J. Griffiths, and J. Kersey (2003). Resource flow analysis: measuring sustainability in construction. *Proceedings of the ICE - Engineering Sustainability* 156, 147–155.
- SOeS (2012). Bilan qualité de l'enquête transport routier de marchandises 2010.
- SOeS (2015a). Contamination globale des cours d'eau par les pesticides. <http://www.statistiques.developpement-durable.gouv.fr/essentiel/ar/246/211/contamination-globale-cours-deau-pesticides.html>.
- SOeS (2015b). Repères - Chiffres clés du climat France et Monde. http://www.statistiques.developpement-durable.gouv.fr/fileadmin/documents/Produits_editoriaux/Publications/Repere-climat-france-monde-ed-2015.pdf.
- Solagro (2014). Un scénario soutenable pour l'agriculture et l'utilisation des terres en France à l'horizon 2050. <http://www.solagro.org/site/393.html>.
- Sorrente, I. (2011). *Addiction générale*. JC Lattès.
- Stiglitz, J., A. Sen, and J.-P. Fitoussi (2009). Commission sur la mesure de la performance économique et du progrès social.

- Strutt, A., J. Turner, R. Haack, and L. Olson (2013). Evaluating the impacts of an international phytosanitary standard for wood packaging material: Global and united states trade implications. *Forest Policy and Economics* 27, 54–64.
- Suh (2004). A note on the calculus for physical input-output analysis and its application to land appropriation of international trade activities. *Ecological Economics* 48, 9–17.
- Talleg, F. and L. Bockel (2005). Commodity chain analysis: constructing the commodity chain functional analysis and flow charts. *Rome: UN Food and Agriculture Organization*.
- Thadakamalla, H., U. Raghavan, S. Kumara, and R. Albert (2004, Sept). Survivability of multiagent-based supply networks: a topological perspect. *IEEE Intelligent Systems* 19, 24–31.
- Theys, J. (2002). Environmental governance: from innovation to powerlessness. In *Participatory Governance*, pp. 213–244. Springer.
- Tillé, Y. (2001). *Théorie des sondages : échantillonnage et estimation en population finie*. Dunod.
- Tillé, Y. (2006). *Sampling Algorithms*. Springer-Verlag.
- Treolar, G. (1997). Extracting embodied energy paths from input-output tables: towards an input-output based hybrid energy analysis method. *Economic Systems Research* 9, 375–391.
- Urfalino, P. (2007). La décision par consensus apparent : nature et propriétés. *Revue européenne de sciences sociales* 136, 47–70.
- Uusivuori, J. and M. Tervo (2002). Comparative advantage and forest endowment in forest products trade: evidence from panel data of OECD countries. *Journal of Forest Economics* 8, 53–75.
- Van Asselt Marjolein, B. and N. Rijkens-Klomp (2002). A look in the mirror: reflection on participation in integrated assessment from a methodological perspective. *Global environmental change* 12, 167–184.
- Van den Bergh, J. C. and H. Verbruggen (1999). Spatial sustainability, trade and indicators: an evaluation of the “ecological footprint”. *Ecological economics* 29, 61–72.
- Van Kerkhoff, L. and L. Lebel (2006). Linking knowledge and action for sustainable development. *Annual Review of Environment and Resources* 31, 445–477.
- Van Kooten, G. and C. Johnston (2014). Global impacts of Russian log export restrictions and the Canada-U.S. lumber dispute: modeling trade in logs and lumber. *Forest Policy and Economics* 39, 54–66.
- Van Reybrouck, D. (2014). *Contre les élections*. Éditions Actes Sud.
- Virtanen, Y., S. Kurppa, M. Saarinen, J.-M. Katajajuuri, K. Usva, I. Mäenpää, J. Mäkelä, J. Grönroos, and A. Nissinen (2011). Carbon footprint of food - approaches from national input-output statistics and a LCA of a food portion. *Journal of Cleaner Production* 19, 1849–1856.

- Vurro, C., A. Russo, and F. Perrini (2009). Shaping sustainable value chains: Network determinants of supply chain governance models. *Journal of business ethics* 90, 607–621.
- Wackernagel, M., C. Monfreda, D. Moran, P. Wermer, S. Goldfinger, D. Deumling, and M. Murray (2005). National footprint and biocapacity accounts 2005 - the underlying calculation method. *Global Footprint Network, Oakland, CA*.
- Wackernagel, M. and W. Rees (1996). *Our Ecological Footprint: reducing human impact on the Earth*. New Society Publishers, Gabriola Island, BC.
- Wahnich, S. (2013). *L'intelligence politique de la révolution française, documents commentés*. Editions textuel.
- Walker, B., C. Holling, S. Carpenter, and A. Kinzing (2004). Resilience, adaptability and transformability in social ecological systems. *Ecology and Society* 9(2), 5.
- Waring, M. (1995). Who's counting? Marilyn Waring on sex, lies and global economics.
- Weber, M. (2002). *Le Savant et la Politique*. Editions 10/18.
- Weidema, B. P. and M. S. Wesnæs (1996). Data quality management for life cycle inventories: an example of using data quality indicators. *Journal of Cleaner Production* 4, 167 – 174.
- Weimar, H. (2009). Der Holzfluss in der Bundesrepublik Deutschland 2009. Technical report, Methode und Ergebnis der Modellierung des Stoffflusses von Holz. Johan Heinrich von Thunen Institut für Forst und Holzwirtschaft, Arbeitsbericht.
- Weisz and Duchin (2006). Physical and monetary input-output analysis: what makes the difference? *Ecological Economics* 57, 534–541.
- Wiedmann, T., R. Wood, J. C. Minx, M. Lenzen, D. Guan, and R. Harris (2010). A carbon footprint time series of the UK - results from a multi-region input-output model. *Economic systems research* 22, 19–42.
- Wirsenius, S. (2003). The biomass metabolism of the food system: A model-based survey of the global and regional turnover of food biomass. *Journal of Industrial Ecology* 7, 47–80.
- Wittke, K. (2014). The contribution of stakeholder theory to supply chain management: A theory evaluation.
- Yu, Y., K. Feng, and K. Hubacek (2013). Tele-connecting local consumption to global land use. *Global Environmental Change* 23, 1178 – 1186.

Appendix

APPENDIX A

Supplementary material to Chapter 3

Additional tables

	Culture of cereals	Seeds and losses	Livestock consumption	Mills	Semolina prod.	Corn semolina prod.	Rice trans-formation	Canned corn prod.	Starch industry	Industrial bakery	Craft bakery	Biscuits factory	Pasta and cous-cous prod.	Compound feed production	Malt prod.	Beer prod.	Bioethanol factory	Supernatant	Exports
Common wheat																			
Durum wheat																			
Maize																			
Barley																			
Other cereals																			
Flour																			
Residues																			
Semolina																			
Corn semolina																			
Canned corn																			
Starch and glucose																			
Bread																			
Biscuits																			
Compound feed																			
Pasta and couscous																			
Transformed rice																			
Malt																			
Beer																			
Bioethanol																			
Common wheat																			
Durum wheat																			
Maize																			
Barley																			
Other cereals																			
Flour																			
Residues																			
Semolina																			
Corn semolina																			
Canned corn																			
Starch and glucose																			
Bread																			
Biscuits																			
Compound feed																			
Pasta and couscous																			
Transformed rice																			
Malt																			
Beer																			
Bioethanol																			

Figure A.1: Supply (above) and Use (below) tables of the study. White cells have to be filled, grey cells mean the corresponding quantity is null. At subnational scales, additional columns for inter-regional trade are added. The starch and glucose category encompass both mid-products and finished products containing those substances. Indeed, the number of products containing starch derivatives is huge, both in food and in non-food industries (chemistry, textile etc.) and tracking them is beyond the scope of this study.

Conversion	Factor
From common wheat to flour	0.77
From durum wheat to semolina	0.86
From maize to cornmeal	0.53
From common wheat to starch	0.53
From maize to starch	0.63
From barley to malt	0.88
From wheat or maize to bioethanol	0.68

Table A.1: Conversion factors (kg of cereal output per kg of cereal input) deducted from the cereals inter-profession yearly report.

Year	Production	Net imports	Stock variation	Apparent consumption
2001	182%	-83%	1%	100%
2002	202%	-97%	-5%	100%
2003	182%	-94%	12%	100%
2004	212%	-102%	-10%	100%
2005	190%	-96%	6%	100%
2006	186%	-89%	3%	100%
2007	173%	-72%	-1%	100%
2008	192%	-87%	-5%	100%
2009	204%	-99%	-5%	100%
Period average	191.5%	-90.9%	-0.6%	100%
	64 453 kt	-30 592 kt	202 kt	33 659 kt

Table A.2: Contribution of production, trade and stock variation to apparent consumption. Net imports includes primary and transformed products, expressed in weight of grain equivalent. When all terms are positive, production and net imports contribute positively to apparent consumption contrary to stock variation (final stock - initial stock).

Animal or product	Embodied cereals (Mt)	Corrected embodied cereals (Mt)
Pigs	6.3	7.1
Poultry	5.5	6.2
<i>eggs</i>	1.3	1.5
<i>chickens and turkeys</i>	3.1	3.5
<i>others</i>	1.1	1.2
Cattle	7.1	8.0
<i>cattle for milk</i>	3.5	4.0
<i>cattle for meat</i>	3.6	4.1
Other	0.7	0.8
Total from nutrition model	19.6	22.2
Total from national accounts	22.2	
Scaling ratio	1.13	

Table A.3: Livestock feed in France

Animal or product	Embodied cereals (kg)	Ratio applied on...
Piglet	71	production
Pig	255	production
Egg for consumption	0.1	production
Egg to be hatched	0.257	production
Chicken, duck, turkey, goose, guinea fowl	see tableA.5	production (balanced by average carcass weight)
Rabbit	2.64	production
Horse	730	livestock
Lamb	11.35	production
Milking ewe	60.83	production
Goat	0	livestock
Milking cow (milk)	see table A.6	livestock (balanced by average milk production per cow)
Nursing cow (meat)	303	livestock
Renewal heifer 1 to 2 years old (milk and meat)	383	livestock
Renewal heifer older than 2 years (milk and meat)	511	livestock
Heifer from 6 months to 1 year (meat)	386	production
Heifer 1 to 2 years old (meat)	824	production
Heifer older than 2 years (meat)	1043	production
Males from 6 months to 1 year (meat)	325	production
Males from 1 to 2 years (meat)	800	production
Males older than 2 years (meat)	558	production

Table A.4: Estimation of livestock cereals intakes. Calculation by the authors, based on Drogoul et al. (2004). Production refers to the number of animals slaughtered a given year. Livestock refers to the number of living animals at the end of the year. Care was taken in order to avoid double-counting. For instance intakes of poultry does not include the cereals fed to the laying hen (which are considered separately under the category "egg to be hatched"). Moreover for each category of animal, either the lifetime approach or the annual approach is used. The underlying hypothesis that we make by summing up the two approaches is that stock variation is negligible.

carcass weight (kg)	cereals feed (kg)
0.75	1.5
1.1	2.4
1.4	3.2
1.7	4.5

Table A.5: Chicken lifetime cereals intakes depending on carcass weight. After Drogoul et al. (2004). A linear interpolation is conducted for weight values inbetween and after.

Maximum daily production without compound feed	Quantity of compound feed per additionnal daily litter of milk	% of cereals in the compound
10 L	0.4 kg/L	60%

Table A.6: Hypothesis used to estimate cereals feed of milking cows depending on milk production quantity. It is assumed that additional nutritional feed is needed (60% cereals, 40% soy cakes) for each additional litter of milk above 10 L per day during the lactation period (10 months) (Drogoul et al., 2004).

Region name	Presence of major harbors exporting cereals	Total exports before redistribution (kt)	Total exports after redistribution (kt)	Absolute difference (kt)	Relative difference
Haute-Normandie	Rouen	5788	5901	+113	+2%
Aquitaine	Bordeaux, Bayonne	2647	2707	+60	+2%
Nord-Pas-de-Calais	Dunkerque	2149	2345	+196	+9%
Poitou-Charentes	La Rochelle	2637	2150	-487	-18%
Lorraine		1880	1781	-99	-5%
Champagne-Ardenne		1633	1578	-55	-3%
Picardie		1523	1486	-37	-2%
Provence-Alpes-Côte-d'Azur	Marseille	606	1204	+598	+99%
Languedoc-Roussillon	Port-la-Nouvelle, Sète	1066	1203	+137	+13%
Alsace		1161	1133	-28	-2%
Midi-Pyrénées		1150	1115	-35	-3%
Pays-de-la-Loire	Nantes-Saint-Nazaire	1140	1083	-57	-5%
Bourgogne		759	701	-58	-8%
Centre		707	680	-27	-4%
Rhône-Alpes		464	368	-96	-21%
Ile-de-France		536	346	-190	-35%
Basse-Normandie	Caen	265	323	+58	+22%
Auvergne		103	101	-2	-2%
Franche-Comté		76	74	-2	-3%
Bretagne		10	15	+5	+50%
Limousin		4	4	+0	+0%

Table A.7: Impact of the sea exports redistribution operation on the total international exports of regions (all modes of transports included). The regions without a harbor tend to lose some exports to the benefit of the regions with a harbor. The most impacted region is Provence-Alpes-Côte-d'Azur whose exports increase twofold with an additional 600 kt.

Region name	Gap with the average bread consumption in France
Ile-de-France	-19%
Champagne-Ardenne	+10%
Picardie	+9%
Haute-Normandie	+9%
Centre (FR)	-1%
Basse-Normandie	+5%
Bourgogne	+1%
Nord - Pas-de-Calais	+5%
Lorraine	+11%
Alsace	-2%
Franche-Comte	+9%
Pays de la Loire	-1%
Bretagne	-2%
Poitou-Charentes	+9%
Aquitaine	+5%
Midi-Pyrenees	+5%
Limousin	+7%
Rhone-Alpes	-2%
Auvergne	+9%
Languedoc-Roussillon	+5%
Provence-Alpes-Cote-d'Azur	-12%
Corse	+9%

Table A.8: Bread consumption variability among French regions in the mid 1990's (Babayou et al., 1996), results partially reconstructed by the authors. Bread is by far the main form under which cereals are consumed in France, which means that a 20% difference with the national average, as in the case of the parisian region, can impact the cereals' MFA significantly.

Handling the correspondence between production and transport classifications

There exists no trade database at subnational scales that perfectly matches our products classification. Therefore, a few traded categories are more aggregated than our own categories. For instance the *wheat* category in the transport database includes both our *common wheat* and *durum wheat* categories. Table A.9 in this annex shows the full correspondence. Below we use the notation agg_k to refer to a group of aggregated goods (e.g. *wheat*).

After modification, the new objective function which is applied to subnational scales is the following:

$$\begin{aligned} \min \quad & \left(\sum_a \sum_i \sum_j \frac{(\hat{V}_{ij}^a - V_{ij}^a)^2}{(\sigma_{V_{ij}}^a)^2} + \sum_a \sum_i \sum_j \frac{(\hat{U}_{ij}^a - U_{ij}^a)^2}{(\sigma_{U_{ij}}^a)^2} \right. \\ & + \sum_a \sum_{i \notin agg_k \forall k} \frac{(\hat{I}_i^a - I_i^a)^2}{\sigma_{I_i^a}^2} + \sum_a \sum_k \frac{(\hat{I}_{agg_k}^a - I_{agg_k}^a)^2}{\sigma_{I_{agg_k}^a}^2} \\ & + \sum_a \sum_{i \notin agg_k \forall k} \frac{(\hat{E}_i^a - E_i^a)^2}{\sigma_{E_i^a}^2} + \sum_a \sum_k \frac{(\hat{E}_{agg_k}^a - E_{agg_k}^a)^2}{\sigma_{E_{agg_k}^a}^2} \\ & + \sum_a \sum_b \sum_{i \notin agg_k \forall k} \frac{(\hat{I}r_i^{a,b} - Ir_i^{a,b})^2}{\sigma_{Ir_i^{a,b}}^2} + \sum_a \sum_b \sum_k \frac{(\hat{I}r_{agg_k}^{a,b} - Ir_{agg_k}^{a,b})^2}{\sigma_{Ir_{agg_k}^{a,b}}^2} \\ & \left. + \sum_i \frac{(\hat{C}_i^a - C_i^a)^2}{\sigma_{C_i^a}^2} \right) \end{aligned}$$

with:

V_{ij}^a	supply of product i by industry j in region a ,
I_i^a, E_i^a	international imports/exports of product i to/from region a ,
$Ir_i^{a,b} = Er_i^{b,a}$	imports of product i to region a from region b equal exports of product i from region b to region a ,
$\hat{X}_{agg_k} = \sum_{i \in agg_k} \hat{X}_i^{\text{degen}}$	where X represents matrices \hat{I} , \hat{E} or $\hat{I}r$

The drawback here (as indicated by the *degen* superscript), is that this triggers degeneracy: there is an infinity of possible solutions for each \hat{X}_i^{degen} although each \hat{X}_{agg_k} is unique, and the result provided by the algorithm will depend on the solver's implementation and on the initialisation of variables. This is not satisfactory, even if the infinity of solutions is in practice bounded thanks to the constraints. We therefore conduct a second optimization that aims at obtaining a unique solution. A new rule (hypothesis) to make an allocation to each product belonging to an aggregate is needed. We choose to minimize the square values of imports and exports, while respecting the output of the first step, which leads to a balanced allocation inside each aggregated group.

The second optimization under constraint is therefore:

$$\min \left(\sum_a \sum_k \sum_{i \in agg_k} (\hat{I}_i^a)^2 + \sum_a \sum_k \sum_{i \in agg_k} (\hat{E}_i^a)^2 + \sum_a \sum_b \sum_k \sum_{i \in agg_k} (\hat{I}_i^{a,b})^2 \right)$$

subject to the following constraints:

All terms are positive:

$$\hat{X} \geq 0 \quad \text{where } X \text{ represents matrices } I, E \text{ or } Ir,$$

For each region, international imports of all products belonging to an aggregate equal the aggregated imports found in the first step of the optimization:

$$\sum_{i \in agg_k} \hat{I}_i^a = \hat{I}_{agg_k}^a \quad \forall a, \forall k$$

Same for international exports:

$$\sum_{i \in agg_k} \hat{E}_i^a = \hat{E}_{agg_k}^a \quad \forall a, \forall k$$

Same for inter-regional trade:

$$\sum_{i \in agg_k} \hat{I}_i^{a,b} = \hat{I}_{agg_k}^{a,b} \quad \forall a, \forall b, \forall k$$

Resource equals use constraint:

$$\begin{aligned} \hat{I}_i^a + \hat{I}_i^{a,b} - \hat{E}_i^a - \hat{I}_i^{b,a} &= \hat{I}_i^{a,degen} + \hat{I}_i^{a,b,degen} - \hat{E}_i^{a,degen} - \hat{I}_i^{b,a,degen} \\ &= \sum_j \hat{U}_{ij}^a + \hat{C}_i^a - \sum_j \hat{V}_{ij}^a \quad \forall a, \forall i \in agg_k, \forall k \end{aligned}$$

Geographical aggregation constraint for international trade:

$$\sum_a \hat{X}_i^a = \hat{X}_i^{fr} \quad \forall i \in agg_k, \forall k \quad \text{where } X \text{ represents vectors } I \text{ or } E.$$

We point out that this process is transparent when results are presented in aggregated forms, such as in figures 3.8, 3.9 and 3.10: everything appears as if only the first optimization had been done.

Product	NST code(s)	NST name(s)
Common wheat	011	Wheat, spelt and meslin
Durum wheat	011	Wheat, spelt and meslin
Maize	015	Maize
Barley	012	Barley
Other cereals	013 - 014 - 019	Rye - Oats - Other cereals
Flour	161	Flour, cereal meal and groats
Residues	179	Bran, cereal by-products and other animal food
Semolina	161	Flour, cereal meal and groats
Corn semolina	161	Flour, cereal meal and groats
Canned corn	NA	NA
Starch and glucose	895 - 136	Starches and gluten - Glucose, dextrose
Bread	163	Other cereal preparations
Biscuits	163	Other cereal preparations
Compound feed	179	Bran, cereal by-products and other animal food
Pasta and couscous	163	Other cereal preparations
Transformed rice	016	Rice
Malt	162	Malt
Beer	122	Beer made from malt
Bioethanol	NA	NA

Table A.9: Correspondence between the NST transport statistics classification (used in the SitraM database) and the product classification used the MFA study (left column). *NA* stands for *Not Applicable* and indicates that no suitable correspondence was found: for those products, the trade data was initially set to zero, before being modified during the data reconciliation process. This hypothesis is conservative in the sense that it minimizes the inter-regional trade of those flows (canned corn and bioethanol).

Regional MFA diagrams

We show below the diagrams corresponding to 5 of the 22 regional MFAs computed. They were chosen because they were representative of the variety of regional profiles.

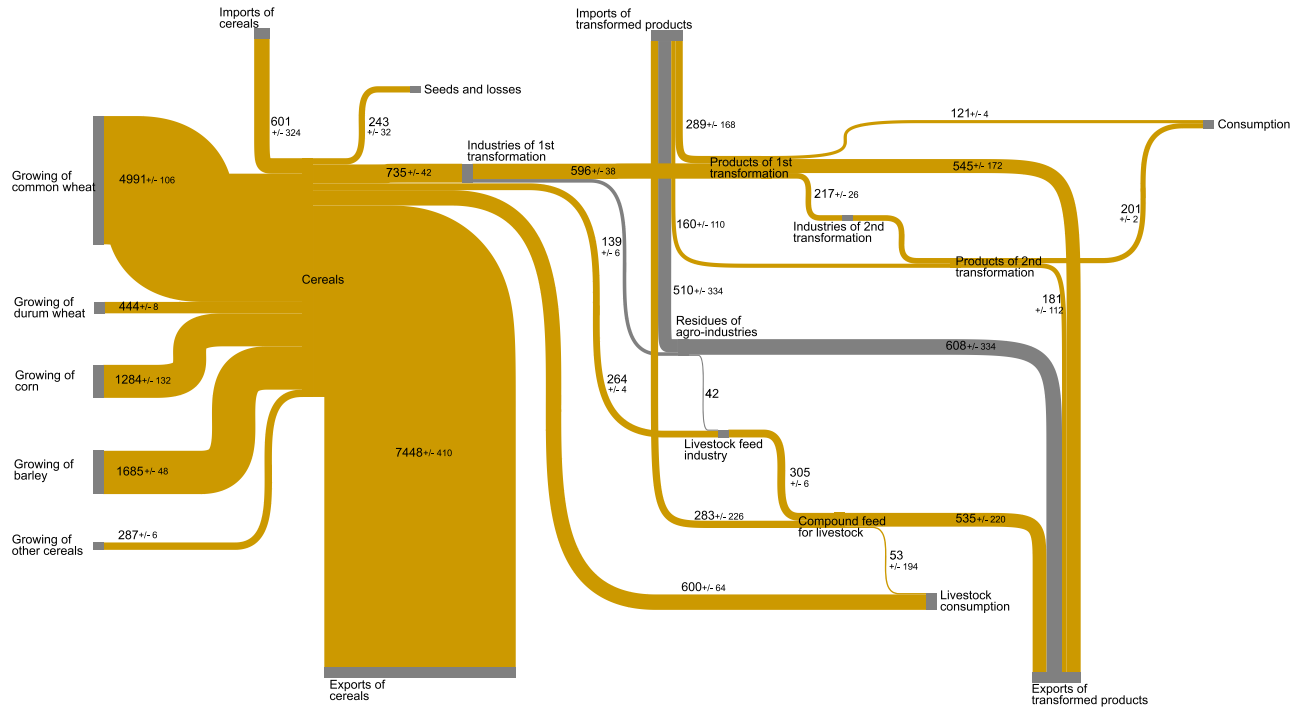


Figure A.2: Cereals MFA at the scale of Centre. Results are shown in kilotonnes for an average year over the period 2001-2009. Centre is the largest producer and exporter of cereals in the country.

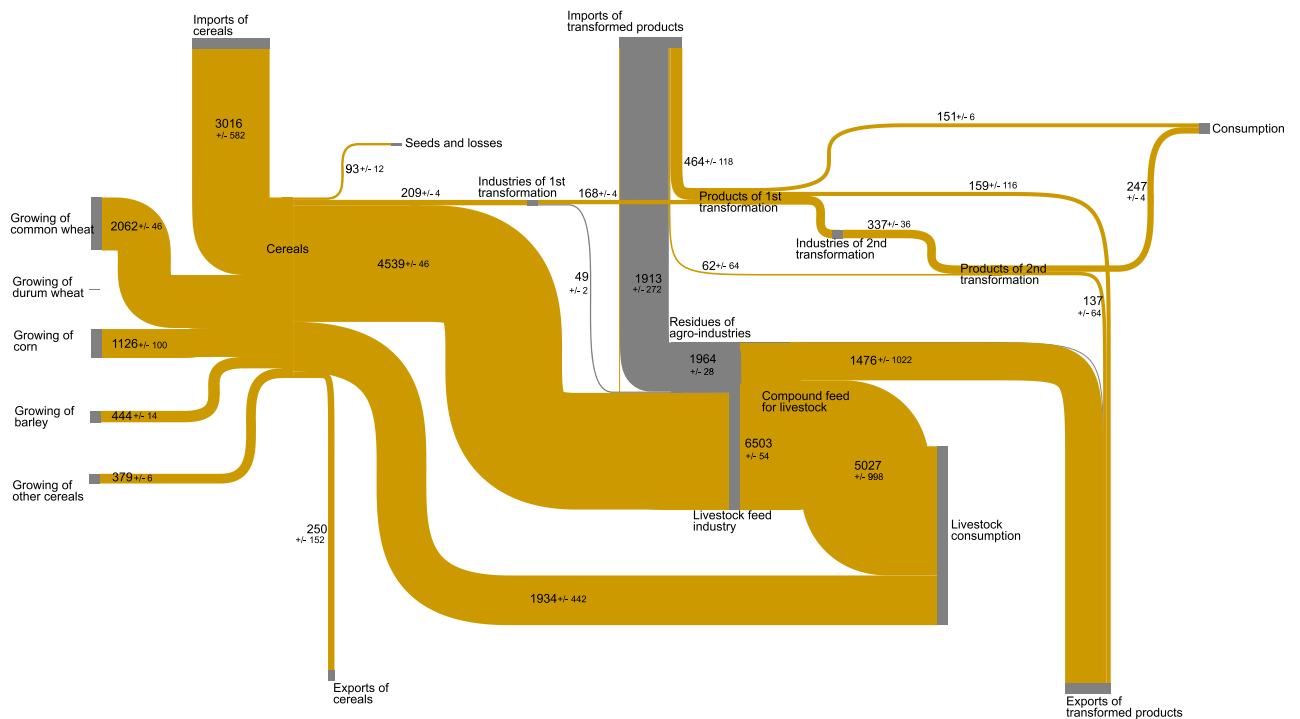


Figure A.3: Cereals MFA at the scale of Bretagne. Results are shown in kilotonnes for an average year over the period 2001-2009. In Bretagne most of the cereal supply is dedicated to livestock.

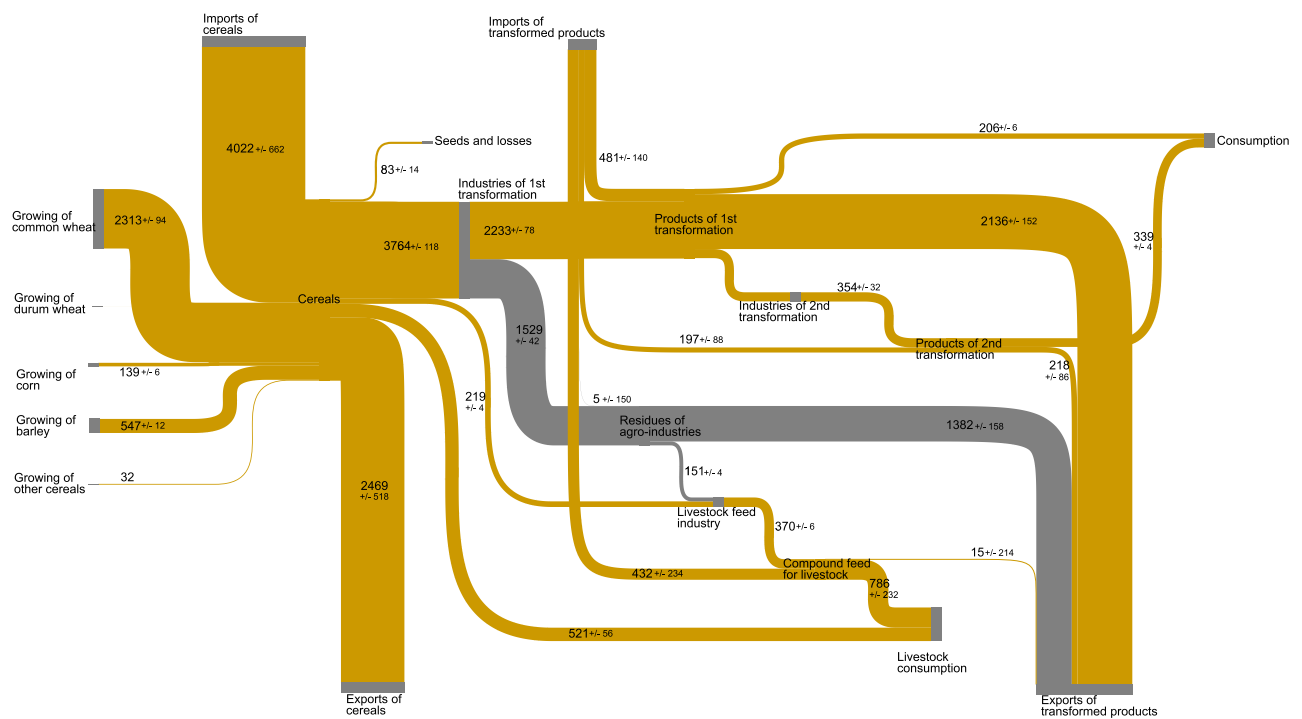


Figure A.4: Cereals MFA at the scale of Nord-Pas-de-Calais. Results are shown in kilotonnes for an average year over the period 2001-2009. Nord-Pas-de-Calais has a strong activity of international export and also has the largest transformation industry in the country.

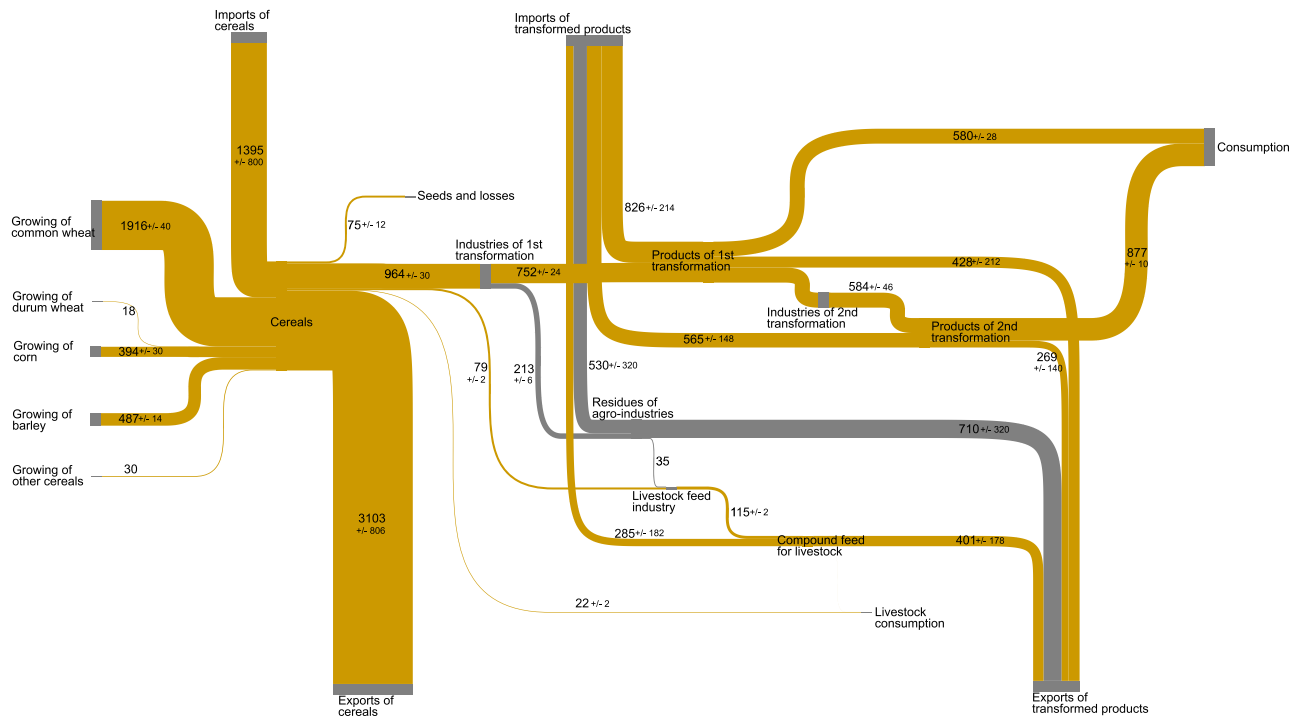


Figure A.5: Cereals MFA at the scale of Ile-de-France. Results are shown in kilotonnes for an average year over the period 2001-2009. The Parisian region exports a lot of cereals but also dedicates a large part of the supply to human consumption since it's the most populated area in the country.

Supplementary material to Chapter 4

The document is structured as follows:

- Section B.1 presents and explains the relevant material and results from survey sampling theory that are used in the main text. *NB: these ten pages have been written by Pierre-Yves Longaretti (co-author of the article and co-director of this thesis).*
- Section 2 is an illustration of data treatment that shows how combinations of aggregates are generated based on basic extrapolations,
- Sections 3 is an annex to the *theoretical results* section of the article, dedicated to model uncertainties for a single year based two other explanatory variables (the number of observations and the tonnes transported),
- Section 4 is also an annex to the *theoretical results* section of the article, but dedicated to the study of uncertainty reduction when averaging over several years: it explains how independent multi-year samples are built and illustrates the results on a dedicated plot.

B.1 Unequal probability survey sampling in a nutshell

The French road freight survey (TRM survey) is statistical in nature, and makes use of a specific unequal probability sampling method without replacement to estimate totals of interest, such as the total number of tonnes, kilometers travelled or tonnes-kilometers transported by road from any given origin to any given destinations and category of goods.

The TRM survey also makes use of constraints from auxiliary quantities of known totals to improve the desired total estimate, but this form of constraint is ignored here, as it provides only a modest correction to the variance in most cases and as its implementation requires information we do not have. However a simple correction for non-response is included.

The TRM survey only provides the error on the aggregated total (for all origins, destinations and categories) while we are interested in the error on the various disaggregated totals. The object of the present discussion is therefore to provide the reader with relevant results and explanations from survey sampling theory in order to perform an estimation of the errors of these various disaggregated totals. It is also intended to provide a minimal guideline to the relevant literature; as a consequence, literature citations are focused on the few books and articles most directly related to the problem at hand.

The following subsection is devoted to introducing important definitions and notations; some of these are already given in the main text, but reproduced here, sometimes in more detail, for

the reader's convenience. The next one will give relevant results for totals and their variances for samplings without replacement. The last one will provide a heuristic justification for the approximation we use in this work. All relations are demonstrated (unless otherwise stated) for the interested reader to get a feel of what these relations are about, and as the technical literature has a mathematical flavor that can be daunting for the non-mathematician.

B.1.1 Definitions and notations

One considers a population of N elements (here vehicles-weeks) denoted i ($1 \leq i \leq N$). Samples of fixed size S are drawn from this distribution. Typically in the problem at hand, $N \simeq 5 \times 10^5$ and $S \simeq 8 \times 10^4$, while the number of usable answers is $\simeq 5 \times 10^4$ (this last figure makes non-response — which includes all unusable answers — non negligible and a correction for this is generally applied).

Several quantities need to be defined to specify what is meant by unequal probability sampling without replacement.

Samples. Samples are designated by $s = (s_1, s_2, \dots, s_N)$ where s_i is the number of times a given element i is present in the sample. The set of all such samples is denoted F . A sample without replacement has $s_i = 0$ or 1, by definition (an element cannot be selected more than once). A sample with replacement has $0 \leq s_i \leq S$ where S is the size of the sample. Samples of fixed, predetermined size are the only ones of interest here; then, by construction, $\sum_{i=1}^N s_i = S$.

Sample design. The sample design is the probability distribution $p(s)$ defined on the set of samples F . As a consequence, both s_i and the inclusion indicators δ_i defined right below are probabilistic quantities¹. Note that in this form of probabilistic description, the elements of the populations are not random variables, as the elementary probabilistic event of interest is the selection of a whole sample, not the successive selections of elements of the population.

Inclusion indicator and inclusion probabilities. The inclusion indicators (or inclusion variables or Cornfield variables) δ_i are defined by $\delta_i = 0$ if $s_i = 0$ and $\delta_i = 1$ otherwise ($s_i \geq 1$), i.e., an inclusion indicator measures the presence of its associated element in the sample and ignores its possible repetitions.

The first-order inclusion probability π_i relates to element i and defines its probability of being present in the sample. By construction the probability of absence is $\bar{\pi}_i = 1 - \pi_i$. By definition of the sampling design and inclusion indicator:

$$\pi_i = \sum_{s \in F} p(s) \delta_i. \quad (\text{B.1})$$

Similarly, the probability that both i and j are present in the sample is the second-order probability $\pi_{ij} = \sum_s p(s) \delta_i \delta_j$. By definition, $\pi_{ii} = \pi_i$. For fixed-size and non-replacement sampling designs, $\sum_{i=1}^N \pi_i = n$, from Eq. (B.1).

Unequal probability sample designs. Unequal probability sampling designs are characterized by the fact π_i is not constant (not independent of i).

¹No distinction of notation is made here between a random variable and its associated realizations.

Characteristic quantity. This refers to any quantity of interest on the whole population, for example the quantity transported per year (tonnes) corresponding to specific criteria (loading and unloading locations, category of product transported). Quantities of interest are denoted y in a generic way. The most important quantity one tries to estimate through survey sampling is the sum total of y on the whole population

$$T = \sum_{i=1}^N y_i. \quad (\text{B.2})$$

In the probabilistic description adopted here, y_i is a parameter, not a random variable.

Subpopulation index and total. We are mostly interested in evaluating totals on well-defined subpopulations, identified by a given origin (o), destination (d) and category of goods (c) transported. These subpopulations are symbolically represented by an index δ_i^c , taking two values: $\delta_i^c = 1$ if i belongs to the desired $c = (o, d, c)$ subpopulation, and $\delta_i^c = 0$ otherwise.

It must be noted that the index δ_i^c is not a random variable. It is a fixed parameter allowing us to sort out the relevant elements in the total population or in a sample. In particular, we do not redraw a subsample of the considered sample within this category, we just post-select the relevant elements within the drawn sample.

The associated total is

$$T^c = \sum_{i \in c} y_i = \sum_{i=1}^N \delta_i^c y_i. \quad (\text{B.3})$$

Subsamples. The members of a subpopulation belonging to a given sample are called a subsample here, although they result from a post-selection process and not a second sampling stage. A subsample size is denoted n .

Sampling algorithms. A sample design is specified by its probability distribution $p(s)$ over the sample set F , and is constructed algorithmically. For the simple equal probability or replacement cases, the first and second order inclusion probabilities can be specified analytically.

In sampling designs without replacement, elements are not reinserted in the original population if selected in one of the successive steps of the sampling algorithm; on the contrary, a given element can be selected any number of times in a sampling design with replacement. Sampling designs without replacement are more complex to implement but their interest comes from the following theorem (see Tillé 2006, section 2.18): sampling designs with replacement are suboptimal in the sense that designs with smaller variance (i.e., more precise, an essential property) and identical first-order inclusion probabilities² can always be found.

Unequal probabilities are useful when the quantity of interest is not evenly distributed in the population. In particular, if one can find an auxiliary quantity X_i that is known to be (at least approximately) correlated to y_i , one can substantially improve the quality of the estimate of the total T at constant sample size S by designing the probability to be proportional to X . For the TRM survey, the first-order inclusion probabilities are proportional to the vehicle's age and payload, with a correction factor for some specific categories of vehicles. The specification

²Second-order inclusion probabilities are necessarily different.

of the first order inclusion probabilities is the first step in the algorithmic construction of a sample design. For more details, see section 2.10 of Tillé 2006.

There is an infinite number of sampling designs with given first-order inclusion probabilities, and sampling design algorithms are selected inasmuch as possible to have desirable properties for the second-order inclusion probabilities π_{ij} . Quite often indeed, the algorithmic evaluation of these quantities turns out to be unpractical for large samples, or to possess undesirable properties making the variance strongly unreliable or even negative. For example, the ordered systematic sampling design (Tillé 2006, section 7.1) is a widely used algorithm due to its simplicity (it is used in the TRM survey), but has the undesirable feature to produce a (large) number of vanishing second-order inclusion probabilities. As a result, the usual expression of the Horvitz-Thomson variance Eq. (B.5) below gives biased results and cannot be used, and an approximate expression must be found by other means.

Finding practical sampling algorithms with simple-to-evaluate and well-behaved π_{ij} or finding useful approximations of the variance based only on first-order inclusion probabilities for known algorithms is still an active area of research in this field (see, e.g., chapters 3 and 7 of Tillé 2006 for more details).

More complex sampling designs can be adopted besides unequal probability sampling without replacement, e.g. stratified or clustered sampling, but these methods will not be discussed here (see Cochran 1977 or Fuller 2009 for more details).

B.1.2 The Horvitz-Thomson estimator and its variance

B.1.2.1 Generic relations

The quantity of interest is the total of any characteristic quantity, Eq. (B.2). The best known and most used estimator is the Horvitz-Thomson one, defined by (Tillé 2006, section 2.17)

$$\hat{T} = \sum_{i \in s} \frac{y_i}{\pi_i} = \sum_{i=1}^N \delta_i \frac{Y_i}{\pi_i}. \quad (\text{B.4})$$

An estimator is unbiased if its expectation value is equal to the desired quantity. Eq. (B.4) shows that the expectation value of the HT estimator over the sample space is unbiased. Indeed, $E_s(\hat{T}) = \sum_s \hat{T} p(s) = T$, from Eq. (B.1), where $E_s(X)$ is the expectation of X over the sample probability distribution.

The variance $V_s(\hat{T})$ of the Horvitz-Thomson estimator follows from its definition, and a straightforward calculation gives:

$$V_s(\hat{T}) = \sum_{i=1}^N \sum_{j=1}^N \frac{y_i y_j}{\pi_i \pi_j} (\pi_{ij} - \pi_i \pi_j). \quad (\text{B.5})$$

In practice, one needs an estimator of this variance that can be evaluated on the sample at hand. As pointed out above, the main difficulty lies in the evaluation of the second-order inclusion probabilities π_{ij} . A common strategy to avoid the problem is to approximate the variance estimator with an expression involving only appropriate combinations of the first-order inclusion probabilities. One of the most simple approximate estimator of the variance

$\widehat{V}(\widehat{T})$ is given by (Tillé 2006, Eq. 7.20 with $S/(S - 1) \approx 1$ due to $S \gg 1$)

$$\widehat{V}(\widehat{T}) = \sum_{i \in s} c_i \left(\frac{y_i}{\pi_i} - \frac{\sum_{i \in s} c_i y_i / \pi_i}{\sum_{i \in s} c_i} \right)^2, \tag{B.6}$$

where

$$c_i = 1 - \pi_i. \tag{B.7}$$

A justification for this approximate variance estimator is given in section B.1.3.

B.1.2.2 Relations for subpopulations

The preceding considerations are straightforwardly transposed to any subpopulation. In particular, an unbiased estimator of the total in the subpopulation, Eq. (B.3), is given by

$$\widehat{T}^c = \sum_{i \in s} \delta_i^c \frac{y_i}{\pi_i} = \sum_{i=1}^N \delta_i^c \delta_i \frac{y_i}{\pi_i}. \tag{B.8}$$

One can check that $E_s(\widehat{T}^c) = T^c$; this follows from the fact that δ_c is not a sampling random variable, but simply a selection or post-selection one. However, the resulting estimator will be precise enough only if the inclusion probabilities are sufficiently correlated with the characteristic quantity in the subpopulation.

Similarly, an estimator of the variance of this quantity is provided by

$$\widehat{V}(\widehat{T}^c) = \sum_{i \in s} c_i \left(\delta_i^c \frac{y_i}{\pi_i} - \frac{\sum_{i \in s} c_i \delta_i^c y_i / \pi_i}{\sum_{i \in s} c_i} \right)^2, \tag{B.9}$$

where c_i is given in Eq. (B.7). This can be seen by a formal substitution of y_i with $y_i \delta_c$ in Eq. (B.6).

Neglecting the $n/(n - 1)$ factor of Eq. (7.20) of Tillé (2006) in Eq. (B.7) is not justified for very small subsample sizes n , but in such cases, the variance is large anyway, and the total estimator unreliable.

B.1.2.3 Rescaling

Weeks vs year The quantities of interest are, e.g., tonnes transported per year, or kilometers travelled per year. On the other hand, our population is made of vehicles-weeks, as the survey selects any vehicle for a single week in the year. As a consequence, Eqs. (B.4) and (B.8) do not give totals per year, but totals per week. On the other hand, the “week” in question is not any particular week of the year, as polls are conducted every single week. It is in effect some year average week total, inasmuch as the the sampling procedure is homogeneous throughout the year. As a consequence, Eqs. (B.4) and (B.8) should be multiplied by the number of weeks $N_w = 52$.

Because the Horvitz-Thomson is linear, this procedure is obviously equivalent to rescaling the quantities of interest y as

$$y'_i = N_w y_i. \tag{B.10}$$

The resulting Horvitz-Thomson estimators Eqs. (B.4) and (B.8) have the same formal expression after this substitution, so that the variance will also be the same except for the substitution

of y' to y in Eqs. (B.5), (B.6) and (B.9). Note however that this substitution does not imply that for any given truck, the total load transported in the year is N_w times what is transported in the poll week, due to seasonal variations; it just means that this is a reasonable extrapolation on average over all vehicles-weeks.

Nonresponse A similar correction is performed to account for nonresponse. Denoting S_{nr} the number of usable forms, nonresponse is taken into account by substituting a scaled first order inclusion probability to π_i : $\pi'_i = S\pi_i/S_{nr}$. A better correction is obtained by performing the same correction by category (origin, destination, product transported) except maybe for the categories with very small number of elements. The inclusion probabilities provided by the public organization (SOeS) in charge of the TRM database are already corrected for nonresponse in this way and the inclusion probabilities used in all formulae are in fact the primed ones, not the original ones, but we have not made the distinction in notation, for simplicity.

B.1.3 Elements of justification of the adopted estimator of the variance

It is possible to provide some justification of Eqs. (B.6), (B.7) and (B.9). This will be done in this section with the help of the following reasoning:

- First, an unequal probability sampling design without replacement is approximated by an unequal probability sampling design with replacement characterized by the same first-order inclusion probabilities. The usefulness of this approximation comes from the existence of analytic expressions for the total estimator and its variance in sampling designs with replacement.
- However, it is known that the resulting variance is not optimal (it is generically overestimated). This will be explicitly shown by taking the limit of a simple random sampling design (equal probability) where the sampling with and without replacement can be analytically compared.
- On can estimate the error introduced by the sampling design substitution procedure by computing the average number of occurrences of any element in a sample. This will allow us to estimate that on average, the number of elements that are multiply present in the equivalent design with replacement is about 1/3 the total size of the sample in the case of the TRM survey. This indicates that the overestimation of the variance is most probably not negligible, so that a tighter estimator would be a welcome improvement.
- A correction is applied through a generalization of the expression of the variance estimator, subject to the constraint that the correct variance must be formally recovered for a simple random sampling design without replacement. The corrected estimator is known to still overestimate the variance for the ordered systematic sampling design, though, so that we still err on the side of safety.

B.1.3.1 First step: approximating a sample design with replacement by a sample design without replacement

Let us define a sample design with replacement that has the same population (size N), same sample size S , and same first order inclusion probabilities π_i as the sample design without replacement of interest. The simplest such sampling design makes use of the probability p_i that element i has to be drawn in the S successive draws that constitute the sample. The probability p_i is directly related to the inclusion probability π_i from the probability of non inclusion in S successive draws $\bar{\pi}_i = (1 - \pi_i)^S$:

$$\pi_i = 1 - (1 - p_i)^S = Sp_i - \frac{(Sp_i)^2}{2} + \mathcal{O}(S^3 p_i^3). \quad (\text{B.11})$$

This relation can be inverted for future use:

$$Sp_i = \pi_i + \frac{\pi_i^2}{2} + \mathcal{O}(\pi_i^3). \quad (\text{B.12})$$

The totals of interest in the population can be estimated on the sample with the help of the Hansen-Hurwitz estimator (Tillé 2006, section 2.16)

$$\hat{T} = \frac{1}{S} \sum_{i \in s} \frac{y_i}{p_i}. \quad (\text{B.13})$$

This estimator is unbiased. To see this, consider first a single term in the sum: $x_i = y_i/Sp_i$; every term of this kind constitutes a realization of the random variable $X = Y/Sp(Y)$. Its expectation value on the population is

$$E(X) = \sum_{k=1}^N p_k \frac{y_k}{Sp_k} = \sum_{k=1}^N \frac{y_k}{S} = \frac{T}{S}. \quad (\text{B.14})$$

The variance of X is readily computed :

$$V(X) = \sum_{k=1}^N p_k \left(\frac{y_k}{Sp_k} - \frac{T}{S} \right)^2 = \frac{1}{S^2} \left[\left(\sum_{k=1}^N \frac{y_k^2}{p_k} \right) - T^2 \right] \quad (\text{B.15})$$

Now, \hat{T} is the sum of S identical random variables identical to X . The expectation value and variance of the estimator are therefore the sum of the expectation value and variance of X , leading to

$$E(\hat{T}) = SE(X) = T \quad (\text{B.16})$$

$$V(\hat{T}) = SV(X) = \frac{1}{S} \left[\left(\sum_{k=1}^N \frac{y_k^2}{p_k} \right) - T^2 \right]. \quad (\text{B.17})$$

Note that the expectation value and variance E and V are computed on the population, and not on the sample space, contrarily to E_s and V_s .

From Eq. (B.17), one obtains an unbiased estimator of the variance:

$$\hat{V}(\hat{T}) = \frac{1}{S(S-1)} \sum_{i \in s} \left(\frac{y_i}{p_i} - \hat{T} \right)^2. \quad (\text{B.18})$$

One can check that this estimator is unbiased from the following intermediate identity, which can be verified by direct calculus:

$$\widehat{V}(\widehat{T}) = \frac{1}{S(S-1)} \sum_{i \in s} \left(\frac{y_i}{p_i} - T \right)^2 - \frac{1}{S-1} (\widehat{T} - T)^2, \quad (\text{B.19})$$

from which one obtains:

$$E(\widehat{V}(\widehat{T})) = \frac{1}{S-1} S^2 V(X) - \frac{1}{S-1} V(\widehat{T}) = V(\widehat{T}). \quad (\text{B.20})$$

Note that as $\pi_i \simeq Sp_i$, the Hansen-Hurwitz estimator is closely related to the Horvitz-Thompson one:

$$\widehat{T} = \sum_{i \in s} \frac{y_i}{\pi_i}, \quad (\text{B.21})$$

Furthermore, for large enough S ,

$$\widehat{V}(\widehat{T}) \approx \sum_{i \in s} \left(\frac{y_i}{\pi_i} - \frac{\sum_{j \in s} y_j / \pi_j}{S} \right)^2 = \sum_{i \in s} \left(\frac{y_i}{\pi_i} - \left\langle \frac{y_i}{\pi_i} \right\rangle_s \right)^2, \quad (\text{B.22})$$

where $\langle \cdot \rangle_s$ is the mean observed on the sample. Note that this relation is of the generic form Eq. (B.6) with $c_i = 1$.

B.1.3.2 Interlude: simple random samplings with and without replacement

It is useful to see why Eq. (B.22) overestimates the variance of a sampling design without replacement. This is most easily seen by considering sampling designs with uniform probability (aka simple random sampling designs), for which all relevant relations can be derived analytically.

Let us examine first a uniform probability sampling design without replacement. In this case, and denoting $C_p^q = p!/q!(p-q)!$ the binomial coefficient,

$$\pi_i = \frac{C_{N-1}^{S-1}}{C_N^S} = \frac{S}{N} \equiv \tau, \quad (\text{B.23})$$

$$\pi_{ii}^{wor} = \pi_i, \quad (\text{B.24})$$

$$\pi_{ij}^{wor} = \frac{C_{N-2}^{S-2}}{C_N^S} = \frac{S(S-1)}{N(N-1)}, \quad (\text{B.25})$$

where the superscript *wor* refers to “without replacement”. Defining $\bar{y} = \sum_{i=1}^N y_i / N$ and $\sigma^2(y) = \sum_{i=1}^N (y_i - \bar{y})^2 / N$, Eq. (B.5) yields

$$V_s(\widehat{T}) = \frac{N^2}{S} \frac{1-\tau}{1-1/N} \sigma^2(y) \approx \frac{N^2}{S} (1-\tau) \sigma^2(y). \quad (\text{B.26})$$

Similarly, defining $\langle y \rangle = \sum_{i=1}^S y_i / S$ and $\tilde{\sigma}^2(y) = \sum_{i=1}^N (y_i - \langle y \rangle)^2 / N$, Eq. (B.22) gives

$$V_s(\widehat{V}(\widehat{T})) = \frac{N^2}{S} \tilde{\sigma}^2(y). \quad (\text{B.27})$$

For large enough samples, $\langle y \rangle \approx \bar{y}$ and $\tilde{\sigma}^2(y) \approx \sigma^2(y)$ so that the main difference between Eq. (B.26) and (B.27) is the $1 - \tau$ factor, known as the finite population correction factor. This denomination has a double justification: first, this coefficient becomes negligible as $N \rightarrow \infty$ at constant S , and second, as shown by Eq. (B.25), selecting one element in the population affects the second-order inclusion probability, which is then systematically larger in sampling designs with replacement. These arguments explain why Eq. (B.22) also overestimates the actual variance in generic unequal probability sampling designs without replacement (see, e.g., Tillé 2006, section 2.18 and Berger 1998).

B.1.3.3 Second step: estimating the need for a correction of the replacement sampling design variance estimator

It has just been pointed out above that a potentially important issue of sampling designs with replacement is that they often lead to overestimate the variance of the population totals; corrected variance expressions have been derived in the literature to compensate for this drawback. Before looking into this question, though, it is of some interest to estimate first if such a correction is necessary in the present case; indeed if the number of multiple draws of the same element in a sample is negligible on average, there would be little interest in performing the correction.

To this effect, one must evaluate the average number of multiple draws of any given element i of the population, from which one can in turn quantify the mean number of multiple draws in samples of size S . From our notations and definitions, s_i is the number of draws of element i in such a sample; let us further define $\langle s_i \rangle_s$, the sample average of s_i , $\langle s_i \rangle_s^{>1}$ the sample average number of multiple draws of i , and $\langle s_i \rangle_s^{\leq 1} = \langle s_i \rangle_s - \langle s_i \rangle_s^{>1}$.

Let us also define the probability $p_i(k)$ that i is drawn k times in a sample of size S ($0 \leq k \leq S$). This probability is obtained by direct counting and reads

$$p_i(k) = C_S^k p_i^k (1 - p_i)^{S-k}, \tag{B.28}$$

where C_S^k is the usual binomial coefficient. Defining $\omega_i = p_i/(1 - p_i)$, one has

$$\begin{aligned} \langle s_i \rangle_s &= \sum_{k=0}^S C_S^k k p_i^k (1 - p_i)^{S-k} = \frac{p_i}{(1 - p_i)^{S+1}} \frac{d}{d\omega_i} \left(\sum_{k=0}^S C_S^k \omega_i^k \right) \\ &= \frac{p_i}{(1 - p_i)^{S+1}} \frac{d(1 + \omega_i)^S}{d\omega_i} = \frac{S p_i}{(1 - p_i)^{2S}}. \end{aligned} \tag{B.29}$$

One also finds:

$$\langle s_i \rangle_s^{\leq 1} = S p_i (1 - p_i)^{S-1}, \tag{B.30}$$

so that

$$\langle s_i \rangle_s^{>1} = 3\pi_i^2 + \mathcal{O}(\pi_i^3), \tag{B.31}$$

where Eq. (B.12) has been used.

The quantity of interest here is the population average of $\langle s_i \rangle_s^{>1}$, $E(\langle s_i \rangle_s^{>1})$:

$$E(\langle s_i \rangle_s^{>1}) = 3 \sum_{i=1}^N p_i \pi_i^2 = \frac{3N}{S} \pi_i^3, \tag{B.32}$$

where $\overline{\pi_i^3}$ is the simple population average of π_i^3 (i.e., not weighted by the probability p_i).

Finally, defining by ΔS the mean (population and sample) average number of multiple draws, one has $\Delta S = SE(\langle s_i \rangle_s^{>1})$ so that $E(\langle s_i \rangle_s^{>1})$ is the relative number of multiple draws in a sample of size S . Note also that the same relation applies for a subpopulation N^c and a subsample n , *mutatis mutandis*.

A similar logic can be applied to evaluate the relative standard deviation of ΔS :

$$\frac{\sigma(\Delta S)}{\Delta S} = \frac{\left[\overline{\pi_i \left(\pi_i^2 - (N \overline{\pi_i^3} / S)^2 \right)^2} \right]^{1/2}}{N^{1/2} \overline{\pi_i^3}}. \quad (\text{B.33})$$

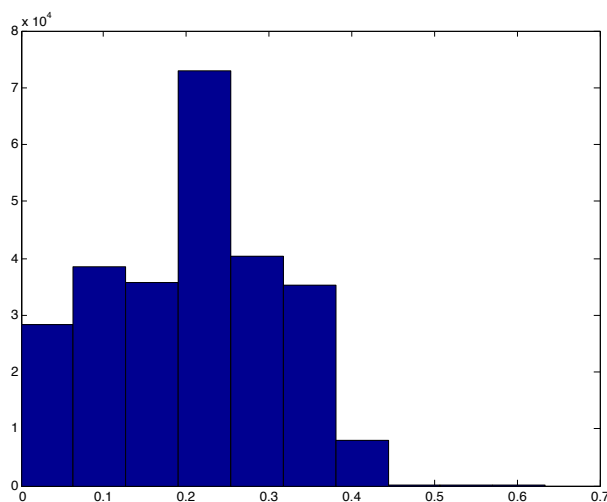


Figure B.1: Histogram of the distribution of the first-order inclusion probabilities π_i for the TRM survey.

For the TRM survey, the histogram of π_i is shown on Fig. B.1. One also has $N/S \simeq 6.76$ (in 2010), $\overline{\pi_i^3} = 0.016$, $E(\langle s_i \rangle_s^{>1}) \approx 1/3$ and $\sigma(\Delta S)/\Delta S \approx 10^{-4}$; i.e., 1/3 of the sample is made of multiple draws in a sampling design with replacement, on average, and with very little variation from sample to sample. This is not a dominant fraction, but it is clearly not negligible either. As a consequence, a correction to Eq. (B.22) is required to tighten the variance estimates.

B.1.3.4 Third step: correcting the variance

A corrected variance estimator can be obtained by generalizing Eq. (B.22) under the form given in Eq. (B.6); a constraint is applied to the parameters c_i to specify their expression. In the case at hand, the constraint adopted is that the variance for a uniform probability sampling design should be formally identical to the variance of the equivalent design without replacement, Eq. (B.26).

By construction, c_i can only depend on π_i : $c_i = g(\pi_i)$. For a simple random sampling design

discussed in section B.1.3.2, $g(\pi_i) = g(\tau)$ from Eq. (B.23), and Eq. (B.6) gives

$$V_s(\widehat{V}(\widehat{T})) = \frac{N^2}{S} g(\tau) \tilde{\sigma}^2(y). \tag{B.34}$$

Comparison with Eq. (B.26) shows that the finite population correction factor will be recovered for $c_i = 1 - \pi_i$, i.e., Eq. (B.7).

The form Eq. (B.22) of the generalized variance is theoretically justified when the sampling design without replacement is “close” to an entropy maximizing sampling design (see Tillé 2006, section 7.5, Tillé 2001, section 6.9 and Berger 1998). This is however not the case for the ordered systematic sampling design adopted in the TRM survey. In fact, it is known that Eqs. (B.6) and (B.7) still overestimates the variance (Berger, 2003) for this sampling design, because the design makes numerous second-order inclusion probabilities equal to zero, so that a non negligible number of legitimate samples is not incorporated in the sample population. Eq. (B.22), on the contrary, implicitly takes into account all possible samples, because the second-order inclusion probabilities can be expressed in terms of the first-order inclusion probabilities in replacement sampling designs³, and are never equal to zero.

B.2 Building all combinations of aggregates: an illustrative example

Figure B.3 shows it is possible to build 19 aggregates based on the three basic extrapolations from figure B.2. Of course, the number of combinations increases when we add new basic flows, levels of products, loading or unloading areas. In the dataset used for the article, about 2.1 million aggregates were built from about 900 thousand basic flows.

Product	Loading region	Unloading region	Tonnes	Subsample size (# trucks)
Wood	Lorraine	Alsace	30	4
Wood	Bourgogne	Alsace	5	2
Fruits	Alsace	Bourgogne	10	3

Figure B.2: Example of 3 basic flows extrapolated from a survey on 9 trucks.

³This expression is not derived here, as it does not provide useful information to further reduce the variance.

Product	Loading	Unloading	Tonnes	Subsample size
All	France	France	45	9
All	France	Alsace	35	6
All	France	Bourgogne	10	3
All	Lorraine	France	30	4
All	Bourgogne	France	5	2
All	Alsace	France	10	3
Wood	France	France	35	6
Fruits	France	France	10	3
All	Lorraine	Alsace	30	4
All	Bourgogne	Alsace	5	2
All	Alsace	Bourgogne	10	3
Wood	France	Alsace	35	6
Fruits	France	Bourgogne	10	3
Wood	Lorraine	France	30	4
Wood	Bourgogne	France	5	2
Fruits	Alsace	France	10	3
Wood	Lorraine	Alsace	30	4
Wood	Bourgogne	Alsace	5	2
Fruits	Alsace	Bourgogne	10	3

Figure B.3: All existing combinations of aggregates based on the 3 basic flows above. In this example, we only distinguish between 2 levels of products, loading and unloading areas.

B.3 Estimating uncertainties for a single year based on explanatory variables

B.3.1 Estimating uncertainties based on subsample sizes: details on the classes used

Subsample size (n)		Number of class members	Cumulative %
Lower bound (lb) n > lb	Lower bound (ub) n <= ub		
0	3	1452697	69%
3	5	179949	78%
5	10	182689	87%
10	25	151391	94%
25	50	63043	97%
50	100	33040	98%
100	250	20745	99.4%
250	500	6551	99.7%
500	1000	3508	99.9%
1000	2000	1749	99.96%
2000	3000	460	99.98%
3000	5000	307	99.99%
5000	7000	53	99.997%
7000	10000	55	99.999%
10000	25000	11	100%

Figure B.4: Number of class members in each class of defined by the size of the subsample. These 15 classes (rows) are used in the *theoretical results* section of the article to build an explicative model.

B.3.2 Estimating uncertainties based on the number of observations

By default, the French statistical office does not provide the size of the subsample on which each extrapolation is based. It provides instead the *number of observations* on which they are based (see glossary in the article). We use the same method as the one described in the article to propose an explicative model based on this variable:

- the sample is divided into 29 classes defined by an interval of number of observations,
- for each class, we compute the 5%, 50% (median) and 95% percentiles of uncertainty,
- we propose a model depicting the low, median, high uncertainty estimations depending on the number of observations.

Figure B.5 displays the calibrated models with their equations and table B.1 shows the lower, median an upper uncertainties for different number of observations.

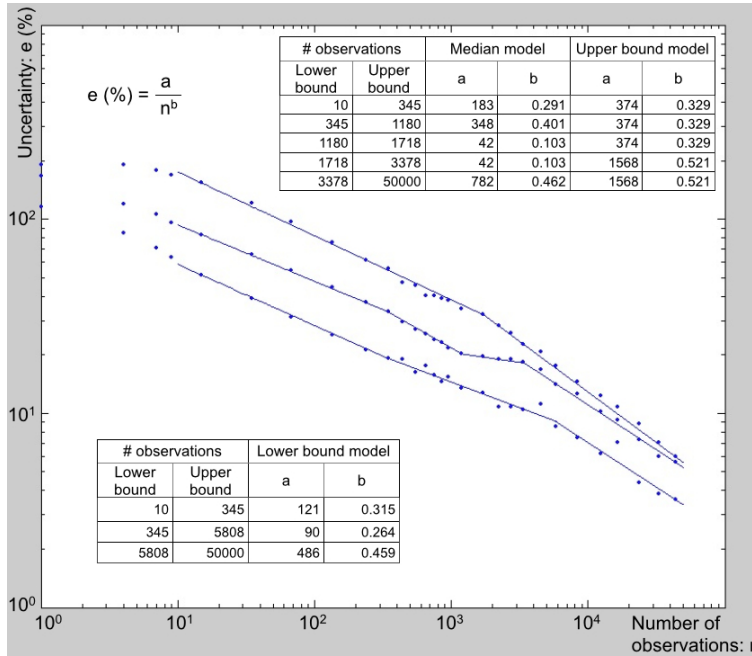


Figure B.5: Evolution of lower bound, median and upper bound uncertainties depending on the number of observations (NB: this is a log-log plot). Looking at the median model, it is striking that part of the slope is almost flat between about 1200 and 3400 observations. This does not occur when the explicative variable is the size of the subsample, which is one reason why the latter is a better predictor.

B.3. Estimating uncertainties for a single year based on explanatory variables 297

Number of observations	Uncertainty (%)		
	Lower bound	Median	Upper bound
10	59	94	176
20	47	77	140
50	35	59	104
100	28	48	82
200	23	39	66
500	17	29	49
1000	14	22	39
2000	12	19	30
5000	9	15	19
10000	7	11	13
20000	5	8	9
50000	3	5	6

Table B.1: Lower, median and upper uncertainties estimations for different number of observations, based on the models depicted in figure B.5. We see that below 50 observations, there is risk for the statistic not to be significant (above 100% of uncertainties), although it can be significant in some cases. Above 500 observations, there is a 95% chance that the uncertainty is lower than 50%, the median estimation being 29%.

The number of observation is a predictor of lower quality than the size of the subsample, generally resulting in a wider interval between lower and upper bounds for a given class. The R^2 of this model is 0.77 compared to 0.87 for the subsample size model. This should encourage the statistical office to publish the information on the sample size by default.

B.3.3 Estimating uncertainties based on the quantities (tonnes) estimated

The number of tonnes is in turn tested as explanatory variable for the uncertainty. Results are shown in figure B.6. the R^2 index of the median model is 0.63. We can conclude that the hypothesis *“the higher the quantity transported the smaller the uncertainty”* is only partially true. Other explanatory variables, such as the subsample size, should be preferred when it is possible.

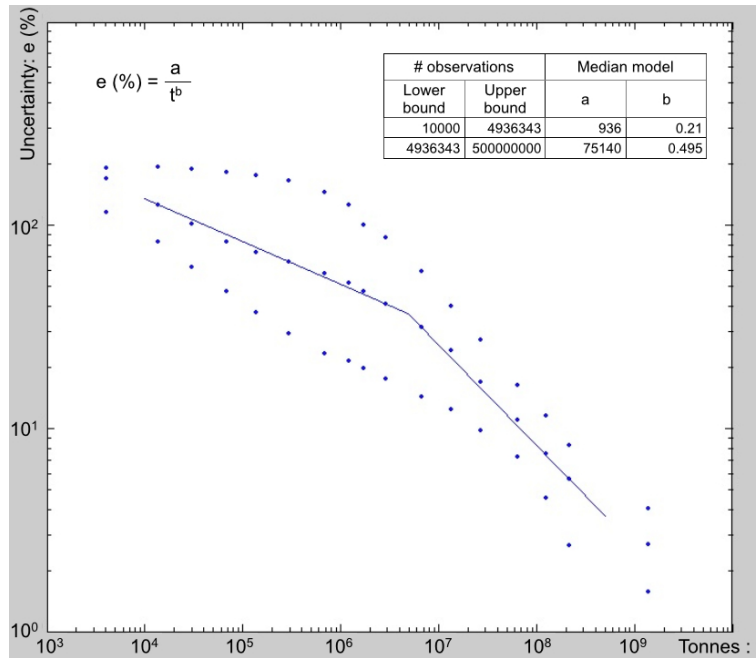


Figure B.6: Evolution of lower bound, median and upper bound uncertainties depending on the number of tonnes extrapolated (NB: this is a log-log plot).

B.4 Uncertainty reduction when averaging over several years

B.4.1 Building independent multi-year samples

In the survey, every year, half of the sample is renewed (half the trucks surveyed year i will also be surveyed year $i + 1$) as shown in table B.2. When averaging over n_y years, there are 2^{n_y-1} independent samples possible. Table B.3 shows 1 among the 16 possibilities for an average over 5 years⁴. Among the independent samples generated, we chose the ones of the largest size.

	Sample 2003	Sample 2004	Sample 2005	Sample 2006	Sample 2007
First half	Draw 2002	Draw 2004	Draw 2004	Draw 2006	Draw 2006
Second half	Draw 2003	Draw 2003	Draw 2005	Draw 2005	Draw 2007

Table B.2: Composition of the sample for each year of the survey: Vehicles belonging to the draw of year i are surveyed on years i and $i + 1$.

⁴Note that sample weights have to be re-calibrated in order to leave the total unchanged: for instance if we remove half of the population surveyed in a given year, we have to double the weights of the remaining half population.

	Sample 2003	Sample 2004	Sample 2005	Sample 2006	Sample 2007
First half	Draw 2002	Draw 2004	Draw 2004	Draw 2006	Draw 2006
Second half	Draw 2003	Draw 2003	Draw 2005	Draw 2005	Draw 2007

Table B.3: A possibility of independent sample for computing a year-average between years 2003 and 2007. White cells are kept, grey cells are removed from the sample. In total, 16 combinations are possible. Note that, if a one-year sample is composed of p individuals, the complete sample would be composed of $n_y p$ individuals while every independent sample is only composed of $p + (n_y - 1)p/2$ individuals.

B.4.2 Results

Results of averaging over the years 2005-2007 (3-year average) are shown in figure B.7. The slope of the model is 0.71 indicating an average reduction of uncertainty of 29%.

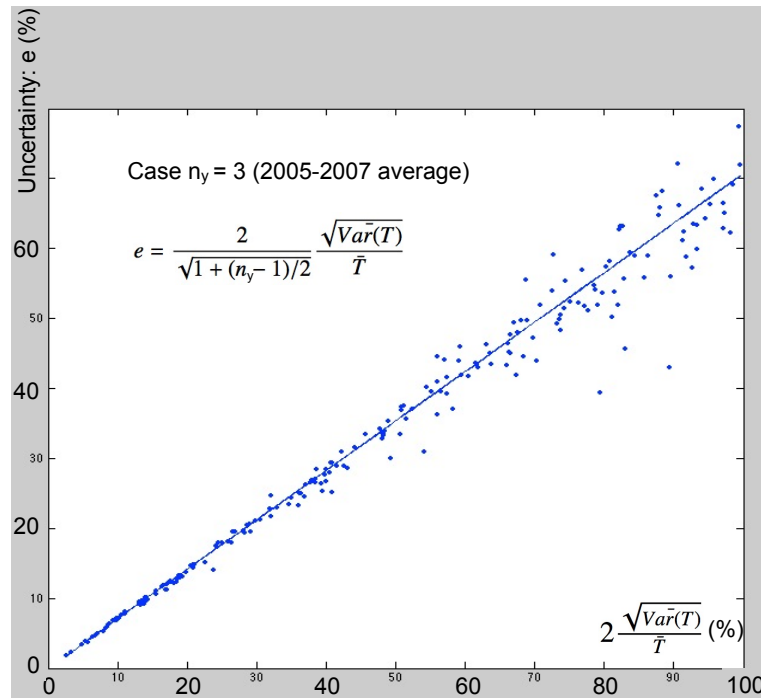


Figure B.7: Uncertainties of a 3-year average (2005-2007) depending on $2\sqrt{\tilde{V}(T)}/\bar{T}$, with $\tilde{V}(T) = 1/3 \times (V(T_{2005}) + V(T_{2006}) + V(T_{2007}))$ and $\bar{T} = 1/3 \times (T_{2005} + T_{2006} + T_{2007})$. The line corresponding to the model proposed is plotted in blue. The R^2 index of the model is 0.97. About 200 data points are sampled over the 31000 datapoints of the (independent 3-year) sample in order to make the graph readable.

Supplementary material to Chapter 6

Excel spreadsheets with additional information are available on the journal's website (look for Supporting Information on this page: <http://onlinelibrary.wiley.com/doi/10.1111/jiec.12431/abstract>).

Classifications used

Industries	Products	Regions	Modes of transport	Environmental pressures
Growing of common wheat	Common wheat	Ile-de-France (FR)	Sea	Energy use
Growing of durum wheat	Durum wheat	Champagne-Ardenne (FR)	Road	Greenhouse gases emissions
Growing of corn	Corn	Picardie (FR)	Rail	Land use
Growing of barley	Barley	Haute-Normandie (FR)	River	Pesticides use
Growing of other cereals	Other cereals	Centre (FR)		Blue water footprint
Mills	Flour	Basse-Normandie (FR)		
	Residues of agro-industries	Bourgogne (FR)		
Semolina production	Semolina	Nord-Pas-de-Calais (FR)		
Cornmeal production	Cornmeal	Lorraine (FR)		
Canned corn production	Canned corn	Alsace (FR)		
Starch factory	Starch and glucose	Franche-Comte (FR)		
Industrial bakery	Bread	Pays-de-la-Loire (FR)		
Craft bakery				
Hypermarket				
Production of biscuits	Biscuits	Bretagne (FR)		
Production of compound feed	Compound feed for livestock	Poitou-Charentes (FR)		
Production of pasta and couscous	Pasta and couscous	Aquitaine (FR)		
Rice transformation	Transformed rice	Midi-Pyrénées (FR)		
Production of malt	Malt	Limousin (FR)		
Production of beer	Beer	Rhône-Alpes (FR)		
Bioethanol factory	Bioethanol	Auvergne (FR)		
Animal farming	Meat and meat products	Languedoc-Roussillon (FR)		
	Milk and milk products	Provence-Alpes-Côte-d'Azur (FR)		
	Eggs	Corse (FR)		
		The Netherlands		
		Belgium		
		Italy		
		Spain		
		Germany		
		Algeria		
		United Kingdom		
		Portugal		
		Morocco		
		Egypt		
		Europe (other)		
		Africa (other)		
		Asia		
		Latin America		
		North America		
		Oceania		

Table C.1: Industries, products, regions, transport modes and environmental pressures implemented in the model.

Pressure ratios used

Transport mode	Energy (kWh / kt.km)	GHG (kg CO2 eq. / kt.km)
Sea	76.7	21.7
Road	780.8	213.2
Rail	17.8	3.7
River	119.8	33.9

Use of pesticides: kg of active substance per hectare	Common wheat	Durum wheat	Corn	Barley	Others (Triticale)
ILE-DE-FRANCE	3.0	1.2	1.9	2.4	1.2
CHAMPAGNE-ARDENNE	2.6	1.2	1.6	2.0	1.5
PICARDIE	2.6	1.2	1.8	2.2	1.2
HAUTE-NORMANDIE	2.4	1.2	2.1	2.6	1.2
CENTRE	1.8	1.6	2.3	2.2	1.3
BASSE-NORMANDIE	2.2	1.2	1.9	2.2	1.6
BOURGOGNE	1.8	1.2	2.1	2.2	1.1
NORD-PAS-DE-CALAIS	2.5	1.2	1.8	2.4	1.2
LORRAINE	1.7	1.2	2.2	1.9	1.3
ALSACE	1.2	1.2	2.9	2.1	1.2
FRANCHE-COMTE	2.2	1.2	2.4	2.8	1.3
PAYS DE LA LOIRE	1.7	1.2	2.3	1.8	1.6
BRETAGNE	1.9	1.2	1.5	1.8	2.1
POITOU-CHARENTES	1.3	1.4	2.4	1.8	1.1
AQUITAINE	1.2	1.2	1.9	2.1	0.6
MIDI-PYRENEES	1.2	1.2	2.2	1.1	0.8
LIMOUSIN	2.0	1.2	2.1	2.1	0.8
RHONE-ALPES	1.2	0.8	2.3	2.1	1.0
AUVERGNE	1.1	1.2	3.0	1.8	0.8
LANGUEDOC-ROUSSILLON	2.0	0.9	2.1	2.1	0.0
PROVENCE-ALPES-COTE-D'AZUR	2.0	0.4	2.1	2.1	1.2
CORSE	2.0	1.2	2.1	2.1	1.2

Algorithm for Structural Path Analysis

Here, we show an algorithm for the structural decomposition of the term B_{ij} , i^{th} row and j^{th} column of matrix B ¹.

Since $B = NR$:

$$B_{ij} = \sum_k N_{ik} R_{kj}$$

Given the structure of matrix R , in each column of R , only one term can be non-zero. Indeed, a column represents the final consumption of specific product in a specific region so the potentially non-zero row corresponds to the same product-region, but expressed in the index numbering of matrix Q ². Let $index()$ be the function that takes a column index of matrix R and returns

¹This procedure can then be easily adapted in order to decompose an entire row or column of matrices B , $\hat{Z}B$, L .

²This simply means that in order for a product to be consumed in a region, it must be first available in this region.

the corresponding row index of matrix Q^3 . Then:

$$R_{kj} = 0 \quad \forall k \neq \text{index}(j) = j_0$$

Hence:

$$B_{ij} = N_{ij_0} R_{j_0j}$$

Following the Taylor decomposition of matrix $N = (I - Q)^{-1}$:

$$B_{ij} = (\delta_{ij_0} + Q_{ij_0} + \sum_k Q_{ik} Q_{kj_0} + \sum_k \sum_l Q_{ik} Q_{kl} Q_{lj_0} + \dots) R_{j_0j}$$

The following table shows the different types of paths and the count of each type (we note n the number of rows (or columns) of matrix Q).

Depth of the paths	Form of the paths	Count
0	$\delta_{ij_0} R_{j_0j}$	1
1	$Q_{ij_0} R_{j_0j}$	1
2	$Q_{ik} Q_{kj_0} R_{j_0j}$	n
3	$Q_{ik} Q_{kl} Q_{lj_0} R_{j_0j}$	n^2
...

In order to decompose the term B_{ij} , using the notation $\text{index}(j) = j_0$ as defined above, we can use the following algorithm:

a. We define the followings variables:

- "threshold" as a cut-off value entered by the user
- "paths" as the list of paths that have a value greater than the threshold
- "path" as the list of visited nodes in the path being explored
- "row" as the last node visited in the path being explored
- "value" as the current value of the path being explored

We initialise the exploration by setting the variables to: value = 1, row = i, path = [i].

b. For each column k of Q , we test if value * $Q(\text{row}, k) > \text{threshold}$. If true, we do c. and e.

c. We test if $k = j_0$ and value * $Q(\text{row}, j_0) * R(j_0, j) > \text{threshold}$. If true, we do d.

d. We add the path [path, j_0, j] and its value, value * $Q(\text{row}, j_0) * R(j_0, j)$ to the list of paths.

e. We repeat the procedure from step b. with updated variables: value = value * $Q(\text{row}, k)$, row = k , path = [path, k].

f. We order the paths found by decreasing value.

³ Q being a square matrix, its row and column indexes are the same.

Supplementary material to Chapter 7

The *Wood fiber* unit

Definitions and abbreviations

M : mass,
V : volume,
p : product,
w : water,
o : other components,
 τ : moisture rate,

$$\tau = \frac{M_p - M_{\tau=0\%}}{M_{\tau=0\%}} = \frac{M_w}{M_{\tau=0\%}}$$

$\tau_{saturation} \approx 30\%$. Water can be present in wood in two forms: *water in wood fibers* and *free water*. Free water appears above the saturation point and has no impact on the volume. Below the saturation point, wood fibers start to lose water and the volume decreases.

wf : wood fiber at the saturation point

The product is made of a single wood specie and no other components

$$\begin{aligned}
 M_{wf} &= M_p + M_w \text{ (evaporated)} \\
 &= M_{\tau=0\%} + M_w \text{ (product)} + M_w \text{ (evaporated)} \\
 &= M_{\tau=0\%} + M_w \text{ (saturation)} \\
 &= M_{\tau=0\%} + M_{\tau=0\%} \tau_{saturation} \\
 &= M_{\tau=0\%} (1 + \tau_{saturation}) \\
 &= M_p \frac{1 + \tau_{saturation}}{1 + \tau_p}
 \end{aligned}$$

then

$$V_{wf} = \frac{M_{wf}}{\mu_{saturation}} = \frac{M_p}{\mu_{saturation}} \frac{1 + \tau_{saturation}}{1 + \tau_p}$$

Note that if $\tau_p = \tau_{saturation}$ (which is the default assumption when no other information is available), then $V_{wf} = V_p$. In the model, this is for instance the case for the production of sawnwood.

Furthermore, given a coefficient of retraction $f(\tau_p)$, defined by $V_p = f(\tau_p)V_{wf}$, we have:

$$\mu_{saturation} = \mu_p f(\tau_p) \frac{1 + \tau_{saturation}}{1 + \tau_p}$$

and:

$$V_{wf} = \frac{M_p}{\mu_p f(\tau_p)}$$

The product is made of a single wood specie and other components

$$M_{wf} = M_p + M_w \text{ (evaporated)} - \sum_i M_{o_i}$$

Then:

$$V_{wf} = \frac{1}{\mu_{saturation}} \left(M_p \frac{1 + \tau_{saturation}}{1 + \tau_p} - \sum_i M_{o_i} \right)$$

The product is made of different wood species and other components

Let α_i be the fraction of wood specie i in the product mix. We have:

$$V_{wf} = \sum_i \frac{\alpha_i}{\mu_{saturation \ i}} \left(M_p \frac{1 + \tau_{saturation}}{1 + \tau_p} - \sum_j M_{o_j} \right)$$

Conversion factors used

Product	Original unit	Conversion factor ($m^3(f)$ / original unit)
Standing timber	m^3	1
Lumber	m^3	1
Roundwood (imported or exported)	Tonnes	softwood: 1.05, hardwood: 1.12, hypothesis: greenwood density
Pulpwood	m^3	1
Fire wood	m^3	1
Forest wood chips	m^3	1
Ties	m^3	1
Staves	m^3	1
Sawnwood	m^3	1
Sawnwood (imported or exported)	Tonnes	softwood: 1.36, hardwood: 1.75, hypothesis: 15% moisture
Sawmill residues	Tonnes	1.1
Sawmill woodchips	Tonnes	1.1
Veneer	m^3	1
Particle board*	m^3	1.25
Fibreboard*	m^3	1.47
MDF board*	m^3	1.39
Plywood*	m^3	0.96
Wood floor	m^2	0.015
Pallets and wood packaging	Tonnes	1.1
Mechanical paper pulp*	Tonnes	2.22
Chemical paper pulp*	Tonnes	2.13
Old papers*	Tonnes	1.54
Paper, cardboards*	Tonnes	1.54
Wood wastes	Tonnes	1.1

Table D.1: Conversion factors (to wood fiber equivalent ($m^3(f)$)) used in the study. Products marked with a * are taken from Weimar (2011), the others are provided by the authors.

	fw	hsw	ssw	pw	panels	pulp
HRW		2.18		1.34		
SRW			2.02	1.34		
IW	1				1	1.67

Table D.2: Input-output coefficients used in the Leontief function of FFSM, calibrated using MFA results. These coefficients represent the quantity of raw products (HRW, SRW, IW) required to produce one unit of transformed product (fw, hsw, ssw, pw, panels, pulp). Some industries are assumed to produce no waste residues (fw, panels) according to MFA. Plywood is assumed to be made of either HRW or SRW.

FFSM Calibration coefficients

Equations of the Material flow analysis

This formalism was already presented in Courtonne et al. (2015). The optimization function has however been adapted for the present study as we explain below.

Table D.3: Supply table and matrices notations.

	industry 1 .. industry m	imports
product 1 .. product n	V_{ij} (n,m)	I_i (n,1)

Table D.4: Use table and matrices notations.

	industry 1 .. industry m	exports	consumption
product 1 .. product n	U_{ij} (n,m)	E_i (n,1)	C_i (n,1)

As shown above, the supply table comprises the supply matrix V and the imports vector I whereas the use table comprises the use matrix U , the exports vector E and the (final) consumption vector C . For instance U_{ij} refers to the quantity of product i that is used by sector j and C_i refers to the quantity of product i that is consumed by end-users on the territory. These tables are subject to constraints (we use hats above letters to refer to data resulting from the reconciliation process, original data are represented without a hat):

- *Constraint 1*: mass conservation of each product (note that stocks are neglected because we are working on a three-years average):

$$\sum_j \hat{V}_{ij} + \hat{I}_i = \sum_j \hat{U}_{ij} + \hat{E}_i + \hat{C}_i \quad i = 1..n \quad (\text{D.1})$$

- *Constraint 2*: mass conservation in every transforming industry:

$$\sum_i \hat{V}_{ij} = \sum_i \hat{U}_{ij} \quad j = 1..m \quad \text{and } j \text{ is a transforming sector} \quad (\text{D.2})$$

- *Constraint 3*: Technical conversion factors between products (e.g. rate of sawmill residues),
- *Constraint 4*: All flows have positive values,
- *Constraint 5*: Matrices \hat{V} and \hat{U} are sparse (mostly empty), for instance the wood panel industry cannot produce nor consume sawnwood.

Our goal is to minimize the discrepancy between original data and estimated/output data while respecting the constraints. This problem can be expressed in many ways depending on the expression of the distance between original and final data. We first used a classic weighted least square optimization:

$$\begin{aligned} \min \quad & \left(\sum_i \sum_j \frac{(\hat{V}_{ij} - V_{ij})^2}{\sigma_{V_{ij}}^2} + \sum_i \sum_j \frac{(\hat{U}_{ij} - U_{ij})^2}{\sigma_{U_{ij}}^2} + \sum_i \frac{(\hat{I}_i - I_i)^2}{\sigma_{I_i}^2} + \sum_i \frac{(\hat{E}_i - E_i)^2}{\sigma_{E_i}^2} \right. \\ & \left. + \sum_i \frac{(\hat{C}_i - C_i)^2}{\sigma_{C_i}^2} \right) \\ \text{subject to the set of constraints 1 to 5} \end{aligned} \quad (\text{D.3})$$

In equation D.3, σ refers to the standard deviation of the data. They make it possible to treat data sources differently depending on the assumed (or possibly measured, or constrained) uncertainties. We however changed the distance used for minimization we because we found weighted least squares could lead to extreme allocations in specific cases. The minimization implemented is the following:

$$\begin{aligned} \min \quad & \left(\sum_i \sum_j \frac{(\hat{V}_{ij} - V_{ij})^2}{\sigma_{V_{ij}}} + \sum_i \sum_j \frac{(\hat{U}_{ij} - U_{ij})^2}{\sigma_{U_{ij}}} + \sum_i \frac{(\hat{I}_i - I_i)^2}{\sigma_{I_i}} + \sum_i \frac{(\hat{E}_i - E_i)^2}{\sigma_{E_i}} \right. \\ & \left. + \sum_i \frac{(\hat{C}_i - C_i)^2}{\sigma_{C_i}} \right) \\ \text{subject to the set of constraints 1 to 5} \end{aligned} \quad (\text{D.4})$$

We divide each term by σ instead of dividing it by σ^2 . We consider this distance a good balance between penalizing *absolute* and *relative* differences. Testing the impact of different plausible distances on results is part of our next research leads.

Supply and Use Tables before and after the data reconciliation process

Comparing material and monetary flows in the lumber chain

Supply	Production	Stock	Marché	Exploitation	Scierie f	Scierie s	Merranderie	Usine de	Usine de	Usine de	Proquettier	Usine de abats	Repartier	Usine	Chaudières	Chaudière	Consommatio	Cons finale	Import	Total
1 Bois sur pied	132228	382																	142	132610
2 BO Feuillus	NULL	NULL	NULL	5139	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	475	15594
3 BO Résineux	NULL	NULL	NULL	15118	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	49	4128
4 BF Feuillus	NULL	NULL	NULL	4079	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	224	7797
5 BF Résineux	NULL	NULL	NULL	7572	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	20	500
6 Autre BF	NULL	NULL	NULL	480	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	62	4071
7 Bois blanc	NULL	NULL	NULL	4009	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	62	4071
8 Plaquettes forestières	NULL	NULL	NULL	1273	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	1273	1273
9 Mélange d'exploitation	NULL	NULL	NULL	15095	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	16095	16095
10 Travers	NULL	NULL	NULL	NULL	307	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	0	175
11 Scierie résineux F1	NULL	NULL	NULL	NULL	1318	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	117	63
12 Scierie résineux F2	NULL	NULL	NULL	NULL	1318	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	117	63
13 Scierie résineux F3	NULL	NULL	NULL	NULL	1318	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	117	63
14 PC3	NULL	NULL	NULL	1062	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	518	9227
15 Plaquettes de sciure	NULL	NULL	NULL	520	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	339	1275
16 Plaquets	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	33	92
17 Paveaux particules & OS3	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	2022	8167
18 Centre-plaque	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	285	594
19 Paquet	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	64	113
20 Paquet et embisilage	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	448	3832
21 Pâte à papier	NULL	NULL	NULL	1273	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	4482	8396
22 Vieux Papiers	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	1231	1231
23 Papiers et carton	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	8209	21202
24 Papiers plats à papier	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	2786	2786
25 Papiers plats à papier	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	0	0
26 Energie	132228	382	0	53764	3029	13391	63	6166	59	308	49	6209	12964	3385	5050	34200	0	0	2115	39250
Total	0	62403	12945	0	3354	14748	63	5655	59	469	0	6752	7796	3935	1349	6000	71	0	22728	0
1 Bois sur pied	NULL	62403	12945	0	3354	14748	63	5655	59	469	0	6752	7796	3935	1349	6000	71	0	22728	0
2 BO Feuillus	NULL	NULL	NULL	NULL	3564	14748	NULL	NULL	27	152	NULL	NULL	NULL	780	NULL	NULL	NULL	NULL	1178	75448
3 BO Résineux	NULL	NULL	NULL	NULL	14748	NULL	NULL	32	224	NULL	NULL	NULL	NULL	780	NULL	NULL	NULL	NULL	5773	15077
4 BF Feuillus	NULL	NULL	NULL	NULL	791	NULL	NULL	NULL	NULL	1127	NULL	NULL	NULL	480	NULL	NULL	NULL	NULL	1095	16073
5 BF Résineux	NULL	NULL	NULL	NULL	2184	NULL	NULL	NULL	NULL	3175	NULL	NULL	NULL	480	NULL	NULL	NULL	NULL	472	2389
6 Autre BF	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	480	NULL	NULL	NULL	1075	6434	
7 Bois blanc	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	480	NULL	NULL	NULL	NULL	19	553
8 Plaquettes forestières	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	480	NULL	NULL	NULL	NULL	623	6623
9 Mélange d'exploitation	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	480	NULL	NULL	NULL	NULL	472	2389
10 Travers	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	480	NULL	NULL	NULL	NULL	93	93
11 Scierie résineux F1	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	480	NULL	NULL	NULL	NULL	0	0
12 Scierie résineux F2	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	480	NULL	NULL	NULL	NULL	0	0
13 Scierie résineux F3	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	480	NULL	NULL	NULL	NULL	0	0
14 PC3	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	480	NULL	NULL	NULL	NULL	0	0
15 Plaquettes de sciure	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	480	NULL	NULL	NULL	NULL	0	0
16 Plaquets	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	480	NULL	NULL	NULL	NULL	0	0
17 Paveaux particules & OS3	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	480	NULL	NULL	NULL	NULL	0	0
18 Centre-plaque	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	480	NULL	NULL	NULL	NULL	0	0
19 Paquet	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	480	NULL	NULL	NULL	NULL	0	0
20 Paquet et embisilage	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	480	NULL	NULL	NULL	NULL	0	0
21 Pâte à papier	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	480	NULL	NULL	NULL	NULL	0	0
22 Vieux Papiers	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	480	NULL	NULL	NULL	NULL	0	0
23 Papiers et carton	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	480	NULL	NULL	NULL	NULL	0	0
24 Papiers plats à papier	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	480	NULL	NULL	NULL	NULL	0	0
25 Papiers plats à papier	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	480	NULL	NULL	NULL	NULL	0	0
26 Energie	132228	382	0	53764	3029	13391	63	5655	59	469	0	6752	7796	3935	1349	6000	71	0	22728	0

Figure D.1: Input SUT for the wood MFA (France, expressed in 1000 m³(F).)

Supply	Production	Stock	Montant	Exploitation	Scierie F	Scierie R	Merranderie	Ulme de	Ulme de	Ulme de	Parquetterie	Ulme de sâbe	Papeterie	Ulme	Chaudières	Chauffage	Consummatio	Cosa finale	Import	Total
1 Bois sur pied	134610	389	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	134999
2 BO feuillus	0	0	0	5043	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5193
3 BO résineux	0	0	0	14680	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15172
4 BF feuillus	0	0	0	3712	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3760
5 BF résineux	0	0	0	6892	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7111
6 Autre BI	0	0	0	463	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	483
7 Bois bléche	0	0	0	4533	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4601
8 Plaquettes forestières	0	0	0	1273	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1273
9 Résidu d'exploitation	0	0	0	16095	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	16095
10 Travers	0	0	0	135	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	180
11 Merrain	0	0	0	1567	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	60
12 Scieries, anivés Fs	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	112
13 Scieries, anivés Rk	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	942
14 PCS	0	0	0	1277	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	114
15 Plaquettes de sciéie	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6217
16 Placages	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2995
17 Panneaux particules & OSB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	35
18 Contre-plaque	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7965
19 Parquet	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	606
20 Pâte et emballage	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	113
21 Pâte à papier	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3919
22 Vieux papiers	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7509
23 Papiers et carton	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1209
24 Résidu pâte à papier	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	21078
25 Résidu Bois	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2511
26 Energie	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1056
Total	134610	389	0	52689	3269	13969	60	5943	60	320	49	6250	13451	3471	4401	29808	526	11613	19852	34269
1 Bois sur pied	0	61379	12712	52689	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	134995
2 BO feuillus	0	0	0	0	3270	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5192
3 BO résineux	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15173
4 BF feuillus	0	0	0	0	0	13970	0	0	0	0	0	0	0	0	0	0	0	0	0	3759
5 BF résineux	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7110
6 Autre BI	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	484
7 Bois bléche	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	18
8 Plaquettes forestières	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	563
9 Résidu d'exploitation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1274
10 Travers	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	16095
11 Merrain	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	60
12 Scieries, anivés Fs	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	87
13 Scieries, anivés Rk	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9347
14 PCS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1483
15 Plaquettes de sciéie	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8785
16 Placages	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9347
17 Panneaux particules & OSB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	610
18 Contre-plaque	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6718
19 Parquet	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2994
20 Pâte et emballage	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	34
21 Pâte à papier	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7965
22 Vieux papiers	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	94
23 Papiers et carton	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	606
24 Résidu pâte à papier	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	16
25 Résidu Bois	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	113
26 Energie	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3700
Total	0	61379	12712	52689	3270	13970	59	5942	59	321	49	6251	13452	3472	4400	29806	14712	17805	23660	0

Figure D.2: Output SUT for the wood MFA (France, expressed in 1000 m³(f).

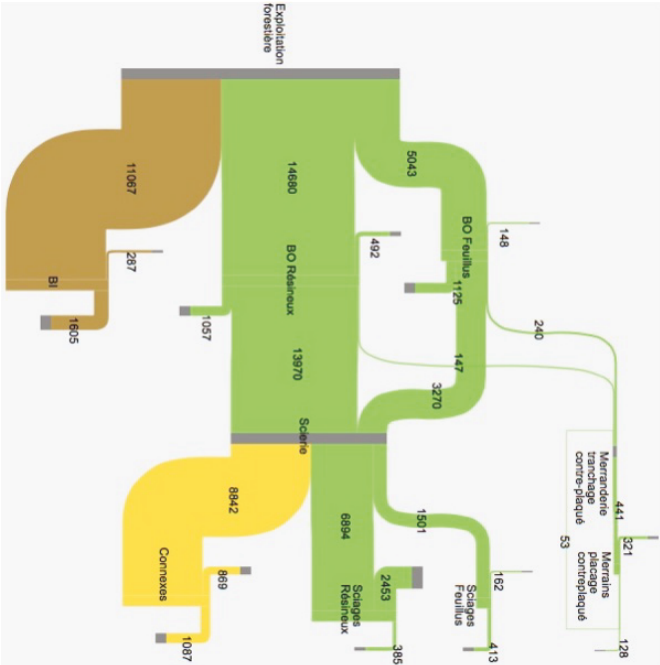


Figure D.3: Comparison of material flows on the left (in 1000 m³) and monetary flows on the right (in M€). Monetary flows are estimated based on average unit prices for each product category. We can see niche products as wood stave and plywood mobilize little material flows but generate significant added value. Conversely, products of lesser quality such as pulpwood and sawmill residues appear a lot less significant in monetary terms.

Consequences of logs leaks reduction policies on material flows

Downscaling of the MFA: results for Lorraine

During our PhD, we participated in the elaboration of the economy-wide MFA of the Lorraine region, supervised by Richard Marcelet of the DREAL Lorraine (Regional direction of environment, planning and housing). After the presentation of overall results, it was chosen to focus more particularly on wood, among four other materials. We therefore provided the following results, based on the *Grand-Est* study presented at the beginning of Chapter 7.

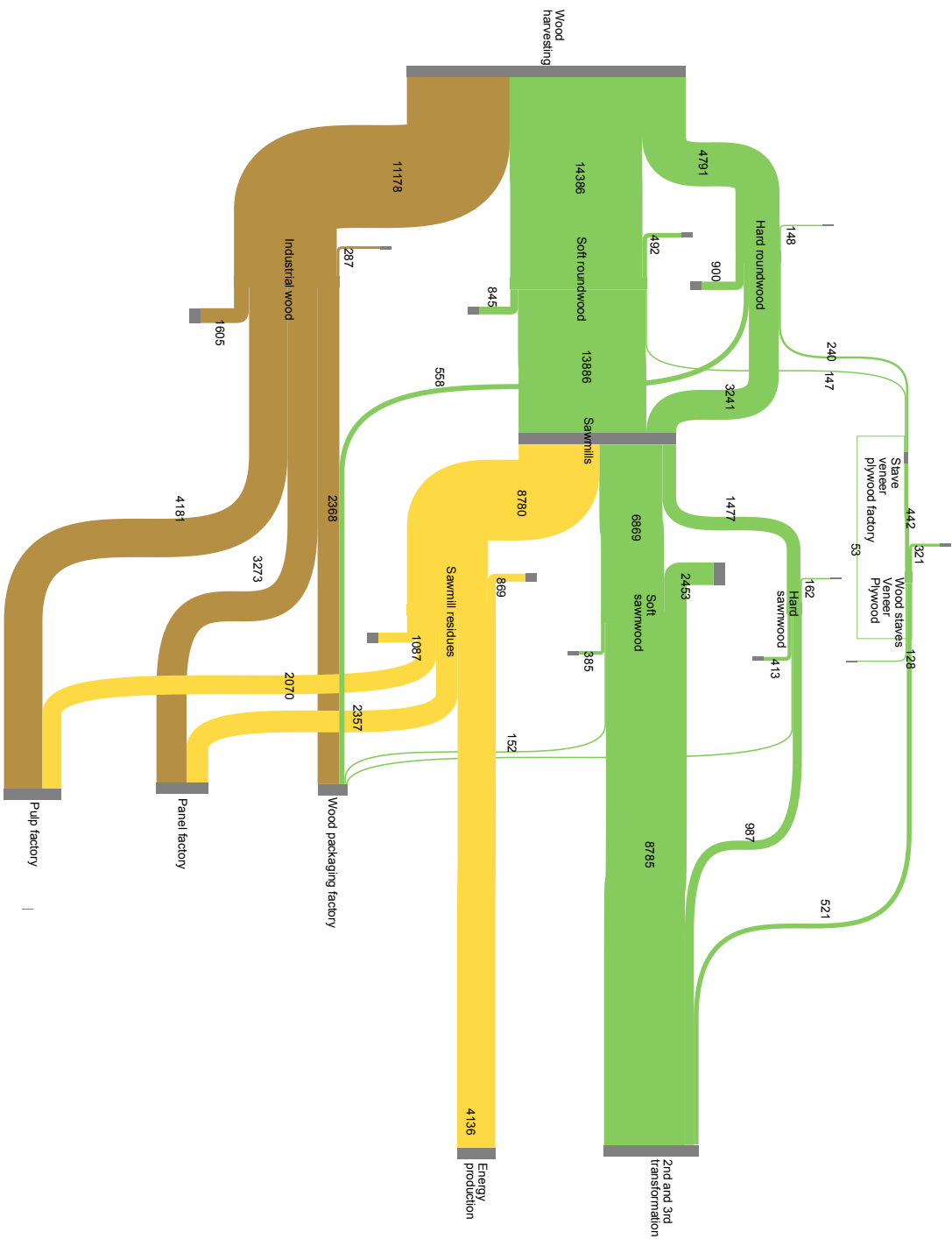


Figure D.4: Consequences of the *Exp* policy on material flows. Only the relevant flows have been drawn.

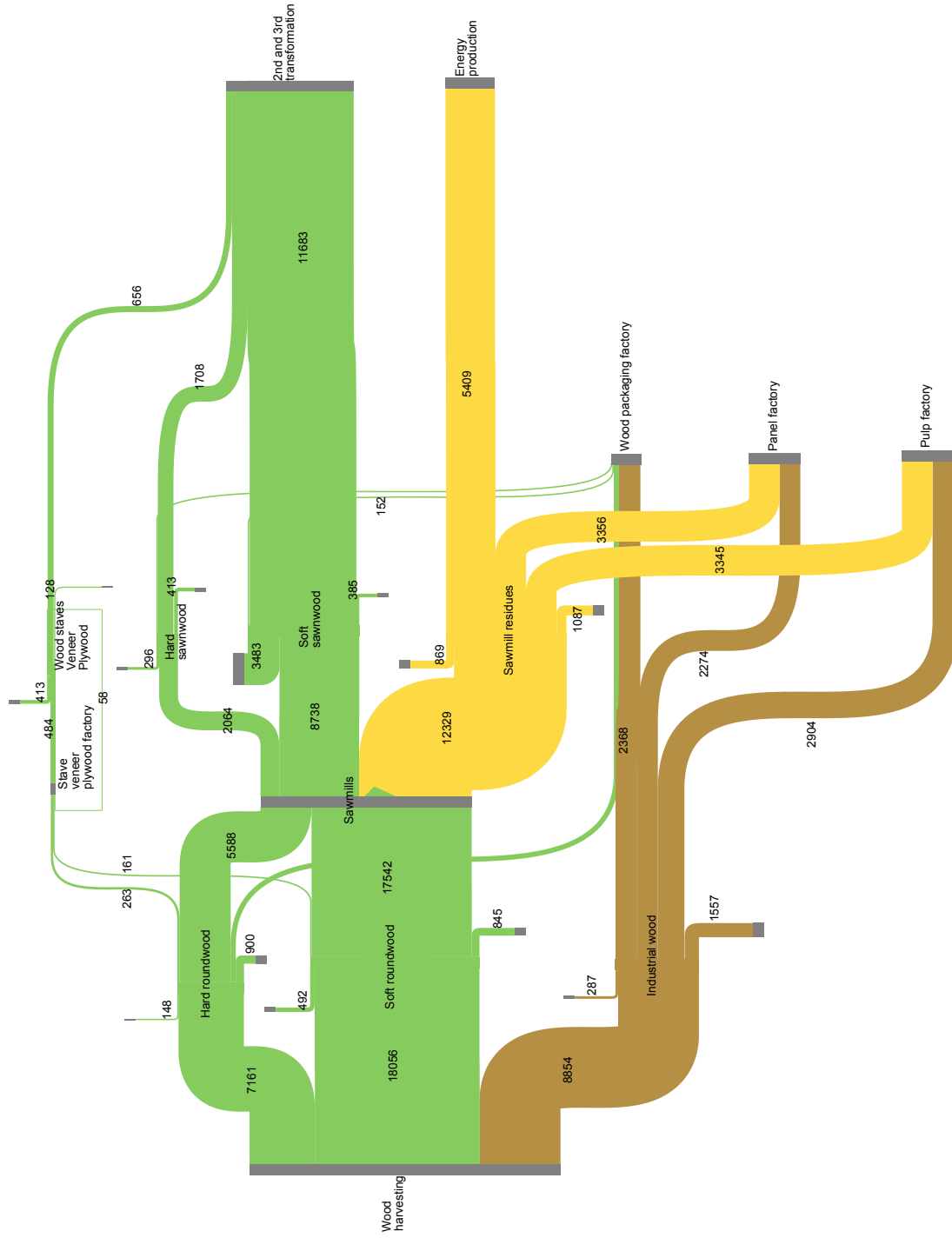


Figure D.5: Consequences of the *Sub_C* policy on material flows. Only the relevant flows have been drawn.

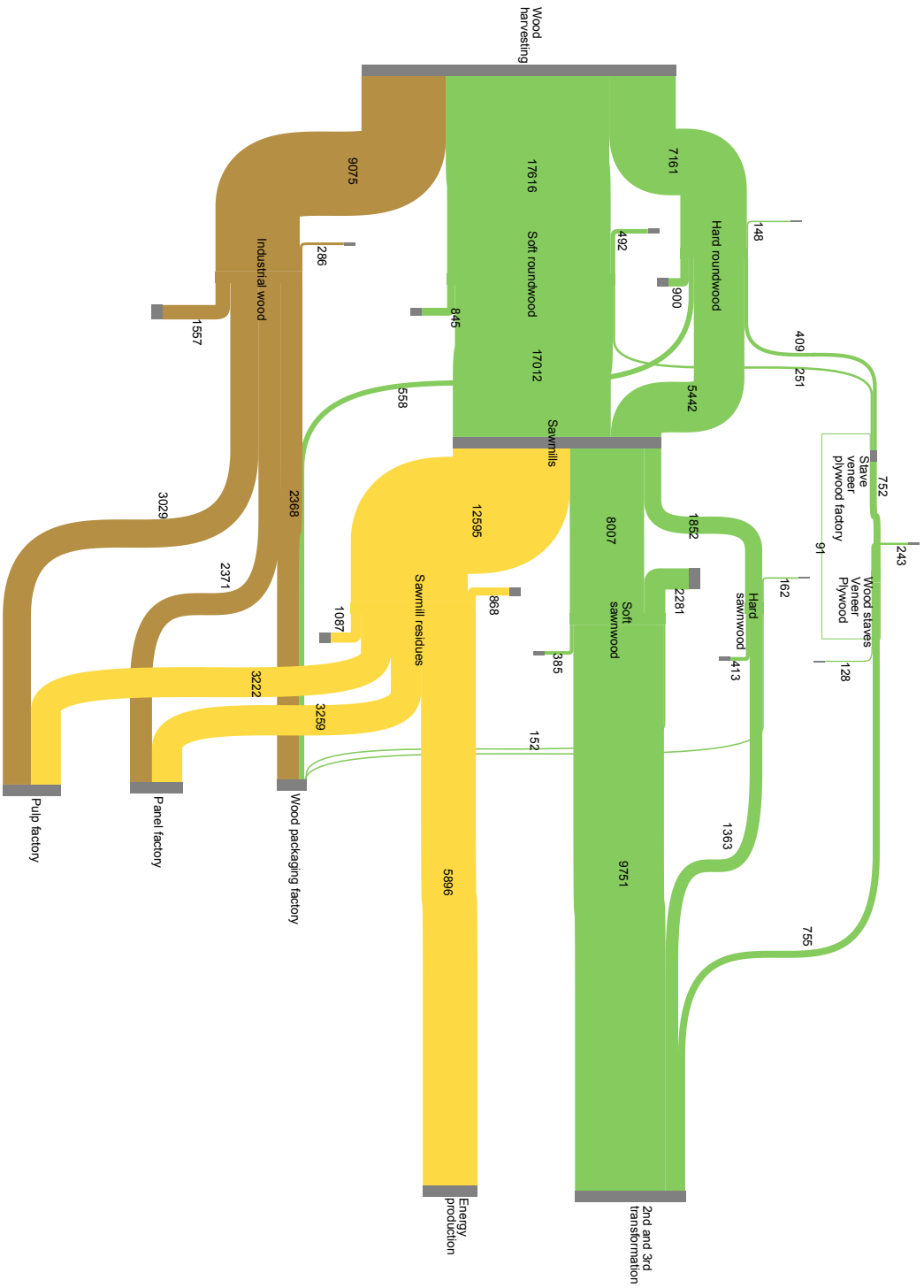


Figure D.6: Consequences of the *Sub_T* policy on material flows. Only the relevant flows have been drawn.

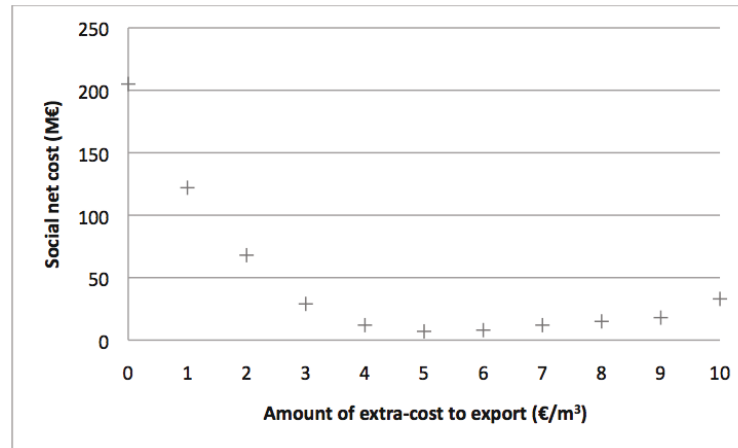


Figure D.7: Evolution of social cost depending on the *Exp* - *Sub_T* policy mix. The graph represents social costs for 11 combinations that all lead to the same decrease in export of 20 %. Only *Exp* value is presented on the X-basis, the level of the *Sub_T* is then chosen by a trial and error process. Results shows a U-shaped curve with a minimum for *Exp*= 5 €/m³ and *Sub_T*=80%. The net social cost is then 7 M€, which is smaller than the *Exp* policy alone and which makes this combination potentially interesting from a cost-efficiency perspective.

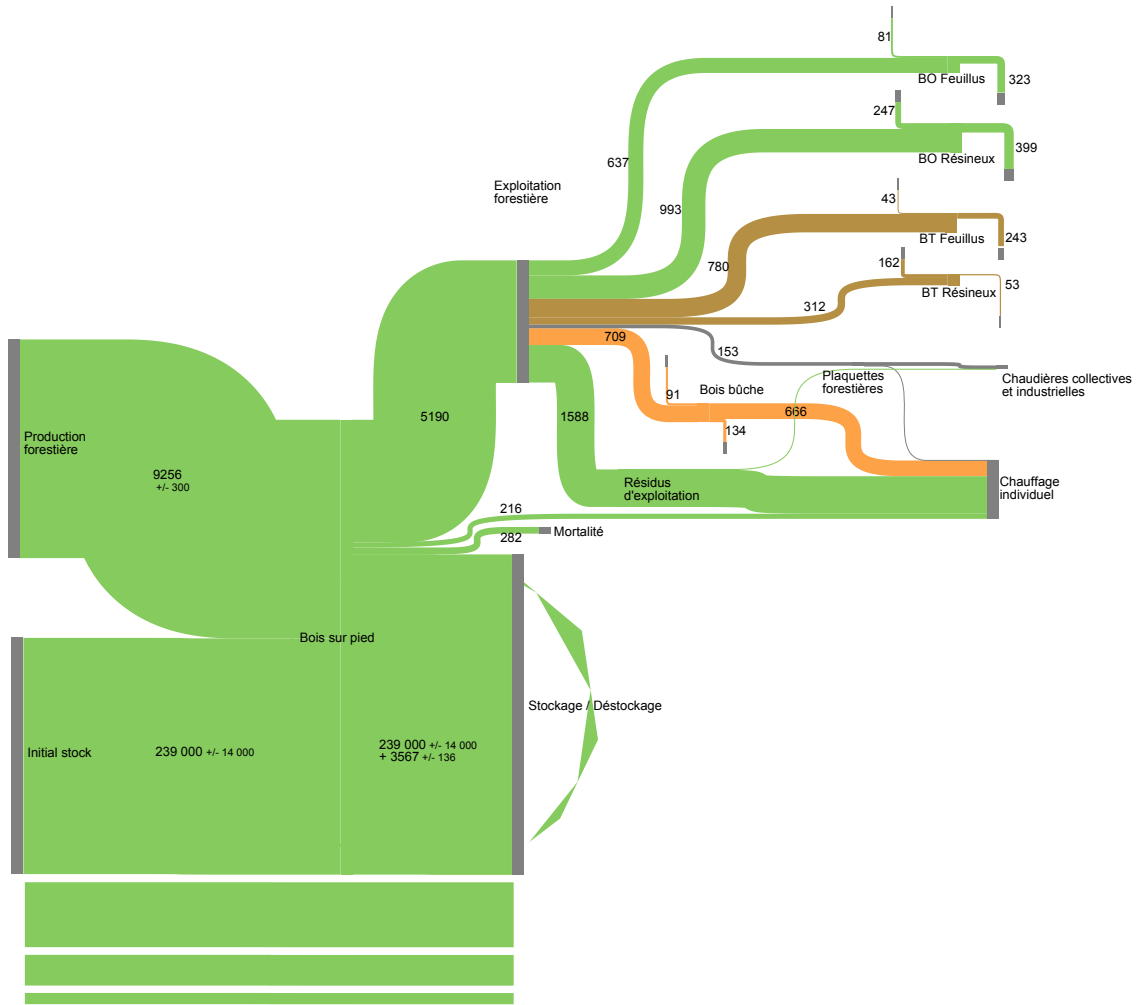


Figure D.8: Flows in the upstream part of the forest-wood chain in Lorraine (1000 m³). We can see that the forest stock is increasing (which as outlined in Chapter 7 doesn't necessarily mean that this stock can be harvested from technical-economic viewpoints). A second observation is that about 50% of the production of hard roundwood is exported abroad (mainly to Belgium and Germany). This issue, already highlighted at the level of France and studied in the course of Chapter 7, is therefore even more striking in Lorraine.

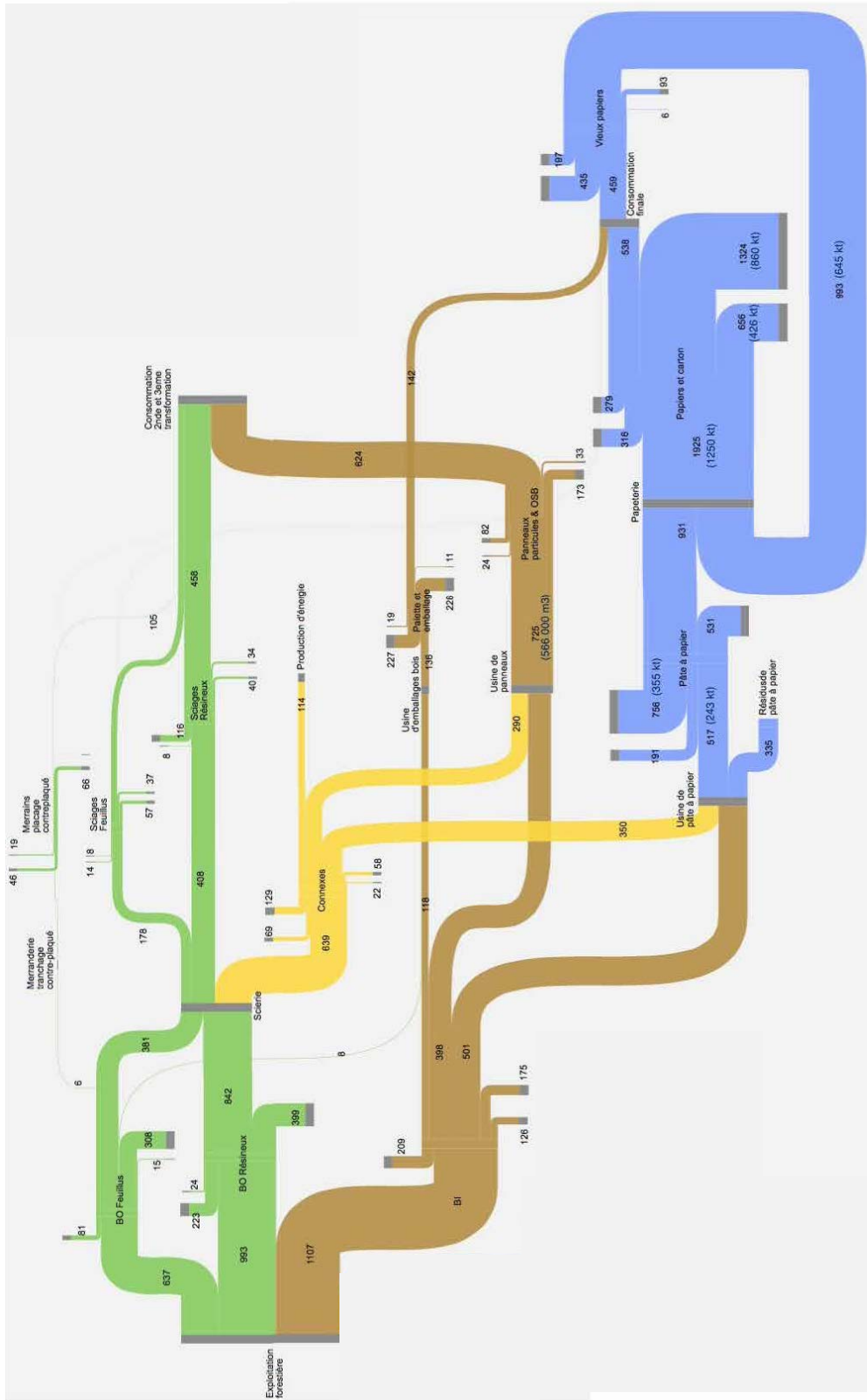


Figure D-9: Flows in the downstream part of the forest-wood chain in Lorraine (1000 m³). Inter-regional imports/exports are located to the left of international imports/exports. Flows of soft roundwood are inter-regional flows (although it is not shown in the diagram, origins of imports and destinations of exports can be retrieved from the model). We can see the importance of the paper industry which is importing significant amounts of waste papers, from other French regions and from abroad, to recycle them.

Appendix to Chapter 8

Source of figure E.1: adapted from MECON (2011).

Source of figure E.2: McGinnis and Ostrom (2014).

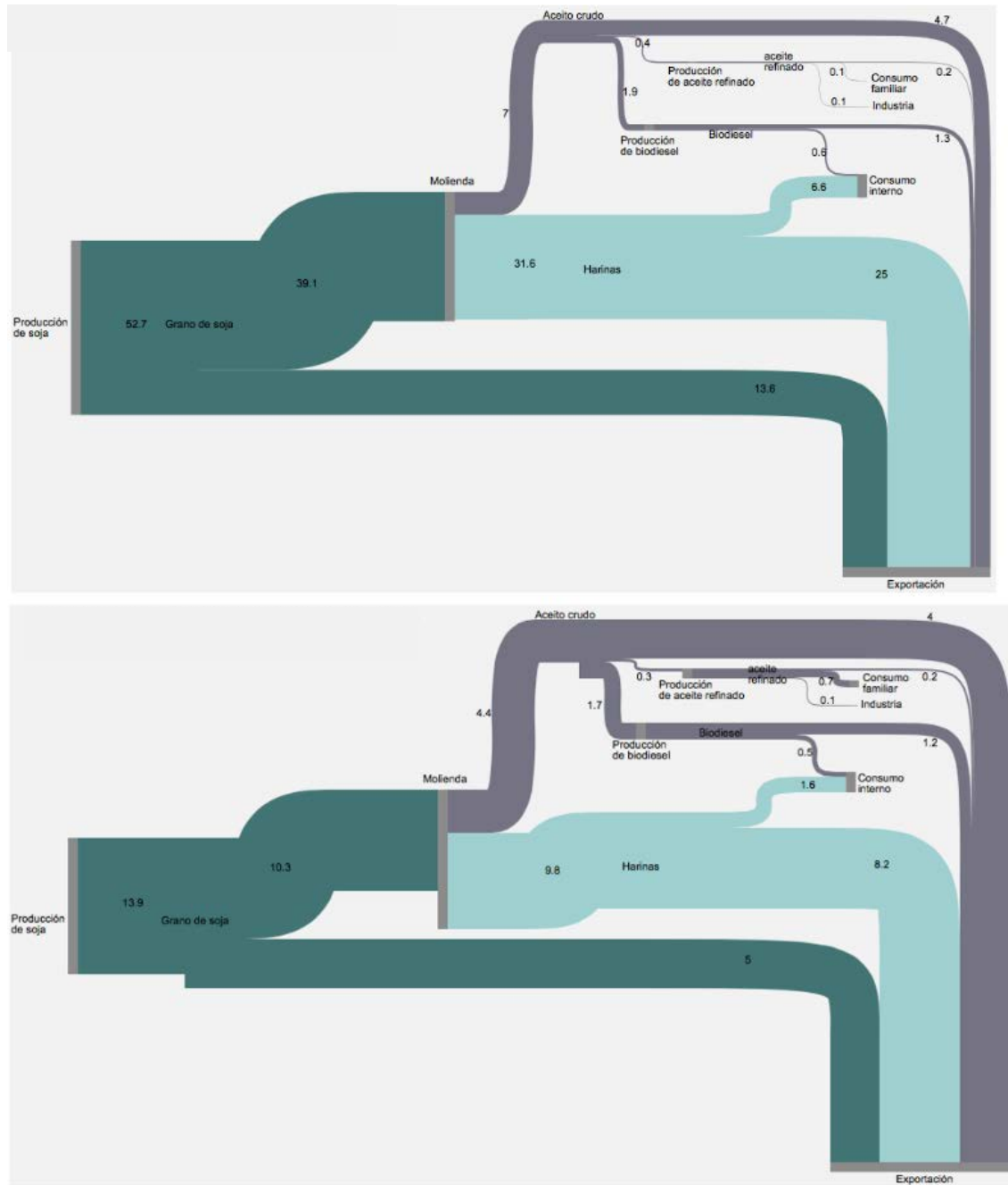


Figure E.1: Comparison between material (top diagram, expressed in Mt) and monetary flows (bottom diagram, expressed in billions of US dollars) of the Argentinean soy supply chain in 2010. The added values of refined soy oil (*aceito refinado*) and biodiesel are clearly identified.

First-tier variable	Second-tier variables
Social, economic, and political settings (S)	S1 – Economic development S2 – Demographic trends S3 – Political stability S4 – Other governance systems S5 – Markets S6 – Media organizations S7 – Technology
Resource systems (RS)	RS1 – Sector (e.g., water, forests, pasture, fish) RS2 – Clarity of system boundaries RS3 – Size of resource system RS4 – Human-constructed facilities RS5 – Productivity of system RS6 – Equilibrium properties RS7 – Predictability of system dynamics RS8 – Storage characteristics RS9 – Location
Governance systems (GS)	GS1 – Government organizations GS2 – Nongovernment organizations GS3 – Network structure GS4 – Property-rights systems GS5 – Operational-choice rules GS6 – Collective-choice rules GS7 – Constitutional-choice rules GS8 – Monitoring and sanctioning rules
Resource units (RU)	RU1 – Resource unit mobility RU2 – Growth or replacement rate RU3 – Interaction among resource units RU4 – Economic value RU5 – Number of units RU6 – Distinctive characteristics RU7 – Spatial and temporal distribution
Actors (A)	A1 – Number of relevant actors A2 – Socioeconomic attributes A3 – History or past experiences A4 – Location A5 – Leadership/entrepreneurship A6 – Norms (trust-reciprocity)/social capital A7 – Knowledge of SES/mental models A8 – Importance of resource (dependence) A9 – Technologies available
Action situations: Interactions (I) → Outcomes (O)	I1 – Harvesting I2 – Information sharing I3 – Deliberation processes I4 – Conflicts I5 – Investment activities I6 – Lobbying activities I7 – Self-organizing activities I8 – Networking activities I9 – Monitoring activities I10 – Evaluative activities O1 – Social performance measures (e.g., efficiency, equity, accountability, sustainability) O2 – Ecological performance measures (e.g., overharvested, resilience, biodiversity, sustainability) O3 – Externalities to other SESs
Related ecosystems (ECO)	ECO1 – Climate patterns ECO2 – Pollution patterns ECO3 – Flows into and out of focal SES

Figure E.2: Second-tier variables from social-ecological systems.

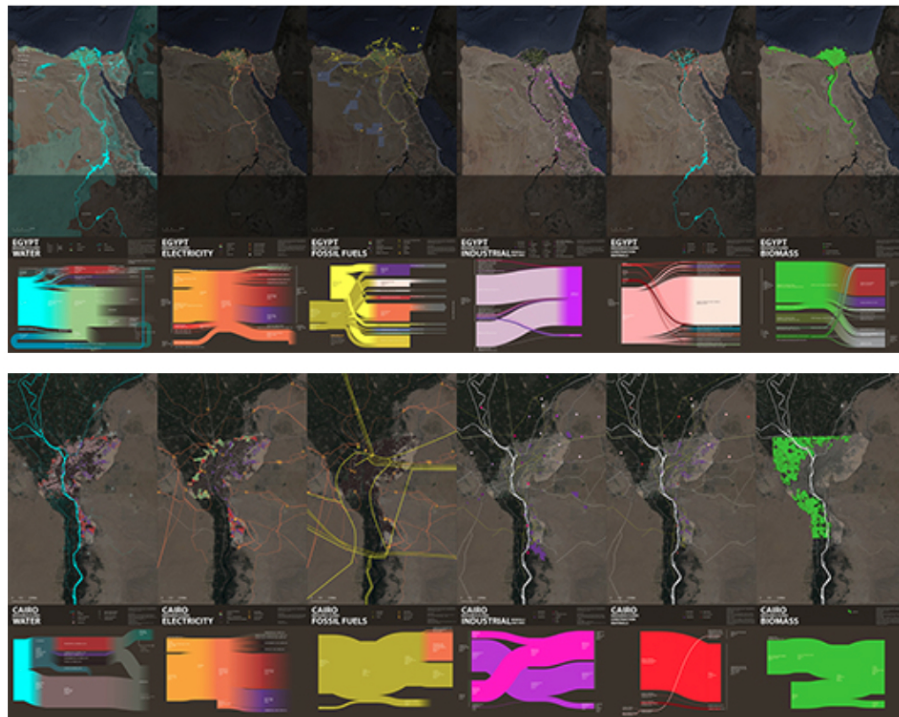


Figure E.3: Example of visualization by the MIT urban metabolism group. Source: Phoebe Dudek, Resources and Urban Africa project.

Appendix to Chapter 10

-
- Involved groups have a direct perception of the risks or of collective goods. Their preferences are well informed.
 - Only the interests or preferences of the present decision makers or stakeholders are directly relevant.
 - The involved group has good access to adequate social procedures to express its preferences (markets, votes, demonstrations, media, conflicts, etc.).
 - The scientific knowledge is stabilized on the aspects relevant for the action:
 - Elucidation of causal chains;
 - Damages non disputable;
 - Unambiguity with regard to the attribution of responsibilities
 - The risks are reversible: The “substantial rationality” model can be applied (cost - benefit analysis).
 - Stable scientific knowledge can be considered as a “common world for all the actions” (as a basis for actions).
 - What is at stake: economic effectiveness and/ or the basis of well founded interests.
-

Figure F.1: Decision making in a stabilized world. Source: Godard (1993) cited in Theys (2002).

-
- Prevailing of the scientific and social construction of the problems over the direct perceptions of involved groups or decision makers.
 - The appropriate representation of non involved parties is at stake: future generations, other countries, natural species, the biosphere, etc.
 - Those missing “third parties“ have contradictory spokesmen.
 - The scientific knowledge is still controversial with regard to the aspects of the problem the most relevant to the action.
 - Due to potential irreversibilities and/ or to the magnitude of potential risks, some stakeholders or involved parties feel that action must be taken immediately, without waiting for a more consolidated knowledge base.
 - The scientific assumption, the “visions of the world”, become strategic variables which give rise to new forms of competition.
 - What is at stake: the building of “epistemic communities” and of “environmental conventions”.
-

Figure F.2: Decision making in a controversial world. Source: Godard (1993) cited in Theys (2002).

		Degree of agreement between actors as to their objectives and values	
		High	Low
Degree of certainty on means, facts and knowledge	High	Programmed process. Automated routines, Technicality, Bureaucratization, Planning.	Negotiated process. Ideological debates, Experiences and traditions, Official controversies and informal compromises.
	Low	Pragmatic process. Involvement of "experts", empiricism, Search for strategic variants (<i>the best we can</i>)	Chaotic process. Avoidance, Decentralization, Recourse to authority, Involvement of a "Man of Providence", Crisis management.

Figure F.3: Nature of the context and process or government styles. Source: translated from Mény and Thoenig (1989).

Evolution of meat consumption	Meat and offals in 2050: 138g/day/cap Meat and offals in 2010: 270g/day/cap =>Division by 2
Evolution of milk and dairy products consumption	Milk in 2050: 332g/day/cap Milk in 2010: 635g/day/cap =>Division by 2
Evolution of agrosystems	In 2050: 90% of utilized agricultural area are under sustainable agriculture practices, including 45% organic and 45% integrated production (direct seeding + rotation + covers), 10% improved conventional practices.
Evolution of cattle population	Distribution in 2050 (number of mothers): Milk: 2,300,000 Meat: 1,300,000 =>Division by 2.2 of cattle livestock (1.6 for milk and 3.2 for meat).
Evolution of cereals' exports	Total exported volume (feed grains and human food): 2010: 30 Mt 2050: 20 Mt However: - Division by 2 of feed grains, - Division by 10 of exports to sub-Saharan Africa (which is able to feed itself) - 50% increase of exports to Northern Africa and the Middle East (stroke by climate change and demographic growth).
Evolution of soy imports	Strong decrease due to: - Livestock reduction, - Increase of French production, extension of granivores' breeding time (less needs of concentrated products).
Evolution of water drawing for irrigation	Overall, on a yearly period, volumes drawn are comparable, however summer irrigation needs are divided by 4: - Reduction of corn surfaces in the south (less needs for livestock feed), - Shift of surfaces to the north due to climatic constraints, - Partial replacement of summer irrigation by starter irrigation (rapeseed) or complementary irrigation (wheat): irrigation in fall and spring.

Table F.1: Main characteristic of the Afterres 2050 scenario. Source: translated from Solagro (2015).

Evaluation environnementale de territoires à travers l'analyse de filières

La comptabilité biophysique pour l'aide à la décision délibérative

Résumé : Les conséquences de nos modes de production et de consommation sur l'environnement mondial sont reconnues et analysées depuis plusieurs décennies : changement climatique, effondrement de la biodiversité, tensions sur de nombreuses ressources stratégiques etc. Dans ce contexte, notre travail vise à fournir un outil comptable d'aide à la décision, en unités physiques, par opposition à une comptabilité monétaire, pour l'évaluation environnementale de collectivités territoriales et en premier lieu de régions françaises. Pour cela, nous nous intéressons aux filières de production que nous analysons à partir des quantités de matières qu'elles mobilisent au cours des étapes de production, transformation, transport et consommation. Nous analysons ensuite les enjeux environnementaux mais aussi socio-économiques liés à ces flux de matières, en distinguant ce qui relève de la responsabilité des producteurs et de celle des consommateurs. Ces informations ayant une visée opérationnelle, nous proposons pour finir une méthode d'aide à la délibération entre plusieurs parties prenantes, inspirée de méthodes multicritères.

Mots clés : Filières, analyse de flux de matières, empreintes environnementales, aide à la décision, analyse multicritère

Environmental assessment of territories through supply chain analysis

Biophysical accounting for deliberative decision-aiding

Abstract: The consequences of our modes of production and consumption on the global environment have been recognized and analyzed for several decades: climate change, biodiversity collapse, tension on numerous strategic resources etc. In this context, our work aims at providing an accounting tool in physical units, in opposition with monetary accounting, for the environmental assessment of local territories and in particular of French regions. To this effect, we focus on supply chains and analyze them through the quantities of materials they mobilize during the production, transformation, transport and consumption stages. We then study the environmental and socio-economics stakes associated with these material flows, by distinguishing producers and consumers responsibilities. Because this line of research is intended to provide policy-relevant information in the end, we finally propose a deliberation-aiding process between several stakeholders, inspired by multicriteria methods.

Keywords: Supply chains, material flow analysis, environmental footprints, decision-aiding, multicriteria analysis
