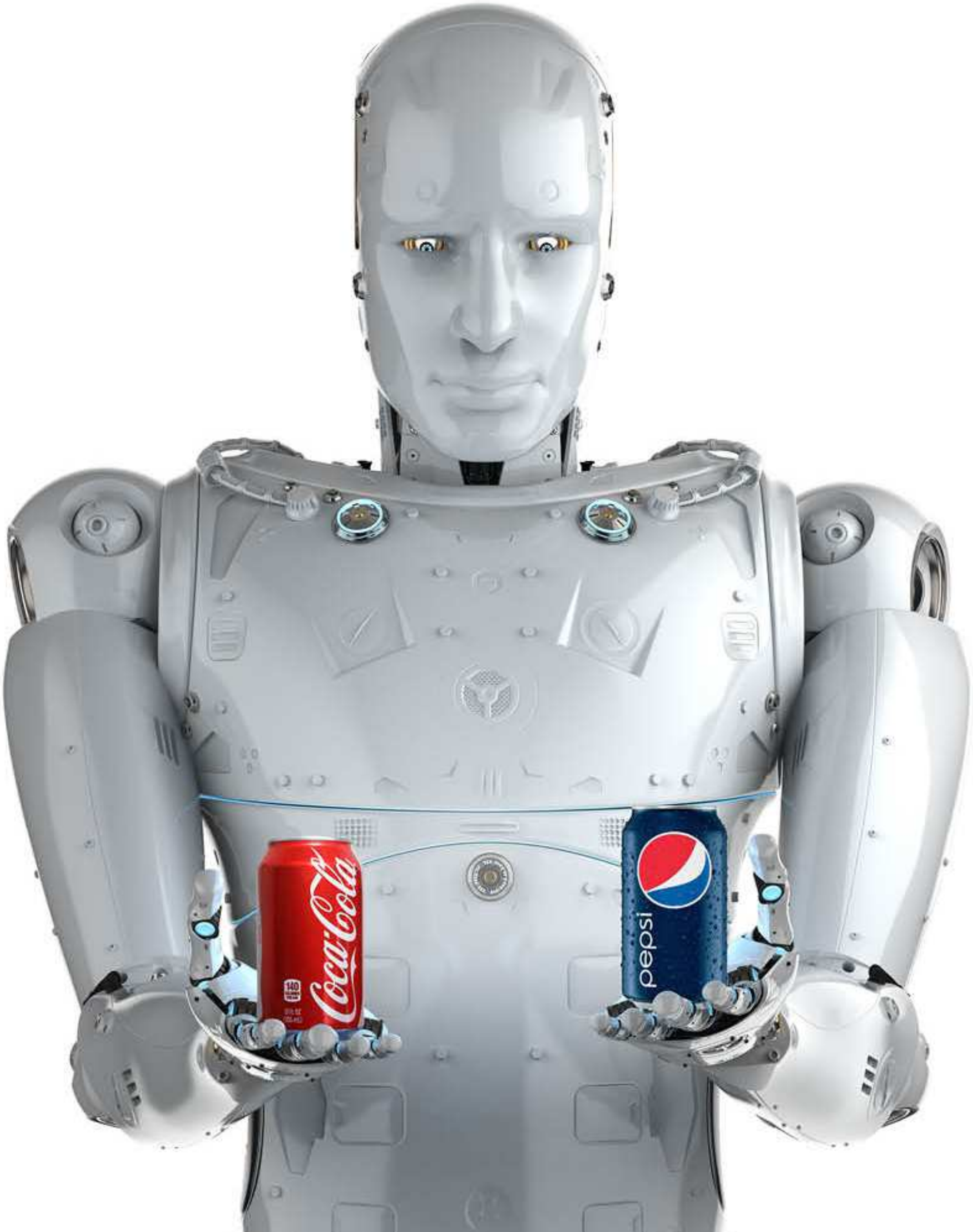
PIETER JOCKIN

Master Thesis

INTEGRATION OF DYNAMICS INTO INPUT-OUTPUT ANALYSIS

Integration of dynamic features representing demand change and production technology change into the input-output analysis framework



TU Delft

Integrating dynamics into input-output analysis:

Exploring the integration of dynamic features representing demand change and production technology change into the input-output analysis framework

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Summary

The transition to a circular economy requires drastic, structural changes to the economy and its production system. Therefore, any policies stimulating a transition towards a circular economy should be carefully considered. One of the macro-economic analysis frameworks that is capable of analysing structural changes to an economy is input-output analysis. Input-output analysis is a planning framework that is widely used by statistical agencies around the world. The framework was proposed by Wassily Leontief in the 1930's and has been expanded over the past decades to its current form. Input-output analysis breaks down the production system of a regional economy into a set of sectors. In input-output analysis, a sector is a group of undertakings which produce goods of the same classification; each sector absorbs inputs to produce output. By mapping the trade relations between economic sectors into a matrix, linear algebra can be used to efficiently compute future trade volumes in different scenarios. Modern day applications extend further than pure economic analysis, environmental impact analysis and life cycle analysis also employ the input-output analysis framework. The transition to a circular economy could be analysed sing input-output analysis.

This research focusses on expanding the input-output framework by replacing some of the fundamental assumptions that support input-output analysis. Two assumptions of input-output analysis are challenged, (1) the assumption that the input requirements of sectors are static, and (2) the assumption that final demand by consumers is static. The main criticism of this research on input-output analysis is that it sticks to these assumptions rather than incorporating advances from other scientific fields. Cognitive psychology, behavioural economics, uncertainty analysis and technological change literature provide frameworks that could be incorporated to replace these assumptions which are known to be wrong. This research replaced two static aspects of the input-output framework with dynamic features. A conceptual model was designed of a national trade model based on the input-output analysis framework with integrated dynamic features. These dynamic features are the representation of the demand-side dynamics (consumer-demand) and the representation of the supply-side dynamics (technological change). The research question was formulated as:

How can supply- and demand-side dynamics be integrated with the input-output analysis framework?

For both the supply- and demand-side of the economy the agent-based modelling formalism was found to be suitable as the goal of both methods is to increase the understanding of the system rather than attempting to predict exact levels of outcome of a system. There is potential for mutual benefit between input-output analysis and agent-based modelling. Historic data is valuable for agent-based modelling for validation purposes. Input-output analysis lacks micro-economic realism and technological detail. However, a fundamental misalignment needs to be resolved before the methods can be integrated; their perspective of the analysed system is different. Input-output analysis decomposes the highest system-level into parts, sectors, until the desired level of precision is reached. Agent-based modelling defines the smallest, autonomous, functional parts and through their interaction the system level behaviour emerges. For the demand-side model the misalignment was dealt with by defining individual consumers' purchasing decisions. For the supply-side model the misalignment was overcome through further decomposition of sectors into firms and defining firms' individual production technology.

The demand-side dynamics model defined an individual consumer, the total final demand of the consumers emerged from the whole consumer population allocating their budget. Consumers' budget allocation procedure was defined as an optimisation problem, where consumers maximise their utility under their budget constraints. A utility function based on notions of Prospect theory was implemented and was able to mimic real-world consumer

behaviour in a promising way. Although the quality of a product was poorly defined in the model that provided proof of concept, final demand of consumers behaves similar to real-world observed behaviour.

The supply-side dynamics model incorporated notions of technological change to describe development of the input-output relation of economic sectors. Two mechanisms of technological change were found relevant, both incremental change and radical change. Radical change is caused by innovations entering commercial deployment. Incremental change increases efficiency due to learning effects. A visual representation of the supply-side model is shown below, in figure 1. Overcoming the alignment challenge for the supply-side dynamics proved difficult due to a lack of data on individual firms or production technologies of the production system. Input-output data is aggregated in sector-level data, defining individual entities requires dis-aggregating this data. However, it proved difficult to provide a substantiation for this dis-aggregation.

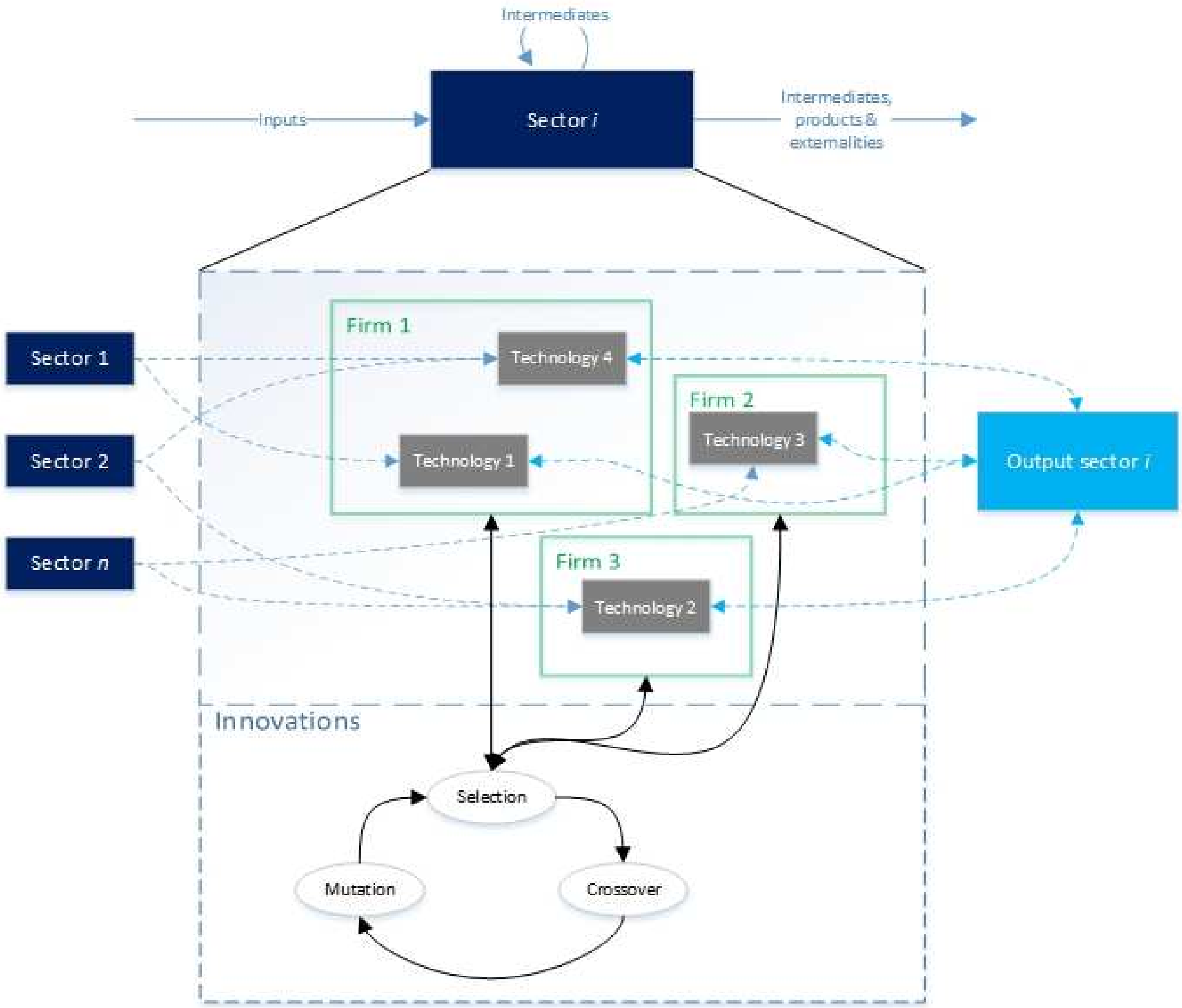

Figure 1: Visualisation of the supply-side dynamics model

The proposed conceptual model of the integration of the frameworks was implemented to provide proof of concept. Through the implementation process, some focal points for future research were defined. Modelling the supply-side dynamics for an economy from individual firms or technologies requires a model of a flexible resolution, accounting for many undertakings and relations. This is deemed infeasible for the near future. A simpler model is proposed; like turnpike growth models but with a growth rate described per individual sector using the Wright curve.

The demand-side dynamics model that was developed using a utility function incorporating prospect theory was found to have the potential to accurately mimic real-world observed consumer final demand. By representing individual consumers, it becomes possible to evaluate policy that targets individual consumers. Macro-economic policy design will be able to focus on individuals' actions like purchasing decisions and recycling behaviour, rather than interest rate, employment rate and gross domestic product. Future research should be aimed at improving the model by accounting for product's quality in more detail. In the proof of concept, quality was represented as a two- and three-dimensional parameter. However, quality is known to be a complex concept which should be broken down into more different aspects. With more different aspects being weighted in the purchasing decision, a more 'wicked' trade-off is made by consumers. With this trade-off, more diverse final demand vectors are generated analogous to real-world observations.

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Chapter 1: Introduction

The first chapter describes the motivation of the thesis. Section 1.1 outlines problems that the thesis addresses; (which is?) the finiteness of the planet resources and inequality of natural replenishment and depletion rates of most resources. Section 1.2 describes the formalization of the problem in the scientific literature as the “circular economy” concept and reasons for stimulations of transition to the circular economy. Section 1.3 provides arguments in favour of usefulness of simulation tools in the context of the transition to a circular economy. The main econometric tool for building understanding in structural changes to economies, input-output analysis, is introduced in section 1.4 along with some of its limitations. Based on these limitations the knowledge gap is presented in section 1.5; the knowledge gap being the lack of dynamic features in the input-output analysis framework. Finally, section 1.6 presents the structure of this thesis.

1.1 Problem area

Our planet is a closed, cyclic system with only energy coming in and going out. Most of the production system of our economy is an open ended, linear system; resources naturally occur in deposits, these resources are converted into products and products are being used. Eventually, used products are discarded as waste or possibly recycled. Problems emerge when the level of depletion of resources is higher than the level of replenishment for a sustained period of time. These problems manifest themselves in multiple different ways, examples of these manifestations can be the depletion of hydrocarbon reserves, continuous rise of atmospheric carbon-dioxide levels and the near-extinction of the bluefin tuna (McKie, 2010).

Deposits of resources can be seen as buffers and most of these buffers are naturally replenished; the path from resource extraction to resource replenishment is called a resource cycle. Problems arise when the replenishment rate of these resource buffers is lower than the extraction rate of these buffers. An example of a resource cycle can be the hydrological cycle; the cycle of water. In most area’s the replenishment rate is greater than the depletion rate (Oki & Kanae, 2006) but in some places the replenishment rate is smaller than the depletion rate.

Unfortunately, not all resources are as abundant as water and even fewer resources are as easily replenished as water through natural processes. An extreme example as an opposite to water in these aspects is lithium. Lithium is needed to produce lithium-Ion batteries, the most commonly used battery. Once lithium is extracted and processed into a battery; it cannot naturally return to its mineral form, the batteries have to be ‘artificially’ recycled. If the world transport system were transitioned into electric-driven systems based on lithium-ion batteries, the lithium depletion rate would be so great that the buffer will need to be replenished by recycling accordingly (Egbue & Long, 2012). Not all resources used for production are extracted from deposits; some materials are already being recycled to a large degree, for instance metals, glass and plastics, and therefore those production systems are to some degree cyclical.

Our economic system is not sustainable on the long term, due to the fact that resources do not just appear; buffers or deposits of resources occur but these are finite or scarce. Our production system should therefore also be a closed system; this idea is known as the circular economy. The level of resources in buffers should be in equilibrium; the long-term average replenishment should equal the long-term average depletion. Back in 1989, Frosch and Gallopoulos showed how our economy is unsustainable and they argue that one manufacturer’s waste should serve as another manufacturer’s resource.

1.2 The circular economy and its challenges

A circular economy is an economy where no waste is created; all discarded products are fully recycled and re-inserted into the value chain. Kirchherr et al. (2017) provide a review of definitions made by many different publications and synthesise a new definition of a circular economy: *"an economic system that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes"* (Kirchherr et al., 2017, p. 229).

In recent years, policymakers address the need for a circular economy. In 2015, the United Nations decided on a number of new global Sustainable Development Goals (U.N., 2015); goal number 12 states *"Ensure sustainable consumption and production patterns.... By 2030, substantially reduce waste generation through prevention, reduction, recycling and reuse"*. Currently the EU takes actions to reach this goal. The EU has implemented its Circular Economy Action Plan in 2015 (European Commission, 2015). The EU aims to stimulate the transition to a circular economy through stimulation of sustainable activity in the key sectors.

Among the planned actions are incentive schemes for both demand-side (e.g. provision of efficiency labels on products) and the supply-side (e.g. taxation and subsidy schemes) of the economy. These planned actions are explicitly described in the policies but for a relatively short term. Longer term policies are difficult to draft because the economic system is highly complex; transition to a circular economy might have a large impact and therefore any action plan should be carefully considered. For instance, lock-in effects are known to emerge and form a barrier for the circular economy (Norton et al., 1998), even when sustainable alternatives become economically viable. A popular example where lock-in formed a barrier for other alternatives is the QWERTY keyboard (David, 1985). However, lock-in can also be a positive phenomenon, leading to globally accepted standards like the intermodal container for transport.

Over the past decade, the research activity in the field of circular economy has significantly increased. Scopus database provides drastically growing number of publications every year with the key words "Circular economy"; figure 1.1 below shows the number of publications in Scopus per year.

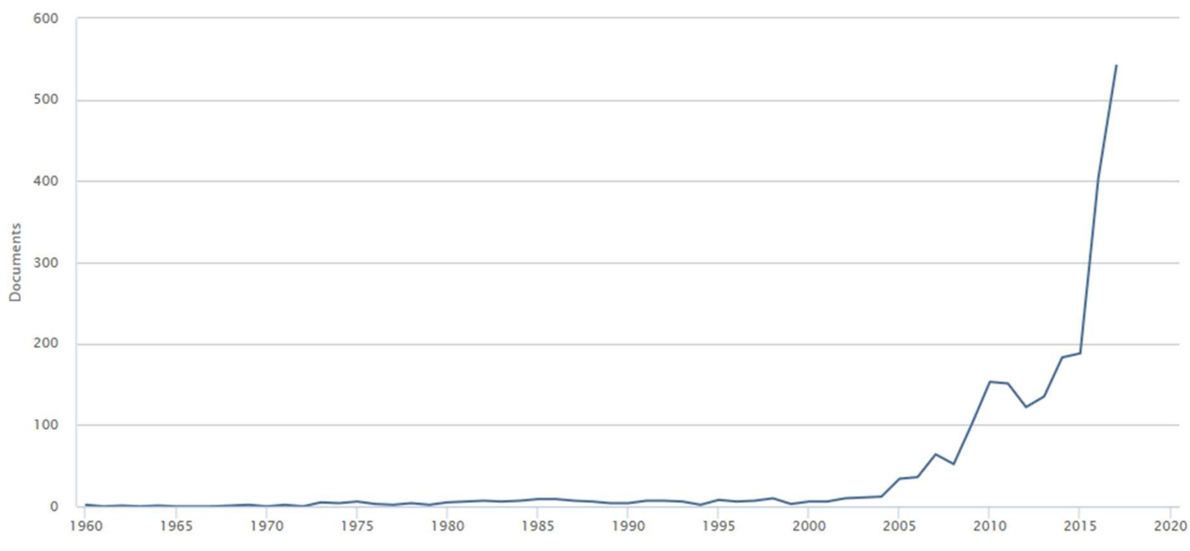


Figure 1.1: Number of Publications in Scopus related to circular economy by year

Transition to a circular economy will require to overcome several challenges and limitations. Korhonen et al. (2018) provide a review of the circular economy concept and give special attention to six of these limitations. Among these limitations that Korhonen et al. mention are thermodynamic limitations, lock-in effects and rebound effects. The rebound effect, or the Jevons paradox, occurs when an increase in efficiency leads to a production level increase (Berkhout et al., 2000) which eventually leads to a net increase of pollution. This is counter intuitive since one would expect that efficiency increase would lead to pollution decrease. Zink and Geyer (2017) show that the rebound effect is likely to emerge in the transition to a circular economy with mere financial incentive schemes.

Transition to a circular economy might require drastic and structural changes of the economy; both at the supply-side and demand-side of the economy. Figure 1.2 represents a visualisation of the resource cycle within an economy; both producers and consumers have influence on the degree of recycling which is achieved in an economy. Any insight and understanding of the required changes in the (regional-) economy and consumer behaviour can prove of great value. In order to fully understand the implications of the circular economy, research should evaluate the full value chain and interactions between different value chains of the economy; properly considering the complex dynamics of an economy.

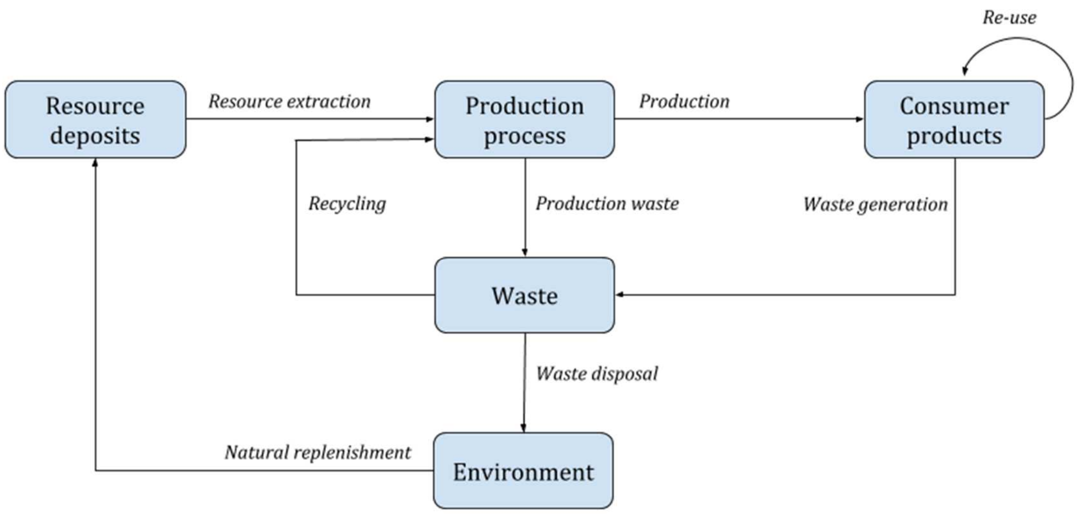
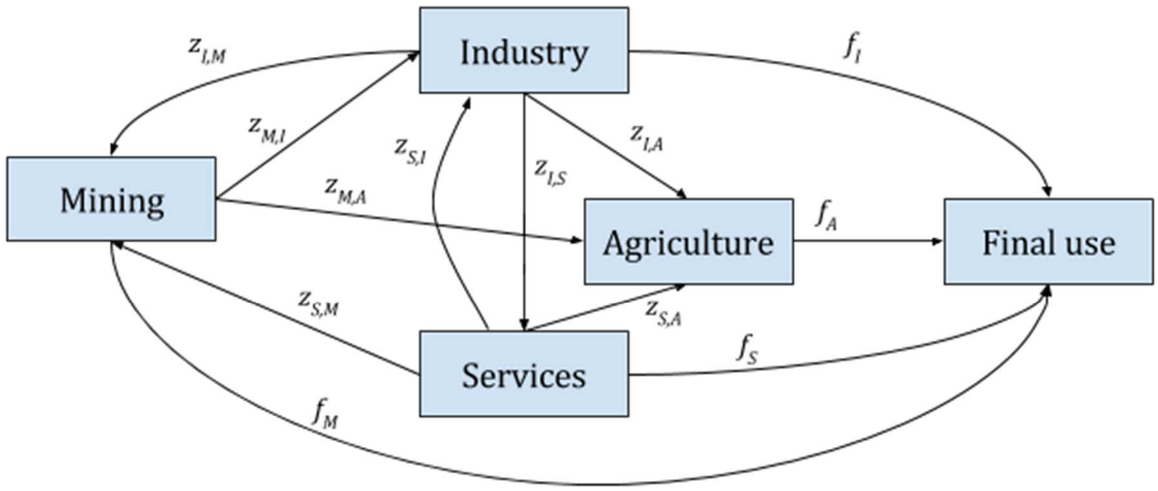


Figure 1.2: Resource cycle within an economy

1.3 The contribution of simulation tools

Many simulation tools exist to support decision-making, policy analysis or building understanding in complex systems where the effects of actions are ambiguous, difficult to project, or more complex than the human mind can comprehend. Simulation tools help to explore pathways of future development. When a system can be synthesized in a computer simulation, many experiments can be conducted and analysed. A simulation model of a national economy and its associated waste streams can be used to conduct experiments that are impossible to perform in the real world. With such simulation model, alternative future development pathways can be implemented and evaluated with no repercussions in the real world. Questions that could be answered with the help of such simulation model are what the economy, as a whole, would look like when a circular economy is implemented to a certain extent and what the move to a circular economy would cost to actors involved.

A common pitfall in simulation is to regard the simulation outcomes as the truth, while simulation outcomes result from codifications of the programmer's perception of the system. As George Box phrased it: *"All models are wrong, but some are useful"* (Box, 1979, p. 202); it is impossible to fully replicate a real-world system in a simulation model, but regardless, simulation models help to build useful insights. Hodges (1991) argues that although a rough answer is better than no answer, the cost-effectiveness might not be worthwhile. The major costs for building a simulation model of an economy would be incurred in gathering data for parameterisation. However, statistical agencies around the world gather data for their econometric analysis tools; one of these econometric analysis tools is input-output analysis.



To / From	Agriculture	Industry	Mining	Services	Final use
Agriculture	$z_{A,A}$				f_A
Industry	$z_{I,A}$	$z_{I,I}$	$z_{I,M}$	$z_{I,S}$	f_I
Mining	$z_{M,A}$	$z_{M,I}$	$z_{M,M}$		f_M
Services	$z_{S,A}$	$z_{S,I}$	$z_{S,M}$	$z_{S,S}$	f_S
total	x_A	x_I	x_M	x_S	

Figure 1.3: An illustration of an economy decomposed into four sectors with its corresponding input-output table representation

1.4 Understanding structural changes to an economy with input-output analysis

Input-output analysis in macroeconomics views an economy as a set of industries, which consume resources or products (inputs), exchange intermediate products and produce consumer products (outputs). An industry is a collection of enterprises, undertakings, firms, etc., which perform economic activities of the same classification (Eurostat, 2008a); this classification is one of the underlying assumptions of the input-output analysis framework. Each industry consumes a set of inputs and generates output from their economic activity; the amount of output generated is equal to the input plus the added value (Eurostat, 2008a). Output can be either an intermediate product or a final product. Intermediate products serve as input for other production processes while final products are not used in economic activity, they are consumed. Input-output analysis is performed with matrices or tables. These tables are used in different predefined formats. Eurostat uses three types of tables: supply tables, use tables and input-output tables. Supply and use tables (SUT) show the supply and use of products to industries (Eurostat, 2008a, p. 17). The supply and use tables are used to compile the input-output table in two different formats, industry-by-industry or product-by-product. The input-output table is formulated in monetary units, giving the value of products exchanged between industries.

Figure 1.3 above shows a simplified example of an economy decomposed into four industries and its corresponding industry-by-industry input-output table. A flow from industry *i* to industry *j* is denoted as $z_{i,j}$; in the corresponding table the rows show the flows from that sector to all other sectors and the column shows per sector from which other sector it receives inputs.

Wassily Leontief is credited for developing the input-output analysis framework. In an attempt to gain more insight in the American economy, Leontief started representing economic systems as a system of interconnected processes; each process generating certain output and absorbing specific combinations of inputs (Leontief, 1986). As Leontief (1974, p. 156) mentions, this input-output analysis framework is "*...essential for a concrete understanding of the structure of the world economy as well as for a systematic mapping of the alternative paths along which it could move in the future*".

Input-output analysis is now widely applied by statistical agencies to provide insight in the performance of (regional-) economies. Due to the magnitude of the effort required to compile actual input-output tables, Eurostat measures the values of trade streams once every five years and values are projected for future years while the tables are published yearly (Eurostat, 2008a).

In recent years, input-output analysis is used in the field of environmental science. The input-output analysis framework has been extended to provide information on industries' associated environmental impact; these extensions are named Environmentally Extended Input-Output Tables (EEIOT). Several environmentally extended input-output tables are developed and are being maintained; examples are EXIOBASE (Tukker et al., 2013) and the WIOD project (Dietzenbacher, Los, Stehrer, Timmer & de Vries, 2013). Wiedmann (2009) provides an adequate review of some environmentally extended input-output analysis frameworks.

While these EEIOT projects share the same goal, they use different approaches to compile the tables. The main difference is the resolution of the tables, in other words the level of detail of the table or the level of aggregation of the industries. For instance, the lowest resolution represents the economy as one industry; a high-resolution representation discerns the economy into many different industries. Some EEIOT projects have a high resolution, discerning many industries while others have a lower resolution. One form of EEIOT that deserves special attention is Waste Input-Output Tables (WIOT) (Nakamura, 1999). WIOT extends traditional input-output analysis by associating the amount of waste generated per industry (Nakamura & Kondo, 2009). However, currently no WIOT databases are being maintained. The Dutch statistical office used to publish a WIOT database, the NAMEA project, but this project has been discontinued. NAMEA reported an input-output table of 25 sectors along with several associated waste streams. The data was collected from 1995 up to 2008 and can still be accessed (CBS, 2011).

The total environmental impact of industries or products can be estimated with the help of environmentally extended input-output tables. It can evaluate not only the direct impact of the economic activity that produces the final product, but also the environmental impact of all preceding economic activities in the value chain. For example, the construction of a building incurs certain environmental impacts such as emissions from heavy machinery. The application of the input-output analysis can easily incorporate the intermediate product impacts into the assessment of entire environmental impact. For example, the assessment of cement and steel production used in the construction of the particular building.

1.5 Knowledge gap: the lack of dynamic features in input-output analysis

This thesis aims to contribute to the main knowledge gap that exists in input-output analysis framework which is the general lack of dynamic features. Most macroeconomic models that build on the input-output analysis framework take the form of computable general equilibrium models. The World Trade model by Duchin (2005) can be an example of a model which attempts to model the entire world economy based on the input-output analysis framework with the use of linear programming. Duchin's World Trade model is *"...intended for analysing scenarios about actions that could be taken to achieve the environmental and social objectives associated with sustainable development"* (Duchin, 2005, p. 142). The World Trade model is intended for empirical analysis of the world economy and continues by presenting requirements for a full-scale model. Among these requirements she mentions that a dynamic framework should be included in a full-scale model to reflect certain phenomena such as innovations, changes in lifestyle and shifts in comparative advantage. Leontief was the first who implemented and solved an input-output model back in the 1950's based on linear equations with the use of a computer. However, since that time, the integration of dynamic components into input-output analysis framework, like those mentioned by Duchin, has not been done. Current input-output analysis uses the same principles of linear equations. Other researchers have also concluded that macro-economic models should move away from computable general equilibrium models. Robert Lucas proposed the Lucas critique (Lucas, 1976); he argues that macro-economic policymaking should not be based on extrapolating historic data but should be based on modelling economic entities in more detail.

The work of de Koning et al., (2016) can be an example of a recent study that brings together consumer behaviour and technological change into input-output analysis. However, in this paper, technological change and consumer behaviour are not represented dynamically but statically, as a parameter, which varies in different scenarios. In this research, de Koning et al. analyse alternative scenarios of economic development with the associated global CO_2 emissions using input-output analysis. De Koning et al. (2016) evaluate three scenarios with respect to the 2°C target. The 2°C target aims to keep the average global temperature rise below 2°C by 2050 compared to pre-industrial temperatures (European Commission, 2016). However, in de Koning's work, the consumer behaviour is captured within three different scenarios which consist of different model parameters (input values and model factors). To expand the understanding created by de Koning the consumers could also be modelled in more detail rather than represented by a set of parameters. Another feature of de Koning's work, which could be expanded, is technological change. De Koning represents technological change by manipulating the technological efficiencies by extrapolating historical trends.

1.6 Structure of this thesis

This thesis consists of two major stages. Chapters three and four have a theoretical orientation and the chapters five and six are design oriented. The theory stage of this thesis aims to establish definitions and research the state-of-the-art methods used to capture input-output analysis, and supply- and demand-side dynamics. The theoretical stage is followed by the design and implementation of the integrated model. The implementation is thoroughly tested and evaluated to assess both the value of the integration and the cost of the full implementation of the conceptual model. Chapters seven and eight recapture all major findings and present the proposition of some focal points for future research.

Chapter 2: Research approach

The second chapter describes the research approach used. In summary, the research approach is as follows: the research goal is an integration, the first step is to decide what to integrate, the second step is how to integrate, and the final step is the design of the actual integrated model. The first section of this chapter provides the problem statement along with the goals of this thesis. The problem statement was synthesized based on the information presented in chapter 1; insight in structural changes of the economy is needed but econometric tools for analysis of such changes lack dynamic features. The goals of this thesis are presented on two levels – the societal goal and the scientific one. The societal goal is to build understanding of the implications of transition to a circular economy while the scientific goal of this thesis is to integrate dynamic features in currently used econometric analysis tools. The second section of this chapter defines the main research question along with decomposition into sub questions. The third section of this chapter presents the research methods that are applied to answer the research questions and to the software tools that are used. Finally, the scientific relevance of this thesis is discussed in the fourth section.

2.1 Problem statement and research goals

Section 1.2 describes how our economy is not sustainable on the long term when average resource depletion rates are structurally higher than the average replenishment rate of these resources. The transition to a sustainable, circular, economy will require drastic changes in the economy; both in the production system and in the consumer population of the economy. These two sides of the economy, the production system and the consumer population, are referred to in this thesis as the supply-side and the demand-side of the economy. Supply-side dynamics refer to changes in the production system. Examples of changes in the production system can be learning effects, increasing resource efficiency, innovations; these are changes in production technology that alter the input requirements of a production process. Demand-side dynamics refer to changes in the population, which lead to a changed demand for final consumption. These demand-side dynamics encompass not only the demographics like age and size of the population but also psychological processes, which drive the individuals' (economic-) decision making. Any insight and understanding of the required changes in the economy can be valuable. Most research in the field of the circular economy is limited to the partial consideration of the economy. To fully understand the implications of the circular economy the research should analyse the full value chain and interactions between different value chains of the economy; properly considering the complex dynamics of an economy. Simulation models can help in building this understanding but the costs of building these models can be high.

Data collection of the trade relations between industries and their associated environmental impacts would be a major cost factor in a simulation model. Fortunately, data is being collected for several decades by almost all national statistics agencies around the world in the form of input-output tables. In recent years many input-output databases have been harmonised, the EU uses the same format among all member states (Eurostat, 2008a). With these input-output tables, currently, analyses of future development are being conducted based on linear extrapolations. Demand-side dynamics are represented by changing the final demand values which changes demand for intermediate products; in this way the whole throughput of the entire economy is adapted. The change in final demand should be represented dynamically rather than statically as a scenario's input parameter. Typically, supply-side dynamics are reflected in input-output analysis in a similar way; per industry the added value of the economic activity is either kept constant or based on extrapolations of historic data.

The problem statement for this thesis follows from the knowledge gap that was presented in section 1.5, in short, the problem statement is formulated as:

Problem statement:

Transition to a circular economy requires drastic changes in the economy, thorough analysis of the implications of these changes is needed. However, the main macro-economic tool for the analysis of changes in the economy lacks realistic representations of supply- and demand-side dynamics.

The high-level, societal goal of this thesis is to build understanding of changes in our economy, which are caused by transitioning to a circular economy. This understanding is generated through development and use of an exploratory simulation model. A simulation model can help to build understanding of the cost and the magnitude of the required efforts to transition to a circular economy. What actions could be taken to promote the transition and what effect would these actions have on the economy?

The research goals are divided into three steps: to select the dynamics that will be integrated with the input-output analysis framework, to synthesize an integration approach and to design the integrated model. The dynamics that will be integrated are selected according to literature on technological change and consumer demand. The search for an approach to the integration is not trivial; a model of an economy is rather large thus the integration of the dynamics should be well structured. To build a simulation model of an economy that integrates dynamic features into input-output analysis, some concrete methodological challenges need to be addressed; overcoming these methodological challenges is the subject matter of this thesis. The integrated model should account for proper information transfer between models, proper alignment of model boundaries and etymological alignment. This integration approach is used to design the integrated conceptual model. This is the main deliverable of this thesis. The conceptual model represents a model of a national economy, based on the corresponding input-output data, which accounts for dynamics of the supply- and demand-side of this economy.

2.2 Research questions

As mentioned in section 2.1, the research objective is explorative; to explore the feasibility and relevance of a national trade model, based on input-output analysis, which captures dynamics of the supply-side and demand-side, to analyse alternative future scenarios of economic development. The main research question of this thesis is formulated as:

Research question:

How can supply- and demand-side dynamics be integrated with the input-output analysis framework?

This main research question is broken down into four sub-questions, which are the following:

1. *Which input-output analysis methods- and databases are adequate for a national trade model with dynamic features?*
   There are multiple input-output databases that differ in the resolution of the data and update methods. This question relates to the uncertainty, which is embedded in the data and the table update methods. High resolution gives a high level of detail of the data and reduces uncertainties, but high resolution also causes more time lag which increases uncertainties. The update methods are the mechanisms by which new table values are projected for changed demand. The objective of this sub-question is to review and select appropriate input-output analysis methods and an input-output database.

2. *How to adequately represent supply- and demand-side dynamics in the input-output analysis framework?*

This sub-question relates to the dynamics that could be incorporated to represent the supply- and the demand-side in input-output analysis. Which dynamics should and could be represented? And how can these dynamics be captured into a model? This sub-question aims to review literature on consumer demand and technological change. This review helps to select relevant concepts that should be represented in the input-output analysis framework.

3. *How can multiple, different models be integrated into a single model of a national economy?*
This sub-question is focussed on multi-modelling; a purely methodological question. The model produced by this research could have multiple sub-models interacting with each other; different sub-models representing the supply- and demand-side dynamics and the input-output analysis framework. These different models are likely to take different perspectives; the input-output analysis framework is defined from a top-down perspective while supply- and demand-side dynamics could be defined from a bottom-up perspective. Integrating multiple models as intended for this thesis brings challenges, arising from integrating the top-down and bottom-up perspective. This sub-question aims to establish an approach to combining the different models of different perspectives.

4. *What are the costs and added value of integrating supply- and demand-side dynamics into the input-output analysis framework?*
This sub-question is closely related to the main research question. After experimentation with a stylised implementation of the conceptual model in a case study, a conclusion can be drawn with respect to the implementation and added value of integrating the dynamics into the input-output analysis framework.

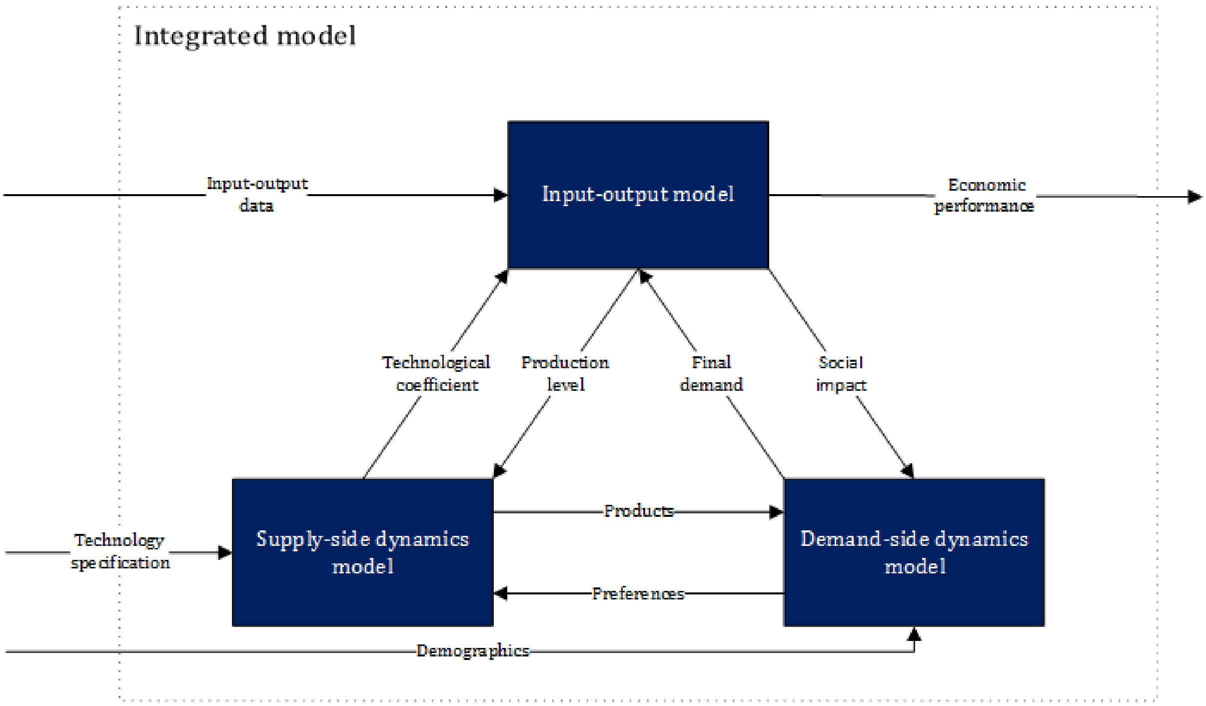


Figure 2.1: abstract outline of the conceptual model of the integrated model

Figure 2.1, above, shows an abstract, low resolution outline of the conceptual model. Three different models exchange information; what exact information is exchanged and how it is used is subject of the research. The inner workings of these models, in figure 2.1 displayed as a “black box”, are subject of the first two sub-questions listed above.

2.3 Research methods

The main research question can be answered with the answers to the four sub-questions. This section, first of all, provides the research methods per sub-question along with a visualisation of the research steps. Secondly, this section introduces the agent-based modelling formalism as a way to represent the supply- and demand-side dynamics. And finally, it presents the software tools that are used to implement and analyse the model.

2.3.1 Research methods per sub-question

Desk research is conducted to answer the first two sub-questions. In the form of a literature review, formal representations are established of the input-output framework, the demand-side dynamics and the supply-side dynamics. Many (environmentally extended-) input-output methods and databases exist, and they have different properties. Based on the selected input-output tools, requirements for the models of the dynamics are formalised to suit the input-output model. The input-output data is expensive and not flexible; therefore, first the input-output framework is selected first and the supply- and demand-side models are regarded as "ancillary models".

The first two sub questions should be answered in order to formulate an approach for integrating the three models. Based on this integration approach, a conceptual model, which captures a national economy based on input-output data, can be designed. The modelling goal of the conceptual model is the same as the goal Leontief (1974) formulated for his world trade model, it is to understand the implications of structural change in an economy. The third sub-question can be answered with a combination of literature research into multi-modelling and design of the conceptual model.

To answer the fourth sub-question an implementation of the conceptual model is required. This implementation will take the form of a proof of concept, a stylised version of the full model. Due to time and data constraints the implementation of the full model will be restricted to a stylised version. The modelling goal of the concept proof is to understand the implications of design choices of the conceptual model on the outcomes of the model. The demand-side dynamics, which have an effect on the economy by changing demand patterns, can be represented with the help of simulation tools. At the same time the supply-side dynamics that change the supply patterns can be simulated as well. The feasibility and relevance of the conceptual model can be evaluated based on the stylised model. Feasibility in this context has multiple facets. Three facets are particularly highlighted in this section: feasibility in terms of data that is reasonably available, feasibility in terms of efforts required to implement such a model and finally feasibility in terms of computational requirements (the model should be 'tractable'). Relevance in this context has two meanings: relevant in terms of the model outcomes (it could be that there is so much uncertainty that the model is highly sensitive, or scenario outcomes might overlap), or relevant in terms of the practical value of the model. Provided that the research concludes that the model is feasible and relevant than any economy with available appropriate input-output tables could be easily modelled by using the corresponding input-output data as parameterisation.

The proof of concept is an implementation of a case study. The availability of data is the main requirement for this case study. Among the required data for an implementation is input-output data, appropriate demographic data, and technology specification data. The proof of concept will model the Netherlands between 2009 and 2060. This time period was chosen because the data is available for that period. For instance, in the most recent publications of extended input-output databases, only the economic data is available, not the environmental data; therefore, an earlier release of the input-output data was used. The time period ends at 2060 because the population projection of the Dutch statistical office is available up to 2060. The case study focuses at the CO_2 emissions caused by the production system. The resource cycle analysis is not possible yet using input-output data because there are no waste streams represented in any database. Environmentally extended input-output tables report certain pollutants, like CO_2. On grounds that CO_2 emission is a well-known issue, this pollutant was chosen as the main focus of the proof of concept.

Figure 2.2 below shows the research flow diagram, which summarises this sub-section.

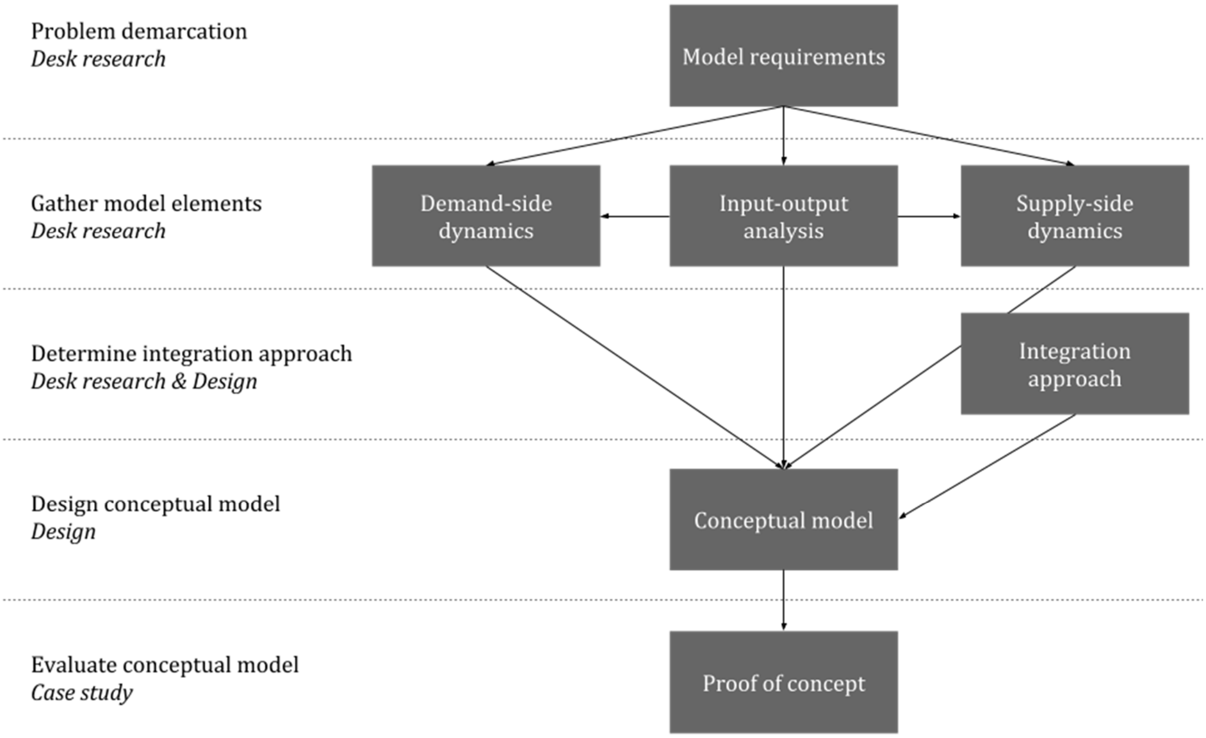


Figure 2.2: Research flow diagram

2.3.2 Bottom-up modelling with agent-based modelling

This subsection briefly introduces the agent-based modelling framework. A more elaborate introduction to agent-based modelling can be found in the tutorial paper from Macal and North (2014). Agent-based modelling is a modelling approach where individual agents and their behavioural rules are modelled in an environment; their interactions lead to higher, system level behaviour, which are subsequently analysed. An agent-based model typically consists of a set of agents, a set of the agent's relations and interaction methods, and the agents' environment. This perspective of modelling is generally referred to as bottom-up modelling; the low-level system components are described, and their interactions lead to the observable high-level system behaviour. Bottom-up modelling takes the opposite perspective of top-down modelling, where high-level system behaviour is considered and broken down until a desired level of detail, or resolution, is obtained. Figure 2.3 below, Nikolić (2009, p. 44), illustrates these different conceptual levels, the high system level, the low agent level and the interaction networks in the middle. An agent (inter-)acts autonomously, pro-actively and reactively; usually agents are conceptualised in a human-like way capturing notions like knowledge and belief (Woolridge & Jennings, 1995). An agent-based model does not focus on reaching some desired end-state, like top-down models are often designed to do; as (Nikolić & Kasmire, 2012, p. 56) state, *"...models become less about seeing what happens and more about seeing what it takes to make something specific happen".* This concurs with the goals of this thesis, as stated in section 2.1; not only to gain insight in the structural changes of the economy following from input-output analysis but also seeing what it would take to move to a circular economy.

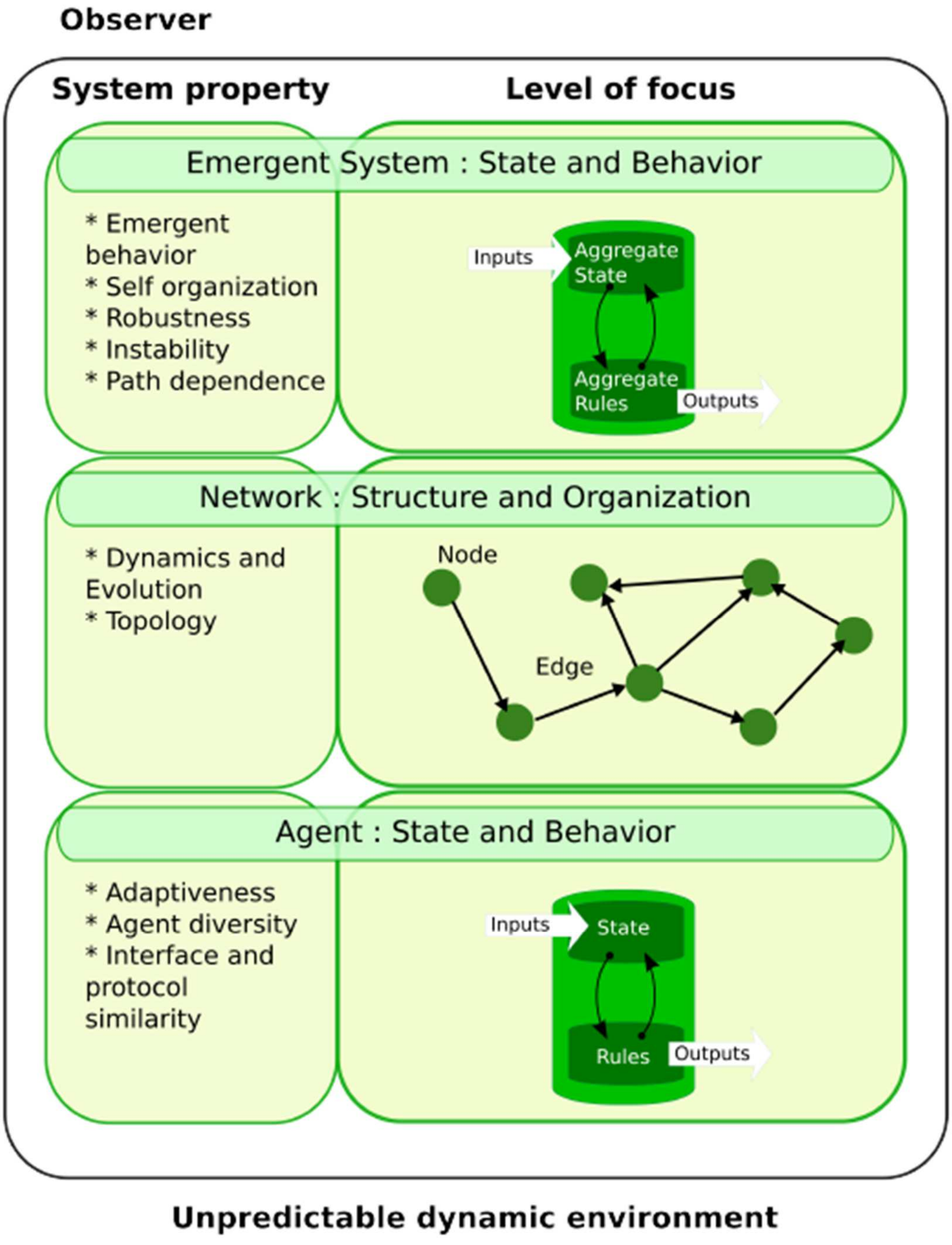


Figure 2.3: Conceptual levels of a system (Nikolić, 2009, p. 44)

The convention of validation in the simulation field is based on statistical methods. In agent-based modelling, validation with statistical methods is very difficult in practice due to the limited amount of real-world data combined with large input-parameter spaces (Louie & Carley, 2008). Alternative methods of validations are provided by (Nikolić, van Dam & Kasmire, 2012, p. 127); among these methods are historic replay, face validation by experts, literature validation and model replication.

Within the economics field, some authors argue to move away from, and are moving away from, equilibrium models. Colander, Holt and Rosser (2004) put it: "*We argue that economics is moving away from a strict adherence to the holy trinity—rationality, selfishness, and equilibrium…*" (p. 485). The authors point out that economics starts to take in the notions of dynamics and complexity theory (Colander, Holt & Rosser, 2004). Mirowski (2002) links the shift away from equilibrium models to the rejection of neo-classical economics since the 1980's; when equilibrium thinking was replaced by concepts like bounded rationality. Evolutionary economics, proposed by Nelson and Winter (1982), is founded on the idea that economic processes should be described as the interactions between firms, traders, consumers, and several other institutions. Nelson and Winter state that the evolutionary economic approach should incorporate economic micro foundations, and the model as a whole should reproduce aggregate parameters; the lowest system level is described, the micro foundations, which can explain the system level behaviour. Agent-based models for economic systems have been proven to be able to describe those systems well; Tesfatsion argues that the agent-based dynamic description can directly implement empirical insights like behavioural dispositions and institutional arrangements (Tesfatsion, 2006). In her earlier work, Tesfatsion (2002) argues that an economy should be regarded in the perspective of complex adaptive systems; agent-based modelling is the most suitable modelling perspective for complex adaptive systems (Holland, 1992a). Moreover, Axelrod (1997) argues that agent-based modelling is the only appropriate simulation formalism to represent decision-making that is not fully rational; consumers can be defined as decision makers under bounded reality, therefore agent-based modelling seems preferable for modelling the demand-side dynamics.

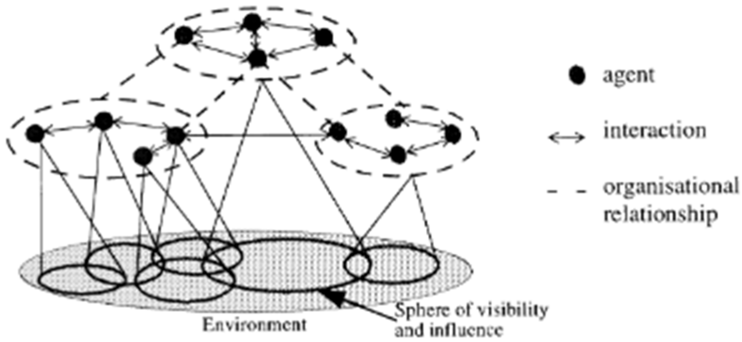


Figure 2.4: Conceptualisation of agents acting in an environment (Jennings, 2000, p. 281)

The suitability of agent-based modelling for any given system is evaluated based on some criteria; for instance, van Dam and Lukszo (2006) propose five criteria for infrastructure systems: "*(1) There are multiple decision makers, (2) Decision makers not only react to events from outside, but also have their own goals and objectives, (3) Communication plays a role in the decision making process, (4) The problem has a distributed character, (5) The subsystems (consisting of one or more agents) operate in a highly dynamic environment*" (p. 891). Heckbert, Baynes and Reeson (2010) state several conditions for agent-based modelling to be the most suitable tool to represent an ecological economy; the system contains dynamic feedbacks, the system can evolve, the agents act autonomously, the agents interact, the agents are heterogenous and finally the agent's decision making is adaptive. To sum up the conditions of van Dam and Lukszo, and Heckbert, Baynes and Reeson, the system must consist of interacting agents and these agents must conform to the definition of an agent. For instance, the definition of an agent that Jennings (2000) gives: Agents are problem-solving entities, situated in an environment, strife to achieve goals, are autonomous and flexible. Jennings provides a quite insightful conceptualisation of an agents acting in an environment, which is shown above, in figure 2.4.

2.3.3 Software tools

The technical analyses in this research will be conducted to assess the meaningfulness of the conceptual model with the use of different software tools. After the conceptual model is designed, a proof of concept is to be implemented in NetLogo, an open source agent-based modelling environment (Wilensky, 1999). The data analysis will be conducted with the use of R. The sensitivity analysis is to be done using a python package called the EMA workbench (Kwakkel, 2017). The EMA workbench is especially useful since it provides, among many other features, off-the-shelf sensitivity analysis methods and it can connect to NetLogo (and, again, to many other simulation tools).

2.4 Scientific relevance

The scientific relevance of this thesis lies in the integration of dynamics into existing econometric tools. This thesis addresses the lack of dynamics by investigating the integration of supply- and demand-side dynamics in input-output analysis tools. With the use of simulation models, the dynamics, named by Duchin (2005), can be integrated into a national trade model, which is parameterised by underlying input-output tables. A larger geographical region like a continent or even the entire planet can be represented through instantiating multiple national trade models based on different countries' input-output tables and linking them together.

Integrating dynamic features into the input-output analysis framework is not straightforward, as it might seem according to figure 2.1, due to the different perspectives. The difficulty lies in the alignment of the models. Input-output analysis takes a top-down perspective; where the economy as a whole is broken down into smaller parts until the desired resolution is attained. Dynamics representing demand- or supply-side mechanics are likely to take the opposite, bottom up perspective; where the properties and behaviour rules of small parts are defined and the interactions of these parts lead to higher level, system-, behaviour. Representation of these dynamics with bottom-up or top-down models will be substantiated in their respective chapters; the argumentation follows the recommendations of van Dam (2009), that bottom up representations suit systems of distributed character in a dynamic environment. Integration of top-down and bottom-up perspectives is possible, and it has been done before, see for example (Davis, Nikolić, & Dijkema, 2009).

The integration of these dynamic features into the, static, input-output analysis framework follows the philosophy of the CoSEM master's programme. Input-output analysis uses a set of linear equations to describe an economy while an economy is a clear-cut example of a complex system. The CoSEM master's programme focusses on the development of skills, which help to deal with such complex systems. The economy is regarded as a complex system in the thesis, and with the use of the methods provided by the CoSEM programme, analysis on this complex system is to be conducted to build understanding of the dynamics of the system. The reference list of this report might indicate the multitude of disciplines that are incorporated in the research. The CoSEM programme mainly focusses on the analysis of socio-technical systems; and even though the institutional aspects of an economy are scarcely represented in this thesis, the human aspect of the economy is explicitly added to the framework.

Chapter 3: Representing a national economy's production system in the input-output analysis framework

This chapter reviews the literature on input-output analysis; to substantiate design choices for the model that is subject of this thesis. This model captures a national economy with endogenous supply-side and demand-side dynamics to analyse structural changes incurred by a transition to a circular economy.

The first section of this chapter digs into the fundamentals of input-output analysis. The second section describes the way input-output analysis is applied. First, it demonstrates the static framework and second, it shows the dynamic framework and its relation to the static framework. The second section concludes with extended input-output frameworks. The third section of this chapter is dedicated to sources of input-output data and their features. It discusses some databases covering the Netherlands and sources of uncertainty in input-output data as well as the way this uncertainty is regarded in the input-output analysis framework. The final section of this chapter summarises the design choices that appeared throughout this whole chapter for a national trade model based on endogenous supply- and demand-side dynamics

Summary

Input-output analysis has been used for many years by statistical offices to report economic performance and to analyse structural changes to economies. An input-output table shows an economy's industries in the rows and columns; each cell shows the trade flow between the corresponding industries. Input-output analysis is based on linear algebra, the input-output table is structured as a linear problem where each of the trade flows sum up to the total sectoral output. In input-output analysis the main question is, how do the intersectoral trade flows change given a certain final demand change? In input-output analysis the input-output table gives information on the current trade flows under current final demand; given a changed final demand, how do these trade flows change? Input-output analysis holds under two key assumptions: (1) the output that a sector produces is fully dependent on the input that this sector consumes and (2) the proportion of required inputs for one unit of output remains unchanged, regardless of the total output. Some dynamic methods of input-output analysis exist; however, these methods are mainly several time steps of the conventional input-output analysis, based on Computable General Equilibrium models.

Many databases containing input-output tables exist; they differ in the level of aggregation of sectors and their time lag. The input-output databases for economic analysis are published by statistical agencies like Eurostat; input-output databases focussed on environmental impact modelling are research projects like WIOD and EXIOBASE.

Uncertainty in input-output data is under-addressed in input-output databases. Several researches have drawn this conclusion, but no input-output database addresses the uncertainty embedded in the data. Quantifying the uncertainty in input-output analysis is practically impossible; approximations are very crude. From a qualitative point of view, literature points out that there is a paradox; disaggregation and aggregation of sector detail both increase and decrease uncertainty in input-output data.

3.1 Introduction to input-output analysis

In the first section of this chapter, the general input-output framework is presented. First, the fundamental mathematics of input-output analysis are demonstrated. The mathematics are first shown in terms of general equations, following these equations the matrix notations are given. Based on these equations the main method for solving input-output models is shown; this method solves the linear problem using matrix algebra. An alternative method for solving input-output models is numeric, based on a power series approximation. This alternative method is described in appendix A.1.

3.1.1 The fundamentals of input-output analysis

The input-output analysis framework was developed by Wassily Leontief (1936); the framework aims to provide insight in the structure of a national economy by showing the interrelations between the sectors of economic activities (Leontief, 1986). The core of input-output analysis is the input-output table. This input-output table shows the trade flows, in monetary terms or physical terms, between the different sectors of the economy.

Input-output analysis breaks down an economy into sectors. Sectors are also referred to as industries; in input-output analysis literature the terms sector and industry are used interchangeably. The decomposition into sectors is a design choice; national statistical offices, which collect the data for input-output table compilation, decide on the sector division. Eurostat has harmonised rules for the European statistical agencies on sector definitions named NACE Rev. 2 (Eurostat, 2008b); these sector definitions are used by national statistical agencies for the data that they supply to Eurostat. The example input-output table shown in figure 1.2 in the introduction of the thesis, on page 5, shows an input-output table with four sectors, agriculture, industry, mining and services.

Trade flows between sectors are called intermediate or intersectoral trade (z_{ij}); these values of intermediate trade are the core of the input-output table. The remaining trade that occurs in an economy is the trade to final demand. Final demand (f_i) means demand for products for other reasons than using these products as input for another production process or transformation into another product. Examples of final demand are consumption by the population, government purchases, investments or export. Final demand is usually presented separately in an input-output table in one or more columns on the right depending on whether the input-output table discerns one or more categories of final demand.

Reading an input-output table from the perspective of the rows shows for the sector associated to that row which other sectors, shown in each column, consume its output and how much of its output. Reading an input-output table from the perspective of the column shows for that sector which input's it consumes from other sectors and how much. The total output (x_j) of each sector is calculated as the sum of a sector's output to each of the other sectors plus that sector's output to final demand. The total output of sector i is computed with the following equation 3.1, the sum of supply to other sectors as intersectoral trade and final demand.

$$x_i = \sum (z_{ij}) + f_i \tag{3.1}$$

A fundamental assumption for input-output analysis is that the output of a sector is fully dependent on the input that this sector consumes multiplied by a scalar (Leontief, 1986); this scalar is called the technological coefficient (a_{ij}):

$$a_{ij} = \frac{z_{ij}}{x_j} \tag{3.2}$$

The main question in input-output analysis is how the intermediate trade flows change under a given change in final demand; this final demand is seen as exogenous. Another key assumption in input-output analysis is that these technological coefficients are constant for changing levels of sector output (Leontief, 1986). In other words, output is produced from inputs in fixed proportions in the input-output analysis framework. With this assumption of fixed technical coefficients, equation 3.2 can be rewritten and substituted in equation 3.1 to compute the total output of a sector:

$$x = a_{n1}x_1 + \cdots + a_{ni}x_i + \cdots + a_{nn}x_n + f \tag{3.3}$$

In equation 3.3 above, f and a are known while x is unknown; f is given and a is deduced from the initial situation's data and assumed to remain constant. In order to find x, the equation is re-arranged into equation 3.4 below. Note that this notation yields the same format as the input-output table, with on the left-hand side the intersectoral trade flows and the right-hand side of the equation is the final demand:

$$-a_{n1}x_1 - \cdots - a_{ni}x_i + \cdots + (1 - a_{nn})x_n = f \tag{3.4}$$

Dividing out the technological coefficients (a) from equation 3.4 above would leave sector output (x) as a function of final demand (f), which is given.

3.1.2 Input-output analysis using algebraic solutions

Input-output analysis uses linear algebra based on the definitions and equations that were shown in section 3.1.1. The intersectoral trade scalars, z, for all sectors is formulated as matrix **Z**. The final demand is formulated as vector **f** and the total output of sectors is formulated as vector **x**. To find **x**, a set of linear equations is solved. First, the technological coefficients are computed in the technological coefficient matrix **A**. In matrix notation, the technological coefficient matrix is found with equation 3.5 below.

$$\mathbf{A} = \mathbf{Z}\hat{\mathbf{x}}^{-1} \tag{3.5}$$

To find new levels sector-output based on changed levels of final demand, each of the technological coefficients are divided by the output; by multiplication of the inverse matrix. To reach the same structure of equation 3.4 the technological coefficient matrix **A** needs to be subtracted from its identity matrix **I** before being inverted. The resulting matrix, $(\mathbf{I} - \mathbf{A})^{-1}$ is known as the Leontief inverse, **L**. Using the Leontief inverse, new levels total output per sector (x) can be found with the new level of total demand due to the assumption of fixed proportions; whatever the level of output, inputs are always consumed in the same proportions. Therefore, the new level of inputs is divided in the same proportions as the initial, given, input-output table. This is the general model of input-output analysis, shown below in equation 3.6.

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{f} = \mathbf{Lf} \text{ or } \Delta\mathbf{x} = \mathbf{L}\Delta\mathbf{f} \tag{3.6}$$

3.2 Application methods of the input-output analysis framework

The general input-output analysis framework, presented in the previous section, 3.1, is mostly applied in its general form as presented in equation 3.6 to analyse changes in the sector outputs induced by a changed final demand. This section shows how this principle is applied in static and dynamic models. Finally, a presentation is given of some input-output extensions; these extensions show impacts for non-economic factors like environmental- or social impacts.

3.2.1 Analysis with the "static" input-output framework

Input-output analysis is centred around the question, how do the intersectoral trade flows change under a given final demand change. In terms of the equations given in section 3.1 this question would be to solve equation 3.6; finding a new intersectoral trade matrix using the Leontief inverse. This analysis starts with an input-output table containing all values for the intersectoral flows z along with a final demand vector for that input-output table. Using the input-output table and final demand vector, the technological coefficient matrix is computed with which the Leontief inverse matrix is determined. Because of the assumption of fixed technological coefficients any new vector for final demand can be split into new intersectoral flows. Economies of scale are disregarded because these coefficients, or in other words the proportions of inputs needed for a unit of output, are assumed to be non-responsive to changes in output flows. This type of analysis is called impact analysis; impact analysis was first conducted by Leontief (1951) and is still applied to this day. The input-output tables are measured by statistical agencies and used in these studies; new final demand vectors are in this analysis endogenous to the model. Impact analysis finds the response or impact of the economy or specific sectors to a certain final demand change; this final demand change is given usually based on a scenario.

Another form of analysis that is conducted on the "static" framework is structural decomposition analysis, SDA. Structural decomposition analysis goes further than impact analysis in the sense that it tries to dis-aggregate components that are analysed. Dis-aggregating components adds precision to the analysis which could lead to a more substantiated conclusion from the analysis; dis-aggregation is mainly focussed on final demand or the technological coefficients. A most straightforward example of how the components are dis-aggregated is decomposing the technological coefficient matrix $\mathbf{A}$. Changes in the technological coefficient matrix $\mathbf{A}$ are determined based on historic data. In this way some form of technological change is resembled in the analysis. The input requirements for a changed situation is computed with the following equation, 3.7 (Rose & Casler, 1996).

$$\Delta(\mathbf{I}-\mathbf{A})^{-1} = (\mathbf{I}-\mathbf{A}^{\boldsymbol{t}})^{-1} - (\mathbf{I}-\mathbf{A}^{\boldsymbol{t-1}})^{-1} \tag{3.7}$$

3.2.2 Dynamic applications of the input-output framework

The distinction between static and dynamic input-output analysis used in this thesis is based on the incorporation of the dimension time. Where static input-output analysis looks at the change of the intersectoral flows, dynamic input-output analysis looks at the development of intersectoral flows over time. Static input-output analysis takes the current situation and reviews changes based on some exogenous parameters which represent a new situation. Dynamic input-output analysis takes an initial situation and reviews how this develops over time based on some exogenous parameters, developments or other influences. These developments over time are mainly represented as different model states of different time steps, for instance years. For each year between the initial time and final time step of the model, new data is computed. Computations are typically based on the static form of input-output analysis; some non-linear forms of input-output analysis have been developed (Dietzenbacher, 1994). Dietzenbacher shows that the conventional input-output analysis model, which is linear, can be rewritten as a non-linear eigensystem; however, this approach has not been implemented in practice.

Appendix A.2 presents three different dynamic input-output analysis methods. All the dynamic frameworks that have been presented in this appendix are based on General Computable Equilibrium models. Future developments in dynamic input-output simulations are in the direction of harmonisation of datasets, larger datasets, incorporating more sectors, regions and factors (Wiedmann et al., 2007; Dietzenbacher et al., 2013b). Duchin mentioned, a solution of these CGE models "*…corresponds to an optimal static allocation of resources.*" (Duchin, 2005, p. 160). She goes on to mention that "*Other dynamic phenomena include changes in technologies and lifestyles: technological innovation and the international transfer of technologies, which affect production capabilities; and innovations in lifestyles and the international emulation of lifestyles, which affect consumption patterns.*". These phenomena are subject to be represented in the integrated model in the next two chapters of this thesis on demand-side dynamics and supply-side dynamics modelling.

3.2.3 Extended input-output analysis frameworks

Conventional input-output analysis focusses on how the intersectoral trade flows change as a response to changed final demand; in other words, the impact analysis of final demand change. Just as intersectoral trade flows, any other impact can be modelled. For the input-output analysis framework, many extensions have been developed and are being maintained to reflect impacts to non-economic factors. Just like economic input-output analysis, extended input-output analysis reflects the impact of sectors on any factor per unit of output. Examples of such impacts are social impacts and environmental impacts; accounting for the contribution to employment, wages, air pollution, land use, water use, waste generation and many more factors. As Leontief (1970a) proposed such impacts are highly likely to be dependent on economic activity.

Social accounting extensions account per sector for factors like wage and consumption of "institutions" (Pyatt, 1991); institutions in this context are legal entities who own assets and incur liabilities and engage in transactions, like households, companies and different bodies of government. Households are seen as providers of labour which adds value to production and are responsible for the major part of final consumption (Miller & Blair, 2009). In the input-output analysis framework, rows and columns can be added to account for these factors. Depending on the design of the framework more or less factors are accounted for and represented in the tables. Using social accounts, analyses can be conducted on the impact of changes in for instance labour force or wages on an economy.

Environmentally extended input-output tables (EEIOT) show per sector the emissions of certain pollutants per unit of output. Environmentally extended input-output analysis appeared in 1970 but the field has seen a large growth over the last decade. Searching the Scopus database for "input-output analysis" in the field of environmental science shows this large increase in the last decade. Figure 3.1 below shows the number of documents that have been published in Scopus per year in the field of environmental science relating to input-output analysis up until 2017. Using these tables, analyses can be conducted of the impact of certain demand changes on the pollution but also analyses reviewing what it would take from the economy to restrict pollution to a certain level. These types of analyses can look at historical data, project future data or consider impacts of structural changes of an economy. An example of research analysing historical data looking into the emissions of sectors is the work of Butnar & Llop (2011); they apply structural decomposition analysis to environmentally extended input-output data to show that total emissions increased because the amount of demand increase offsets the efficiency increase. An example of research that attempts to forecast a future situation is the work of Choi, Bakshi and Haab (2010); in their paper they analyse the effects of a carbon tax on the US economy. A final research that is mentioned here is the work of Mattila, Pakarinen and Sokka (2010); they show the benefits of industrial symbioses in terms of environmental impact based on input-output analysis.

A special form of environmentally extended input-output tables are waste input-output tables; these tables show waste streams that are created by associated sectors. The concept was proposed by Nakamura (1990). Any analyses named before in this chapter can now be related to waste streams; alternatively, waste streams can be related to any of the economic, social or environmental factors named in this chapter, as long as the input-output data accounts for these factors. An example of an input-output analysis is Matsubae, Nakajima, Nakamura and Nagasaka (2010); they analyse the impact of metal recovery from waste on CO_2 emissions.

3.3 Input-output data sources and their features

Input-output data is being collected by almost all national statistical agencies; higher level aggregations or larger geographical areas are also published by for instance the World Input-Output Database or the Asian Development Bank. This section will introduce input-output databases which contain data for the Netherlands and present their features; the resolution of the input-output table (the number of sectors that are discerned), which social and environmental factors are accounted for, the time lag of the data and their update frequency. This section is limited to databases which contain data for the Netherlands because the aim of this thesis is to provide a proof of concept by modelling the Netherlands. The second part of this section is dedicated to the uncertainty embodied in input-output databases.

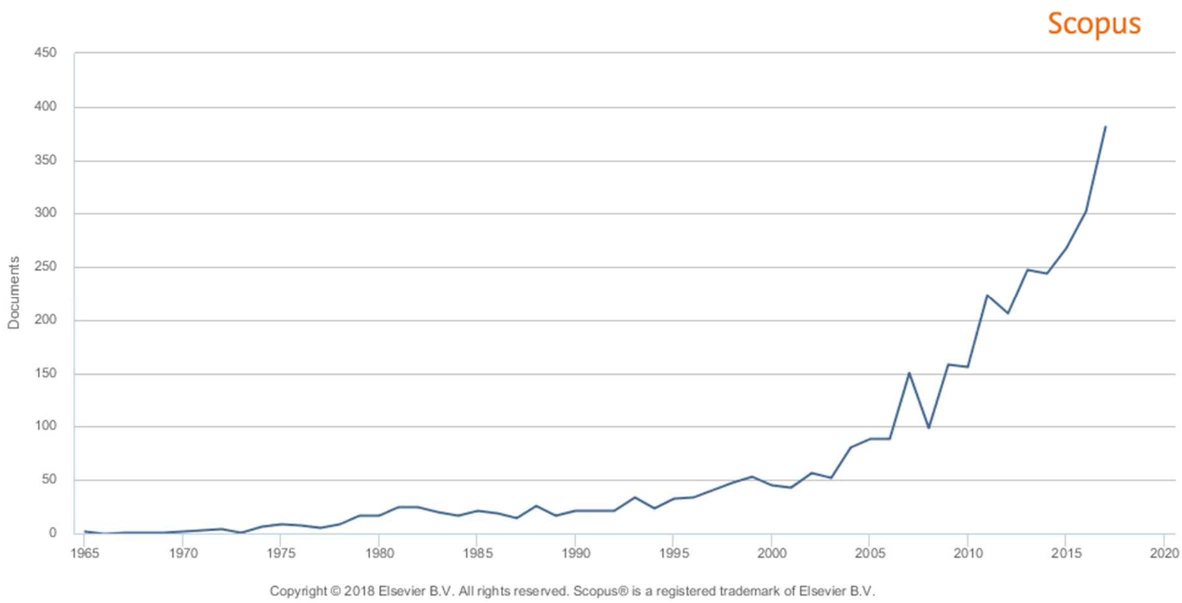


Figure 3.1: Publications in Scopus per year in the field of environmental sciences relating to input-output analysis

3.3.1 Input-output databases covering the Netherlands

An obvious data source for input-output data of the Netherlands is the database maintained by the national statistical office, CBS (2016). The focus of this database is economic analysis; the impact of factor changes on the structure of the economy. The CBS input-output database discerns 76 different sectors. Social factors that are represented in the database are those that would be represented for economic analysis: wages and consumer demand. No environmental factors are accounted for in the CBS database. The most recent table in the CBS database dates from 2015; the database is updated every year.

Eurostat publishes input-output databases for every member state of the EU, candidate countries Macedonia and Turkey and EFTA country Norway (Eurostat, 2014). All input-output tables in the Eurostat database are compiled according to the same framework; they all share the same features. The resolution used by Eurostat is 65 different sectors. The Eurostat input-output database is used for economic analysis; there are separate EU projects that serve non-economic analyses using input-output tables. Therefore, the Eurostat input-output database contains no social or environmental factors. The most recent data is from 2010; new data is published yearly.

A database with the explicit goal of analysing environmental impacts is EXIOBASE or EXIOPOL (Tukker et al., 2013). EXIOBASE is initiated by the EU and still being maintained; it contains data for all 27 EU member states and an additional 16 other countries and 5 “rest of world regions” to account for the whole world. EXIOBASE has the highest resolution of all environmentally extended input-output tables (Tukker et al., 2013); it discerns 129 sectors, 80 resources and 40 emissions. The economic data is the same as presented in the Eurostat database since EXIOBASE builds on the Eurostat data; in terms of social factors EXIOBASE extends the Eurostat data by discerning three skill levels for employment data. Due to its high resolution, EXIOBASE has a large time lag and a low update frequency; the latest data is from 2007 and the only other dataset is from 2000.

Similar to EXIOBASE, the WIOD project is set up to analyse environmental impact in relation to economic development (Timmer et al., 2015; Dietzenbacher et al., 2013b). The WIOD project has a significantly lower resolution than EXIOBASE; 35 sectors for 40 different countries are represented. Social factors represented in WIOD are wages and employment by skill type, divided in three skill levels. Environmental factors accounted for are energy use, 8 types of emission to air (CO_2 is broken down in a matrix per sector which fuel type accounts for CO_2 emission and therewith how much is emitted). WIOD is updated yearly and the last data is from 2014. An additional note to be made here is that WIOD's resolution of 35 sectors matches the resolution of the EU KLEMS database (Timmer, 2012); this database gives accounts for economic growth and productivity.

A final database that is worth mentioning here is the NAMEA project, published by CBS (CBS, 2011). This project focusses on waste streams; however, this project is no input-output database. It does follow the input-output analysis framework, but it does not give any intersectoral trade; the database can be seen as a waste vector for different waste categories. NAMEA discerns 25 sectors and seven waste categories. Unfortunately, the NAMEA project has been discontinued in 2011, the latest data is from 2008; there is yearly data from 1995 up until 2008.

3.3.2 Uncertainty in input-output data

Analysis of uncertainty or errors in input-output analysis follows a set of assumptions regarding the nature of the errors in input-output data (Lenzen, Wood & Wiedmann, 2010). This set of assumptions being that uncertainty in input-output data is normally distributed, uncorrelated and that the errors are stochastic. These assumptions originated in early work regarding uncertainty analysis in the input-output analysis framework by Richard Quandt (1958); these assumptions are still being upheld by recent studies on uncertainty in input-output analysis.

Lenzen (2001) provides a clear overview of uncertainties in input-output analysis. Lenzen names eight sources of uncertainty in input-output analysis and provides approaches to approximate all these eight components. Sources of uncertainty in input-output analysis named by Lenzen are: "*(1) uncertainties of basic source data due to sampling, reporting and imputation errors, and uncertainties resulting from (2) the assumption made in single-region input-output models that foreign industries producing competing imports exhibit the same factor multipliers as domestic industries, (3) the assumption that foreign industries are perfectly homogeneous, (4) the estimation of flow tables for domestically produced and imported capital commodities, (5) the assumption of proportionality between monetary and physical flows, (6) the aggregation of input-output data over different producers, (7) the aggregation of input- output data over different products supplied by one industry, and (8) the truncation of the "gate- to-grave" component of the full life cycle.*" (Lenzen, 2001, p. 136).

The first and fourth point, data source uncertainty, is difficult (or practically impossible) to quantify. The reason for this difficulty is that the data on survey errors of the source data is generally unavailable. None of the data sources listed in sub section 3.3.1 provide any information on this uncertainty. In his paper, Lenzen quantifies this uncertainty based on data extracted from a personal communication with the statistical office responsible for the collection of that data. From a qualitative perspective, Lenzen points out that the standard error decreases as the magnitude of the data item increases; in other words, the lower the data source resolution the smaller the uncertainty. This is because there are more data entries summed into this data point.

On the second, third and fifth point, Lenzen mentions that there is also generally no information available; no information on foreign factor input or capital flows. Input-output analysts emphasize that the model assumes homogeneity within sectors; in this way this uncertainty is communicated and left for interpretation.

The sixth and seventh point relates to aggregation uncertainty. As mentioned for the first and fourth point, uncertainty decreases when aggregation increases. Aggregating data brings about its own uncertainty and is discussed by Lenzen. Lenzen mentions that "*In general, the aggregation uncertainty associated with a particular interindustrial transaction A_{ij} from industry i* *into industry j decreases with (1) decreasing number P_i of producers in the supplying industry i, and (2) increasing number p_{ij} of producers participating in that transaction." (*Lenzen, 2001, p. 137). He mentions that in practice p_{ij} can be estimated and that P_i is generally available from statistical offices; for the EU information on the number of producers per industry is published (Eurostat, 2017). For point 7 Lenzen mentions that "*Allocation uncertainties can in principle be overcome by further disaggregation of the input-output model."* (Lenzen, 2001, p. 140).

The eight and last point Lenzen mentions is the uncertainty in impact beyond the factors in an input-output table; for environmental input-output analysis only environmental impacts are considered for production of goods, so called 'gate-to-grave' impacts are left out like decommissioning or demolition. However, Lenzen cites several sources that these impacts are typically negligibly small, under one percent of total lifetime emissions.

In conclusion, either there is no data available to substantiate the uncertainties, the impact of the uncertainty is negligible, uncertainty is decreased by aggregation or uncertainty is decreased by dis-aggregation. In accordance with Lenzen's findings on the lack of data on errors in input-output data, Rey, West and Janikas (2004) mention that the inherent uncertainty associated with input-output data are hardly addressed in applied input-output analysis. Despite efforts like the work of Gerking (1979), who proposed framework to associate input-output data with standard errors. Lenzen quantifies the eight different sources of uncertainty in his paper; most data sources are either very crude or based on crude estimations. However, Lenzen does come up with a number: an average total relative standard error of 85% (Lenzen, 2001).

3.4 Input-output analysis framework for simulating a national trade model with endogenous supply- and demand-side dynamics

Throughout this chapter a good understanding of input-output analysis has been attained. In this final section, some design parameters for an input-output analysis model are be discussed; parameters with respect to a national trade model with endogenous supply- and demand-side dynamics to analyse the impact of a transition to a circular economy. Taking supply- and demand-side dynamic endogenously means that final demand and the Leontief inverse are part of the integrated model. Where conventional input-output analysis takes a final demand vector as given, in the integrated model the final demand vector will be the outcome of the demand-side dynamics model. Conventional input-output analysis assumes fixed technological coefficients; in this integrated model with supply-side dynamics endogenous, these technological coefficients are not fixed but develop over time based on the supply-side dynamics model.

Input-output databases come in many different formats; differing resolutions, non-economic accounts, physical or monetary units, etc. Regarding units, the choice for physical or monetary units is not straightforward. Miller and Blair (2009) point out that generally monetary units are preferable because the measurement of physical units becomes very fuzzy when sectors combine several enterprises, as is the case in input-output tables on a national level. Weisz and Duchin (2006) point out that mixed units should be used, depending on the characteristic output of each sector. In terms of data sources, two obvious candidates exist; EXIOBASE and the WIOD project. EXIOBASE has the highest resolution but the time lag is high, and the update frequency is low. The WIOD project has a substantially lower resolution but because of this low resolution this database seamlessly matches other databases on for instance capital flows (the KLEMS database). Additionally, the WIOD project has a high, yearly, update frequency and has a low time lag.

While EXIOBASE and WIOD cover many non-economic impacts, both are unable to provide complete insight in the waste streams within an economy. These environmentally extended databases give the associated pollution for several individual substances, like carbon dioxide and many more. To be able to fully understand the resource cycle through an economy as shown in figure 2.1; the database must keep track of the level of depletion and the level of replenishment of resources. The level of depletion can be adequately represented similar to environmental impacts in environmentally extended input-output tables. The level of replenishment is not easily represented in the format of input-output tables, because this depends of not only physical capacity of recycling plants but also the waste separation of consumers and the state of natural recycling processes. By modelling the population endogenously in the demand-side model, replenishment of resources can be made explicit to provide a more complete representation of the resource cycle through an economy.

The final demand vector is often not a vector but a matrix, discerning different types of final demand. Consumer demand, government spending, investment and export are four types of final demand that are mostly used. Because the subject of this thesis is a national model, export remains exogenous. Government spending is a function of governmental policy. Also, governmental policies are exogenous to this model. Final demand for investment means final demand for production equipment, working capital, stocks etc.; investment is also kept exogenous to the model. Finally, consumer demand is the main model outcome of the demand-side model. Regarding relative sizes of final demands, historically consumer demand has made up of the largest part of all final demand for developed countries; Miller and Blair (2009) report that in 2013 in the USA, final demand was made up by 71% consumer demand, 15% investment, 19% government spending and -5% export.

The function of the supply-side model is to substantiate changes to the technological coefficient matrix. The model takes the initial input-output table as parameterisation and extracts the technological coefficients from the data. Increased or decreased production efficiency, as well as non-economic impacts, can be a function of capital investments; which can be either scenario based or endogenous to the supply-side model. In case of endogenous investment; databases like the WIOD project provide capital flow data.

In conventional input-output analysis the central question is, how does the structure of the economy change (intersectoral trade), given a specific change in final demand. In this thesis, final demand is endogenous; the central question is changed to, how does the structure of the economy change, given that the circular economy is implemented in a certain way and given the different supply- and demand-side model parameters. The structure of an economy is represented in the input-output table format. The updated input-output tables are computed using the core method of the input-output framework, using the Leontief inverse and a new final demand vector.

Chapter 4: Modelling demand- and supply-side dynamics for a national trade model

In the previous chapter, input-output analysis was presented as a means to analyse the production system of economy. Conventional input-output analysis takes consumer demand and technological change exogenously; in this thesis consumer demand and technological change will be endogenous to the model. The goal of this chapter is to come to a representation of demand- and supply-side dynamics. Demand-side dynamics lead to final demand by consumers, which is to be supplied by the production system. Supply-side dynamics influence the relation between output and input of a sector, which is in other words the technological coefficient. The first section discusses literature on demand-side dynamics; among which utility theory, prospect theory and identity economics. The second section investigates literature on the supply-side dynamics. The third section evaluates the suitability of agent-based modelling to represent the demand- and supply-side dynamics. The fourth section reviews existing (computer-) simulation literature on demand- and supply-side dynamics. The final section presents the framework used in this research to represent the demand- and supply-side dynamics.

Summary

In this chapter, representations are synthesised of the demand- and supply-side dynamics. The demand-side dynamics can be represented using an agent-based model consisting of utility-optimising consumer-agents. Recent studies in neurobiology using modern brain imaging technology show that humans choose between different rewards using a common currency. In economic theory this common currency is known as utility. Macroeconomic behaviour theories on consumer behaviour have expanded the consumer-behaviour literature to account for realistic, empirically valid, behaviour; incorporating bounded rationality, individuals' identity and emphasising imperfect, asymmetrical, information. Consumers can be adequately represented with agents in an agent-based model; they have a certain budget and maximise the utility from this budget, they are flexible in how they allocate their budget and consumers interact with each other in social settings. Consumers attribute utility to changes in wealth rather than a state of wealth; wealth is a function of anything valued by the consumer. As value can be seen quantity, quality and any associated social or environmental impacts with products.

For the supply-side dynamics, agent-based modelling was also shown to be an adequate tool. Supply-side dynamics, or the development of technologies, can be divided into two stages; pre- and post-commercial deployment. The pre-commercial deployment stage of technologies is the stage where a technology is not yet fully developed; where technologies are still innovations. Technological development due to innovation is radical while the development of main-stream technologies is gradual. This gradual development can be described using Wright's law, also known as learning curves. Radical development of innovations is more difficult to describe, mainly because it is not known what inputs will be combined into output in future technologies. A good proxy for innovation are evolutionary algorithms; although some degree of realism is sacrificed. Evolutionary algorithms describe how new technologies are created by combining aspects of current successful technologies and random mutation. Combining these approaches, the total economy's technological development is captured; Wrights law can describe gradual development and evolutionary algorithms propose radical innovations.

4.1 Theories on demand-side dynamics

In order to come to a representation of demand-side dynamics in a national trade model, this section presents a review of literature regarding consumer decision-making. In the first subsection, literature on classical economic demand theory is discussed; classical economics is based on utility theory. The second sub-section presents prospect theory as an additional framework describing the dynamics of consumer decision making. Finally, Identity economics is presented as a theory that explains how social interaction among consumers influences their decision-making process. This section presents the most important findings of the literature review; a more in-depth discussion of utility theory as well as a review of information asymmetry can be found in appendix A.2.

4.1.1 Consumer demand theory in classical economics

Classical economics regards consumer decision making as an outcome of a comparison of rewards in terms of a certain "currency"; meaning that a consumer makes a trade-off which goods will yield the most of this currency. This currency is generally referred to as utility. The validity of utility as a decision-making driver can be demonstrated from a biological perspective. Levy and Glimcher (2012) provide a meta-analysis of several neurobiological studies which all show that the human brain has a "common currency" for choice, analogous to the economic concept of utility. Their review points out that choosing between different rewards is guided by a common valuation path for these different rewards. As will be shown in the following parts of this section, the process of decision making using a common currency adequately fits most economic theories.

The concept of utility goes back a long way. The proposal of the utility-concept is often attributed to Bernoulli in the 18th century; the concept of utility as we know it now was formalised simultaneously by William Jevons, Carl Menger and Léon Walras in the 1870's (Stigler, 1950). Subsequent development of the utility concept can be divided into two streams, the ordinal utility theorist and the cardinal utility theorist. The main difference between the two lies in the structure of utility. Cardinal utility theory quantifies utility as a dimensionless value; ordinal utility theory rejects the quantification of utility but ranks different goods in order of preference. Modern day ordinal utility theory is founded on the works of Samuelson (1938) and Houthakker (1960); the ordinal approach to utility is therefore known as the Samuelson-Houthakker approach. Cardinal utility theory was formalised independently by Slutsky (1915) and Hicks (1956) and is now known as the Slutsky-Hicks framework.

Alternative to utility-theory, another approach to model decision making is regret theory. Where utility theory assumes that a decision-maker maximises gains, regret theory assumes that a decision-maker minimises losses. Utility-theory is driven by positive emotion, regret minimisation is driven by negative emotion (Chorus, Arentze & Timmermans, 2008). Regret theory is especially attractive to decision analysis of products with several attributes. However, one downside of regret theory is the risk of combinatory explosion; as the number of alternatives increase, the number of required computations to find the minimum regret increases exponentially (Chorus, Arentze & Timmermans, 2008).

Current economic practice still upholds utility theory from either the Slutsky-Hicks perspective or the Samuelson-Houthakker perspective; however, macroeconomic behavioural economists have expanded the frameworks regarding consumer choice to account for observed, empirically valid, behaviour. Two additional streams of theories on consumer behaviour are discussed in this section; prospect theory of Kahneman & Tversky and Akerlof's notions of information asymmetry and identity economics.

4.1.2 Prospect theory

Prospect theory was proposed by Kahneman and Tversky in 1979; it was fine tuned in their later publication (Tversky & Kahneman, 1992). Prospect theory describes decision making processes of any economic decision by an individual. Prospect theory assumes that decisions are made within a bounded rationality; meaning that the rationale behind decisions is constrained by time pressure and cognitive ability. These constrains often lead to unexpected behaviour resulting in sub-optimal decisions. According to Kahneman and Tversky, decisions are made either from intuitive thinking, which is governed by perception, or decisions are made by reasoning. Reasoning would lead to making optimal decisions, but reasoning takes a lot of time, and information; in practice either time or information or both is not available for the decision maker. Intuitive thinking is known to be able to handle very complex issues, like a chess game or judging a social situation; however, intuition is also known to be subject to some biases, following from notions on perception (Kahneman, 2003).

The first notion on perception that makes intuition subject to biases, is that perception focusses on changes of states rather than levels of states. Kahneman (2003) illustrates this with the following example: person A had four million and lost 1 million, person B had 1 million and gained 0.1 million, according to utility theorists person A is happier because he has 3 million, according to prospect theorists person B is happier because he gained wealth. This is in line with psychological theories surrounding anchoring or mental frames.

The second notion on perception is that in an individual's mind or perception, categories or sets are represented by prototypes like averages; more complex statistics like sums are not computed for intuitive thinking. To illustrate that the perception considers averages over other statistics, Kahneman refers to a study by Rendelmeier, Katz and Kahneman (himself) (2003); in this research it was shown that, during some medical procedure, patients experienced more pain with a larger pain intensity average than patients with a lower pain intensity average but a larger sum of pain intensity over time.

Biases in our perception lead to violations of the logic dominance and to insensitivity of the set size (Kahneman, 2003). As Kahneman and Tversky argue in their initial 1979 paper, carriers of utility are changes in states, gains and losses, not the state of wealth. This contradicted the utility theorists, as described in section 4.1.1; who relate utility to the state of wealth. The value function, as hypothesised by Kahneman and Tversky (1979) is shown below, in figure 4.1. In observing the prospect theory value function, two interesting observations can be made: individuals are more sensitive to losses, and individuals are risk seeking in the negative domain (where losses are evaluated) (Kahneman, 2003).

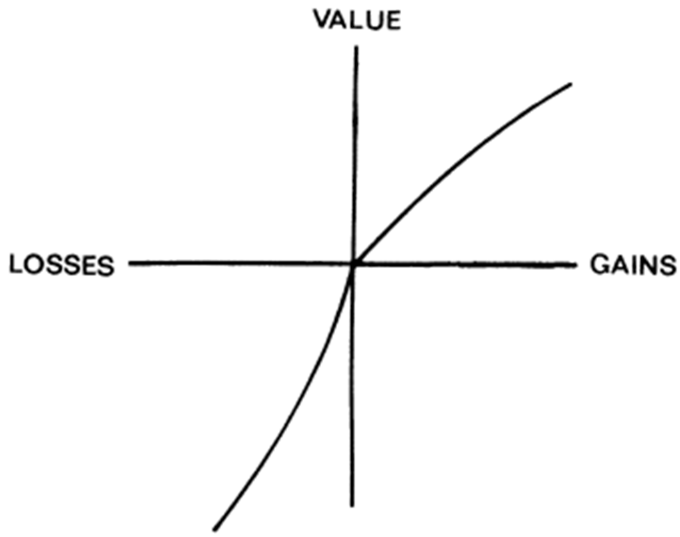


Figure 4.1: Hypothetical value function of prospect theory (Kahneman & Tversky, 1979, p. 279)

4.1.3 Identity economics

One of George Akerlof's most influential contributions to consumer behaviour theory, together with Rachel Kranton, is the introduction of Identity economics (Akerlof & Kranton, 2000). Their research was focussed on explaining the self-destructive behaviour of African-Americans in the U.S.A. The essence of identity economics is that individuals make economic decisions either based on their identity or contradicting societal norms; within a society several identities exist in correspondence with social groups. Literature from consumer marketing research also points out that consumer decisions are significantly segmented by social groups, see for instance (Williams, 2002). Individuals have identities and these identities come with prescribed set of norms or "ideal behaviours" (Akerlof & Kranton, 2000); this set of ideal behaviours can be interpreted as a lifestyle as mentioned by Duchin (Duchin, 2005). The case of individuals that follow their identity occurs where individuals perceive it as costly to make economic decisions inconsistent with their identity. Alternatively, individuals may have the, sub-optimal, tendency to pursue decision outcomes that contradict their identity. The implications for consumer decisions of identity economics is that among social groups the value attribution to goods differs; if an individual must choose between two substitutable goods and their price is equal, the choice is made based on conformity to the individual's identity norms.

4.2 Theories on supply-side dynamics

The ratio of inputs required to produce one unit of output for a sector is not constant; this is where this thesis departs from one of the fundamental assumptions of input-output analysis. This section investigates how the development of this relation is described in existing literature on technological change. Two types of technological change are described; change incurred from the introduction of new production processes, or innovation, and change incurred from learning effects, or experience. These two types of learning correspond with roughly two stages that a technology goes through in its life; the initial stage of a technology, where it is developed corresponds with innovation, technological learning corresponds with the second stage of a technology from where a technology is commercially used up until the end of its life (Sagar & van der Zwaan, 2006). The multi-level perspective (Geels, 2002) describes how technologies develop over time; both the development of main-stream technology, and the development of new technologies. The first subsection of this section will describe the multi-level perspective and how it applies to modelling supply-side dynamics. The second subsection shows how Wright's law, or learning curves, can be integrated into the multi-level perspective.

4.2.1 Technological transitions from the multi-level perspective

Transition management was aims to provide theories that explain how a socio-technical system transitions from one state to another. The main goal is to use this understanding to substantiate a nudge of the socio-technical system into a more sustainable state (Markard, Raven & Truffer, 2012). The multi-level perspective, which was developed by Frank Geels and René Kemp (2000; Geels, 2002), will be used in this thesis as a reference frame to regard technological change.

The multi-level perspective views an economy as three interacting levels; the landscape, the regime and the niches. The regime is the main stream of the economic system; here incumbent technologies reside and conduct their business as usual. The regime contains cultures and operating methods; changes to the regime are uncommon to spontaneously occur. Niches operate on a different level than the regimes; niches contain technologies who are not in a commercial stage and require protection to continue existing. This protection is given by either public bodies in the form of subsidy or from private parties such as business angels. The landscape is the overarching level which sets the rules of the economy. From the regime itself, or alternatively from landscape pressure, friction can emerge within the regime; because of this friction a window of opportunity can arise. This window of opportunity provides a chance for niche technology to enter the regime, replacing an incumbent regime technology. The multi-level perspective is illustrated below in figure 4.2. Changes to the economic system from the regime are slow and steady while changes in the regime incurred from niche technology usually have large implications.

The multi-level perspective is one of several similar, related, frameworks explaining transitions; these frameworks greatly overlap, and no others will be discussed here in detail. Other frameworks concerning technological transitions are the multi-pattern approach, which adds a level between the niche and regime (de Haan, 2010), transition contexts, which emphasises selection pressures and coordination (Smith, Stirling & Berkhout, 2005), and technological innovation systems, which emphasises the dynamics of innovation systems (Hekkert et al., 2007). These different frameworks define similar characteristics of transitions (Halbe et al., 2015); transitions are multi-domain, multi-level, path-dependent, and the regime is self-reinforcing but subject to change from the niche level.

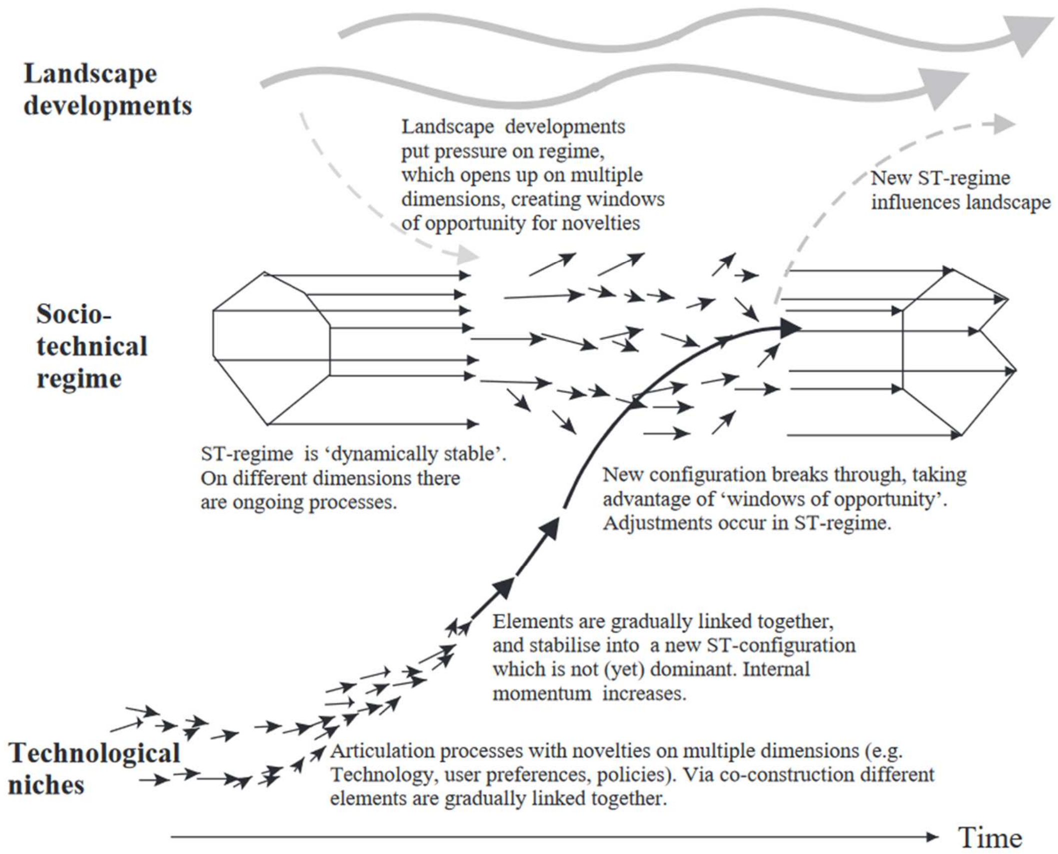


Figure 4.2: The multi-level perspective (Geels, 2005, p. 685)

What is taken from the multi-level perspective for the conceptual model is that the regime level production technology does not structurally change but steadily becomes more efficient. Another level exists which does not interact with the regime until a window of opportunity exists where new innovations emerge and compete among each other to step through the window of opportunity into the regime to start commercial deployment, replacing a discarded technology. These innovations can be very different from incumbent technologies which it replaces. Instead of accounting for all components of the regime, only the technological coefficient per sector is of interest in this thesis. The multi-level perspective provides substantiation of how niche innovations come into the regime, technology substitution literature, as described in appendix A.2.4, provides conditions for when niche innovations enter the regime. Technology substitution literature showed that the substitution of an old technology by a new technology happens as the old technology is in decline, it happens exponentially, and once substitution sets in it cannot be reverted.

The approach for this thesis is that different sectors exist in the economy; a sector is the sum of undertakings that conform to some categorisation of the statistical office that collects input-output data. Therefore, a sector is a collection of different production technologies; the sum of these technologies is the technological coefficient vector for a sector. Any technology starts off as an innovation; as a window of opportunity arises the technology can enter the sector and start commercial production, supplying the sector's output to other sectors or final demand. Once a technology is part of the sector, its development continues, but in a much more stable and gradual way; this type of development is discussed in the next subsection.

4.2.2 Technological learning according to Wright's law

Technological learning refers to learning effects or experience in production processes; where increased cumulative production reduces unit production costs with a diminishing return. This learning effect was first mentioned by Wright (1936); as he reviewed cost curves of airplanes. Subsequently the Boston Consulting group applied learning curves in their strategic consultancy practice; since BCG's application, learning curves are being used in many different fields (Kahouli-Brahmi, 2008).

Learning effects have been studied in detail; Sagar and van der Zwaan (2006) as well as Kahouli-Brahmi (2008) decomposed the effects of learning into several different types of learning effects. This decomposition includes learning-by-manufacturing, learning-by-copying, learning-by-operating, learning-by-implementing, learning-by-doing, learning-by-researching, learning-by-using, learning-by-interacting and finally economies of scale. These decompositions greatly overlap; they can be grouped as follows: (1) learning by implementing and researching and economies of scale, (2) learning by manufacturing, operating, doing and using and (3) learning by copying and interacting. The first group refers to new technology; gains from implementing refer to streamlined institutional processes, gains by researching refers to R&D efforts. The second group encompasses learning effects from increased production rates. Gains follow from for instance tacit knowledge building by employees, reduced capital costs per unit of output and user experience feedback. The final, third, group captures learning effects from other production processes or competitors; these gains stem from "spill-over" effects, where components become cheaper, or incorporating competitors', more efficient, production methods.

Mathematically, the learning curve, or Wright's law, can be described as shown below, in equation 4.1 (Kahouli-Brahmi, 2008).

$$C(Q) = aQ^{-b} \tag{4.1}$$

Here, C is the specific cost of one unit, a is the cost of the first unit produced, b is the elasticity of the learning effect and Q is the cumulative production. With this formulation the progress rate can be expressed as a function of the elasticity. The progress rate, *Pr,* is the rate at which the production costs decreases for each time the cumulative production doubles. The progress rate can be calculated with equation 4.2, below.

$$Pr = 2^{-b} \tag{4.2}$$

One interesting finding of Badiru (1992) is that multivariate models only outperform this univariate model by a very small margin. This very simple representation of technological progress of a technology in commercial use has proven to be empirically valid. A recent study pointing out the validity of learning curves is the work of Lafond et al. (2018); they show that forecasting price development can be adequately predicted with (univariate) experience curves.

While empirically the validity of learning curves is accepted, the theory has attained some criticism. Three weak points of learning curves were found in literature; these are (1) the bias toward successful technologies, (2) sensitivity to parameters and (3) the black box character. These criticisms are discussed in more detail in appendix A.2.5. In conclusion, the criticism toward learning curves argues that the curves poorly explain why technologies have success, and that learning curves should not be used to predict cost development of a certain technology. The lack of explorative power is not of concern for this thesis; the interest lies not in how costs are reduced, rather in what cost development pathways look like. In this respect, learning curves are fit for the purpose of providing development pathways. In this thesis, learning curves will be applied to technologies already in commercial stage and to many technologies concurrently. The aim of the curves is that, for all technologies in one sector, the sum of the cost structures of each sector is approximately correct. With the assumption that the errors are normally distributed, the cost development of each sector over time should be accurately described by learning curves. Note that the errors of all technologies are not normally distributed because of the bias to successful technologies; however, this thesis only applies learning curves to successful technologies therefore the assumption of normally distributed errors can be made.

4.3 Suitability of agent-based modelling

In the previous chapter, traditional macroeconomic modelling, using input-output analysis, was shown to be heavily depend on computable general equilibrium modelling, accompanied with monte Carlo simulation to proxy variability. In previous chapters it was also pointed out that these equilibrium models do not account for dynamic phenomena that influence economic outcomes in practice. In section 4.1 economic theory was presented that accounts for phenomena that brings economic outcomes out of equilibrium, like perception biases and information asymmetry. In this thesis, another simulation formalism than CGE will be applied to simulate consumer behaviour while properly incorporating these phenomena as well as technological change. In sub-section 2.3.2 an introduction was given of the agent-based modelling formalism, as well as the suitability of agent-based modelling for a given system. In this section, the suitability of agent-based modelling for both the demand- and supply-side dynamics is discussed.

Table 4.1: Analogies between Jennings' (2000) agents and consumers

Agents:	Consumers:
Are problem solving entities	Have to allocate a limited budget to fulfil their needs under limited assessment abilities
Are situated in an environment	Live in social groups in a society or economy
Strife to achieve goals	Maximise some form of utility or value
Are autonomous	Make their own buying decisions
Flexible	Goods can be substituted to keep the sum of utility constant. Consumers can conform or oppose their identity. Consumers can move between social groups.

4.3.1 Suitability of agent-based modelling for demand-side dynamics

Based on the first section of this chapter, a consumer's activity can be summarised as maximising their utility under certain constrains. Utility is an immeasurable common currency among goods; utility is either the product of a state of wealth (if utility theory is followed as described in section 4.1.1) or the product of a state change, gain or loss, of wealth (if prospect theory is followed as described in section 4.1.2). The utility attributed to goods (either state or state change) depends on economic factors like price, quantity and quality, but also on psychological factors like identity or lifestyle. Identity, or lifestyle, is a set of rules that holds for a set social group; several different groups or identities exists in a society, certain individuals choose to oppose their group's identity.

Consumers are constrained by their ability to assess utility and their available budget. The ability to assess utility of goods by consumers is distorted by cognitive ability, access to information and time. The available budget for a consumer has not been discussed in detail, but it seems safe to assume available budget to be the result of the individual's income corrected for some savings factor. Looking back at Jennings definition of an agent in agent-based modelling, the consumer as described in section 4.1 and 4.2 fit this description. The table 4.1 above summarises the analogies between agents and consumers for each point that defines an agent.

4.3.2 Suitability of agent-based modelling for supply-side dynamics

There is a strong alignment between the concepts agent-based modelling and technological transitions; many publications exist combining the two subjects. The core concepts of the multi-level perspective concur with concepts surrounding complex adaptive systems (Geels, 2010); the main idea that regimes are in a stable state of equilibrium and that after friction, windows of opportunity occur can be seen as analogous to the adaptive cycle in complex adaptive systems as described by Holling (2001). Another core concept of the multi-level perspective is the hierarchical organisation of the levels, these levels are well aligned with the system levels, defined for agent-based modelling. Figure 4.3 below shows the hierarchy of the three levels, conceptualised by Geels (2002). This hierarchical organisation is similar to the hierarchy of an agent-based model as defined by Jennings, which is shown in figure 2.4 on page 13.

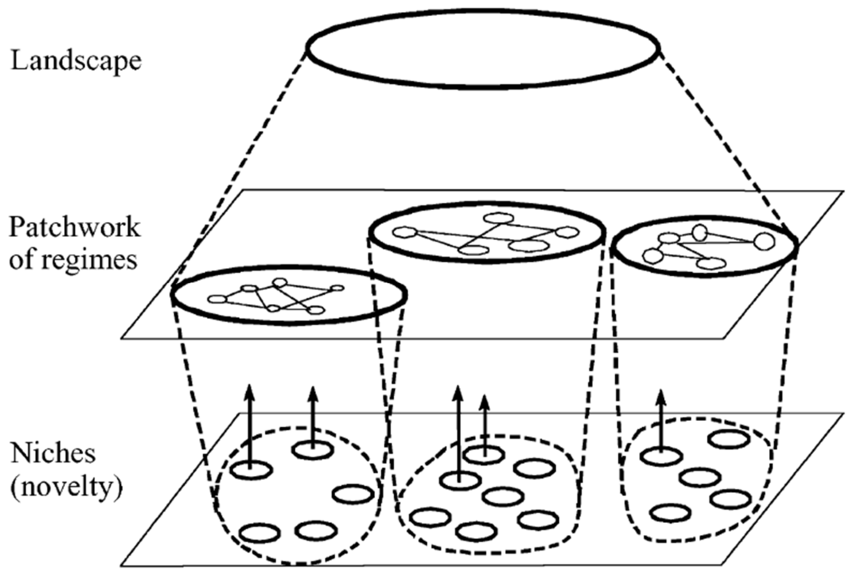


Figure 4.3: Hierarchy levels of the multi-level perspective (Geels, 2002, p. 1261)

As mentioned in subsection 4.2.1, a sector is a combination of technologies; together these technologies consume a set of inputs and produce the same output. The sum of these technologies of the same sector is captured in the data entries of that sector in an input-output table. A single technology can be seen as an agent; belonging either to a regime or the niche corresponding with that regime. New technologies are born as innovations and either die off unsuccessfully or the innovations survive the niche level and step through a window of opportunity into the regime or sector level. Technologies' development over time in the regime or sector level can be characterised by Wright's law, or a learning curve. As was discussed in subsection 4.2.2, if the errors of Wright's law are assumed to be normally distributed, the law provides a valid representation of the sum of the cost development of a sector.

Agent-based modelling is a suitable formalism to represent a system, when that system consists of interacting agents and these agents conform to Jennings' (2000) definition of an agent. Like table 4.1, table 4.2 below shows the main characteristics of an agent according to Jennings and how a technology, in the context of this thesis, conforms to these characteristics of an agent.

Table 4.2: Analogies between Jennings' (2000) agents and technologies

Agents:	**Technologies:**
Are problem solving entities	Must acquire and attain market share to stay alive
Are situated in an environment	Are part of a sector within an economy
Strife to achieve goals	Maximise their efficiency to be attractive for consumers
Are autonomous	Produce their output according to their unique technological coefficient vector
Flexible	Can produce any amount of output, depending on the total demand. Their technological coefficient vector changes over time.

4.4 Demand- and supply-side dynamics in computer simulation

In section 4.1 and 4.2 theories of demand- and supply-side dynamics were presented. In this section, literature is presented where such dynamics are implemented in computer simulation. First, computer simulated decision-making frameworks are presented that can be used to proxy human decision making. Second, literature is presented that implements technological transition in the agent-based modelling formalism. Finally, literature on simulating the appearance of innovations is presented in the third sub-section.

4.4.1 Human decision-making in computer simulation

Representing human decision making in computer software is of interest in different scientific fields; social sciences, artificial intelligence and computer sciences produce a large amount of literature on the subject. Three different decision-making frameworks have been reviewed; these are BDI, 2 and 3APL and PECS. The BDI framework is the most influential frameworks on human decision making, it is used in many models and has a huge amount of citations; the BDI framework stems from the computer sciences field. The second framework that is the 2 and 3APL framework which originated in artificial intelligence field; 2 and 3 APL extend the BDI framework in representing pro-active and reactive decision makers. Finally, PECS was developed in the field of social sciences; the strength of PECS is that it focusses on representing realistic human behaviour by incorporating emotional and physical factors. A more thorough discussion on these three frameworks can be found in appendix A.2.6.

4.4.2 Agent-based models of technological transitions

For this subsection, a number of simulation studies of technological transitions using agent-based models were reviewed. The studies were reviewed based on the relevance for this thesis. Relevant points for this thesis are how individual technologies are represented, which attributes they have and these change, and how do technologies interact with the regime, technologies incumbent to the regime but also niche level technologies. For a complete overview of different simulation studies, see (Timmermans, de Haan & Squazzoni, 2008; Holtz, 2011; Li, Trutnevyte & Strachan, 2015). In appendix A.2.7, two of these studies are discussed in more detail; these two are discussed because they are highly relevant for this thesis.

From the papers presented in appendix A.2.7, and other works that have been reviewed by (Timmermans, de Haan & Squazzoni, 2008; Holtz, 2011; Li, Trutnevyte & Strachan, 2015), it can be deduced that most transition simulation models discern gradual and radical technological change; incumbent technologies develop gradually, and radical change occurs when a new technology enters the market. Interaction between regime technologies is usually not considered in the models; niche technologies do interact with other technologies, where incumbent technologies serve as inspiration or a reference point for the attributes of a new niche technology. A technology has different parameters which consumers consider for their buying decisions; usually different quality parameters and price are modelled. The appearance of a new innovation cannot be easily generated by the simulation models; in the reviewed works for this section, new innovations were pre-defined by the modellers. In the next sub-section, general evolutionary algorithms are proposed as a way to generate new innovations by the simulation model.

4.4.3 Agent-based modelling and general evolutionary algorithms to represent innovation

Models of technological transitions, like those presented in subsection 5.2.2, do not substantiate the appearance of new technologies in the niche level. For this thesis, substantiation for radical innovation will be drawn from the innovation literature and the models following those theories. Innovation literature began with Schumpeter's theory of economic development (1934); in this work Schumpeter describes innovation as a process of '*creative destruction*', where new businesses replace the old. In his book, Schumpeter emphasises that innovation structurally changes the market structure over time; the temporal aspects should be accounted for. In the 1960's, mathematical modelling of innovation became popular (Kiesling et al., 2012); a most influential work is that of Bass (1969) which proposed the Bass model, that describes individuals' probabilities to adopt innovations as a function of relation to individuals who have adopted and some external influences. In other words, the Bass model describes the spreading, or adoption, or diffusion, of an innovation is a continuous process that is influenced by word to mouth and mass communication.

Just like economics are moving to agent-based modelling, the field of innovation research is developing agent-based models because these models can be defined on the individual's level (Kiesling et al., 2012). Both innovation and economics' attraction to agent-based modelling is driven by the idea that evolutionary mechanics explain the development of these fields (Nelson & Winter, 1982); agent-based modelling can accurately reproduce these evolutionary mechanics. Dawid (2006) summarises that these evolutionary mechanics are characterised by three stages, *"…(i) generation of variety by means of individual innovations; (ii) selection based on some measure of 'success'; (iii) reduction of variety due to diffusion and adaptation."* (p. 1244). This evolutionary approach can generate new production technology; therefore, this approach will be followed in this thesis, rather than other approaches that rely on pure mathematical models, like the Bass model. Appendix A.2.8 gives a brief introduction of general evolutionary algorithms as well as a description of Chris Birchenhall's framework. Chris Birchenhall (1995) developed a framework to generate innovations for an agent-based model of technological change, based on evolutionary algorithms.

The perspective on innovations for the conceptual model is that innovations exist on the niche level, shielded from the regime, and are being developed and refined for commercial deployment. Each sector of the input-output framework is represented by a regime level; each regime level has a niche level corresponding to that sector. The attributes of a technology are the mix of inputs from different sectors and its associated environmental and social impact. The fitness of an innovation is dependent on the utility-weights of the population model, differing per social group depending on quality and price. Based on the fitness assigned to each innovation, some of them are discontinued, or killed, the others stay in the niche level and reproduce and mutate to create a new generation of each remaining innovation. For each member of the new generation, if this innovation is fitter than its parent or predecessor, it is kept in the population and the parent is discontinued or killed.

4.5 Representing demand- and supply-side dynamics in a national trade model

To represent the demand- and supply-side dynamics in a model, a thorough literature review was conducted. In this section, the consolidated views on the demand- and supply-side dynamics are presented based on the literature that is presented in this chapter and appendix A.2.

4.5.1 Representing demand-side dynamics

In this chapter, economic decision-making and computer simulated decision-making was reviewed. In this sub-section, an overview is presented of the design choices for the demand-side dynamics model; whether or not this can be modelled or parameterised within the constraints of this thesis will be addressed in chapter six of this thesis, this sub-section presents an ideal model based on the reviewed literature. Throughout this chapter, two perspectives were identified which are present in these scientific fields. One perspective that assumes individuals to make optimal economic decisions, the other perspective assumes that decision-making is imperfect leading to sub-optimal economic outcomes. In decision making theories, one point that is agreed upon is that there is a valuation mechanism that is common for different rewards. From neurobiology, classic economic theory and behavioural economic theory it can be concluded that individuals make choices between different goods based on an immeasurable common mental currency. It is named either utility, prospect or preference.

Utility theory as well as BDI related frameworks for computer simulation assume the individuals to make optimal (economic-) decisions. Information is processed by the decisionmaker where utility or preferences are assigned to goods. Subsequently, given budget constraints the utility is maximised. Utility for goods is derived as a value or a ranking index related to price, quality and quantity of goods.

Behavioural economics, accompanied by the PECS framework, disagree on the notion of optimal decision-making as defined in classical economics; these theories argue that individuals take decisions under bounded rationality. They believe that the individual’s rationale is constrained by biases that follow from an individual’s perception. As discussed in the first chapter of this thesis, the goal of this thesis is to integrate dynamic behaviour into existing macroeconomic methods. The assumption of optimal decision making is justifiable to compute equilibrium solutions. In this thesis the departure from equilibrium thinking is proposed; therefore, the behavioural economy’s approach is followed. A point can be made of the accuracy or predictive power of behavioural economics over neo-classical economics, but this is beyond the scope of this thesis.

As Akerlof and Kranton (2000) pointed out, and as most marketing literature describes (Williams, 2002), and as the PECS reference model prescribes (Schmidt, 2000), economic decisions are strongly influenced by non-rational drivers of individuals; identity, social classes and emotion are significant drivers of human choice. Marketing literature points out that social classes have different preferences or utility weights; high income classes do not necessarily buy high quality, expensive goods. Different definitions of value or utility weights are assigned to different social classes. As Williams (2002) argues, social class is predicted by income with a high degree of significance. Williams shows that social class is mainly dependent on education, occupation and income, education predicts occupation and income fairly well; there are outliers, think of university education in gender studies which might have little high-salary job opportunities while professions with low level education exist with high salaries such as construction workers or underwater welding. The role of emotion in the decision-making process of individuals is difficult to address in the context of this thesis; emotion fluctuates rapidly while the input-output analysis part of the proposed model has a time step of one year. The knowledge that an individual possesses is not necessarily in correspondence with reality, perception is known to be biased by psychological and economic-competition related factors. From prospect theory the notion is drawn that perception focusses on changes of the state of wealth rather than level of the state; this means that an individual takes its current situation as a reference point and derives utility from changes in that, gains or losses. From Akerlof's work on information asymmetry is drawn that as assessment of quality of goods is initially distorted but by repeated transactions this distortion decreases (Akerlof, 1979).

The outcome of the demand-side dynamics model should be a vector for final demand; specified in either monetary value or physical quantity per sector. The focus of this chapter, for the demand-sided dynamics, was to define a model which describes the underlying dynamics of individuals which drive choices in consumption. Choices in the reviewed literature always referred to individual products or goods; in the context of this thesis, choices refer to sectors. This relation, choosing a quantity to consume from a sector is rather abstract and is difficult to quantify. An implementation of this model can be parameterised or "calibrated" using historic data; a large body of literature exists on calibrating models, for a detailed description of model calibration techniques please refer to (Thiele, Kurth & Grimm, 2014). Observed final demand vectors from historic data can be used to set quality parameters of goods; the calibration process searches the parameter space for certain quality parameter values that result in consumer's choices that are in correspondence with the observed final demand. Fortunately, there is a large amount of historic data of most input-output frameworks, including environmental impact vectors and final demand vectors. WIOD has yearly data from 1995 up until 2016. Unfortunately, the most accurate input-output framework, EXIOBASE, only provides data of two years, 2000 and 2007; however, EXIOBASE uses an EU standardised format so Eurostat data, which has the same availability as WIOD, could be used as proxy.

Analysing waste streams within an economy requires adequate modelling of waste-related decisions of consumers. The effects of circular economy policies have been evaluated using agent-based models of consumer behaviour (Brouillat & Oltra, 2012); Brouillat and Oltra argue that recyclability can be seen as a dimension of product quality and consumers weigh the recyclability to some degree in their buying decisions. Another aspect of consumer buying decisions regarding waste generation is the consumer's criteria for product obsoleting, in other words the consumer's threshold for renewing products. What Brouillat and Oltra do not mention is the consumer's willingness or ability to separate waste; this is a relevant factor for the potential of resource recycling. Not only the quantity but also quality of recycled resources depends on the degree of separation.

To summarise this sub-section, the profile of a consumer is summarised as follows: a consumer has utility weights per quality of a good; this weight can differ among social classes. Utility is either generated by a consumer's state of wealth or a change in state of wealth. If a consumer's utility is generated by change in state of wealth, losses weigh more heavily than gains. A consumer is a member of a social class; this membership is not fixed but can change due to interactions with members of other social classes. A consumer has an income class; this income is determined by the consumer's education and employment state. Consumers exist as either unemployed, employed or retired. Unemployed consumers receive income in the form of social benefit, retired consumers receive income from pensions; both are a fraction of their last salary. A consumer saves a certain percentage of it income; this savings factor is related to its social class. The main activity of consumers is to allocate their salary to the different sectors and maximise their utility; utility is generated from a change in consumption compared to the last time step. Not only quantity of products is considered for utility, but also externalities such as environmental impact and social impact.

4.5.2 Representing supply-side dynamics

In this chapter, theory and application have been discussed for representing technological change in computer simulation. The supply-side dynamics that will be represented in this thesis are taken from these theories of technological change. Where conventional input-output analysis assumes constant technological coefficients, describing the relation between input and output of a sector, in this thesis the technological coefficients of each sector will develop over time based on the theories presented in this chapter.

The perspective taken in this thesis of a sector, is that a sector is a constellation of different firms that are grouped into a sector by the categorisation of the statistical office responsible for the input-output data. All the firms together in a sector use technologies to produce their output; therefore, a sector is a constellation of production technologies, used by firms. Each technology produces a unit of output with a set of inputs from other sectors. In an input-output table, a sector's input is the sum of all the technologies' inputs employed in that sector.

Throughout different theories, two stages or types of development of technologies were identified: gradual development and radical development. In transition literature frameworks, like the multi-level perspective, these two stages correspond with the incremental change of regime technology and radical change due to niche innovations. The incremental development of technologies is seen as an increasing efficiency according to Wright's law or learning curves. Wright's law is proven empirically valid; a simple univariate model with cumulative quantity produced suffices to describe a technology's efficiency. Simulation of the emergence of innovations is commonly based on evolutionary algorithms.

Based on the reviewed literature, the following picture is drawn of the supply-side of the economy. The economy's sectors produce an amount of output as a function of input. Output is used for two purposes and the required output of a sector is the sum of these two factors, the final demand for that sector's output and the intermediate demand for that sector's output; intermediate demand is the demand required for other sectors to produce their output.

In a sector, several firms are active using different technologies, combining different inputs into the same output. These technologies that are employed in each sector are considered the incumbent technologies. These incumbent technologies develop gradually, their input requirements for one unit of output slightly decrease over time. This development follows Wright's law, as a function of the technology's cumulative output, or in other words the maturity of the technology. This gradual improvement has diminishing returns, the diminishing of returns of efficiency corresponds with technological limitations.

The inputs of a technology in terms of input-output analysis are always intermediate trade; natural resources are not explicitly part of the model. Integrating a dynamic supply-side model presents a chance to revise this. To discern resources in input, and to explicate recyclable waste in output, the streams can be made explicit that would be required to analyse the resource and waste streams throughout the economy. That way, designing and reviewing, in detail, policies stimulating the circular economy is made possible.

Based on changing composition and preferences of the society or the demand-side of the economy, within a sector a technology might lose market share. Technology substitution literature shows that, when a window of opportunity arises, an old technology is substituted for a new technology at an exponential, irreversible, rate. A window of opportunity occurs when a technology's market share falls below a certain threshold for a certain duration.

New technologies originate in the niche level of the economy; this level is shielded off from the competitive, regime, side of the economy. In the niche, new technologies are constantly invented and discontinued. On the niche level, innovations compete among each other to be able to seize these windows of opportunity and enter the regime to start commercial deployment. Innovation literature showed that the emergence of new innovations can be described using evolutionary algorithms. The evolutionary cycle begins with innovations existing in the niche level which are ranked in terms of fitness or utility for the consumers, based on this ranking some innovations are discontinued, the others are recombined and mutated into new technologies and the cycle starts over. There is some disparity in the way innovations are discontinued, or die, between general evolutionary algorithms and the implementation of evolutionary algorithms in innovation simulation. Birchenhall's framework (1995) simply keeps a new version of an innovation if it is fitter than the previous iteration, after mutation or recombination, while general evolutionary algorithms use a probability to survive or die based on fitness or diversity.

Having innovation endogenous requires some major sacrifices in terms of realism; the model has to create the new technologies as innovations according to the input-output analysis framework, defining all attributes such as quality but also a technological coefficient for new technologies. If innovation is taken endogenous, one could question how much sense the model outcomes make, because technologies that are being used in these model outcomes might make little sense in reality. It should be noted that as the aggregation of the input-output data increases, the more sense the assumptions make required for endogenous innovation but the less sense the model conclusions make. To illustrate this point, with a two-sector representation, any new technology will have a very high probability of having the other sector as input, with the increasing number of sectors representing the economy the probability of a technology using input from a given sector decreases. Therefore, endogenous innovation based on evolutionary algorithms make more sense with more aggregated sectors. Similarly, more aggregated sectors make less sense in terms of model conclusions; again, using the two-sector example, what conclusions can be drawn with such model results?

In the supply-side dynamics model, a technology begins as an innovation, and if successful it ends up in the regime as a part of the sector. A technology has the following characteristics: it's cumulative production level, a price, quality, technological coefficient vector, social impact vector and environmental impact vector. The three vectors are part of the input-output framework. Price is near impossible to define in monetary terms, alternatively price could be represented per technology in ordinal terms or as a factor correlated with quality. Quality is a complex term, Garvin (1984) defines eight dimensions of product quality; Sebastianelli and Tamimi (2002) used factor analysis to group these eight dimensions and found a representation of product quality in three dimensions. A major difficulty for the model proposed with endogenous innovation will be to define a mapping between technological coefficients to quality and price.

Chapter 5: Integrating dynamics into the input-output analysis framework

The previous two chapters described input-output analysis and the way supply-side and demand-side dynamics could be represented in the input-output analysis framework; these concepts were all discussed separately. The goal of this thesis is to integrate dynamics with the input-output analysis framework. This chapter aims to design a conceptual model of this integration. The integration of different models with different perspectives is not straightforward. The first section of this chapter presents the multi-modelling paradigm and devotes special attention to integration of bottom-up and top-down modelling approaches. The second section of this chapter recaptures the design choices of the individual models for the integrated model, and presents the integrated conceptual model based on the integration approach. In the second section, first the hierarchy of the production system as seen in the context of this thesis is presented. The second subsection shows that the top of that hierarchy can be recognised in the input-output analysis framework. The bottom of the hierarchy is what is modelled in the supply-side dynamics model. The third subsection shows the conceptual model of the supply-side dynamics and how it links to the input-output analysis framework. With the supply-side model conceptualised, the fourth subsection completes the conceptual model by placing the consumer into the model. Finally, this chapter ends with giving an overview of the integrated conceptual model.

Summary

This chapter brings together the two previous chapters where individual models were proposed, in this chapter these individual models are brought together and integrated into a single model. First, the integration approach is defined. With this approach, the three different models are conceptualised and integrated in the second section of this chapter.

The integration approach is based on three different streams of literature concerning the integration of the models. These three approaches are multi-modelling ecologies, computer automated multi-paradigm modelling and hybrid models. From these three multi-modelling approaches, a common approach is synthesised; initially the focus lies on defining the interaction between the models to set out the foundations of the fully implemented model. Later expansions of the model should focus on adding detail in the supply- and demand-side models to add technological explicitness and microeconomic realism. In the first implementations of the model, generic, computer automated, sector models will be used to assess the meaningfulness of the integration of these different modelling perspectives.

Both the supply- and demand-side model are built from the bottom up. In the supply-side model, technologies are used by firms to produce input from output. By classifying these firms with respect to their output type, a sector decomposition can be obtained that links to the sector decomposition of input-output analysis. The demand-side dynamics model is a set of consumer agents that interact with each other and the production system; consumers allocate their budget to purchase goods from the production system and in order to produce these goods the production system requires workers and pays these workers' wages which is in turn spent on purchasing goods.

5.1 Integrating multiple models with different perspectives

Combining different simulation models is more difficult than just facilitating information exchange between the models; alignment has to be reached in terms of attributes, variables, worldview, abstraction level and the concept of time. This section present literature from the multi-model simulation field; the first subsection presents literature on the integration of multiple models. The second subsection discusses computer automated multi-paradigm modelling, which integrate models of different paradigms. Finally, the third subsection discusses hybrid models which integrates economic models taking the top-down perspective, dividing an economy into different activities with dynamic models taking a bottom-up perspective.

5.1.1 Multi-model ecologies

As the computer simulation field advances, as simulation models become more popular decision-making support tools, and as computing power becomes more easily accessible, simulation models are featuring more detailed and complex functionalities. As these models increase in detail, it becomes more cumbersome for a single modeller or group of modellers to develop these models, especially considering that most simulation models are built for a single problem or case. Bollinger et al. (2015) argue that instead of models, environments should be designed for models in which they interact; models in this environment can continually be updated or evolved. These environments are called multi-model ecologies; in these multi-model ecologies existing, individual models are *"...reused, combined, expanded or adapted to address new questions that arise."* (Bollinger et al., 2018, p. 3441). Bollinger et al. (2018) provide a review of different multi-model ecology researches and identified different design approaches; these design approaches appear to have implications on the model outcomes. Therefore, the design approach must suit the system or problem that is modelled. Bollinger et al. (2018) analysed different multi-model ecologies and found that these projects either feature a high diversity in the models or a high connectivity between the models. This was explained by the fact that it is difficult to design interactions between model elements that are conceptually and semantically different. It was also found that ecologies that came close to both high connectivity and diversity also featured a high level of hierarchy in the model elements; it appears that hierarchy helps to align different ontologies. Bollinger et al. (2018) identified two distinct development paths of multi-model ecologies; initially either focussing on diversity or connectivity, through further development the opposing feature (diversity or connectivity) emerges.

The approach that appears most suitable for this thesis is to prioritise connectivity; initially the model will lack technical detail, but the standards will be set for further development of the ecology. By defining the hierarchy between the model elements, the technological detail or diversity can emerge over time as the development of the model continues. Departing in the technical diversity path seems to be naïve, because on the scale of a national economy achieving technical diversity, by detailing the inner workings of all sectors, is an immense challenge. Such a challenge should not be taken on before it can be proven to be worthwhile. Instead of detailing each sector, a meta model will be designed; a model of a model of any sector, defining the interactions between other sectors and generalising all sectors initially. When such a model is developed it can be tested in terms of its meaningfulness. If this model is found meaningful, further development can go into adding detail to each of the sectors. By following the standards set by the meta model, technical detail will emerge over time while keeping the technical connectivity.

5.1.2 Computer automated multi-paradigm modelling

Different modelling and simulations paradigms or modelling techniques exist, based on continuous or discrete time advancement or state transitions and perspective (bottom-up or top-down). No one single paradigm is overall superior to represent a certain system; the deciding factor in the selection of paradigm applied to a case is dictated by the modellers skillset, the goal of the modelling effort or the system's characteristics. Multi-paradigm simulation and modelling is a branch of the modelling and simulation field that aims to integrate different paradigms or modelling techniques to represent a complex system. Multi-paradigm modelling is mainly concerned with the integration of different top-down modelling perspectives; this is because bottom-up models are in a way already coupled models, of agents, defined in a common language. If models of the same paradigm are to be integrated, the coupled model can be transformed into a single, atomic, model; when the models to be integrated are different in paradigm, a single atomic model cannot easily be developed. In their review, Hardebolle and Boulanger (2009, p. 697) find five categories of approaches to integrate multi-paradigm models: *"...translation of models, ... composition of modelling languages, ... composition of models, ... joint use of modelling tools, ... unifying semantics."*. Vangheluwe, de Lara and Mosterman (2002) proposed computer automated multi-paradigm modelling, CAMPaM. They describe three ways to integrate models of different paradigms, either (1) express the different model in the same super-formalism, like for instance DEV&DESS (Ziegler, 2006), or (2) transform the different models in a common formalism and transform the models into a single atomic model, or (3) execute the models separately in parallel. The "computer automated" part of CAMPaM means that rather than defining single-use models, designed for a single case or problem, a more efficient approach could be taken by designing a meta-model, a model of a model. Instantiating this meta-model for a certain case produces that single use model required to analyse that case.

This is exactly the approach envisioned for this thesis based that was already found in the previous subsection based on multi-model ecology literature, to design a model of a national economy that can be instantiated and parameterised with that nation's input-output data. This thesis integrates three models, the supply-side, demand-side and input-output table; the supply- and demand-side are defined in a common formalism, while input-output analysis is defined from the, opposite, top-down perspective.

5.1.3 Hybrid economic models integrating top-down and bottom-up approaches

In terms of modelling perspective, input-output analysis takes a pure top-down approach; the economy as a whole is divided into different sectors which all consume inputs and produce outputs. The models representing supply- and demand-side dynamics were found to be best represented with a bottom-up approach, in chapter four of this thesis. In terms of economic modelling, bottom-up and top-down approaches each have their benefits and disadvantages. Top-down modelling has proven to be a valuable tool in long term macroeconomic planning, however, there is no flexibility of technology, in input-output analysis it is assumed that the technological coefficients remain constant (see subsection 3.1.1 for a more detailed discussion on the underlying assumptions of input-output analysis). Another disadvantage of top-down modelling is that it pushes decision makers to design economy wide policies, because macro-economic models aggregate individual firms into sectors the model outcomes are framed in this same aggregation. The main disadvantage of existing economic bottom-up models is that there is no macroeconomic feedback of different pathways on the economic structure which affects economic growth (Hourcade et al., 2006).

Hourcade et al. (2006) reviewed eight papers which integrate top-down and bottom-up models to analyse macroeconomic policy. As described in this subsection, top-down and bottom-up modelling perspectives have their respective benefits and disadvantages, the purpose of integrating the two perspectives is to provide a more complete model. Instead of merely focussing on macroeconomic factors like employment rate, interest rate and GDP other factors are also accounted for like technological progress and psychological factors. Integrating the two approaches into a single, hybrid, economic model allows the incorporation of all these factors. In their analysis, Hourcade et al. (2006) review papers with regards to three dimensions relating to the strengths of bottom-up models and top-down models; these dimensions are technological explicitness, microeconomic realism and macroeconomic completeness. An ideal model is rich in all these three dimensions. Figure 5.1, below, illustrates these three dimensions, and positions conventional top-down and bottom-up models. The integrated model envisioned in this thesis starts off with a conventional top-down model, input-output analysis; the technological explicitness is enriched by detailing the inner workings of sectors with the supply-side model, and the microeconomic realism is enriched by detailing the emergence of consumer demand in the demand-side model. In this way, input-output analysis is enriched and brought closer to the 'ideal model', also referred to by Hourcade et al. as the 'holy grail' model. This approach is referred to as a composite hybrid model, which includes all major theoretical and structural characteristics of the top-down model while it also includes technological detail and behavioural factors from micro economics.

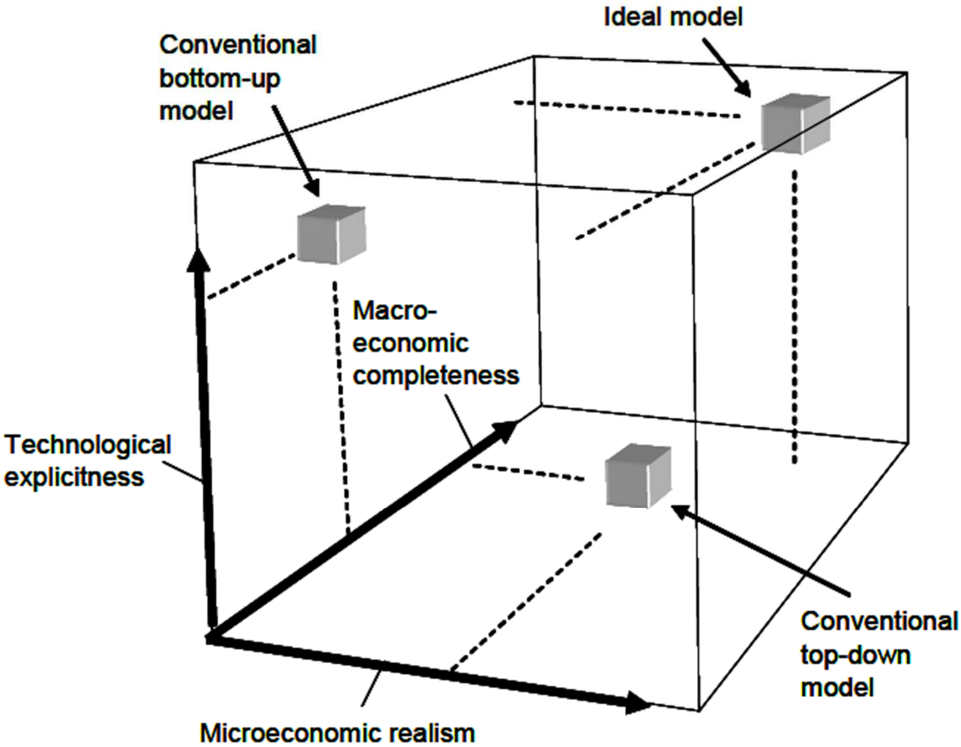


Figure 5.1: Three-dimensional assessment frame of hybrid models (Hourcade et al., 2006, p. 7)

5.1.4 Integration approach for a 'computer automated, composite hybrid, multi-paradigm, multi-model ecology'

In the three different streams of literature regarding the integration of several complex and heterogeneous models a common approach was found which will be applied in this thesis. From multi-modelling ecologies is taken that a large and complex model as envisioned for this thesis cannot be modelled by a single modeller; therefore, the approach needs to be modular and defined in different levels of abstraction. With this approach, detail can be added by elaborating models on lower levels of abstraction. Initially the focus will be on the interactions between the three models and components of these models. When this abstract, high level, layer of the model is deemed meaningful and further explication seems feasible, more detail can be added by defining the dynamics of each individual sector of the input-output model. The abstract version of the model features generic sector models, each sector's model is generated automatically based on the meta-model that will be designed for this sector; this meta-modelling approach is taken from the computer automated multi-paradigm modelling approach. A direct link between the dynamic models and the input-output analysis model is not possible; this is because input-output analysis has a high level of abstraction aggregating data into the sectors' resolution while the dynamic models focus on individual behaviour. This aggregation gap is to be bridged in this thesis by aggregating and transforming individual data into the input-output level data using the historic data that is available. Using historic data, sector-specific quality parameters can be extracted in such a way that the simulated population of consumers produce a final demand vector interpretable for input-output analysis; consumers base their consumption decisions on their utility function, which is dependent on product quality. By adding more and more detail to the dynamic models, technological explicitness and microeconomic realism is added and the integrated model will move closer to the ideal 'holy grail' economic model described in hybrid modelling literature.

5.2 Conceptual model design

Chapters three, and four provided the theoretical concepts that were required to design a conceptual model of a national trade model; in this section that conceptual model that is designed, based on these theoretical concepts. The goal of the conceptual model is focussed on connectivity, to provide definitions of the relations between the different model elements; in this way technological detail can emerge in the model in subsequent development. First, the hierarchy of the model is shown; the hierarchy is important because, as discussed in subsection 5.1.1, this model should be developed as a model ecology due to its magnitude. Second, the structure of input-output analysis is taken to represent the regional production system, as a set of trading sectors. Third, the part of the model concerning the inner workings of sectors is shown and how this is modelled from a bottom-up perspective. Finally, the place of the consumer in the model is discussed and the full, integrated, model is presented.

5.2.1 Hierarchy in the conceptual model

The hierarchy of the model is discussed first, because the hierarchy enables the demarcation of different sub-models of the conceptual model. Differentiating different sub-models, or modules, is important because of the size and level of detail of the model. In section 5.1.1 it was argued to take a modular approach to cope with the magnitude of the model; by defining the hierarchy and the interactions between the models, technological detail can emerge over time as development continues.

In figure 5.2, below, the hierarchy of the conceptual model is shown; in this figure, the scope of input-output analysis and the supply-side dynamics model of this thesis is shown. Input-output analysis' top-down perspective is reflected that the top portion of the hierarchy lies within its scope. Because the supply-side dynamics model is designed to integrate with input-output analysis, the bottom-part of the hierarchy is explicitly accounted for.

According to the hierarchy of input-output analysis, as can be seen in figure 5.2, there is one global production system, of the world's economy. In the model, all regional production systems together form the global production system. The model in this thesis focusses on a single regional production system. When one wishes to model the global production system, the model designed for this thesis should be fully re-useable; modelling the global production system would require instantiating a regional model for every relevant regional production system and linking them together. The lowest hierarchical level of input-output analysis is the sector level, which is the highest hierarchical level of the supply-side dynamics model. A regional production system is a set of sectors, which consume inputs and produce outputs.

As the supply-side dynamics model is represented using a bottom-up perspective, the lowest level of the hierarchy of the supply-side dynamics model are the production technologies. These technologies are representations of methods that firms use to produce their products. Firms use one or more technologies; different firms can use the same technologies and technologies can be exclusive to certain firms. Firms are autonomous entities that produce goods from resources according to their technologies. Firms are grouped into sectors according to the goods that they produce, this division is made by statistical agencies; the sector division made by Eurostat for instance is described in (Eurostat, 2017).

The two model's scopes overlap on the level of sectors; the supply-side dynamics model generates sector-level behaviour, this sector-level behaviour is taken as input for the input-output analysis parts of the model to aggregate this behaviour into nation-level behaviour.

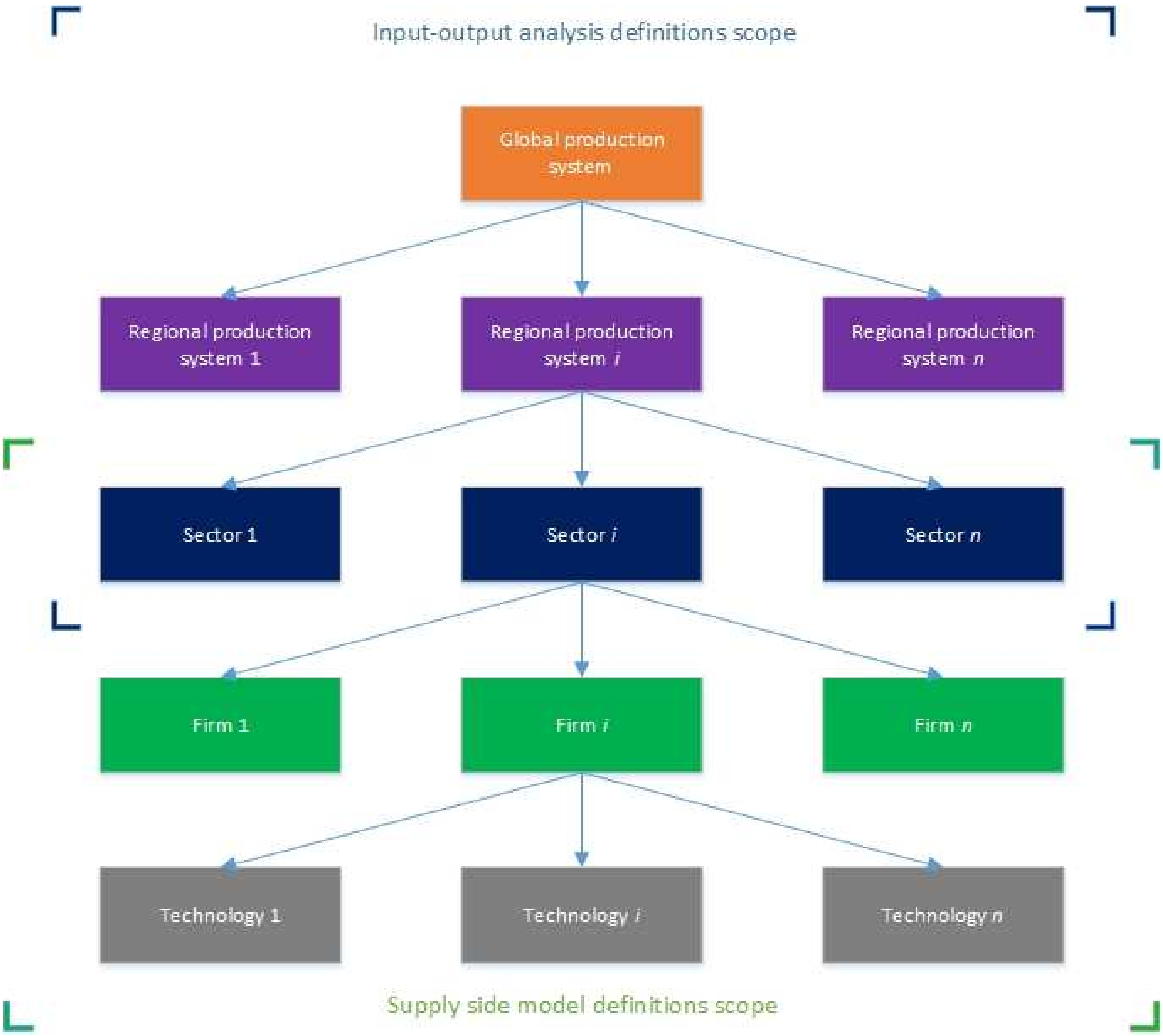


Figure 5.2: Hierarchy of the conceptual model

5.2.2 A regional production system according to the input-output analysis structure

The input-output analysis' structure and methods are represented by the regional production system structure in the model. Figure 5.3 below shows this regional production system. The resources flowing into the regional production system are shown in grey, because this flow is not present in input-output data. A regional production system produces intermediate goods, consumer products and associated externalities. Associated externalities are both positive and negative side-effects of the production system's main activities; positive externalities are social impact like employment and wage contributions, negative externalities are for instance pollution. Intermediate goods are products that are consumed by other production processes in order to produce their product; an example of an intermediate good is copper wire, that is used to produce consumer electronics. Input-output analysis is founded on the idea that consumer products are not made from resources alone, but a set of intermediate goods as well as resources. A sector producing a certain product requires a set of intermediate goods from other sectors; the proportion of intermediate goods, required for one unit of output, can be read from the row of the technological coefficient matrix, as described in subsection 3.1.1 on page 16. The total production level of the regional production system is the amount of products required to supply the final demand, together with the amount of intermediate goods required to produce these products. The total amount of production required is calculated using input-output analysis methods; by multiplying the required final demand vector with the Leontief inverse matrix, for a more detailed description on the methods of input-output analysis see section 3.1.

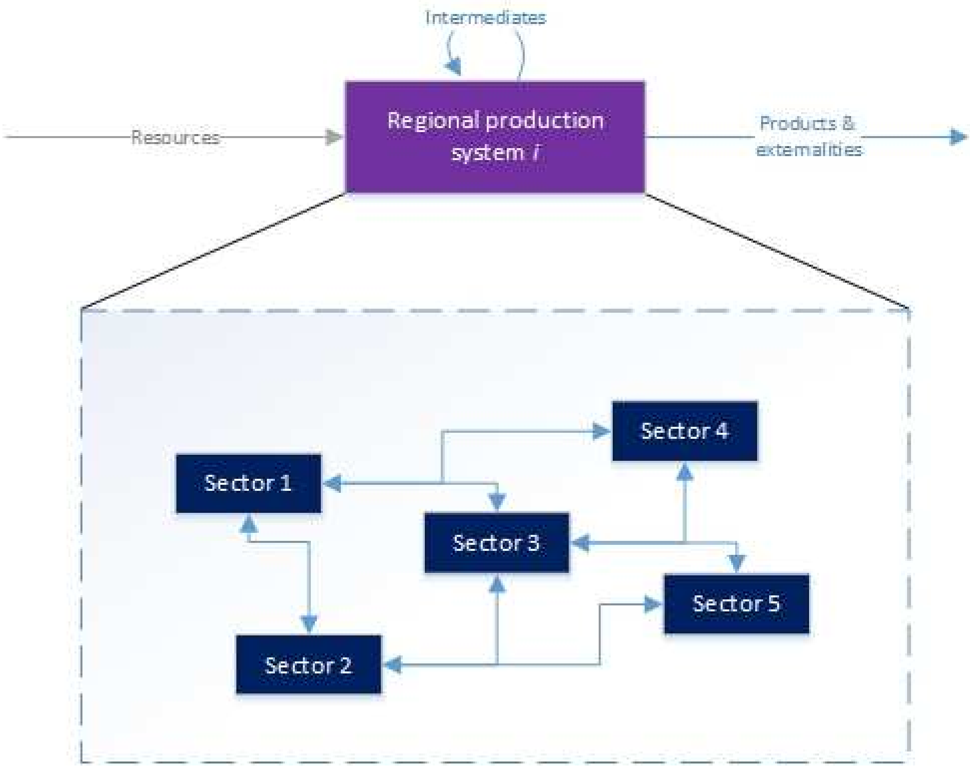


Figure 5.3: Overview of a regional production system according to input-output analysis

5.2.3 A bottom-up representation of the sector's production systems

Supply-side dynamics were found to be adequately represented taking a bottom-up approach with agent-based modelling; modelling technologies and their relations in the production system. A group of firms together form a single sector; the firms that belong to the same sector are those firms producing products of the same classification made by the region's statistical office. Each firm uses a production technology which dictates what inputs are required to produce a unit of output. This relation between technology and output is rather abstract and is not easily illustrated for real-world situations; a good example of this relation is electricity production, many different technologies exist to produce electricity, taking as input different fuels and using different types of generators. In reality, individual technologies exist that produce a sector's output while input-output data is only concerned with the sector level behaviour; this abstract relation is caused by aggregating different production technologies into uniform units of output.

Technologies take as input other sectors' output, and output from other technologies from the same sector, or technologies could use their own output as input; these are intermediate products. For most sectors in input-output data, the largest source of intermediate products is the sector itself; this is reflected in the input-output tables by the diagonal of the technological coefficient matrix, where the largest values are found. The output of all technologies of a sector are aggregated into the sector's total output. Technologies change their input requirements and externalities over time. Technological change is either incremental, marginal efficiency increases due to learning effects, or technological change is disruptive due to innovation, causing radical changes in input requirements and associated impacts. The Wright curve adequately describes this incremental change, as described in subsection 4.2.2. Evolutionary algorithms have shown to be able to simulate the emergence and development of innovations, which was discussed in subsection 4.4.3. In figure 5.4 below this evolutionary perspective is reflected by the crossover and mutations of innovations before selection occurs; either a firm adopts the production innovation, or the innovation remains 'niche' and enters another round in the evolutionary cycle.

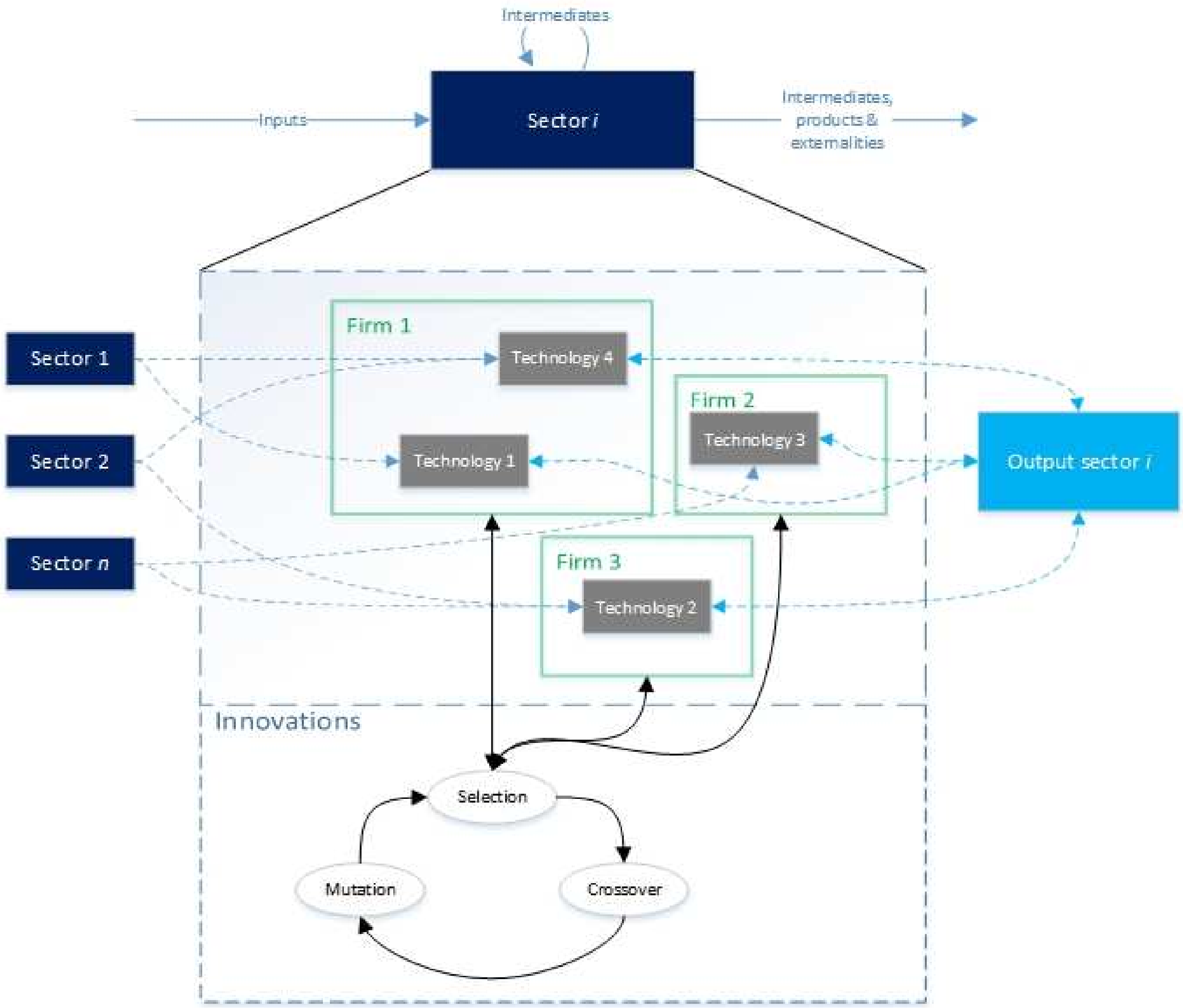


Figure 5.4: Relation between individual technologies and the sectors

5.2.4 Inserting the bottom-up sector model into the top-down regional production system

In the previous two subsections, the input-output analysis' structure and the supply-side dynamics models have been discussed and visualised. The goal of this thesis is to integrate the dynamic features; because the supply-side model is part of the same hierarchical chain as the input-output analysis part this integration is given further attention. In the first section of this chapter, the integration approach was determined to be computer automated, focussed on interconnectivity. The supply-side dynamics model shown in figure 5.4 is rather general, skipping over many nuances that might exist for individual sectors. The model is generalised because the focus does not lie with technological detail of the model but rather on the relations between the model parts. This supply-side model can be seen as a proxy model for any sector; it can be generated automatically based on input-output data. Over the course of further development of the model, any sector can be modelled explicitly and in more detail, replacing its generic sector model.

5.2.5 Placing the consumer into the model

Now that the supply-side of the conceptual model has been established, the consumer can be placed into the model. Consumers are represented by agents that choose to buy products produced by the production system. Products are purchased from the consumer's budget which is either wage paid by a firm, benefits paid by the government or from savings acquired from these two entities earlier in time. The products a consumer chooses to purchase are selected based on some utility function; in chapter four, prospect theory was discussed which argues that utility is generated by gains and losses. Some consumers also weigh externalities into their buying decisions, favouring less polluting products. Social groups are known to influence these non-economic preferences. These consumer's characteristics are summarised below, in table 5.1, including references to sections in this report and literature references.

Table 5.1: Consumer characteristics with internal and literature references

Feature	Internal reference	Literature reference
Utility weights per attribute are heterogeneous over consumers	Sub-section 4.1.1	(Marshall, 1920); (Williams, 2002)
Utility weights of consumers are prescribed by norms within social groups	Sub-section 4.1.3	(Akerlof & Kranton, 2000)
Utility is an adequate representation of the driving force behind economic decision making of consumers	Section 4.1	(Levy & Glimcher, 2012)
Utility is generated by gains and losses	Sub-section 4.1.2	(Kahneman & Tversky, 1979)
True utility cannot be assessed by consumers	Sub-section 4.1.2 & A.2.3	(Akerlof, 1978); (Kahneman & Tversky, 1979)
Non-economic attributes are also considered in economic decisions	Sub-section 4.5.1	(Brouillat & Oltra, 2012)

The place of the consumer in the model is shown by first illustrating the relations between the classes of the model in a UML class diagram. The UML class diagram is presented in figure 5.5 below; the diagram shows the attributes, methods of the classes of the conceptual model and the relations between the classes of the model. With this representation, the relation between consumers and the different levels of the hierarchy of the production system becomes clear. These attributes, methods and relations have been discussed for the demand-side and supply-side separately in chapter four; figure 5.5 visualises and combines these sections.

The consumer population is made up from different social groups, in the current aggregation level of the demand-side model these groups are again grouped in skill level and subsequently correlated income levels. A consumer keeps track of its purchases in the last purchase period and the current period in order to reflect decision-making biases as described in prospect theory (Kahneman & Tversky, 1979, see subsection 4.1.2). The social norms a consumer complies with or resists against holds a set of weights for the utility function that a consumer uses to value different goods, following from (Akerlof & Kranton, 2000; Williams, 2002). Consumers have an income which is either social benefits paid by the government, pension, or wage from labour; the consumer spends its income lowered by the savings factor on goods with the highest utility.

The supply-side model is shown as a hierarchical chain; this top-down perspective is inherited from the input-output analysis framework. A regional, or national, economy is considered to be a set of input consuming, and output producing, sectors. The regional economy

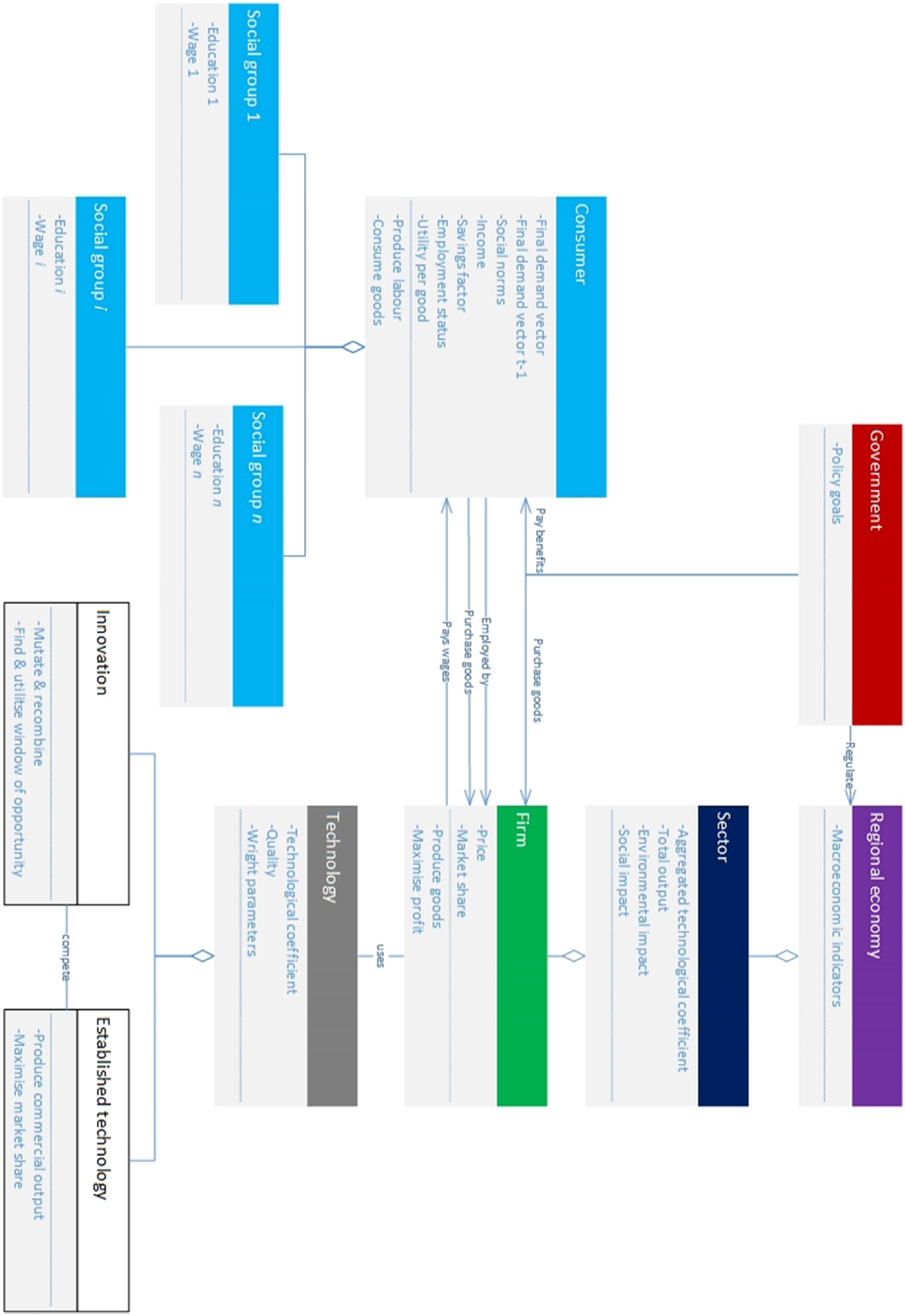


Figure 5.5: UML Class diagram of the conceptual model

is characterised with macroeconomic indicators such as for instance GDP, employment rate and inflation rate. Sectors contain some sector level attributes, like the aggregated technological coefficient of all technologies within that sector, the total output of the sector, the total environmental and social impact of that sector. Where the decomposition stops in the input-output analysis framework, in this thesis it is continued; sectors are made up from different firms, and firms use one or more technologies. A single firm maximises profit and might optimise some impacts; for instance, lower environmental impact or increase (positive-) social impact. A firm's products have a price and a firm holds some market share of the sector. Technologies begin as an innovation and either end up as a failed innovation or as an established technology. Technologies have an individual technological coefficient, the required inputs of other sectors to produce one sector level unit of output. Technologies also hold some quality parameters and Wright parameters. Quality is typically decomposed into several factors, see for instance (Garvin, 1984). Wright parameters are parameters of the Wright curve that describe the development of a technology's efficiency over time as a function of the output of that technology (Wright, 1936).

5.2.6 The relations between the dynamic models and the input-output analysis framework

With all the individual model's established; in this subsection some elaboration is given on the interrelations between the different sub-models. The regional production system represents the input-output analysis part, the consumer population represents the demand-side model and the supply-side model is represented by the technological change model.

The regional production system requires input from both the consumer population model and the technological change model to compute the total output per sector; these two inputs are the final demand vector **f** and the technological coefficient matrix **A**.

The consumers in the demand-side model decide which products to buy, the level of final demand per sector, based on the utility of all different products, while the consumers are constrained by their budget. The budget of consumers is paid by firms in the form of wages but also some consumers are paid social benefits. When more products are consumed, more output of sectors is required which in turn increases the amount of wages paid to the population; this feedback enforces economic growth and in macro-economic literature is referred to as the economic-, or Keynes multiplier (Keynes, 1933).

Waste is generated by consumers consuming products; this waste is disposed of by releasing it into the environment. Also, the production system releases pollutants into the environment; pollution is shown in figure 5.6 below as environmental impact. To produce goods, resources are drawn from the environment by the production system. Natural systems in the environment create natural replenishment of resources; synthetic production of resources, for instance recycling, occurs within the system boundaries of the regional production system.

Technological change was shown to be either incremental efficiency increases or radical changes due to innovation. This technological change changes the values in the technological coefficient matrix which is used in the regional production system model.

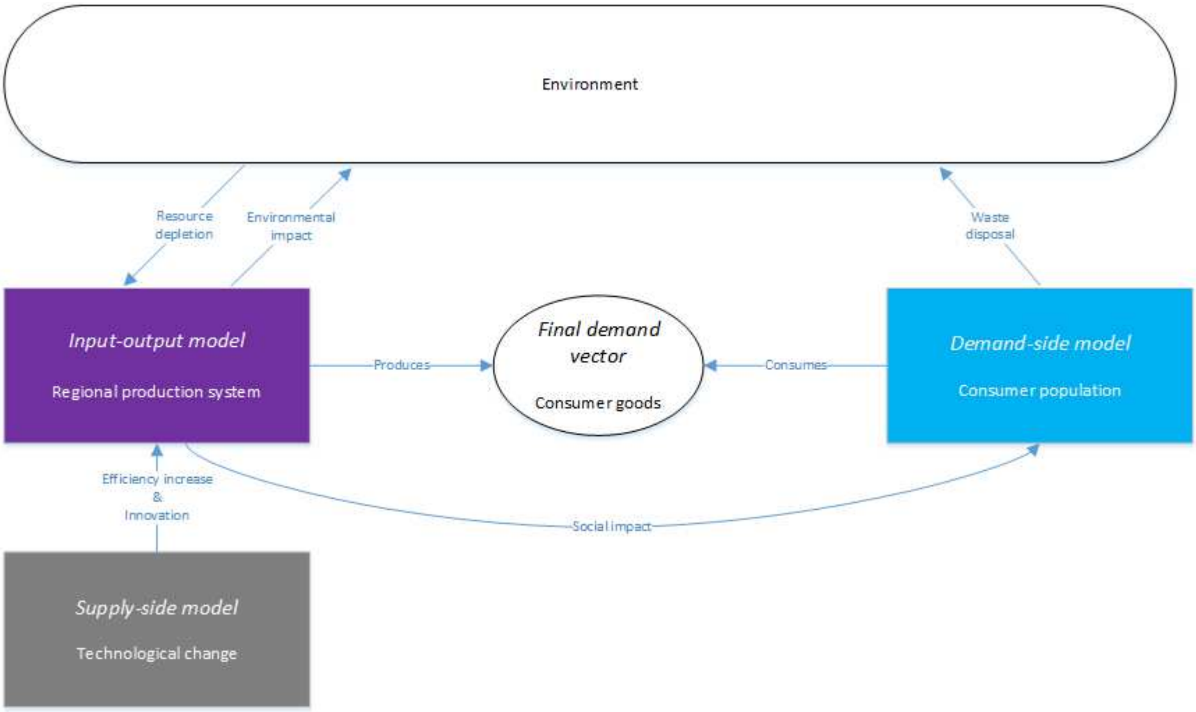


Figure 5.6: Relations between the demand- and supply-side models and input-output analysis

Chapter 6 Assessing the conceptual model with a proof of concept model

In the previous chapter the conceptual model was presented. The conceptual model is the main product of this thesis; the conceptual model made a consensus on the design choices for the integration of dynamic features in the input-output analysis framework. This chapter provides an assessment of the conceptual model. This thesis set out to find the meaningfulness of the integration of dynamic features into input-output analysis framework. By implementing a stylised version of the conceptual model, an assessment of the implementation costs of the model can be made. By analysing the model results an assessment is made of the relevance of the model. This chapter discusses, first of all, the implementation steps: implemented features and more importantly the deviation of the proof of concept from the conceptual model. Second, it analyses the output of the proof of concept and presents a number of conducted experiments with the proof of concept model which were used to assess the implications of the different dynamic features for the mode. Finally, it estimates the implementation costs of the implementation of the full conceptual, with respect to the added value of having these dynamic features incorporated into the model.

Summary

In this chapter, a model is implemented to provide proof of concept of the conceptual model, which was presented in chapter five. By conducting a stylised implementation of the conceptual model, challenges were identified for a full implementation as well as the strengths of the approach. The supply-side dynamics model was not fully implemented. Evolutionary algorithms to represent innovations were not implemented. Instead, technological change was represented by increasing technologies' efficiency along the Wright curve. The main challenges lie in the dis-aggregation of sector data from the input-output tables into individual technologies. The demand-side dynamics model shows that, with this abstracted implementation, it is able to imitate the historic final demand behaviour for a number of sectors. However, due to the abstract representation of product quality the consumer agents were not presented a difficult trade-off in their budget allocation. Adding a dimension to the quality parameter of sector products showed a significant improvement to the simulated final demand. The most promising development pathway seems to be to decompose the performance parameter and perhaps add a baseline final demand vector for consumers, describing the minimum final demand vector; this baseline final demand vector is supplemented by consumer agents allocating their budget according to a utility function.

6.1 Implementation of the conceptual model

This section describes the implementation of the proof of concept model. First, the abstractions and deviations from the conceptual model are mentioned. The conceptual model requires data that is not available and contains features that require a master's, or even doctoral, thesis by themselves to properly implement. After the abstractions have been discussed, the features that were included are described. Finally, the parameterisation of the proof of concept is briefly discussed; the parameterisation led to important conclusions, because not everything was as easily parameterised as initially estimated.

6.1.1 Abstractions and deviations of the proof of concept

Abstractions had to be made in order to come to a proof of concepts within the time- and data constraints of this thesis. This subsection describes what the proof of concept model does not feature; where the model deviates from the conceptual model. The abstractions are discussed in three parts, first the abstractions from the input-output analysis parts of the model are mentioned. Second, the abstractions of the demand-side dynamics model are discussed and finally the abstractions from the supply-side dynamics model are named.

In the proof of concept, no resource streams are incorporated. This could not be realised because there is a general lack of data in the input-output analysis framework which describes resource- and associated waste streams reasonably available for implementation. Also, because data on waste steams or recycling steams was not reasonably available this could not be incorporated. Instead, the model focussed on the associated CO_2emission of the production system as a negative externality. In a full implementation of the conceptual model waste streams would be present and treated in a similar way as the proof of concept treats CO_2 emissions; however, model-mechanics to recycle these streams would need to be added.

Another deviation from input-output analysis is that one sector was left out of the model. This sector is 'Private Households with Employed Persons'; the reason to leave this sector out is because it does not consume any intermediate products, therefore including this sector would cause the model to be unable to compute sector output. The reason for this, is because if a sector consumes no intermediate products, the row in the intermediate trade matrix contains all zero's producing a row of zero's in the technological coefficient matrix; the technological coefficient matrix in turn needs to be inverted, however, inversion, like division, cannot be done with a row of zero's. Together with this notion, the sector has a minimal output volume meaning that the sector has an insignificant impact on the model outcome.

The implementation of the proof of concept model was done in the free, open source, agent-based modelling tool called NetLogo (Wilensky, 1999). NetLogo has built in features supporting agent-related computations required for the, bottom-up, supply and demand-side dynamics. NetLogo also features a matrix extension which is capable of performing all matrix operations required for input-output analysis. With NetLogo, the proof of concept could be programmed into a single model. One downside of NetLogo is its inability to handle models with an extremely large number of agents; the limit for the proof of concept model appeared to be around 2,000 agents. This led to another abstraction, instead of having each consumer represented by an agent, an agent represented 10,000 consumers. Because of this aggregation level of consumers, the concept of social groups has little meaning. The consumer agents that were modelled had some heterogeneity; skill level was incorporated in a three-point scale and correlated with income and environmental concern. Another abstraction is that consumers only consider one non-economic attribute of goods in their purchase decisions. Because the model only features CO_2 emissions as externalities, this is also the one non-economic attribute consumers appreciate in their purchase procedure.

In the supply-side dynamics model, a major abstraction was the removal of firms from the model; instead, technologies were simulated which were member of a sector. The reason to leave firms out of the model was because firms do not, yet, have any function in the conceptual model; this is one of the technical details which should emerge over time. Incorporating micro-economic realism is one of the qualities of the bottom-up approach; however, currently such mechanics like profit maximisation are not yet part of the model.

Innovation was left outside the model scope. The conceptual model incorporates innovation as the source of radical technological change. Innovations were mentioned to be simulated with evolutionary algorithms. However, at this time no off-the-shelf package for NetLogo exists that would easily interface with the other model elements to incorporate evolutionary algorithms to imitate innovation. Packages do exist that provide and interface between NetLogo and Python (by hacking the JVM with a package called Jpype); for Python, packages are readily available that can implement evolutionary algorithms, like Platypus. However, formally implementing innovations is quite challenging, this is by itself an interesting subject of a master's thesis if not a full doctoral thesis.

Finally, the quality parameters of technologies or products was abstracted to a single dimension; in other words, the quality of a single technology was represented by a single value. In the conceptual model different sources were referenced discerning several parameters of quality; to parameterise 34 different sectors each containing two technologies, discerning several quality parameters could not be achieved within the scope of this thesis.

6.1.2 The features included in the proof of concept

This subsection discusses what the proof of concept model does include; which features are incorporated and how the model calls these features to simulate economic activity. The interested reader is referred to Appendix B, in this appendix the model logic is discussed in detail, in a step by step description of the model's procedures in the form of a narrative.

The model begins by setting up the environment and instantiating all agents First, the intermediate trade matrix is loaded into the model; with the intermediate trade matrix the technological coefficient matrix is computed according to conventional input-output analysis as described in subsection 3.1.2 in equation 3.5. In this setup procedure, two technologies are created per sector and assigned their respective attributes. Within each sector, one technology exists that focusses its learning-effect gains on improving the quality of their product and the other technology focusses its learning-effect gains on reducing the environmental impact per unit of output. Per 10,000 consumers, one consumer agent is created; each consumer agent is assigned a skill level corresponding with the ratio of education levels in the Netherlands.

When the environment and the agents are instantiated, the model can begin to compute the time steps of the model. In one time step the model executes five procedures; the budgets of consumers are assigned, the final demand of consumers is determined, the total sector output is computed, the technologies are updated and finally the population is updated.

Budgets are assigned based on the social impact of technologies. WIOD provides data on social impact, the wage contribution for all three skill levels, per unit of output per sector, is taken directly from the database. Based on the total output of technologies, the total wage of the three skill levels is computed. The total wage is distributed according to an exponential distribution among consumers with corresponding skill level. In cases of too few high-enough skilled workers, lower skilled workers are retrained. In cases of too few consumers for the amount of wage generated, a new consumer is created, analogous to immigration. Each consumer sets its budget, available for consumption, as its wage income lowered by a savings factor.

When consumers are assigned budgets, these budgets can be spent on goods. The next procedure determines the final demand of consumers per sector by letting consumers allocate their budget to the technologies with the highest utility. Equation 6.1 below shows the composition of the utility function of an individual consumer, *j*, for an individual technology, *i*.

$$U_{i,j} = DW_{i,j} * (\frac{performance_j}{performance_{max}} - \frac{env.impact_j}{env.impact_{max}} * env.impact\ weight_i) \tag{6.1}$$

As consumers have different utility weights for environmental impact, the utility differs among consumers if all other attributes are the same. In equation 6.1, above, DW denotes the 'difference weight'. The difference weight of a technology reflects that the consumer generates utility from changes in the state of wealth, from gains and losses. The difference weight is computed as shown below, in equation 6.2.

$$DW_{i,j} = MAX(0, 0.5 + \frac{Q_{i,j,t-1} - Q_{i,j,t}}{Q_{i,j,t-1}}) \tag{6.2}$$

The lower bound of the difference weight is zero to avoid negative utility. In equation 6.2, *Q* denotes the final demand of consumer *j* for technology *i* in the current timestep, *t,* or the previous timestep, *t*-1. With the difference weight defined as shown in equation 6.2, the consumers tend to spread out their budget rather than optimising the total utility by allocating their entire budget to a single sector. Figure 6.1 below shows a gradient plot of the difference weight as a function of final demand in the previous timestep (on the x-axis) and realised purchases in the current timestep (y-axis). The difference weight is maximal when the previous timestep's purchases were large, and a small amount of purchases were realised in the current timestep; this reflects the notion of prospect theory that a loss of state of wealth generates utility rather than the total state of wealth. Gains are appreciated proportionally less than losses because consumers were found to be risk-seeking in the negative domain but risk averse in the positive domain.

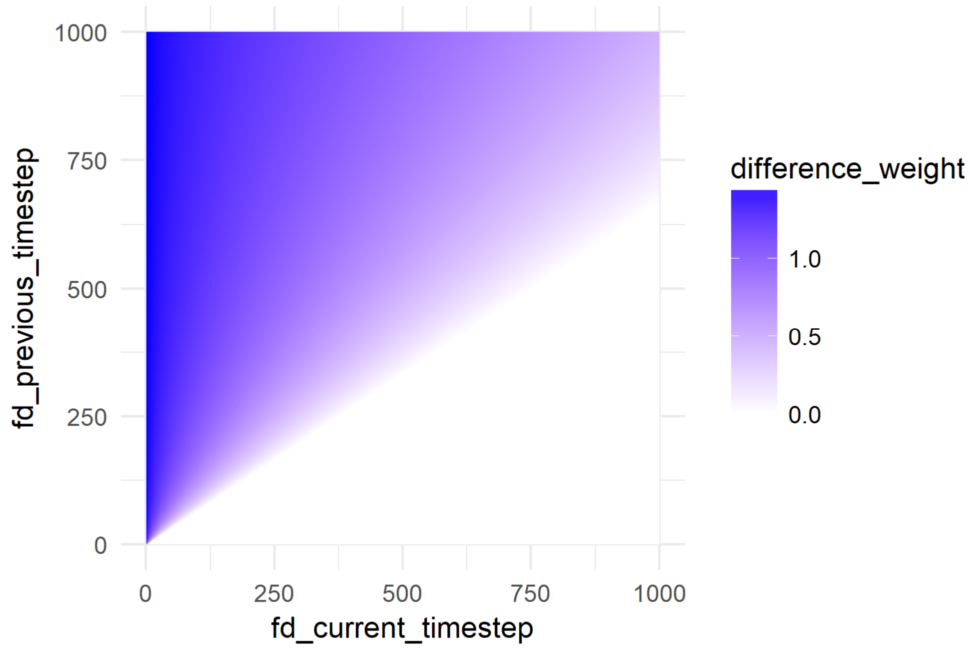


Figure 6.1: Difference weight as a function of final demand of the previous timestep and realised purchases in the current timestep

Once the consumers have allocated their entire budget, the final demand of consumers is set; final demand of consumers is stored in a vector with the sum of final demand of consumers per sector. With the final demand, the total output of sectors can be computed. Before the total output is computed, the final demand by other sources than consumers are added. Final demand from other sources than consumers is exogenous to the model; the vectors for non-consumer demand were taken from WIOD and assumed to remain constant throughout the model-runs. The total sector output vector is computed following the definitions made in subsection 3.1.2, presented in equation 3.6; computing the Leontief inverse from the technological coefficient matrix and multiplying this with the total final demand vector.

With the total output vector, technologies are updated. First, a technology causes pollution; the total output of each technology is multiplied with the technology's environmental impact coefficient. Next, a technology changes its attributes based on the Wright curve. The Wright curve describes technological development as a function of the cumulative output. The current timestep's total output is added to each technology's cumulative output and a relative efficiency increase is computed. The technological coefficient, and either the performance or environmental impact are changed by this relative efficiency increase.

Finally, at the end of the timestep the population is updated. From CBS data a projection was taken of the size of the consumer population. If the population size decreased or increased, the number of consumers was changed accordingly, relative to the consumer aggregation.

6.1.3 Parameterisation of the proof of concept

With the model logic established as described in the previous subsection, the proof of concept only needs parameter values to instantiate the model before it can be run. This subsection describes how certain important parameter values were determined and which values would form a barrier for a complete implementation of the conceptual model. The full description of the parameterisation of the proof of concept can be found in appendix C; this subsection discusses the settings of important parameters that posed difficulties.

Performance: To assess the utility of technologies, consumers appreciate both the environmental impact and the performance of sectors. Environmental impact per sector was directly taken from WIOD. However, performance is an abstract attribute with no practical meaning. To set a value for the performance of sectors and technologies, historic data was used for a calibration experiment. From WIOD a reported final (consumer-) demand vector was taken to assess the fitness in the calibration experiment. As optimisation method simulated annealing was used to set performance values for each technology in an efficient way; when the model with a newly set performance values produced a final demand vector that deviated less from the reported final demand vector than the current 'best' fit, those performance values were set as the new best fit. The experiment was conducted until the fit converged to the final fitness value. A more detailed description of the calibration experiment can be found in section 3 of appendix C.

WIOD data: The main value of input-output analysis for this thesis is the data contained in the input-output tables. The input-output table from the WIOD database was used. Unfortunately, for the latest WIOD release (2016), environmental- and social impact data was not yet available, so the earlier, 2013, release was used. From the WIOD, several parameters were used. The parameters that were equal for technologies within a sector were the technological coefficient and the wage contributions. The environmental impact, taken from WIOD, was assumed to be higher for technologies focussing on performance improvement, than for technologies focussing on environmental impact reduction; performance-minded technologies were assigned a 25% higher environmental impact while environment-minded technologies were assigned a 25% lower environmental impact. Besides technology attributes, final (non-consumer-) demand data was extrapolated from WIOD data. For the final demand by non-consumers, the average was taken over the years 2009-2011; this was done because the data of 2009 was heavily influenced by the financial crisis of 2008.

Wright parameters: Using the Wright curve brings an empirically validated and simple representation of technological change; but it also comes at a cost. The Wright parameters are rather abstract in the context of sectors and might be impossible to correctly set. The Wright curve requires three parameters, the cost of the first unit produced of the technology, the cumulative output of the technology and the progress ratio. A progress ratio of 0.8 was used for all technologies, this number is quite arbitrary but in general, measured values of the progress ratio differ between 0.7 and 0.9 (Barreto, 2001). The cost of the first unit produced is one parameter that cannot be assessed in the context of sectors because a sector does not have a common first unit. In the proof of concept, a workaround was implemented by which this variable could be omitted from the model; by taking the *relative efficiency increase* rather than the level of efficiency. Finally, the cumulative output was estimated by taking all the WIOD data, between 1995 and 2011 and taking the sum of the reported output per sector. With this sum and the assumption that performance minded technologies are responsible for 2/3 of this output the cumulative output of technologies could be set. The Wright parameters are discussed in more detail in appendix C.2.

Environmental impact utility weight: In the utility function of consumers, environmental impact is taken into account. It is known that certain consumers account for environmental impact in their purchasing decisions, but it is not known to what extent. Arcury (1990) showed that environmental concern is correlated with education level; together with (Arcury, 1990) and the assumption that education level correlates with skill level, the model assigns environmental impact weights based on consumer's skill level. The utility weight is drawn from a random uniform distribution, the boundaries of the distribution differ per skill level.

6.2 Analysing the proof of concept

With a fully implemented proof of concept model, experiments were conducted which are discussed in this section. Before the experiments were conducted, the proof of concept model was verified; in the verification the proof of concept was thoroughly checked to be confident that the model code does what is should do according to the definitions made in the previous section. A description of the verification procedure can be found in appendix D. After the model code was verified, the model was validated, the first subsection discusses the validation of the proof of concept. After the validation, the experimental design for the proof of concept is discussed; three dynamic features were switched on and off to find out what effect these dynamics have on the model behaviour. The third subsection discusses the important outcomes of these experiments. The final subsection discusses the sensitivity analysis that was conducted with the proof of concept; analysing the implication of the uncertainty of certain parameters on the model outcomes.

6.2.1 Validation of the proof of concept

A major challenge in agent-based models is validating the behaviour of these agent-based models, generally because there is a lack of historical data combined with large parameter spaces (Louie & Carley, 2008). In subsection 2.3.2 it was already mentioned that an alternative method of validation, other than comparing with historic data, is literature validation (Nikolić, van Dam & Kasmire, 2012). Both these two methods have been applied to verify a part of the model. To verify the demand-side dynamics model, the final demand vector produced by consumers is compared with historic levels of final demand. The validation of the supply-side model is founded on the validation of the literature that this model is based on.

The supply-side dynamics model improves efficiency of technologies along the Wright curve based on their cumulative output. The Wright curve has been extensively used and researched; this was one of the reasons to use this curve to simulate (incremental-) technological development. A recent example of a study that shows the validity of the Wright curve can be found in Lafond et al. (2018). While the Wright curve is known to be sensitive to the parameters, the behaviour resulting from using the wright curve is about right. The proof of concept model is not intended to make forecasts of the economy, so the validity of the supply-side model based on the Wright curve with the estimated parameters is deemed sufficient for purpose.

The validity of the demand-side model can be addressed by comparing the model outcomes with historic data. Because of the availability of data from WIOD, final demand vectors are available that have been reported between 1995 and 2011. The final demand produced by the model can be compared with the final demand reported in WIOD. One notion should be made; the historic data covers the years 1995-2011 while simulated data starts at the year 2009. Validation with a more recent WIOD publication is not possible, because in WIOD2016 a different sector-classification is used. Another caution should be made; the data contains the notorious financial crisis of 2007, where the production system started to show heavy distortions. The model shows that it is capable, for some sectors, to generate behaviour that looks like the behaviour observed in the historical data. Three types of behaviour can be observed, growth, decline and jitter around a mean. Similar behaviours can observed from the model with all dynamics enabled, but scarcely within corresponding sectors. However, many sectors seem to be not consumed at all. This can be explained by the fact that consumers only appreciate the quality in one dimension and this dimension is optimised. A lack of consumption by consumers of a sector does not necessarily invalidate the model. As input-output data is reported retrospectively, if a sector appears to have died out, this sector would be merged with another sector by the statistical office. The currently used alternative to the dynamic demand-side model is to extrapolate the current final demand. The discussion of the model results will address the implications of final demand extrapolation.

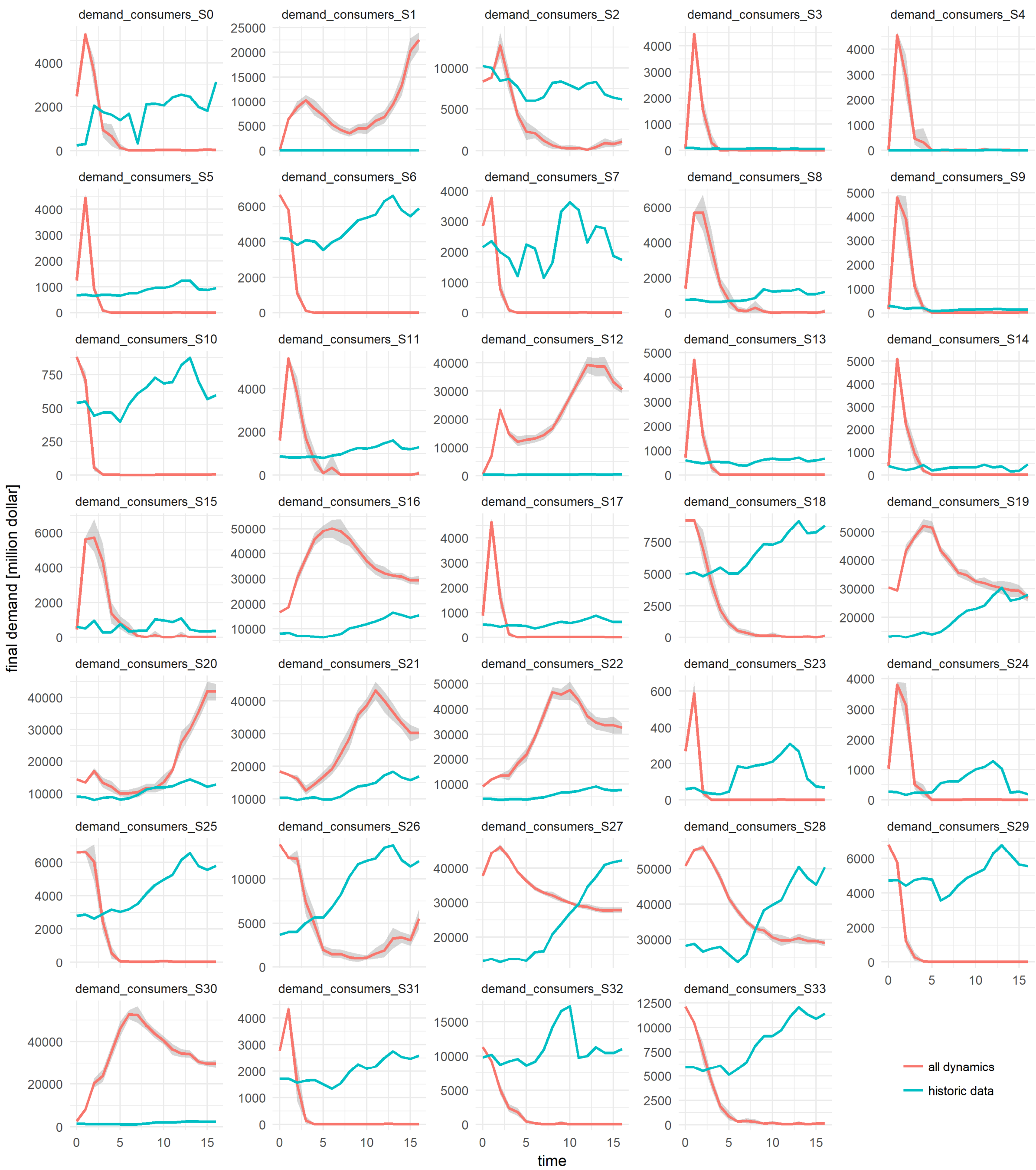


Figure 6.2: Modelled final demand for 2009-2025 and reported final demand of 1995-2011

6.2.2 Experimental design

To explore the implications of the different dynamics that have been included in the proof of concept model, experiments were conducted with the model. In the experiments, the uncertainty in all parameters was accepted and assumed to be negligible. This is of course unrealistic; the implications of the uncertainties are addressed in the subsection 6.2.4, featuring the sensitivity analysis.

Three features were switched on- and off throughout the experiments; the supply-side dynamics, changing the technologies' attributes over time, the demand-side dynamics, letting final demand be generated by a population of consumer agents, and finally the difference weight was enabled and disabled. This last setting was included in the experimental design because the implementation of the difference weight, as discussed in in subsection 6.1.2 of this chapter, has not been used in such a way in any literature that was encountered. Typica; agent-based models implementing utility use cardinal utility functions generating utility from the state of wealth. Therefore, the implications of this difference weight should be thoroughly analysed.

In the plots, switch-settings are labelled. With the supply-side dynamics disabled, the technologies' attributes are fixed throughout the model-runs. With the demand-side dynamics disabled, final demand is extrapolated for the number of consumers. If the difference-weight is disabled, utility is generated from the state of wealth; of difference-weight is enabled, utility is generated by changes in state of wealth. For reference, and to clarify the switch-settings labels, the different labels that have been used with the respective dynamics settings are shown below, in table 6.1.

Table 6.1: Experiment switch-settings labels reference table

Label	Supply-side dynamics	Demand-side dynamics	Difference weight
"all dynamics"	Enabled	Enabled	Enabled
"cardinal utility with SS dynamics"	Enabled	Enabled	Disabled
"DW with SS dynamics"	Enabled	Disabled	Enabled
"only DS dynamics with DW"	Disabled	Enabled	Enabled
"only SS dynamics"	Enabled	Disabled	Disabled
"only DW enabled"	Disabled	Disabled	Enabled
"only cardinal utility"	Disabled	Enabled	Disabled
"no dynamics"	Disabled	Disabled	Disabled

This experimental design resulted in eight distinct parameter settings. To account for stochastic uncertainty, all experiments were replicated 10 times. Appendix C.5 shows that 10 replications is enough to account for stochastic uncertainty while it is few enough to keep the computation time feasible. In some figures of the model output in this section, the mean of all replications with certain parameter settings is plotted with a coloured line and a grey area is plotted around the mean to indicate the (bootstrapped-) 95% confidence interval to reflect the stochastic uncertainty.

6.2.3 Model outcomes

The goal of this thesis is to integrate dynamics into the input-output analysis framework. The conceptual model proposed an approach to this integration. The proof of concept model intends to prove that the integration, proposed in the conceptual model, is feasible and relevant. This sub-section analyses the implications of the different dynamics which were integrated in the input-output model. The next section, 6.3, addresses the feasibility and relevance of the proof of concept. The feasibility is assessed based on the experience gained from implementing the proof of concept model. The relevance of the conceptual model is assessed based on the model outcomes that are presented in this sub-section. A thorough analysis of all experiment results can be found in appendix E. Throughout this sub-section, the dynamics settings are labelled as presented in table 6.1. The different sectors are labelled as S0 through S33, in table E.1 on page 114 the reference table for sector labels can be found.

Figure 6.3: Recorded final demand in WIOD (1995-2011) and simulated final demand without dynamics (2009-2025)

In conventional input-output analysis, final demand is exogenous to the model. Either a fixed value is used, or the final demand is extrapolated. The proof of concept model features two different ways to represent final demand endogenously. In reality, final demand by consumers for sector-products shows different types of behaviour. Historical data gives some idea what this behaviour looks like in successful sectors. Historical input-output data is compiled retrospectively, unsuccessful sectors for which consumers have lost interest, will no longer be reported as an individual sector but these sectors will be aggregated into another sector. For instance, once upon a time telegrams were a large business, nowadays telegrams are barely used. Figure 6.3 above shows for every sector the final demand reported in WIOD between 1995 and 2011 and the simulated final demand between 2009 and 2025 with the model with all dynamics disabled. The model with all dynamics disabled simply extrapolates the final demand vector for the number of consumers. Final demand of the base year (2009) is divided over consumers. The final demand per consumer is constant but the number of consumers increases according to the CBS population projection. The behaviour of the curves generated with "no dynamics", the extrapolation, show the same behaviour in every sector and show a steady growth over the time period. The historic data shows different types of behaviour, growth (e.g. S27), decline (e.g. S1), extreme peaks(e.g. S24) and jittering around a mean value (e.g. S15). The extrapolation does not generate behaviour that is similar to real world observations.

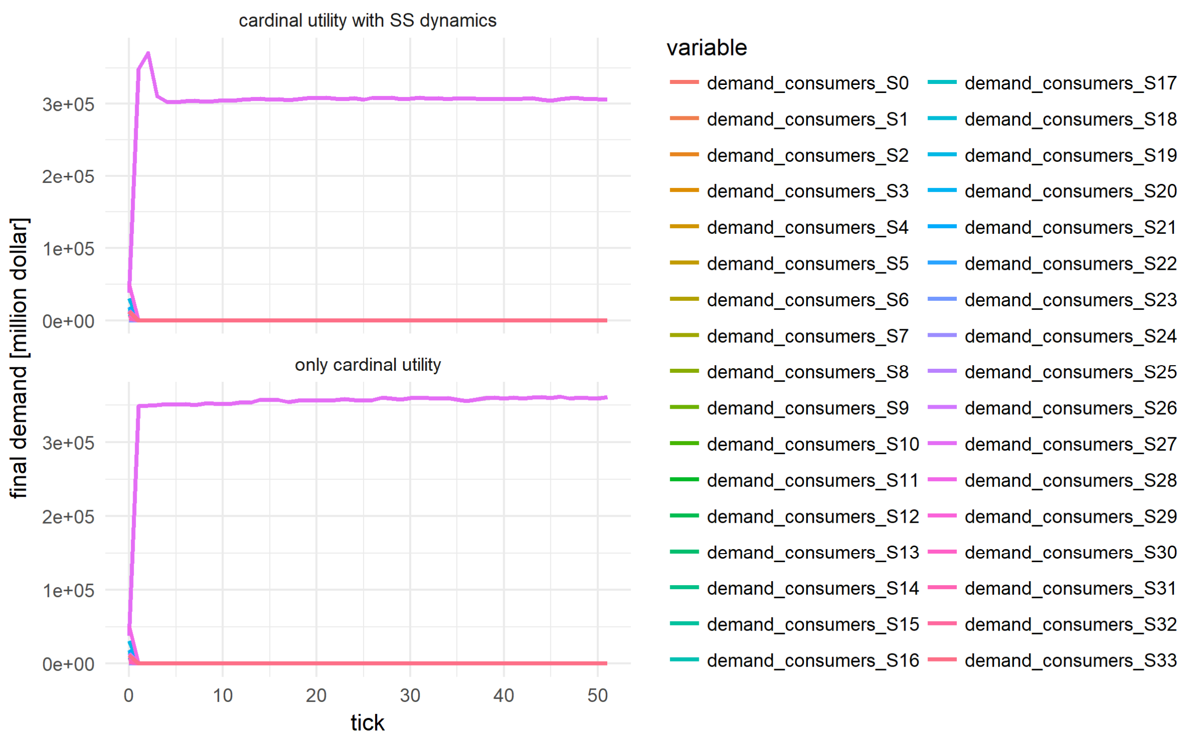


Figure 6.4: Final demand all sectors simulated with simple cardinal utility with supply-side dynamics switched on and off

As an alternative to exogenous final demand, the demand-side dynamics model was proposed. The demand-side dynamics model contains two approaches to generate final demand from consumers. The first approach to modelling final demand endogenously that was implemented is a simple, cardinal, utility function. Figure 6.4 above shows the final demand for all sectors of the model with only a cardinal utility function and a cardinal utility function together with supply-side dynamics enabled. Both plots show the same thing. Every consumer optimises its utility by allocating the entire budget to a single sector. This single sector is labelled as S27, which is financial intermediation. Financial intermediation is chosen by all consumers despite the consumers heterogeneity in environmental impact weight; this is because financial intermediation scores well on both performance (0.98 while the mean performance is 0.28) and environmental impact (0.007 while the mean environmental impact is 0.18). Single sector dominance is clearly not an improvement compared with the extrapolation.

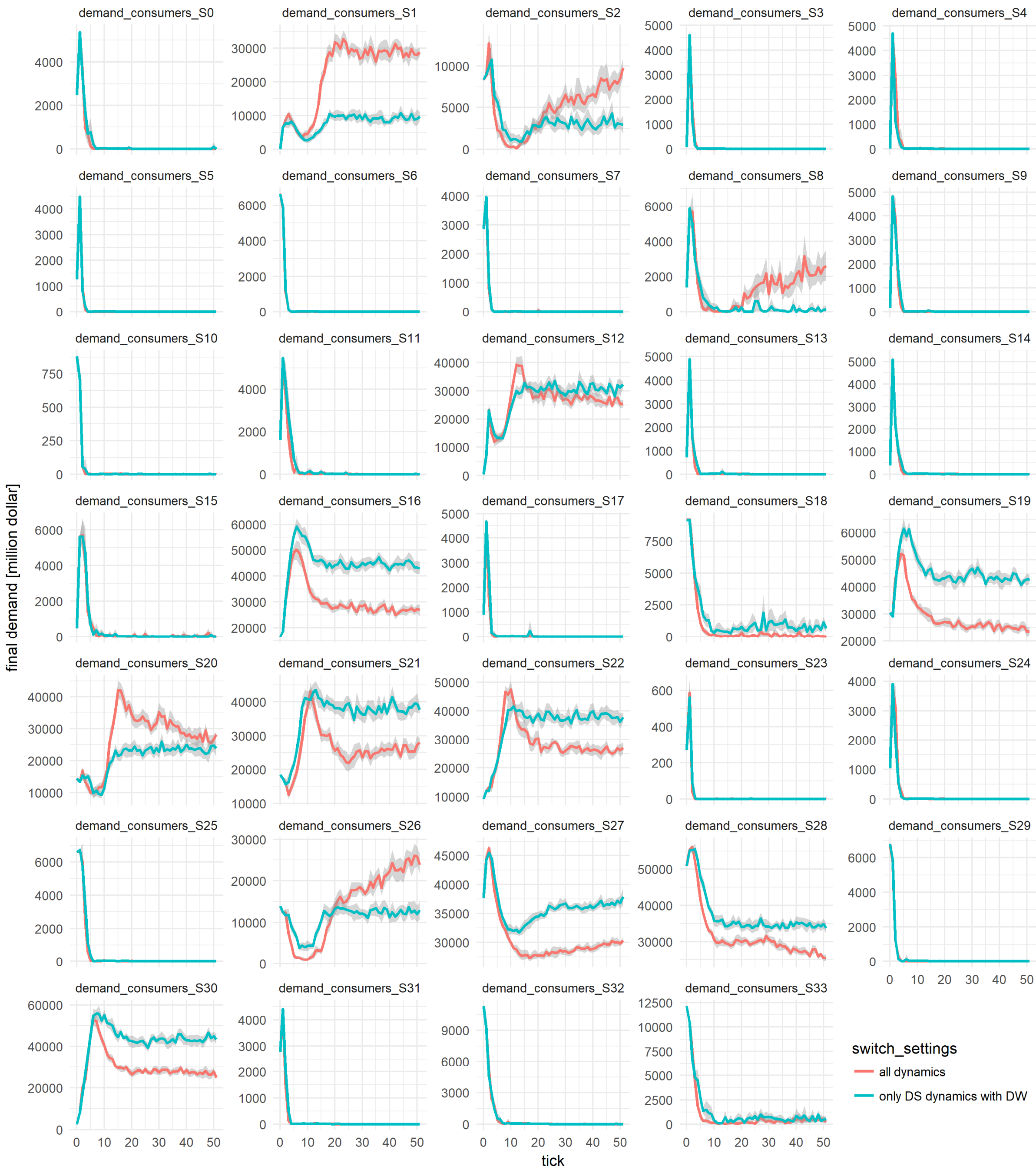


Figure 6.5: Simulated final demand per sector with all dynamics and with only supply-side dynamics disabled.

The second approach to generate final demand from consumers is by generating utility with Difference Weight enabled, as defined in equation 6.2. Figure 6.5 above shows the final demand by consumers per sector simulated by the demand-side dynamics model with the difference weight enabled and with the supply-side dynamics enabled and disabled. In figure 6.5 the same behaviours can be observed as in the historical data, S28 shows a decline, S26 shows growth, S20 shows a sharp spike and S8 shows jittering around the mean. However, in many sectors in figure 6.5 there is no activity at all, consumers only purchase from around 15 sectors. While it could be possible that consumers lose all interest in a sector, it is highly unlikely. Settling with a few sectors is a consequence of having quality as a one-dimensional parameter; information is lost with this single parameter. In reality, consumers might have several needs with different priorities which are served by specific sectors; first, a consumer might want some amount of food and shelter, and once these demands are satisfied a consumer might look to satisfy some demand for leisure activities or self-actualisation. Further development of the demand-side dynamics should investigate implementing the concept of quality of products with respect to consumer needs, to improve the utility function. The well-known Hierarchy of Needs, of Maslow (1970), might serve as a framework for what needs a human being might have, along with an ordinal scale of these needs. To show the effect of adding a dimension to the performance parameter, the model has been expanded to incorporate a more detailed representation of product quality. This expansion is briefly discussed in section 6.3.1, the final demand plots per sector with two-dimensional performance are shown in figure 6.9 on page 68.

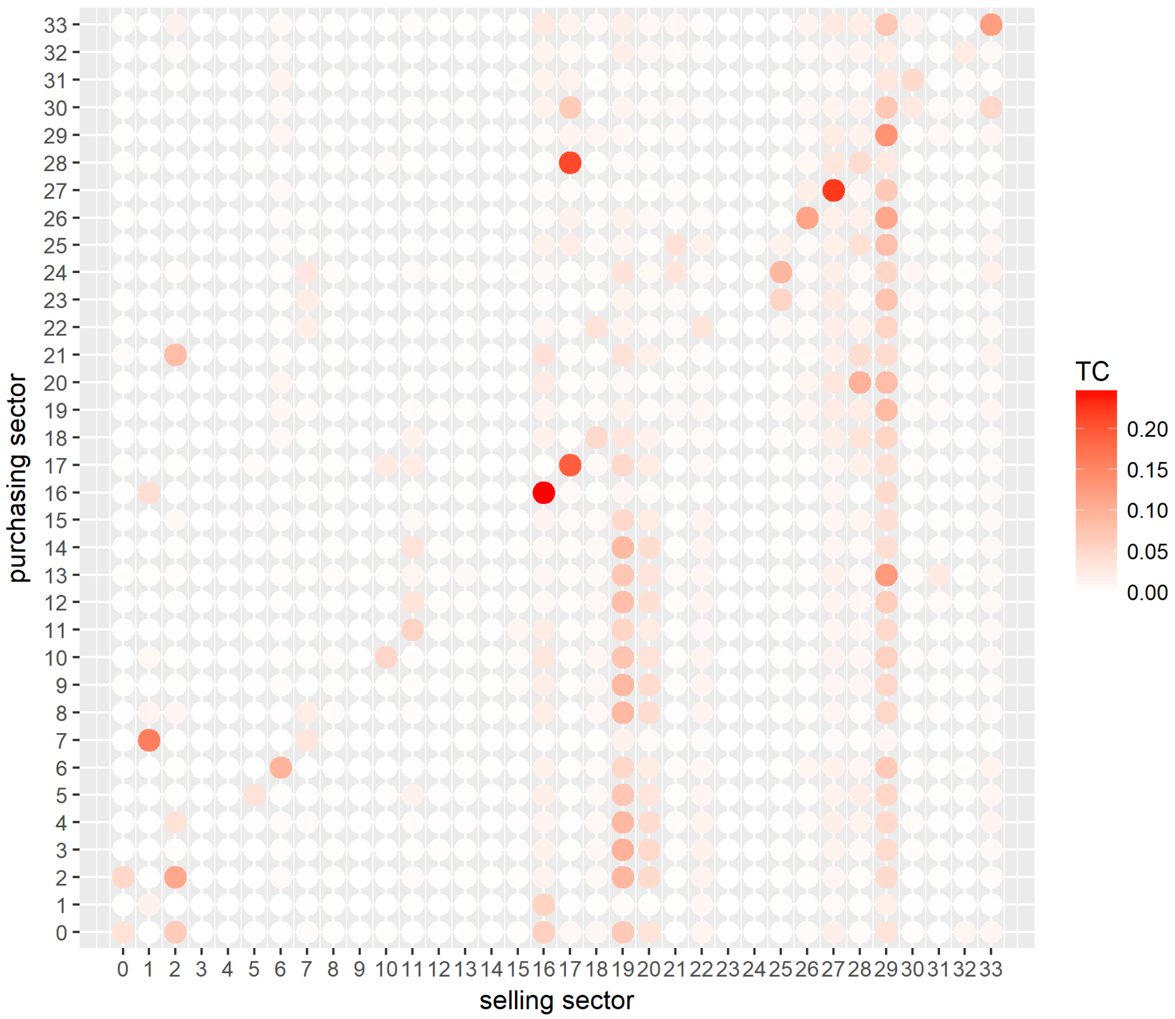


Figure 6.6: Technological coefficient matrix at the model instantiation (t=0) plotted as a gradient scatter-plot

The supply-side dynamics that are incorporated in the proof of concept are quite simple; technologies change their performance or environmental impact attribute as well as their technological coefficient vector. The changes in attributes of technologies follow the Wright curve, as a function of technologies' increased cumulative output. The output that technologies have to produce can be broken down into four categories, consumer demand (generated by the demand-side model), intermediate demand (calculated with conventional input output analysis, dependent on the total output and the technological coefficient matrix), non-consumer demand (exogenous and constant throughout the model-runs), and export. The model-runs where only cardinal utility is enabled, show that all consumer final demand is concentrated in a single sector, this sector gains an enormous output growth while the other sectors remain more or less stable. The secondary effects of S27 becoming the dominant sector are rather small, in other words the effects of the demand for intermediate products by the financial intermediation sector are small. The technological coefficient on the row of S27 peaks at its own column while the other values are all equally marginal. In other words, to produce output the financial intermediation sector requires a lot of its own products, and a small, equal, margin of other sectors. The full technological coefficient matrix is plotted and shown above in figure 6.6 to give an idea how intermediate trade is distributed. In figure 6.6 one can observe that S27 requires very little intermediate products from other sectors. Figure 6.6 shows large values along the diagonal, indicating that most sectors require mostly their own input, and high values along rows of the y-axis, indicating that some sectors produce a lot of intermediate products for other sectors. Some off-diagonal high values can be observed in figure 6.6, for instance the real estate activities sector (S28) consumes a lot of products from the construction sector (S17), the coke, refined petroleum and nuclear fuel sector (S7) consumes a large amount of output of the mining and quarrying sector (S1). While there are not many large 'buyer' sectors, sectors that purchase a lot of output from one or different sectors, there are many 'seller' sectors, seller sectors have high values in the columns of figure 6.6. The technological coefficient matrix is changed throughout the model-runs. As technologies learn, their efficiency increases, and their costs decrease. The input-output table is in monetary units, therefore decrease in costs is reflected in the model as a decrease in technological coefficient. As the model does not incorporate innovations, new intermediate trade-relations do not occur, only the existing trade relations steadily change as cumulative output increases.

Figure 6.7 below shows the output of sectors of a model-run with all dynamics enabled, the output is broken down by demand source. There are four sources of demand, non-consumer demand, export, intermediates and consumer demand. Non-consumer demand and export are exogenous to the model, these demand sources are kept constant throughout the model-runs. Final demand by consumers is generated by the demand-side dynamics model, as discussed previously in this subsection. The final demand by consumers is irregular in runs with all dynamics enabled. Intermediate trade peaks due to peaks in consumer demand, and the intermediate shows a steady decrease due to the learning effects. Two off-diagonal trade-relations between sectors were mentioned in the previous paragraph, these trade relations can be observed in figure 6.7. Sector 1 supplies sector 7 and sector 17 supplies sector 28. The peaks in output of sector 7 and 28 are accompanied with peaks in intermediate trade-output in sectors 1 and 17. When the demand-side dynamics are disabled, the final demand by consumers also becomes exogenous; in these model-runs the output by sectors is stable, and relatively constant throughout the entire model-run. While the supply-side dynamics model is implemented with a very simple model, due to the interactions with the demand-side model complex behaviour emerges in the output of sectors.

Figure 6.7: Total output per sector of a single run with all dynamics enabled, broken down by demand source

6.2.4 Sensitivity analysis

The results presented in the previous subsection were of the experimental design where all parameters were constant, except for the dynamics-settings; even the uncertain factors were not varied. This section is concerned with the impact of these uncertain factors on the model output; in other words, the sensitivity of the model to the uncertainties. In the parameterisation many factors were found to be uncertain, and in section 3.3.2 was discussed that values in an input-output table are highly uncertain. To gain robust insights from a model, it is required to know how the output of the model responds to these uncertainties. Another outcome of the uncertainty analysis is to focus further research goals. If uncertain parameters have a large impact on the model outcomes, efforts into reducing these uncertainties are highly effective to increase the robustness of the insights from the model.

This subsection will focus on attributing variance in the model output to uncertain input factors. The proof of concept model contains many uncertain factors. The main uncertainties in the supply-side model originate from two categories; the Wright parameters and the composition of sectors. It is known that a sector uses several technologies, two in the proof of concept; but it is unknown how many technologies are active in a sector and how the sector-level attributes are divided over these technologies. The main uncertain factor in the demand-side dynamics model is the utility function. The structure itself, of the utility function, is uncertain, and the values of the utility weights are uncertain. Lastly, the input-output data contains a lot of uncertainty. To analyse the attribution to the variance of the output of the model from all these uncertainties, many experiments need to be conducted. For example, if only the uncertainty containing the intermediate trade matrix is to be analysed, there are 34 rows by 34 columns which means that there are 1156 uncertain factors. Adding that to the other vectors taken from WIOD (which contain the wage contributions per skill level, the initial final demand, the final demand by non-consumers, export, initial sector output, and the environmental impact), a great many uncertain factors have to be analysed. This must be left outside the scope of this thesis. Rather than testing a great number of uncertain factors, a small number of uncertain factors is tested, but tested very thoroughly.

The relation between the input and output of the model is quite complex because of the many interaction in the models; therefore, a global sensitivity analysis is applied. A local sensitivity analysis would vary the input parameters one at a time to see the effect on the output. A global sensitivity analysis varies multiple input parameters at the same time and attempts to attribute the uncertainty to the different input parameters. The method of sensitivity analysis applied to the proof of concept is the Sobol' method (Sobol, 2001); in this method, the variance of output of the model is attributed to the different uncertain parameters. Both the effects of the individual uncertain parameters, and the interaction effect between different uncertain parameters is assessed. In this subsection, a presentation is given of the results of the sensitivity analysis by reporting the first order effects, S1, and total Sobol index, ST. The first order effect attributes the variance in output to each individual uncertain factor. The total Sobol index, ST, describes the total effect per uncertain parameter on the variance of model output; the total effect includes both the factor's individual effect and all interaction effects, with all other uncertain factors, on the variance of the model output. A downside of the Sobol' method is that it requires a large sample size per uncertain factor. The relation between the sample size and the number of uncertain factors for the Sobol method is $n(2k+2)$, where k is the number of uncertain factors and n is the number of experiments; typically, a Sobol sensitivity analysis requires n to be between 500 and 1000 to converge. Because the uncertainties should be tested thoroughly, only three uncertain factors are tested. Adding more uncertain factors is not an issue, but the computation time of more factors is an issue.

The factors that have been tested are the progress ratio, the environmental impact utility weight and the difference weight base value. The efficiency improvement per unit of added output is known to be quite sensitive to Wright parameters, therefore one of the two used Wright parameters was tested. Because the cumulative output was better substantiated than the progress ratio, the reported output in WIOD over the years 1995-2011, the progress ratio was deemed less certain and therefore was tested. The progress ratio bounds were set at 0.65-0.95. The environmental impact weight had, like the progress ratio, a complete lack of theoretical or empirical foundation, and is suspected of having a large impact on the model outcomes. Therefore, a deviation term was added to the model code and this deviation term was tested on the range of 0-3. The consumers are heterogeneous in their environmental impact weight, in the sensitivity analysis model the consumers are asked to multiply their environmental impact weight with this deviation term. The difference weight base value is a second utility function component that is an uncertain factor. The difference weight base value used in the model experiments was 0.5; meaning that when a consumer has reached its last timestep's quantity of products purchased, the cardinal utility of that product has half its original value. The sensitivity analysis tested difference weight base values ranging between 0 and 1. The output that is analysed based on these uncertain factors are the total CO_2 emissions, the total sector output and the total final demand. Of all these output factors, the mean over all the replications and all the time steps is taken.

For the sensitivity analysis a new experiment was conducted with the proof of concept model. A Sobol sequence was used to sample values for the uncertain input parameters. The SALib library in python provides an off-the-shelf toolkit to generate this Sobol sequence. The EMA workbench (Kwakkel, 2017) in python uses the SALib library to draw the Sobol sample. In order to get the sample from the python environment to the NetLogo environment, and the model output back into python, the PyNetLogo package (Jaxa-Rozen & Kwakkel, 2018) is used by the EMA workbench, which in turn uses the JPype package (Menard & Nell, 2014) to interface between python and java. By using the EMA workbench, the sensitivity analysis is fully executed from the python environment without major efforts.

In table 6.2, below, the results of the sensitivity analysis are presented. The results of the sensitivity analysis were generated with 500 experiments. This is typically the minimum number of experiments required to reach stable indices.

Table 6.2: First order- and total Sobol indices with confidence interval per uncertain factor per output measure

Factor	**Base DW (dw-0)**				**Environmental impact weight**				**Progress ratio**			
	First order effect		Total effect		First order effect		Total effect		First order effect		Total effect	
	S1	C.I.	ST	C.I.	S1	C.I.	ST	C.I.	S1	C.I.	ST	C.I.
Total CO_2 emissions	0.01	[0, 0.06]	0.10	[0.09, 0.11]	0.83	[0.73, 0.94]	0.91	[0.82, 1.00]	0.07	[0.04, 0.10]	0.08	[0.07, 0.09]
Total output	0.36	[0.29, 0.43]	0.37	[0.33, 0.42]	0.01	[-0.01, 0.03]	0.03	[0.02, 0.03]	0.64	[0.55, 0.73]	0.66	[0.60, 0.73]
Total final demand	0.47	[0.37, 0.58]	0.65	[0.57, 73]	0.17	[0.10, 0.25]	0.33	[0.29, 0.37]	0.17	[0.10, 0.23]	0.33	[0.29, 0.38]

As one could expect, he environmental impact weight influences the total CO_2 emissions quite strongly; the other two uncertain factors have a small influence on total CO_2 emissions even with interaction. As the literature on the Wright curve describes, the total output is sensitive to the progress ratio. Environmental impact weight has a negligible impact on the total output. All three uncertain factors have some degree of impact on the variance of the total final demand, but the base difference weight's influence is the strongest (especially when interacting with the other two uncertain factors). Not all of these effects are straightforward, this is caused by the feedback between the supply-side and the demand-side. In figure 6.8, below, this feedback is illustrated; the uncertain factors are coloured orange and the output measures are coloured green. The difference weight and environmental impact weight heavily influence the spread of consumer's final demand over the different sectors. A different division of final demand leads to a different vector of total intermediate trade. Intermediate trade together with direct final demand forms a significant portion of the total sector output. The total sector output is the dependent variable in the model for the CO_2 emissions and the wages. The wages determine the budget of consumers which is directly transformed into total final demand by consumers, divided over the sectors. The progress ratio affects the total output of the production system as it decreases the required amount of input for one unit of output (in monetary terms).

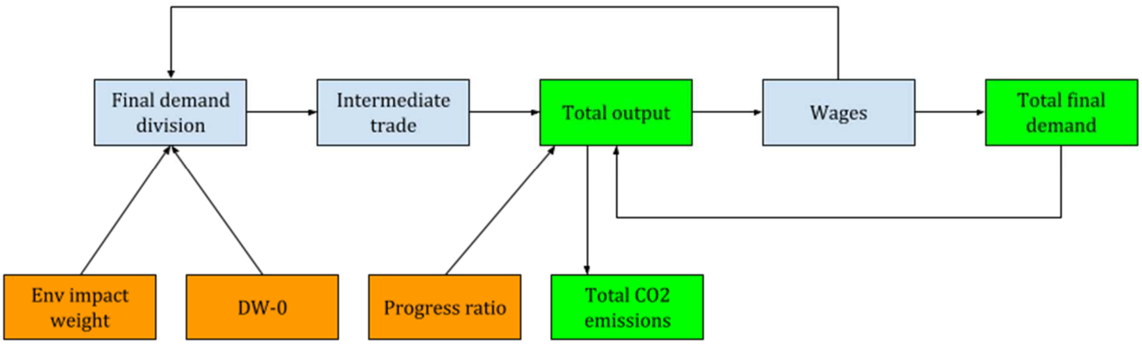


Figure 6.8: Feedback between dynamics models

6.3 Feasibility and relevance of the integration based on the proof of concept

An assessment of the integration is made based on the trade-off between the benefits of having the integrated features endogenous to the model and the costs of implementing the integrated model. First, an assessment is made of the feasibility of implementing the integrated model based on the implementation cycle of the proof of concept. Second, an indication is given of the relevance is given based on the added value of having the integrated features endogenous to the model.

6.3.1 Feasibility of implementing the conceptual model

The feasibility of an implementation of the conceptual model is assessed for both dynamics models separately. First, an assessment is made of the supply-side dynamics model and second, an assessment is made of the demand-side dynamics model.

For the supply-side dynamics model, the major difficulty lies in defining the heterogeneity within sectors. It was assumed that a sector is a collection of firms, and these firms use some production technology. Because input-output data reports sector level data, dis-aggregating this data and assigning different attributes within a sector is impossible to substantiate. The inability to substantiate these attributes makes it difficult to implement the supply-side model. This problem was encountered in the implementation of the proof of concept and was resolved by making crude estimations. Three options to deal with this problem are suggested.

First, the sectors, and its containing firms or technologies, can be modelled individually. This will require a tremendous modelling effort, basically modelling the entire production system in detail. Therefore, this first option is deemed infeasible.

Second, rather than modelling each sector in detail, the sectors can be classified into archetypes. General models of these archetypes can be developed and parameterised independently. This second option lies between the conceptual model's approach and the first suggestion's approach of individual sector models. This approach is unlikely to be more feasible than the first approach because two (similar) problems emerge but to a lesser extent. These problems are, (1) input-output data must be dis-aggregated to instantiate the models and (2) different archetype models have to be developed. However, the different models can be developed in parallel which makes it less problematic; but, input-output databases are known to change the classifications of sectors. This could mean that some of the archetype models can become obsolete if Eurostat decides to aggregate- or dis-aggregate that sector.

The third and final option is to stick with the input-output analysis' assumption of homogeneous sectors; however, development of the sectors over the model run is heterogeneous and modelled in some more detail. This approach is similar to the turnpike growth model (Carter, 1974) which is discussed in the last paragraph of appendix A.1.2; however, rather than having an economy-wide growth rate, the sectors develop independently. Sectors can be modelled to make incremental efficiency improvements following the Wright curve. By taking historic data, the Wright parameters can be fitted. Using the relative efficiency increase, the cost of the first-unit can be omitted from the model. The progress ratio and the cumulative output can be estimated by analysing the development of the technological coefficient per sector with respect to the sectors' increased output in historic data.

While the proof of concept model was a quite crude implementation of the conceptual model, the demand-side dynamics model shows promise; a more detailed implementation can result in an adequate representation of final demand by consumers. In this paragraph, two options to improve the demand-side model are discussed.

A first possible improvement of the demand-side model is to represent quality of products more realistically. In the proof of concept, the performance term grouped together all quality aspects of technologies, apart from CO_2 emission. However, quality is known to be a complex term, grouping together several aspects. Consumers purchase products to satisfy their needs; quality-parameters could be aligned with human needs in order to properly reflect a consumer's trade-off in purchasing decisions. In psychology literature, it has been established that humans have a diversity of needs that should be represented in more terms than the two presently represented in the model (the performance parameter and environmental awareness). The Maslow Hierarchy of needs, which has proven to be a valid framework (Graham and Balloun, 1973), can serve as an ordinal scale for needs of consumers that are to be supplied by the production system. Using this hierarchy, the quality parameter can be incorporated in the model in more detail. If several, different, quality parameters are represented, consumers are faced with a more difficult trade-off in allocating their budget and a more diverse final demand vector will emerge which would represent the historic data more accurately. Factor analysis could be used to estimate consumers' utility weights per quality parameter. By performing another calibration experiment, and the outcome of this factor analysis, these quality parameters per sector can be estimated. To further substantiate this improvement option, figure 6.9 below presents the final demand of a model run with a two-dimensional performance parameter. To produce figure 6.9, the model code was adapted to incorporate two performance parameters. All consumers attribute a utility-weight of 0.7 to the secondary performance parameter while the utility weight for the first performance parameter is one. This reflects a consumer's primary, important, need, and a secondary, nice-to-have, need. Apart from the consumer's utility-weight, the model treats the secondary performance parameter in the same way as the original performance parameter. A new calibration experiment was conducted to parameterise both performance attributes per sector. From figure 6.9 can be seen that more sectors are active, an active sector being one that supplies consumer-demand. Where the, original, one-dimensional performance model had around 14 active sectors, the two-dimensional performance model has about 19 active sectors. This is already a significant improvement, further development along this path seems promising.

The second option to improve the demand-side dynamics model, to increase the model's ability to reproduce historic final demand behaviour, is to add a baseline final demand vector; a final demand vector that is always purchased before the rest of the budget is allocated using the dynamic model. This baseline final demand could ensure a more representative final demand for the smaller sectors. These smaller sectors were found in the historic data to have a small final demand level. The baseline final demand is supplemented by the final demand emerging from the consumer-agent's decision-making process.

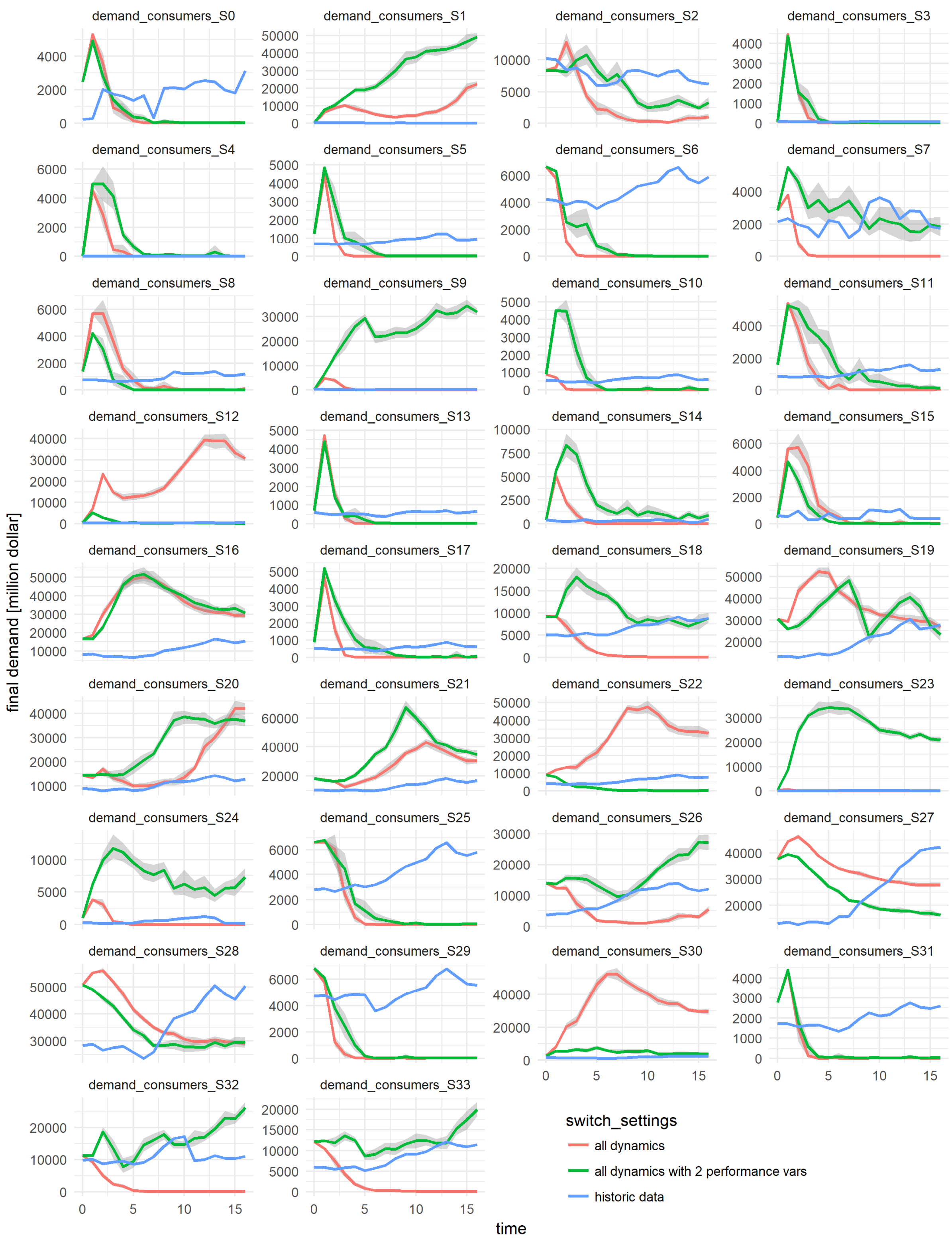


Figure 6.9: Final demand per sector of historic data, and of model runs with no dynamics, all dynamics, and with two-dimensional performance and all other dynamics

6.3.2 Relevance of implementing the conceptual model

Integration of the two modelling perspectives, input-output analysis and agent-based models makes a lot of sense in terms of their goals and purposes. Both frameworks aim to provide insight in a system. However, both frameworks take the opposite approach of compiling the system.

Where input-output analysis decomposes the system from a top down perspective, agent-based modelling builds the system from a bottom-up perspective. This poses difficulties for the alignment of the models. These difficulties have been discussed in the previous sub-section, this sub-section will discuss the benefits of reaching this alignment and integrating the models.

Where agent-based modelling generally suffers from a lack of historic data for validation or calibration purposed, input-output data is able to provide. The data is rich in detail and highly structured. In the proof of concept, calibrating the model was rather simple. The model logic was implemented, and random variables were assigned until the model output produced the best fit with the historic data. Also, the validity of the demand-side dynamics model could be assessed to a certain extent thanks to the availability of this historic data.

For macro-economic models, a common criticism is that they lack in technological detail and micro-economic explicitness. Being able to bring together these aspects into a single model is referred to as the 'holy grail' of economic models. Agent-based modelling is certainly able to provide this micro-economic realism. Providing the technological detail would, as discussed in the previous subsection, be a tremendous task. However, agent-based modelling provides the means to implement technological detail. By adding the technological detail of the dynamics models, the integrated model can become more precise in a more meaningful way than tweaking the scenarios of final demand or technological coefficient-change.

Input-output analysis is founded on some basic assumptions that have not been tampered with over the development of the framework. The assumptions seem to be made to support computability of the system. However, over the last eighty years, since the framework was proposed, the availability of computing power has exploded. Besides the availability of massive computing power, theories that can readily be implemented in the model are available. Rather than ignoring advances in cognitive psychology, behavioural economics, uncertainty analysis and technological change literature, these theories could be used to be able to reproduce observed behaviour.

For future development of the input-output analysis framework, at this point it seems best to represent the supply-side dynamics with a simple model. Homogeneous sectors seems to be the best approach for now, but with individual sector-growth. The demand-side dynamics model shows that empirically validated theories can readily be incorporated into the model to replace some of the fundamental, and obviously wrong, assumptions of the input-output analysis framework. Advances in uncertainty analysis should be considered, rather than ignoring the uncertainty present in the input-output data these errors should be accounted for in order to design robust policy.

Chapter 7: Conclusions, discussion and reflection

In the preceding texts, all research (sub-) questions have been answered. In this chapter, these answers will be recaptured to come to the ultimate conclusion of this thesis. First, the research sub-questions are briefly re-answered with a reference to the thesis sections where these findings are described; these answers are then brought together to answer the main research question. Second, a discussion of these findings in light of their societal and scientific relevance is presented as well as some suggestions for future research directions. Finally, the last section of this thesis reflects on the research that has been conducted; both a look back onto the product of this research, and the process by which this research was conducted.

7.1 Revisiting the answers to the research questions

In the research approach, described in chapter two of this thesis, the main research question was proposed and decomposed into sub-question. In this section, the main research question is answered by looking back on the different chapters that have been produced which answered the sub-questions. The main research question is:

How can supply- and demand-side dynamics be integrated with the input-output analysis framework?

The breakdown of this research question into four sub-questions is as follows:

1. Which input-output analysis methods- and databases are adequate for a national trade model with dynamic features?
2. How to adequately represent supply- and demand-side dynamics in the input-output analysis framework?
3. How can multiple, different, models be integrated into a single model of a national economy?
4. What are the costs and added value of integrating supply- and demand-side dynamics into the input-output analysis framework?

7.1.1 Input-output methods and database to represent a national trade model with integrated dynamic features

The first sub-question was answered in the third chapter of this thesis. An overview was provided of input-output analysis as a method to gain structural understanding of a production system. Input-output analysis was found to be an elegant method to describe a production system, which has been in use for a long time. New levels of output in response to final demand changes can easily be calculated using the Leontief inverse, this procedure is shown in equation 3.6 on page 17. However, due to the simplicity of the model, a lot of information is lost. Linear relations are assumed, and many factors are kept exogenous to the model. Input-output data contains a large degree of errors. The input-output analysis paradigm's consensus about uncertainty seems to be to ignore it and attempt to reduce it by increasing the resolution of the tables. This development is a response that will not easily facilitate a more sophisticated handling of the uncertainties; rather than accepting the uncertainty, perhaps policy makers want to explore the uncertainties and their implications for policy making. When exploring uncertainties of a complex system, the number of factors greatly affects the tractability of the sensitivity analysis; the proof of concept model's uncertainty was analysed using the Sobol' method which usually requires over 1,000 experiments per uncertain factor.

To analyse implications of the circular economy, information about the flow of resources and waste should be accounted for. Environmentally extended input-output tables exist but not much information of these streams is present. Usually these extended tables account for some pollutant streams like CO_2 emissions, but in general the resources requirements of products are aggregated into certain sectors. For the proof of concept, the focus was placed on CO_2 emissions; further development of the model can be dedicated to incorporating the other pollutants accounted for in the input-output data. However, to assess the resource depletion and resource replenishment fully, to assess the level of 'circularity' of the economy major revisions are required to the input-output table's format. Resource requirements as well as recycling activities should be dis-aggregated from the current sector decomposition. The proof of concept is based on WIOD data; while WIOD has a low resolution, its resolution aligns with many other databases. These other databases cover many topics that are relevant for a national trade model. Further development of the model can benefit from these databases. An example is the KLEMS database, this database contains information on the level of capital investments of sectors. Increasing the micro-economic realism of the model could involve modelling investment strategies of firms. The KLEMS database provides data on the current investment streams of sectors.

7.1.2 Demand- and supply-side dynamics representations for input-output analysis

The second sub-question was answered in the fourth chapter; how can the demand-side dynamics be adequately represented and how can the supply-side dynamics be adequately represented in the input-output analysis framework?

The demand-side dynamics were scoped to consumer demand. The final representation of consumer decision-making leading to levels of demand per sector was implemented in the proof of concept in two different ways; the implementations differed in the utility function. Consumers were found to be decision making agents, optimising the utility under their available budget constraints. Utility has proven to be a valid concept, but the implementation of this concept is subject of debate among the different utility theory streams. The two different implementations that have been tested in the proof of concept were a cardinal utility function and a utility function based on Prospect Theory. Prospect Theory argues that utility is generated by changes of state of wealth, by gains and losses. Cardinal utility is perhaps the most popular and well-known type utility function, where utility is a function of the amount of goods consumed times a scalar. In the proof of concept, utility evaluated two attributes of products: a performance attribute and an environmental impact attribute. Using a cardinal utility function, consumers optimise their utility by finding the one sector with optimal utility and allocating their full budget to that product. The prospect theory-based utility function proved to be able to replicate the type of behaviour reported for final demand in historic, input-output, data. However, the final demand was still concentrated to a limited number of sectors, little under two-thirds of the sectors were not at all consumed by consumers. Adding more attributes to be evaluated in the utility function presents consumers with a more complex dilemma, how to allocate their budget. Aligning the product attribute with different categories of human needs was suggested as a possible direction for future research. A preliminary implementation of a two-dimensional quality parameter showed a significant improvement.

The supply-side dynamics focussed on substantiating and quantifying changes to the input-output relation and output-externality relation of sectors. The supply-side was conceptualised as a set of sectors, which in turn are composed of a set of firms producing output of the same classification; these firms employ a production technology which prescribes the firm's product-attributes. In the proof of concept, firms were not explicitly modelled, technologies themselves were directly modelled. The reason to leave out individual firms was because there was no relevant data available on firms active in each sector. Firms are included in the conceptual model because their individual strategies influence the economic outcomes. Future development of the model might aim to add micro-economic realism. Micro-economic realism includes firm-level behaviour like profit maximisation. The conceptual model proposes that innovation can be simulated with evolutionary algorithms. This was not tested in the proof of concept model;

simulating innovation with evolutionary algorithms itself has been achieved by other researchers, see for instance (Birchenhall, 1995). Beside innovation, technological change also occurs incrementally. Incremental technological change was found to be adequately described by the Wright curve, describing the cost of products as a function of the Wright parameters. These parameters are the cost of the first unit produced, the cumulative output of the production technology and the progress ratio of the production technology. The proof of concept did simulate this incremental technological change as a function of the Wright curve; by calculating the relative improvement rather than the absolute cost one of the Wright parameters could be omitted from the model, the cost of the first unit produced. The other two Wright parameters were still required for the model. These were estimated and the sensitivity of the model-output with respect to the progress ratio was tested. Because the proof of concept model held all final demand that was not caused by consumers exogenous, the model outcomes did not show complex behaviour. Export appeared to be a huge part of final demand and therefore the interaction between the supply-side and demand-side dynamics were small.

The demand-side dynamics and the supply-side dynamics interact in the model; consumers from the demand-side generate the final demand, final demand is supplied by sector output of the demand side model. In turn, sector output generates wages for the consumers. The height of the wages both affect the level of total final demand as well as the division of final demand. The division of final demand is affected by wage because utility (based on Prospect Theory) has diminishing returns. This feedback is visualised and can be found in figure 6.8 on page 66.

7.1.3 An integration approach for integrating the dynamics models into the input-output analysis framework

In the first half of chapter five, the integration approach was defined. Integrating models of different paradigms can be challenging but is a subject of research for quite some time. Especially the integration of top-down and bottom-up models poses difficulties for this thesis. Different frameworks of models integration were reviewed and these frameworks appeared to have a common approach; in the approach, synthesised for this research, this common approach was used. A fully integrated input-output analysis structure in an agent-based model required building towards the sector structure from the elementary parts of the economy: production technologies and consumers. This was shown to be an immense task and therefore the multi-model ecologies approach was incorporated; focus the initial development on the relation between the models and let the technological detail emerge over time as development continues. Before the technological detail is present, a proxy must be used for these details. In terms of this thesis, these statements mean that sectors, how diverse they may be, are all represented with the same model. Further development should be focussed on adding the required details to these sectors. Computer automated multi-paradigm modelling argues for an approach where a model is generated automatically based on a meta-model; this meta-model was designed for sectors and instantiated the different, generic, sector models. Extracting sector-level behaviour from the demand-side dynamics was realised by incorporating Prospect Theory in the utility function of consumers. A conventional, cardinal, utility function drove consumers to fully allocate their budget to a single sector, with maximal utility. By incorporating changes of state of wealth, gains and losses compared with the previous timestep, consumers appear to allocate their budgets in a more realistic way; the Prospect Theory-based utility function appears to give a more realistic, sector-level, final demand vector that complies with the input-output analysis structure.

7.1.4 Feasibility and relevance of the integration

Judgement of the feasibility and relevance of the integrated, conceptual, model is based on the experience gained from implementing the proof of concept. The majority of the difficulties in implementing the conceptual model were related to the supply side model. Mainly, dis-aggregating the sector-level data of the input-output data into heterogeneous sectors. This data simply does not exist, and many estimates were made. Alternative approaches to the conceptual model should be followed. The most reasonable future path is to implement a simple supply-side model similar to turnpike growth models already in use in input-output analysis. However, rather than using a single, economy-wide, growth factor the sectors could be assigned individual growth based on the Wright curve. By analysing historic data of the technological coefficient development of individual sectors, the cumulative output and progress ratio per sector can be estimated.

The demand-side model was characterised by a smooth implementation and the results look to have great potential. Due to the abstract implementation of the concept of quality, consumer agents were presented a relatively easy trade-off in their purchase decisions. Representing quality in more detail can be achieved by defining the needs of consumers which are to be fulfilled by the production system. Aligning the quality parameters with these needs will force consumers to value different quality aspects and serve their individual needs. Finding the utility-weights per need can be done using factor analysis. Subsequently, using these weights a calibration experiment can be conducted in the same way as was done to set the performance variable in the proof of concept.

The relevance of the integration lies in the mutual benefit that the two perspectives can attain. With dynamic models, observed empirical notions can be incorporated into the model. A difficulty for agent-based modelling is the lack of historic data. Input-output data solves this issue to some extent; the calibration that could be performed for the proof of concept is testimony to this statement. Where input-output analysis is founded on assumptions which are known to be wrong, theories are available and could be implemented in dynamic models. Advances in cognitive psychology, behavioural economics, uncertainty analysis and technological change literature should not be ignored but used in the input-output analysis framework.

7.1.5 Answering the main research question

This sub-section brings together all insights that have been gained throughout this research. The main research question, concerning how to integrate dynamic models with input-output analysis is answered. To integrate the demand- and supply-side dynamics into the input-output analysis framework, the final model should be feasible. The conceptual model of the supply-side appears to be too ambitious to implement or at least parameterise. While evolutionary algorithms were not tested, the Wright curve can easily be implemented into the model. This way, the assumption of static technological coefficients is replaced with the assumptions of the Wright curve, which were found to be mode valid throughout the encountered literature. The demand-side model was proven to be feasible to implement into input-output analysis. Thanks to the insights gained from Prospect Theory, a utility function was formulated that was able to imitate historic final demand levels. The current implementation of the demand side model was quite crude and has huge potential for improvement. This way, the assumption of known and exogenous final demand is replaced with the assumptions underlying utility functions and Prospect Theory. Again, these concepts have been proven to match empirical observations much more closely than the original input-output analysis assumptions. Uncertainty was found to be ill accounted for in the input-output analysis framework. The magnitude of the errors in input-output tables was found to be impossible to assess. The field of uncertainty analysis has developed sophisticated methods to analyse the implications of uncertainty to design robust policy. The size of the input-output tables presents an issue for thorough uncertainty analysis, because each cell of the input-output table should be considered an uncertain factor.

In order to be able to evaluate policy regarding the circular economy, input-output tables do not provide the required data. To assess the circular economy, an appreciation is required of the depletion of resources as well as the replenishment of resources. A sustainable, circular, economy is one where the depletion of resources does not exceed the rate of replenishment of these resources. While these rates can be modelled, input-output data does not report data required to quantify these rates. Waste streams are required to evaluate the rate of replenishment and resource streams are required to evaluate the rate of depletion. The structure of input-output analysis is suitable for such analyses, this was shown with the proof of concept for CO_2 emissions. However, as long as the data is lacking, in the format of sectors, circular economy policy analysis using the input-output analysis framework is not possible.

7.2 The implications of this research

Having answered all the research questions, this section takes another step backwards to reflect on the implications of this research. How are the research outcomes relevant for society? And how are the research findings scientifically relevant? These two questions are answered first in this section, and finally some focal points for future research are proposed.

7.2.1 Societal relevance of this research

This thesis is concerned with a methodological question about a macro-economic policymaking tool, input-output analysis. Such tools are usually quite far from most people's interests and comfort zone. However, these tools are quite relevant for anybody. Policymakers rely on them to make substantiated decisions which can have grave implications for individuals and society as a whole.

The purpose of input-output analysis is to gain understanding in the structure of an economy. With environmentally extended input-output analysis the scope is enlarged to gaining understanding of economic and environmental implications of policies. To find sectors which have a large effect of emissions and design policies to reduce these sector's emissions, policymakers attempt to reduce negative environmental impact. However, an economy is a complex system of interacting producers and consumers. Solving climate problems should also focus on the consumers. Integrating the consumer into the framework allows policymakers to account for consumer behaviour and assess possible influences. Using the right analyses, robust policies can be designed which account for, or target, consumer behaviour.

Having heterogeneity of people reflected in the model, as the conceptual model does, can be a double-edged sword; either people feel better accounted for in policy making, or people might be offended by being ill accounted for in policy making, as it would be near impossible to account for every person in a demand-side dynamics model. Either way, accounting for individual's behaviour in the context of environmental policymaking can help to show the individual consumer how their everyday decision making affects the environment, and that making a difference can be as simple as bringing your own bag to the shop.

When adding more detail to the supply side model; danger lurks of publishing too much and too detailed information about firm's operations. In the current input-output analysis framework, some databases already reached a level of resolution where the data must be modified to protect corporate secrecy. Trade flows of firms are strategic information, if a model would accurately depict the trade flows certain firms might be harmed because their competitors could attain this strategic information. If the conceptual model as proposed would be implemented, confidentiality of individual firms' trade flows could become an issue.

7.2.2 Scientific relevance of this research

The integration of agent-based modelling into input-output analysis seems to have potential for mutual benefit. Agent-based modelling is attractive to input-output analysist as it is a tool to incorporate micro-economic realism as well as technological detail. This is considered to be the 'holy grail' of economic models, a model rich in technological detail, micro-economic realism and on top of that macro-economically complete. The other way around, input-output analysis appeals to agent-based modellers because of the vast amount of available data. Input-output data has been collected for decades; the data is carefully structured and well documented.

Due to the fundamental differences in the paradigms there lies a major challenge in aligning the perspectives. Input-output analysis takes a top-down perspective while agent-based modelling is founded on the bottom-up approach. While the proof of concept was not able to provide evidence that the supply-side dynamics model adds substantial value to input-output analysis framework, the demand-side model that was incorporated in the proof of concept shows a lot of promise. To align the top-down and bottom-up parts, either input-output data needs to be transformed into single product dimensions. Alternatively, the demand-side dynamics model should produce a demand vector of sector-output dimensions. The latter is more desirable since the demand-side dynamics model generates the data by modellers definitions while the input-output table is a product of the statistical office. One of the major novelties of this research is the formulation of a utility function that manages to produce sector-level demand vectors which shows similar behaviour to observed final demand vectors. A straight-forward, cardinal utility function proved to generate unrealistic behaviour, incorporating the difference weight proved to solve this issue. However, this observation could not be thoroughly validated in the proof of concept model other than observing data patterns.

Another benefit for input-output analysis that can be taken from agent-based modelling, or simulation modelling in general, is the body of knowledge on the treatment and handling of uncertainties. Input-output data is littered with uncertainty and these errors seem to be ignored. The proof of concept evaluated the sensitivity of a few uncertain factors with the EMA workbench; such tools are readily available and would greatly benefit input-output analysis-based policymaking.

A main conclusion about input-output analysis in general is that it is an elegant, sophisticated method. It has been under constant development for years. However, its main feature, computing the technological coefficient matrix and using this to compute new levels of sector output, has remained mostly unchanged since its inception. Input-output analysis does not seem to capitalise on the exploding computer capacity available. In terms of the Wright curve vocabulary, conventional input-output analysis has a large cumulative output, it is quite mature. Focussing development on increasing the resolution of the input-output tables seems to be an ineffective way to improve the framework. In this thesis it was shown that with a crude and simple proof of concept model, it was possible to take final demand endogenous. While final demand is only a small part of the total final demand compared to export, export is also in fact final demand by consumers but just in another region. Developing the input-output analysis framework by integrating dynamic features seems to be a more promising direction to head for with a large potential for improvement.

7.2.3 Options for future research

By designing the conceptual model and subsequently implementing a, stylised, proof of concept a good understanding is created of where the literature stands and where potential improvements lie in terms of integrating dynamic features into the input-output analysis framework. In this subsection, some suggestions are given for directions of future research. The suggestions are split up into two categories, research developing the dynamics-models and research into restructuring the input-output analysis data format.

Developing the dynamic models further would increase the technological detail enclosed in these models. Some models already exist that could enrich the integrated model further, like the representation of innovations with evolutionary algorithms. One exogenous part is the environment; however, many environmental models exist and could be incorporated into the integrated model. Currently, environmentally extended input-output analysis typically uses a threshold of tons of CO_2 that can be emitted over a certain period of time. To analyse the 'circularity' not only the production but also the replenishment of resources should be modelled. Models of the planet's atmosphere and how it responds to adding or subtracting individual CO_2 molecules exist. Because input-output data reports tons of CO_2 per unit of output, the transformation to individual molecules could easily be done. Many other examples exist, of a wide range of different resources of pollutants. As long as the interactions between the models is defined, and these models can be aligned, the integration is possible.

Adding more detail to the demand-side dynamics model is another possible option for future research. The simple implementation shows promise but is not exactly ready to replace extrapolations in input-output analysis. Adding components to the utility function to force a trade-off within budget constraints was shown to improve the demand-side dynamics model. Future research could explore these additional components and their implications on the model's behaviour.

The major difficulty in parameterising the supply-side dynamics model is the dis-aggregation of sector-level data into individual firms' or technologies' data. It would be interesting to assess what ratio individual firms' data is required from an entire sector to confidently estimate the total sector's disaggregation.

In general, the supply-side dynamics model in its current, generalised, form lacks detail, both technical detail and micro-economic detail. Input-output databases report many different sectors, but in reality, those sectors are not all completely heterogeneous. A valuable addition to the model would be to differentiate all these sectors into several archetype sectors; for instance, the Eurostat manual of input-output analysis uses four sectors in their numeric examples. Designing a more detailed model of these archetype sectors and parameterising these models based on the input-output data would greatly enrich the model. However, the challenge would remain to dis-aggregate the sector-level input-output data within the archetype sectors. Micro-economic detail could be added by defining firms' cash flows; a firm would incur costs from production and generate income from sales. This way, firms would optimise profits and micro-economic realism is increased.

A final suggestion for future research concerning the dynamics models is to come to an approach of linking the demand- and supply-side models between several instantiations of the conceptual model, each instantiation representing another geographical region. The proof of concept model was instantiated based on data of the Netherlands. It would be quite simple to instantiate a model of any other region for which WIOD has data available; WIOD covers the entire world as 44 separate regions, all 27 EU member states, some other non-EU countries and a few rest-of-world groups. It would be very interesting to take export endogenously, in other words to instantiate several models and facilitate trade between the country models. In this way, the major part of final demand is endogenous to the model, but also international trade policies can be evaluated, like a tax on foreign products like aluminium or steel.

This research set out to analyse the implications of moving towards a circular economy. Quite early in this report, input-output analysis was found to have a lack of resource and waste streams data. Therefore, some suggestions are given here to restructure the input-output framework to better account for these streams.

The, discontinued, NAMEA project reported up to 2009 some waste streams in an input-output analysis-style table. Currently, no single input-output database has such data. Analysing changes with respect to a circular economy will be impossible until the framework finds a way to reflect these waste streams and resource streams.

Another point about input-output data is that it is highly aggregated while the data is collected by surveying. Providing the raw data in such a way that corporate secrecy is not violated is not possible. A point of attention for further research might be how to dis-aggregate the data while respecting this corporate secrecy.

A final suggestion for future research efforts in the input-output analysis field is to come to a consensus of how to deal with the uncertainties other than to ignore them. Uncertainty in input-output analysis is a scarcely published topic while the handling of uncertainty in policy making is a rich field of literature. Lenzen provided a paper in 2001 which was greatly appreciated for this thesis, not many other, recent, papers appreciating uncertainty or errors in input-output data exist. Future research should be dedicated to this topic and with these findings, the development pathway of input-output analysis itself should be evaluated.

7.3 Looking back onto the research

At the end of this thesis, some room is left for personal reflection. In this final section, first, a reflection is given on the product of this thesis: the conceptual model. Second, attention is given to the process by which this thesis was completed.

Preceding the design of the conceptual model was a very thorough literature research. The reference list of this report reflects the amount of papers and books that have been reviewed before coming to a consensus on design options of the conceptual model. By having included both demand-side and supply-side dynamics in the scope, a comprehensive understanding of the economy and its interactions was built. The conceptual model is designed in such a way that technical detail can emerge over time. Eventually individual firms could be represented directly in the model. One can ask whether such precision is needed, if at all desirable. In an early stage of the research, my second supervisor, Jan, referred me to one of the works of Jorge Luis Borges, "*On Exactitude in Science"*. In this, single paragraph, story published in 1946, Borges sketches a picture of an empire where a map is commissioned with a one to one scale and how this map was magnificent but at the same time unusable. During my research I thought a lot about this story and the similarities of a one to one representation of firms in an economic model. However, I also realised that nowadays, such a map does indeed exist but just not the way Borges imagined it. In google maps there is indeed a one to one correspondence while still being arguably the greatest map available. Besides the scale it features live traffic data which is incredibly accurate. In this section I will not argue that an implementation of the conceptual model is as good as google maps; the point I make here is that with increasing computer power such large constructs become more feasible and workable. Looking at the integration potential of input-output analysis and agent-based models, there is a lot of mutual benefit. The potential to reach micro-economic realism and technological detail in a model which is complete in macro-economic terms is known as the 'holy grail' of economic models. For agent-based modelling, there is not any complex adaptive system that I can think of with such a vast amount of, freely, available and well-structured data as input-output analysis. However, the misalignment between the perspectives might continue to be a barrier for the integration; this might explain why such an integration is referred to as the 'holy grail' and not the 'grail that was found last week'.

Looking back on the process by which this thesis was completed I must say that most activities went quite smoothly, after the kick-off meeting. One thing I would retrospectively change, if I could, would be the scope. Even though my research proposal was deemed a little ambitious, I was stubborn enough to go ahead and execute the proposal. Looking back, it would have been better to leave either the supply- or the demand-side dynamics outside the scope. However, as I argue one paragraph ago, having both supply- and demand-side dynamics inside the scope made that I built a good understanding of both systems; and after all, economic performance emerges based on the interactions between the two. In the mid-term meeting I was wiser and listened to my supervisors; their advice was to not implement evolutionary algorithms for innovation in the proof of concept. Now, I am thankful for that piece of advice because the proof of concept turned out to be a lot more complex than I intended it to be. The reporting activities were conducted throughout the project, this turned out to be a great decision. For each of the subjects of my literature review, the input-output part, demand- and supply side dynamics, I conducted separate literature researches and presented the results separately. As I reviewed the literature I made a lot of notes; but I made sure to transcribe these notes into report-worthy texts soon after writing the notes. This way I could switch between writing and reviewing, which makes both activities less tedious. The modelling cycle went without any major issues; I attribute that to using NetLogo because I have a lot of prior experience in NetLogo. Contrary to NetLogo, I had no noteworthy experience using R; all results were analysed using R which was surprisingly easy to master. There were some issues with the sensitivity analysis, mainly because it requires using Python with which I had no experience at all. For the sensitivity analysis I am thankful to Marc Jaxa-Rozen who took the time to show me his python script, and Jan for referring me to Marc.

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Appendix A: Supplementary literature

The theoretical concepts that were used in the conceptual model were described in chapters three, and four. This appendix gives an overview of additional literature that has been reviewed. This supplementary literature might be useful in understanding and expanding the conceptual model.

A.1 Additional literature of the input-output analysis framework

A.1.1 Input-output analysis using a power series approximation

Whether a solution for equation 3.6 exists depends on whether matrix **A** is singular, in other words whether it's inverse exists. Basic linear algebra defines situations where a matrix is singular; however, it is unlikely that the technological coefficient matrix **A** is a singular matrix.

In this case, where a technological coefficient matrix is singular, a solution can still be found using a non-algebraic, numerical, method called power series approximation. This method of approximating the Leontief inverse matrix was proposed in 1950 by Frederick Waugh; the development of this method was driven by the lack of computing power. In those days the time to solve the linear equations was a major constraining factor in performing input-output analysis; Leontief (1951) reported that inverting a 42-sector input-output table took around 57 hours in 1939 using the (at that time) state of the art computer at Harvard. Power series approximation requires significantly less computing power than actual matrix inversion; this is because computers are much better at multiplying matrices than inverting matrices. In his paper, Waugh proves that the following equation 3.7 will approach the algebraic solution using the Leontief inverse when n reaches infinity. Moreover, n does not have to go all the way up to infinity to approach the algebraic solution, about n=7 or n=8 typically yields terms insignificantly different from zero.

$$\mathbf{x} = \left(\mathbf{I} + \mathbf{A} + \mathbf{A}^2 + \mathbf{A}^3 + \cdots + \mathbf{A}^n\right)\mathbf{f} = \mathbf{f} + \mathbf{Af} + \mathbf{A}^2\mathbf{f} + \mathbf{A}^3\mathbf{f} + \cdots + \mathbf{A}^n\mathbf{f} \tag{A.1}$$

In general linear algebra, equation 3.7 does not hold; however, two specific features in input-output tables enables the use of this equation. These two features are (1) **A** is always a non-negative matrix and (2) the sum of one sector's technological coefficients, in other words the sum of a column of **A**, is always smaller than one (not all input goes into output, there are payments for labour and tax for instance). For the full proof of equation 3.7 the reader is referred to Waugh's paper (1950).

Using equation 3.7 above, each new term is acquired by multiplying the previous term with **A**, starting with **f**; this process stops when sufficient or desired precision in **x** is reached. This numerical method of approximating the Leontief inverse has an economic interpretation, the multiplier effect. Each added term are the repercussions of additional spending (a changed final demand **f**); this effect in macroeconomic theory is known as the multiplier or the Keynesian multiplier (Keynes, 1933).

A.1.2 Three dynamic input-output analysis methods

The first dynamic method presented in this section is sequential input-output analysis. This method cannot be regarded as fully static because it analyses a sequence of static optima. In other words, it is a sequence of updated input-output tables made up from several time steps. Sequential input-output analysis adds an explicit time dimension; with time explicitly modelled the temporal aspect of the input-output multipliers can be properly represented. When final demand changes, the demand for intermediate products is also increased; for example, when demand increases for cars, demand will increase for steel to produce those cars. In reality there is usually a time delay in these repercussions but in conventional input-output analysis this effect occurs instantaneous (Mules, 1983). Sequential input-output analysis resolves this discrepancy by using the power series approximation of the Leontief inverse which is presented in equation A.1 in subsection A.1.1.

Leontief himself proposed a dynamic version of his input-output analysis framework dubbed the dynamic Leontief model (Leontief, 1970b). In this dynamic version the input-output multipliers or technological coefficients are dynamic, they change over time. This change of the multipliers over time is a function of the capital accumulations of each sector; for this model capital accumulations must be separately measured in the input-output table. In this model, capital stock is denoted as k, with k the capital coefficient, b, can be computed as the ratio of k over x. The capital coefficient shows the amount of a sector's product that is held as stock to produce one unit of output; the capital stock is sometimes also referred to as investments. These capital coefficients between every sector are stored in the capital coefficient matrix **B**. Using the equation A.2, the new sector outputs are computed:

$$\mathbf{B}\mathbf{x}^{t+1} = (\mathbf{I} - \mathbf{A} + \mathbf{B})\mathbf{x}^{t} - \mathbf{f}^{t} \quad \text{(A.2)}$$

Solving equation above requires multiplication by the inverse of the capital coefficient matrix **B**; however, it is likely that **B** is singular. Input-output tables are compiled based on standardised frameworks often for many different countries like the EU. In the case where a sector exists in the table but does not supply any capital goods to any other sector, this sector would have a row containing only zero's. Having a row or column with only zero's in a matrix means that this matrix has no inverse; a matrix with one or more rows or columns with only zeros has a determinant of zero for that matrix and therefore that matrix is singular.

Many other researchers have expanded on the dynamic Leontief model. For example, ten Raa adapted the dynamic Leontief framework to circumvent the singularity issue and to incorporate many forms of capital (ten Raa ,1986; ten Raa, Chakraborty & Das, 1989). However, for this method practical implementations are very limited because there is hardly any detailed data on capital coefficients being gathered by statistical agencies. Currently Eurostat gathers data on three categories of capital (gross fixed capital formation, changes in inventories and acquisitions less disposals of valuables) (Eurostat, 2008); ten Raa, Chakraborty & Das (1989) encountered, and account for, many more categories of capital. Another adaption of the dynamic Leontief framework is the dynamic variable input-output model by Chung Liew (2000). Liew formulated technological coefficients and capital coefficients as a function of price; in his paper these equations are given. The model solves these equations in a CGE model.

Finally, turnpike growth is briefly discussed here; turnpike growth assumes economy-wide growth (or decline) to be equal (Carter, 1974). The model uses the turnpike growth rate lambda; this is multiplied by the output vector to find the output vector of the next time step. However, the turnpike growth model requires the input-output model to be closed which is not the case for a national economy; this is both a logical consequence and a design choice (the sums of columns do not add up to 1 in the input-output table because not all value is shown). However, this method is suitable when a closed economy, the entire world, is modelled like Duchin did for her 2005 paper.

A.2 Additional demand-side and supply-side dynamics literature

A.2.1 Classic utility theory

In classical economics, consumer demand is generally regarded as the result of consumers seeking to maximise the utility in spending their budget. The concept of utility has been in use in economics for a long time. The "classical" utility theory was introduced into mainstream economics in the 1870's after contributions of Jevons, Menger and Walras (Stigler, 1950). What Jevons called utility (Jevons, 1871), Menger called Grenznutzen (Menger, 1871) and Walras called rareté (Walras, 1874), refers to the usefulness or perceived value a consumer subconsciously attributes to goods. Jevons proposed utility as a unitless measure driving consumer decisions. The behaviour of consumers in markets results from consumers seeking to maximise the utility while being constrained by a certain budget. As it was proposed in classical utility theory, the utility of a certain good is a function of its price and quantity. Classical utility theory makes two assumptions to analyse behaviour due to utility; (1) utility is additively separate, and (2) marginal utility is positive and decreasing. The first assumption means that the total utility of a set of different goods is equal to the sum of the utility of each good, therefore utility of different goods is independent; the second assumption means that the utility of a larger quantity of a single good is less than the sum of the single unit-utility of this good. These assumptions have been challenged over the development of the utility theory paradigm. Marshall provided subsequent works of the classical utility theory, between 1890 and 1920, he shifted the focus of utility in his theories; instead of regarding a market or a population of consumers, his works focus on the behaviour of a single agent (Marshall, 1920). In Marshall's framework, prices are assumed to be fixed and households or consumers trade in monetary unit rather than commodities.

The first major deviation from the two assumptions proposed by the classical utility theorists was the work of Edgeworth (1881); Edgeworth attempted to formulate a more general utility theory. Edgeworth believed that the assumption of additive utility was invalid, because some goods' utility is dependent on the quantity of goods already acquired of another good. This utility dependency was first mentioned by Marshall in 1895 (Marshall, 1920), this notion is now known as the Giffen paradox: if the price of bread is increased, the demand for meat will decrease from the poorest consumers because bread is relatively the cheapest source of food. In his attempt to formulate a general utility function, Edgeworth added interdependencies among goods allowing substitution based on marginal utility. Edgeworth's work was said to be original but containing flaws; Edgeworth kept the convexity of the indifference curve while substitution relationships should be able to result in concave indifference curves (Moscati, 2007). Nonetheless, Edgeworth's work addressed valid shortcomings of the classical utility theories.

A.2.2 Cardinal and ordinal utility theory

Due to the lack of empirical meaning of quantified (or cardinal) utility of classical utility theory, Pareto proposed another approach; utility should be based on observable consumer choice behaviour (Pareto, 1900). Pareto argued that consumer choice behaviour could still be captured with utility, but that utility should be regarded as a ranking index rather than a value. This was the introduction of what is now known as the ordinal utility theory. Based on Pareto's work, Hicks and Allen further developed the ordinal utility theory; Hicks and Allen found and solved some inconsistencies present in the work of Pareto (Hicks & Allen, 1934). Hicks and Allen state that if utility is immeasurable, as Pareto does, then marginal utility is also immeasurable. Hicks and Allen introduced marginal rate of substitution, MRS; this is defined as the amount of a certain good that is substitute for a marginal unit of another good. The MRS is quantifiable and empirically derivable; with the MRS, Hicks and Allen found the relationship between demand, price and consumer income.

A most important, and initially unrecognised, work on general utility functions was written by Slutsky in 1915; his work did not receive any attention until his findings were independently discovered in the mid-1930's by Hicks and Allen (Weber, 1999). Slutsky provided a formal equation, the Slutsky-equation, that shows how demand change in response to price change are the result of substitution effects and income change. Currently, this approach to utility theory, now known as the Slutsky-Hicks framework, is considered one of the two most complete approaches to consumer behaviour based on consumer utility.

Where the Slutsky-Hicks framework is one of the two most complete approaches to consumer behaviour, the Samuelson-Houthakker framework is the other. The difference in the two is that Slutsky-Hicks take a cardinal approach, quantifying utility, and that Samuelson-Houthakker take an ordinal approach; ranking goods in terms of their utility in accordance with Pareto's arguments on the immeasurability of utility. Samuelson argued that quantifiable utility does not exist, but consumers choose goods based on their preferences of certain goods over others (Samuelson, 1938 & 1947). Samuelson believed that the theory should only be expressed in terms of price-quantity relations rather than derivatives of demand functions. Samuelson's ideas are now known as the revealed preference theory; according to consumers' fixed preferences, they choose certain goods over others at constant prices. Houthakker expanded on Samuelson's work by providing empirical evidence; Houthakker provides empirical substantiation for consumers' preferences and the additivity of preferences (Houthakker 1950 & 1960).

A.2.3 Information asymmetry

George Akerlof's Identity economics was one of the theories mentioned in section 4.1. Information assymetry is another influential work of Akerlof (1978) in the field of consumer behaviour theory. The point Akerlof makes about information asymmetry, which opposes the foundations of the mainstream (neoclassical) economic theories, is that consumers cannot make an optimal decision because they do not have perfect information about the product they are considering; there is an asymmetry in information between buyer and seller (Akerlof, 1978). Akerlof first showed the effect of information asymmetry in the car industry and later proved that information asymmetry occurs in practically any market. An optimal decision would make a trade-off between price and quality, but this information is not equally available to the buyer and seller. Most obviously quality can be obscured by the producer; but also, price information is not fully disclosed in some markets to the consumer at the time when a decision is made. Akerlof argues that resolving information asymmetry requires repeated sales or building reputation; however, this creates market power.

A.2.4 Technological substitution literature

Another body of literature, the technology substitution literature, provides for this thesis a more detailed model for how technologies substitute each other, than the multi-level perspective; when regime technologies are substituted for niche innovations. This is relevant because this model prescribes how a technology, which market share is in decline, is substituted by a new technology, which market share is on the rise. The most commonly used model is the Fisher and Pry model (1971). The Fisher and Pry model describes that technology substitution can be seen as a new technology taking over market share of an old technology; new (niche) technologies compete over market share with old (regime) technologies, the ratio of the old and new technologies' market share changes exponentially. The mathematical description of the Fisher and Pry model is as follows:

$$\frac{f}{1-f} = e^{\alpha t+\beta} \tag{A.3}$$

Where f denotes the market share of the old technology, $1-f$ denotes the market share of the new technology, t denotes the independent variable, usually time, and α and β denote constants.

A.2.5 Criticism on Wright 's Law

Three weak points of learning curves are discussed and addressed; these are (1) the bias toward successful technologies, (2) sensitivity to parameters and (3) the black box character. The first point of criticism come from the fact that learning curves are founded in empirical observations; they have been determined from real world data. The bias towards successful technology addresses the fact that the real-world data from which the curves are determined, do not contain items of unsuccessful technologies; because these unsuccessful technologies did not survive to become part of the dataset (Sagar & van der Zwaan, 2006). In this thesis the learning curves will only be applied in commercial stages of technologies which have reached a commercial deployment stage; for these technologies that have proven successful and reached commercial stage That means that learning curves are only applied to successful technologies in this thesis which makes this bias unproblematic.

The second point is that the curve is sensitive to its defining parameters, the elasticity *b* and the initial conditions which make up *a*. Figure A.1 below, taken from (Barreto Gómez, 2001), illustrates this sensitivity. This becomes problematic when these parameters are uncertain; for this thesis these parameters will contain a large degree of uncertainty because for each technology in use in the economy these parameters cannot be accurately determined, estimations will be applied. Therefore, this sensitive will amplify the uncertainty embodied within the parameters of the learning curves.

The final point of criticism argues that the learning curves are black-box models; Learning curves do not explain why these cost reductions occur. A black box model refers to a process of which the relation between input state and output state is known, but the underlying mechanics creating this relation are unknown. A black box model lacks in explanatory power. However, for this thesis this point of criticism is less relevant because the purpose of learning curves in this thesis is not to explain cost developments or predict the cost of one technology; the purpose of learning curves is to proxy the cost development of all technologies together for each sector.

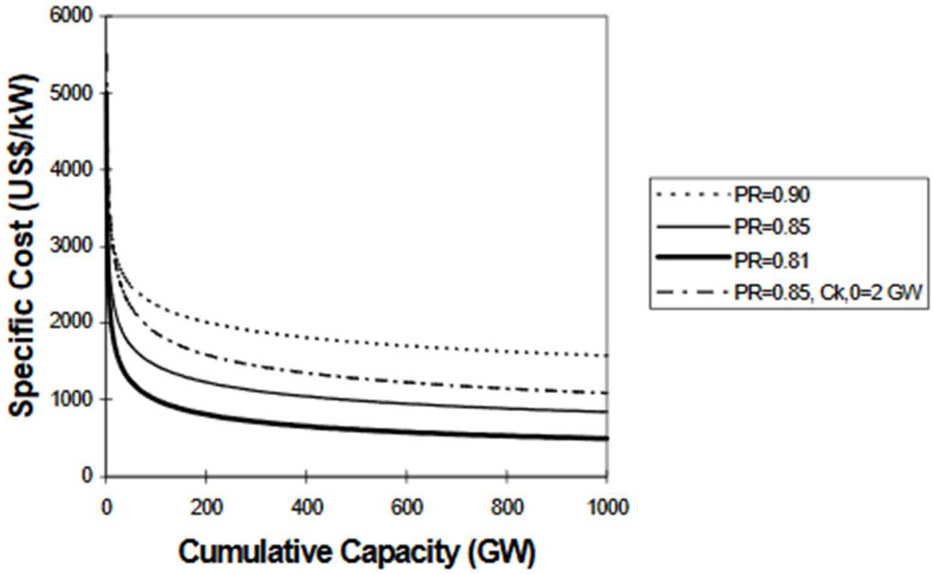

Figure A.1: Learning curves with progress rate of 0.9, 0.85 and 0.81 and initial capacity of 2 and 5 (Barreto Gómez, 2001, p. 15)

A.2.6 Introduction to BDI, 2 and 3APL and PECS

BDI, which stands for beliefs, desires and intentions, is the most commonly used model for human behaviour; the model was developed by Rao and Georgeff (1991, 1995). In the BDI framework, agents are represented as decision makers having beliefs, desires and intentions. Belief is the information or knowledge that the agent possesses. Based on the agents reasoning, following the intention theory of Bratman (1987), an agent formulates its intentions as a means to achieve its goals (desires). In other words, intentions contain the deliberations of the agent and desire contains the motivations of the agent. Decisions are made based on these three mental states; an agent has desires which it wants to fulfil, the agent formulates intentions based on what it believes to be true. A typical representation of the BDI architecture is shown below, in figure A.2. Usually, decision trees are compiled and the path leading to the highest utility with respect to the agent's desires is followed. The BDI framework was developed by computer scientists; this could account for a shortcoming in terms of realistic human behaviour, the BDI framework would result in optimal behaviour by the agent. The BDI framework assumes that reasoning leads to decisions in humans; as Prospect theory (Kahneman & Tversky, 1979) argues, most decisions are made by intuitive thinking, and these decisions are subject to certain biases; sub-optimal behaviour occurs and should be accounted for to accurately replicate real-world behaviour.

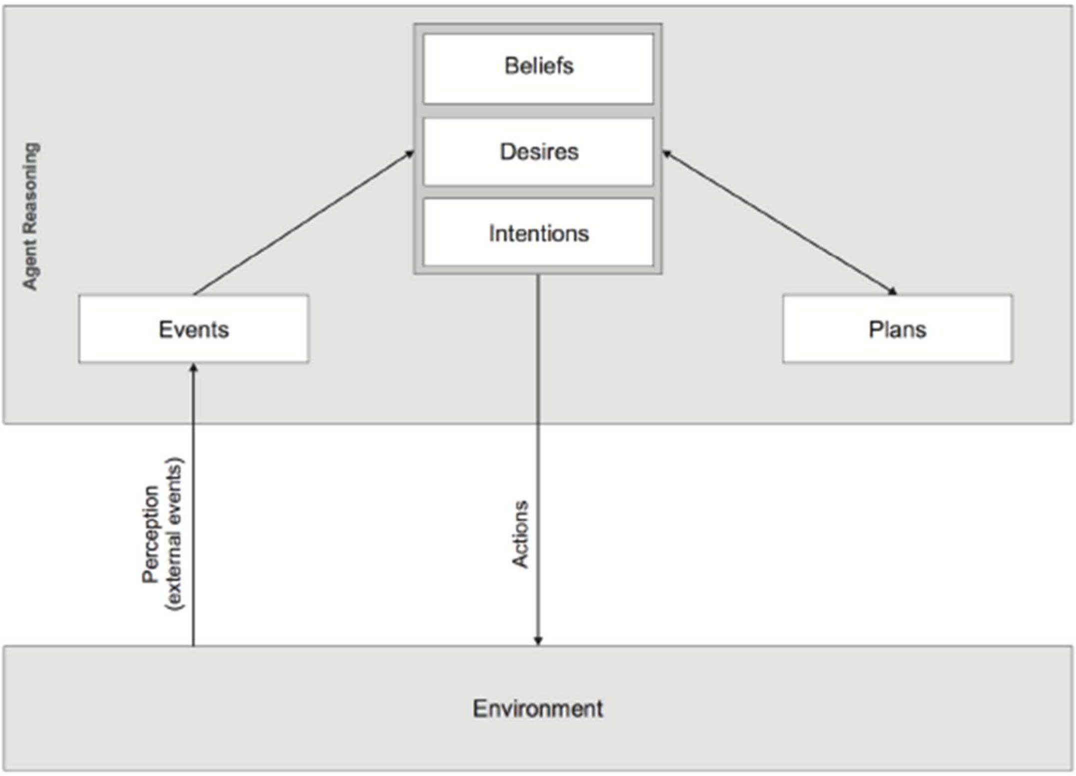

Figure A.2: A conceptual representation of the BDI architecture (Balke & Gilbert, 2014, p. 4)

The 3APL or 2APL framework is another human decision-making framework; this framework was developed in the artificial intelligence field at the University of Utrecht (Hindriks et al., 1998). The 3APL framework was the result of an integration of two existing frameworks Agent-0 (Shoham, 1993) and AgentSpeak (Rao, 1996); this integrated imperative programming and rule-based decision making. Being based on Rao's AgentSpeak, 3APL has a strong connection with the BDI framework. 3APL excels in making agents highly pro-active and reactive, attempting to adequately plan ahead and adapt these plans as events occur; in a much more comprehensive way than the BDI framework prescribes. 3APL agents use "practical reasoning rules" to select actions from its means ("basic actions") to achieve goals but also to reflect on, and adapt, current plans.

The 3APL framework was designed for single- or few agent simulations; in 2008, Mehdi Dastani extended and renamed the framework into 2APL (Dastani, 2008). To cater for an environment in which multiple agents interact, agenda's, external environments, access relations and communication relations were added to the framework. Another addition of Dastani was the introduction of two new sets of procedures, one set of procedures which serves to repair broken or failed plans and one set of procedures to allow for communication and handling external events. Agents in 2APL follow a deliberation cycle; this cycle is executed for all agents in parallel; the deliberation cycle of 2APL agents is shown below, in figure A.3.

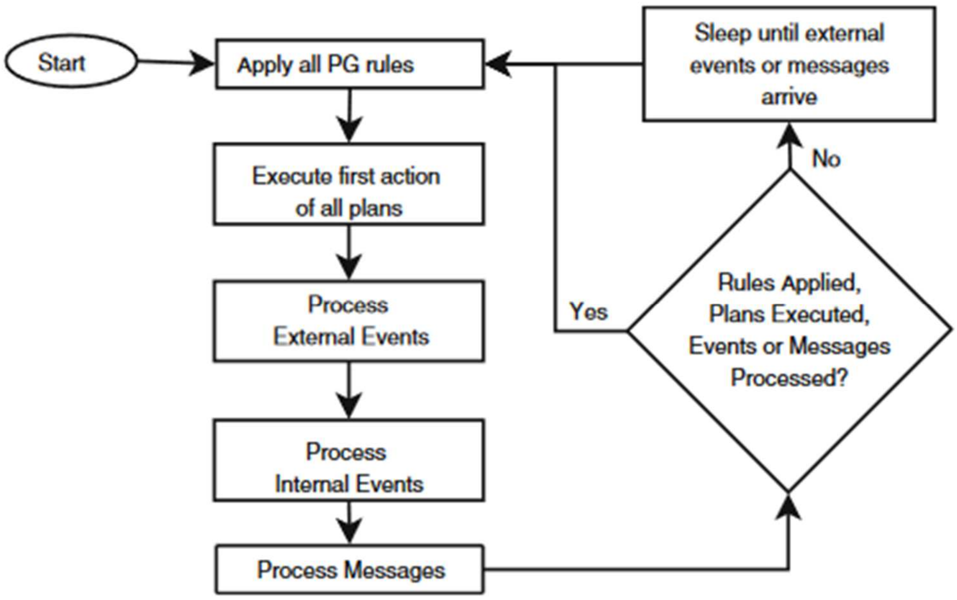

Figure A.3: 2APL agent deliberation cycle (Dastani, 2008, p. 241)

The third and final human decision-making framework in computer simulation to be discussed here is PECS; PECS was developed in close collaboration with social sciences researchers with the aim of representing realistic human decision making (Schmidt, 2000). Unlike 3APL, PECS was conceived to replace BDI rather than expand on it. The acronym, PECS, stands for Physical conditions, Emotional state, Cognitive abilities and Social status; these four terms compromise the internal state of the PECS agent. A conceptualisation of the PECS agent architecture is shown below, in figure A.4. As figure A.4 shows, information flows between different components of the agent affecting its behaviour via the internal states. Information enters the agent by means of sensor; either sensory input is directly used in the physis of the agent, like the temperature or age of the agent, or the sensory input flows through perception influencing the agent's states. Figure 4.6 also shows the causal dependencies; from perception to internal states, internal states among each other and from internal states to the agent's behaviour. In the PECS framework, the agent's internal states drive the agent's motives; these motives compete among each other to determine the agent's actions. The agent has four motives which are related to the four internal states: social desire, drive, emotional intensity and strength; whichever motivation has the highest intensity, caused by the agent's internal states, is prioritised for the actions to be performed. Behaviour of PECS agents is divided in two types, reactive and deliberate; these two categories are similar to Kahneman and Tversky's (1979) intuitive thinking (reactive) and reasoning (deliberate). The type of behaviour that is executed depends on the intensity of the agent's motives (Schmidt, 2000). The PECS agents are less focussed on achieving goals compared to BDI and related frameworks; this is in line with Kahneman's notions on individuals' inability to act on long term benefits (Kahneman, 2003).

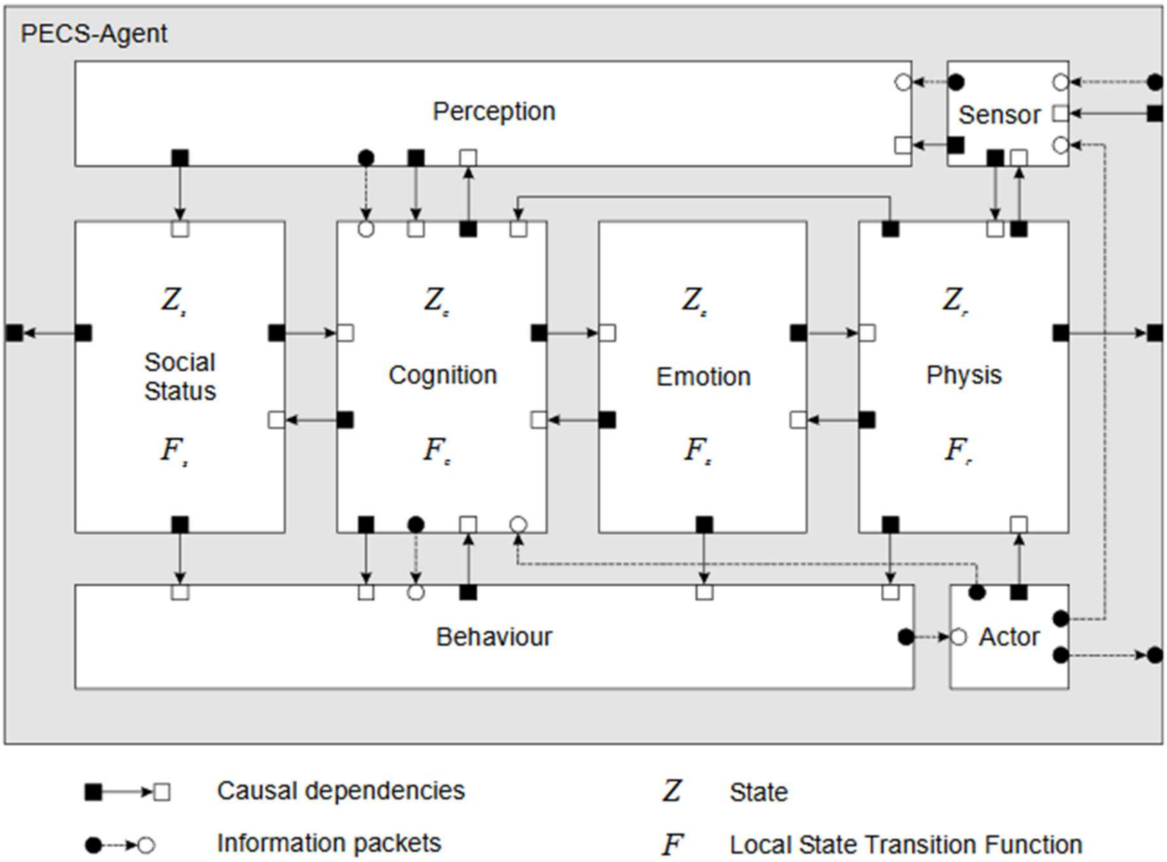

Figure A.4: PECS agent architecture (Urban & Schmidt, 2001, p. 2)

A.2.7 Two relevant simulation studies of technological transitions using ABM

The first paper that is presented here is (Safarzyńska & van den Bergh, 2010); this work is highly relevant for this thesis because the interactions between demand dynamics and supply dynamics are investigated. The goal of the paper is to investigate *"…how distinct increasing returns affect the likelihood of market lock-in."* (Safarzyńska & van den Bergh, 2010, p. 301); the authors developed a co-evolutionary model where firms and consumers are represented as agents. Safarzyńska and van den Bergh use firms instead of technologies, because individual goods are modelled and their market; firms sell goods, make investments and develop their product. Firms are assumed to have a partial monopoly, serving a particular market with the good that the firm produces; a market is a collection of consumers belonging to a class. In terms of interaction, firms are isolated from each other because of this partial-monopoly assumption. Each time-step of the model, firms go through a simple cycle where they invest in capital expansion and invest remaining budget into quality improvements through either R&D or marketing efforts. Quality of products have an upper limit to represent technological limitations. Effects of quality improvements are uncertain, can also decrease market share. If the sales of a firm go down significantly this firm will look to innovate radically. If a firm's sales are poor for a certain time, the firm leaves the market and 'dies'; at such an event a new firm is 'born' and enters the market. The model assumes that technological breakthroughs are realised by outsiders rather than incumbent firms of the market; with this assumption, in the model, new-born firms produce a good with higher quality than goods already on the market, with a certain probability. The parameters of a firm, which produces one good, in this model are the production level, the price, cost, quality, maximum quality, and market share. Interactions of a firm limited to interactions with consumers, based on the partial-monopoly assumption.

The second paper that is presented here is (Chappin & Afman, 2013); this work follows the multi-level perspective more closely, and this model is thoroughly validated. This paper analyses the effect of government policy on consumer's purchasing behaviour of lamps. Technologies in this paper are represented by different lamp technologies. In this paper, lamp technologies have certain attributes that develop over time, but the technologies do not interact; they are not represented as agents. Also, no new technologies are introduced during the simulation run, only gradual technological development of the existing technology occurs in the model. For the modelled consumers to decide on which type of lamp to buy, lamp technologies have different quality parameters that are relevant for lamps; for instance, lifetime, light output, power consumption, colour temperature and so forth. Besides quality parameters lamp technologies have a price per lamp and a year of introduction. The development trajectories of these attributes of lamp technologies is modelled exogenously, based on trend extrapolation.

A.2.8 General evolutionary algorithms and the application in innovation simulation

John Holland (1992b) developed a general evolutionary algorithm which can be applied in an agent-based model to simulate these evolutionary mechanics. The general evolutionary algorithm is based on how evolution occurs in nature; evolutionary algorithms have been praised as being the 'master algorithm', because this algorithm created all intelligence that we know, but it has also been criticised being a naïve interpretation of nature, because in fact evolution is still not fully understood. General evolutionary algorithms work as follows, to begin with a population exists where each individual consist of a random set of components or variables, these individuals act in the world and are assigned a certain fitness value based on how well they perform. Those individuals with the highest fitness survive and are able to reproduce or recombine into new individuals for the next generation; individuals with low fitness die off. Two individuals that reproduce, exchange and recombine into new individuals. Reproduction entails exchanging components or variable values of two individuals into new individuals. Besides reproduction, some degree of random mutation occurs, randomly changing the components or variables of individuals, either in reproduction or between steps of the algorithm. After the reproduction is completed, a new generation is formed; with this new generation the algorithm is started over. The algorithm requires some choices which have a strong influence on the outcomes of the process; these choices are the rate of reproduction, the magnitude of mutations, the fitness determination mechanism, the determination of the probability of survival and finally the translation from genotype to phenotype. Genetic algorithms are being applied as an optimisation algorithm, but also in simulation of innovations (Dawid, 2006).

Chris Birchenhall (1995) provides a framework to apply evolutionary algorithms in the context of innovations simulation. Birchenhall concentrates on modular technologies, technologies that contain a set of components; in this thesis, technologies can all be regarded as modular, combining a set of inputs into a unit of output. Birchenhall's perspective is built upon the notion that the boundaries of technical feasibility are unknown, innovation can take any shape. When considering an economy in abstract and aggregated terms like input-output analysis does, this notion can be accepted; there is no detail in what input leads to a unit of output, any input-output relation can be defended. In Birchenhall's framework, two models co-evolve, one technical and one representing investors. Birchenhall needs this investor model as a selection model; in the model of this thesis, consumers and their utility models are endogenous. Assuming that investors invest in projects based on what is attractive to consumers, the investor side of Birchenhall's framework can be omitted and replaced with selection by the population's utility model. The main difficulty of Birchenhall's framework is mapping characteristics to components, in evolutionary terms the translation from genotype to phenotype, or in economic terms the relation between the technology's attributes and quality. Another difficulty lies in the determination of the probability of survival of a technology; roughly three approaches exist, based on relative fitness, based on fitness rank, like simulated annealing, or finally a combination of fitness and diversity. Birchenhall showed that evolutionary algorithms can also be applied to innovation, the process is similar: from a population a fitness is determined, the fittest are kept in the population, these fittest technologies reproduce and are mutated. Each new technology, after reproduction and mutation, is compared to its predecessor, if the mutation or reproduction resulted in a fitter technology, the new technology is kept in the population and the old technology is omitted from the population.

Appendix B: Narrative of the proof of concept model

This appendix describes the logic of the proof of concept model in humanly readable language. First, the different procedures that the model follows are given. Second, the instantiation, or setup, of the model is described. Finally, the different run procedures of the model are described along with the supporting assumptions for each procedure.

Procedures of model per time step:

- Assign budgets
- Determine final demand – demand-side dynamics model
- Determine sector output – IO model
- Update technologies – supply-side dynamics model
- Update population

Setup or instantiation of the model: *before running the model, parameters must be set. The model takes input-output table data and assigns variables to agents and the environment.*

Setup globals: In the instantiation, first the values of global variables are assigned. These variables available to any entity of the model; examples are the average wage per skill level and the population size.

Setup technologies: Setting up the technology agents of the model requires loading the input-output table into the model, extracting the technological coefficients and social and environmental impact per sector. Subsequently these sectors are decomposed into two different individual technologies: one focussing on improving performance and one focussing on reducing environmental impact.

Setup population: Consumer agents are created based on CBS data on population size and CPB data on education distribution. The population is aggregated to keep the computational requirements of the model feasible; one consumer agent represents 10,000 real-world consumers. The distribution of education level is known, the population size is also assumed to be correctly projected by CBS; with this information the population instantiated. An environmental impact utility weight is randomly assigned between a lower- and upper bound; this bound is given by the education level and the distribution is uniform. Persons with a low education level weigh environmental impact between 0 and 0.25, persons with medium education level weigh environmental impact between 0.125 and 0.375 and persons with a high education level weigh environmental impact between 0.25 and 0.75.

Run procedures: *once the model has been set up, or instantiated, the run procedures are each completed for every time step of the model.*

Assign budgets: *Consumers receive income, either from unemployment benefits, pension or wages. The available budget to purchase goods is the individual's income lowered by a savings factor.*

WIOD has data on labour for three different skill groups, low-mid-high skilled labour. Consumers have an education level (3 pt. scale), income group is equal or lower than their education level depending on whether enough high-skilled work (wage) is available. Wages are exponentially distributed in each income group. If there are too few highly skilled workers, a worker with a lower skill level is retrained to upgrade the skill level and employed. In cases of too many workers, over skilled workers are chosen over under skilled workers. In cases where no single workers are available, a new worker is introduced in the model, to simulate immigration.

Wages might not be large enough to employ all consumers, unemployed consumers are assumed to receive 0.7 * minimum wage as either pension or unemployment benefits.

Assumptions supporting this procedure:

- All unemployed (pensioners/unemployed) persons receive a fraction (0.7) of the minimum wage.
- Income is exponentially distributed.
- Income is either wage or profit, profit is assumed to predicted by wages: profit equals 20% of total wages paid. This profit is added to the wages and distributed over the population as though it was earned in the same way as salary.
- Wages are reassigned every timestep (every year) per 10000 persons.
- Salary fully correlates with education level unless there is scarcity in labour or wage. With scares labour, under skilled workers are retrained and employed; with scares wage over skilled workers are employed. When no workers at all are available, new workers are introduced into the model to supply the labour (analogous to immigration).
- All persons save a fraction (savings-factor) of their income.
- All persons spend their entire income minus savings.
- All salaries grow proportionally to the corresponding technology's output.

Determine final demand: *With a utility function (prospect theory based) consumers choose sector output to purchase with their budget.*

Utility is dependent on the change of state of wealth; in other words, the difference between the amount of a good purchased in the current and previous time period. In the model, this is represented by weighting a cardinal utility function. This difference weight causes the budget allocation procedure to be recursive; therefore, the budget is allocated in increments, to account for goods already purchased in the current time step. In the utility function of consumers, two attributes of a technology are considered to come to a base utility value; the base utility value is multiplied with the difference weight to find the final utility value per technology. These two attributes are environmental impact, CO_2 emission per unit of output in the proof of concept, and quality. In literature quality was found to be composed of several factors, performance, features, reliability, conformance, durability, serviceability, aesthetics, and perceived quality (Garvin, 1984) – grouped by Sebastianelli (2002) into performance & features, conformance, and aesthetics & perceived quality. However, for the proof of concept the abstraction was made that quality is represented by a single parameter, performance. The cardinal utility function is the relative performance of a good lowered by the relative, weighted environmental impact of a good. Price is not explicitly part of the function because goods in the model are in monetary units; if a good doubles in price, the performance and environmental impact are halved. The environmental impact weight depends on the extent to which an individual consumer considers environmental impact in buying decisions.

The utility of technology *i* as assessed by consumer *j* each budget-allocation-iteration is formulated as shown below, in equation B.1.

$$U_{i,j} = DW_{i,j} * \left(\frac{performance_j}{performance_{max}} - \frac{env.\,impact_j}{env.\,impact_{max}} * env.\,impact\ weight_i\right) \qquad \text{(B.1)}$$

The difference weight, *DW,* is computed with equation B.2:

$$DW_{i,j} = MAX\left(0, 0.5 + \frac{Q_{i,j,t-1} - Q_{i,j,t}}{Q_{i,j,t-1}}\right) \qquad \text{(B.2)}$$

Q denotes the quantity of products of sector *j* bought by consumer *i* in timestep *t.* Because losses outweigh gains for consumers, 0.5 is added to the difference weight; if the final demand realised in the current time step equals the final demand of the previous time step, the difference weight is equal to 0.5, when double the previous time step's quantity is purchased, the difference weight equals zero.

Assumptions supporting this procedure:

- Consumers discern goods produced within the same sector. In other words, consumers might prefer a single technology within a sector.
- All quality parameters can be adequately represented with a single parameter, performance.
- Utility is generated from changes of the state of wealth, rather than being generated from the state of wealth. This assumption is taken from prospect theory (see subsection 4.2.1).
- Consumers avoid losses more than they look for gains
- A cardinal utility function, weighted for difference in state of wealth compared with the previous time step, is an adequate representation of consumer's decision-making process.
- The weight of the difference in state of wealth is adequately represented with the reported function.
- The base weight of the difference weight function is 0.5 reflecting the loss aversion of consumers.

Determine sector output: *With a new final demand, and technical coefficient matrix from last time period, new total sector outputs are calculated. The total sector output is the output required to supply final demand plus the output required as intermediate products which in turn are required to supply final demand.*

Final products for consumption are produced by technologies; producing a unit of output requires the 'consumption' of certain inputs, as prescribed by input-output analysis. Each technology has a technological coefficient vector, which gives the input requirements from every other sector for one unit of output. All technological coefficient vectors are put into the technological coefficient matrix, **A**. As shown in subsection 3.1.2 (in equation 3.6) the total sector output vector, **x**, is found using this equation, repeated below in equation B.3.

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\,\mathbf{f} \tag{B.3}$$

Total sector output is then distributed over the different technologies used to produce goods within each sector. Consumers generate final demand for each technology; within a sector, the proportions of final demand for each technology is used to distribute the intermediate trade. This is done to preserve consumer preference for product aspects.

Assumptions supporting this procedure:

- Technologies have no scale limit. This implies that any technology can produce any level of output, irrespective of previous output levels.
- Intermediate trade, products purchased by producers as input, is divided within a sector over technologies in the same proportions as final demand is distributed by consumers over the different technologies.

Update technologies: *Technological advancement is simulated based on the cumulative output of every technology, using the Wright curve. With total output, each technology advances on the learning curve and changes their technological coefficient and performance or environmental impact.*

Per technology the output of that time period is added to the cumulative output of that technology. The increased output increases the sector's efficiency by reducing the input requirements and associated environmental impacts or performance according to the Wright curve. As discussed in section 4.2.2 the Wright curve is a function of cumulative production, the cost of the first unit produced and an elasticity parameter. The elasticity parameter is used to compute the progress ratio. In the model of the proof of concept, these parameters are estimated. The progress ratio is easier to assess than the elasticity parameter; the progress ratio is equal to the cost reduction that occurs when the cumulative production doubles. Therefore, the wright curve is rewritten as a function of progress ratio into equation B.4.

$$WC(Q) = a * Q^{\log_2 Pr} \tag{B.4}$$

To calculate a new technological coefficient and new impact vectors, the relative efficiency increase based on the Wright curve is computed with the following equation, B.5:

$$Relative\ efficiency\ increase = 1 - \frac{WC_{t-1} - WC_t}{WC_{t-1}} \tag{B.5}$$

By calculating the relative efficiency increase, parameter *a* of the Wright curve, the cost of the first unit, no longer needs to be specified because it does not influence the relative efficiency increase. The new technology attributes are computed by multiplying each element with the relative efficiency increase. The improvement of performance and reduction of environmental impact is slowed by the inertia of these improvements, reducing the amount by which these attributes change.

Assumptions supporting this procedure:

- The Wright curve provides an adequate representation of technological advancement in this national trade model.
- The Wright curve parameters can be adequately estimated for this simulation (the progress ratio, the cost of the first unit and the cumulative output prior to the simulation start time).

Appendix C: Parameterisation of the proof of concept

In appendix B the logic of the model has been described. In order to run the model, parameter values need to be set for the model to run with. Correctly determining the values of these parameters has proven to be difficult or impossible; this led to one important conclusion of this research, that the parameterisation of this model is a major barrier for implementation.

This appendix discusses how the parameters were set for the proof of concept and what the values are based on. The first part of this appendix discusses the estimation of parameters, the second part discusses the calibration of the performance parameters of sectors and the final, third, part discusses the setting of the budget allocation increment.

C.1 Parameter values

All parameters of the model are listed in the tables C.1, C.2 and C.2, below, sorted on the owner of the parameters; global variables can be accessed by any entity of the model, consumer and technology parameters are attributes of those agent classes. Each parameter has an estimated value accompanied by a comment of what the estimation is based on or a reference to an external source providing either the data or a good estimation.

Table C.1: Global variables

Variable	Estimated value	Comment or reference
Avg wage high	50k	Average wage for high skilled workers (CBS, 2012).
Avg wage med	32k	Average wage for medium skilled workers (CBS, 2012).
Avg wage low	27k	Average wage for low skilled workers (CBS, 2012).
Population size list	CBS data all inhabitants minus 0-20 years old.	Consumers in the model are persons above 20 years old, this age group is reported by CBS and this age group does not add a lot of autonomous consumption. The number of persons above 20 years old per year is taken from the CBS projection (CBS, 2017).
Welfare fraction	0.7	Norm of social welfare, not unusual for pension amount.
Budget allocation increment	5	More detailed discussion on this parameter can be found in the fourth part of this appendix.
Performance improvement inertia	0.75	Based on the assumption that environment minded technologies are less mature and have more potential for improvement.
Environmental improvement inertia	1	Performance improvements are more inert than environmental impact, based on the assumption that environmentally-friendly technologies are less mature than technologies that focus purely on performance.
Consumer aggregation	10,000	Persons (real-world) per consumer agent.
Intermediate trade matrix	WIOD 2013 release	Intermediate trade matrix is directly taken from the 2013 release of WIOD (2013). The newer, 2016, release could not be used because it is not yet accompanied with an environmental impact matrix.

Final demand non-consumers	Average of 2009-2011 WIOD release 2013	Non-consumer demand is demand for either import, government spending or investment
Profits to wage ratio	0.25	Profit of companies per unit of wage paid to labourers, around 0.25. While WIOD does not have data on profits incorporated into the table, this figure was taken from the American bureau of economics' data (Bureau of Economic Analysis, n.d.) reporting corporate profits by industry.

Table C.2: Consumer variables

Variable	Estimated value	Comment
Number of consumers	CBS projection	Number of persons with age > 20 years old, taken from CBS projections (CBS, 2017).
Education/ skill level	10% high (master's degree), 20% med (bachelor/HBO), 70% low (below bachelor)	Taken from, for persons aged > 30 (CBS, 2018).
Environmental impact utility weight	H: 0.25-0.5 M: 1/8 – 3/8 L: 0 – 0.25	Correlation education-environmental concern follows from (Arcury, 1990).
Savings factor	0.3-0.5	With the assumption that higher income consumers save (proportionally-) more than lower income consumers.

Table C.3: Technology variables

Variable	Estimated value	Comment
Technological coefficient vector	Taken from WIOD data	As described in 3.1.1, $\mathbf{A}=\mathbf{Z}*\hat{\mathbf{x}}^{-1}$
Performance	Based on calibration of model -performance minded: Sector-performance + 10%	More detailed discussion on this parameter can be found in part three of this appendix.
Environmental impact per output	-Performance-minded: Sector-impact + 25% -Environment-minded: Sector-impact – 25%	Based on the assumption that environmental impact negatively correlates with performance.
Progress direction	1 environment minded, 1 performance minded	Technologies put learning effects either to improving performance or reducing impact.
Social impact (wages)	Equal for technologies within a sector	Wages paid to high, medium, low skilled workers; data is directly reported in WIOD (2013) per skill level.
Wright parameters (cumulative output, cost first unit, progress ratio)	Cumulative output: from WIOD Progress Ratio: +- 0.8	Cumulative output of sectors between 1995 and 2011 is taken from WIOD data of those years. It is assumed that environment minded technologies provided around 1/3 of that output and

		performance minded technologies around 2/3 Progress ratio is generally higher than 0.7 but lower than 0.8 (Barreto, 2001).

C.2 Wright parameters

Wright parameters are known to have a large impact on efficiency of production technology (Barreto, 2001). The Wright curve requires three parameters (Wright, 1936); these parameters are the cost of the first unit produced by the technology, the cumulative production level of the technology and the progress ratio.

- Cost first unit: this parameter is not needed for the proof of concept model. The proof of concept model applies technological learning by means of relative efficiency increase; by calculating the relative improvement of the cost according to the wright curve (See appendix A for a more detailed description of the relative efficiency increase).
- Progress ratio: throughout literature this parameter is found to lie between 0.7 and 0.9 (Barreto, 2001).
- Cumulative output: WIOD data gives output between 1995 and 2011. The total output of sectors is taken of all these years. In reality several production technologies have produced this amount of output; in the proof of concept model two technologies exist. On the other hand, these sectors have existed long before 1995 so this amount of output is also an underestimation.

C.3 Calibrating the performances of sectors

Not all parameters of the model that have been incorporated can be assessed or estimated easily; specifically, the performance of individual technologies is unknown which is used by consumers to assess the utility of an individual technology. Due to the abstract representation of technologies in the proof of concept model, this performance parameter has no practical meaning and therefore cannot be measured directly. In order to assign performance to technologies in such a way that the total, system level, behaviour corresponds with reality, this parameter is deducted from the model calibration process. This is also known as inverse modelling; in a smart way performance is assigned to technologies and the model is run, if the model outcomes correspond with real-world observed behaviour the performance parameter value is assumed to be about right (Thiele, Kurth, & Grimm, 2014). Many different parameter values have been tested, the settings with the highest fit were used in the actual model run. For this proof of concept model, real-world data is available to calibrate the performance parameter value. The fitness of a set of parameter values is evaluated based on the final demand vector produced by the consumers in the model; the final demand for each sector is known from the WIOD database, the set of parameter values that comes closest to the known final demand is used in the model. Thiele, Kurth and Grimm (2014) present two different strategies for fitting model parameters; categorial calibration is one of these two strategies and is the suggested strategy for fitting parameters to uncertain data. As input-output data is highly uncertain, categorial calibration is applied here. Categorial calibration allows model output that is fitted to observed data to deviate from the observed value and still become the preferred parameter setting. A conditional equation calculates the sum of the deviations of the historical data and the values produced in the model if the deviation is larger than the tolerance; in the case of this proof of concept the final demand for each sector is given, and an uncertainty is assumed, if the model replicates the observed value plus or minus the uncertainty this is also assumed to be a good fit. For the proof of concept, a tolerance of 10% is applied. Because of large parameter space, 34 sectors with 34 distinct performance values and a computationally expensive model, an optimisation method is applied for the calibration procedure. Genetic algorithms can be applied in this case because of the computational efficiency compared to an experimental design but also the ability to avoid landing in a local optimum if the diversity setting is sufficient. Simulated annealing was used as the algorithm to assign performance values to each technology, this algorithm produced the best fitting performance values within a reasonable runtime.

C.4 Setting the budget allocation increment

The utility function in some model runs is recursive; namely the utility function that incorporates the difference weight, based on the assumption that utility is generated by changes in the state of wealth. The proof of concept model was simulated in a discrete simulation tool, NetLogo. In order to compute a recursive function in this discrete software tool the allocation of the consumer's budgets had to be implemented in a series of rounds. Each round the consumer considers the utility of all available goods based on the purchases made in the previous timestep and in the current timestep in previous budget allocation rounds. The consumer divides its available budget by the budget allocation increment to determine the number of purchase rounds. The number of budget allocation rounds that a consumer goes through affects the behaviour of the model; therefore, the budget allocation increment should be set carefully. The smaller the budget allocation increment is, the more rounds consumers make to allocate their budget and therewith the more accurately the difference weight is incorporated into the utility function of the model. However, a budget allocation requires a lot of computing time. To find a compromise in computing time and model accuracy, the model has been run with different budget allocation increments and the resulting final demand of these runs was recorded. The budget allocation increment settings that have been tested are 100, 20, 5, 0.5 and 0.1; for reference, an average consumer has a budget of around 300 with a standard deviation of 300 (this large standard deviation is caused by the exponential distribution of wages).

In figure C.1 below the results of the experiments with changing budget allocation increments is shown; each plot is for a different value of the budget allocation increment showing the final demand of all sectors. For this experiment, five replications were computed for each budget allocation increment setting; figure C.1 shows a coloured line for the mean of each set of replications, the grey area around each line represents the (bootstrapped-) 95% confidence interval. For large values of the budget allocation increment, consumers settle at few sectors; this is because a larger increment allows for fewer purchase rounds for the same budget. Theoretically, to incorporate the difference weight accurately a small budget allocation increment is desired, but due to the computational requirements a budget allocation increment of 5 is chosen. The plots for 0.1 and 5 differ marginally and the computation time for one timestep of the model is decreased by a factor 10.

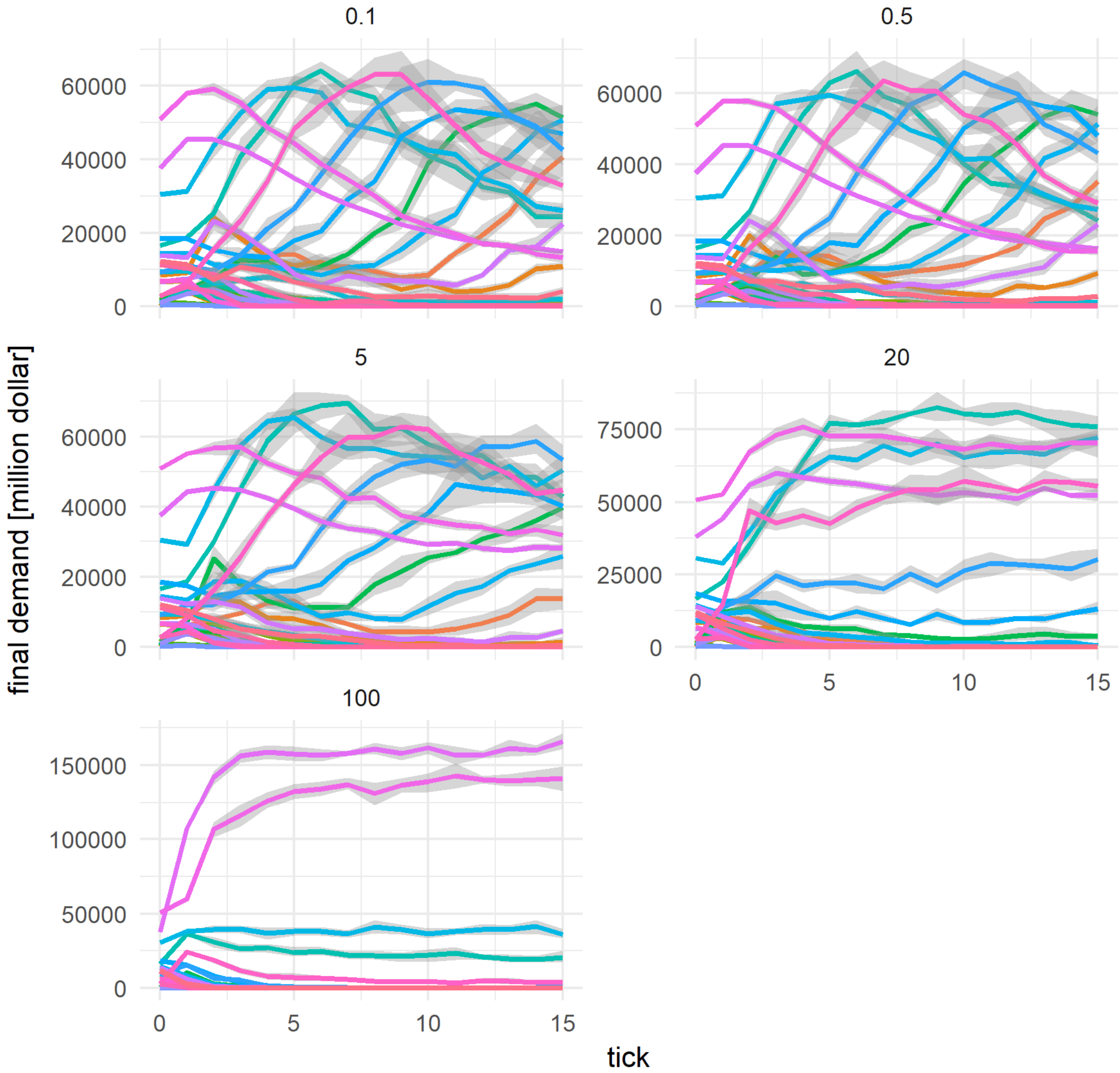

Figure C.1: Final demand of sectors for different budget allocation increment settings

C.5 Number of replications

Any model with stochastic uncertainty produces different output for the same input-settings. Therefore, model runs with the same input-parameters should be replicated to account for this stochastic uncertainty. The number of replications required to account for the stochastic uncertainty might vary per model. Ideally, a high number of replications is run. However, due to the computational requirements of the model, a reasonable number of replications has to be set; the number of replications should be low enough to restrict the computing time but high enough to account for stochastic uncertainty. The model for the proof of concept was run with 10 replications. This section presents the model outcomes of 5, 10, 20, 50 and 100 replications. The final value, after 50 time steps, is presented of these numbers of replications in box-plots. In the figures C.2, C.3, C.4, and C.5 below these different boxplots are presented. In each of these figures it can be observed that the median of 10 replications always falls within the interquartile range (the box of the box plot) of the output of 100 replications. Therefore, 10 replications is enough to produce output that accounts for the stochastic uncertainty.

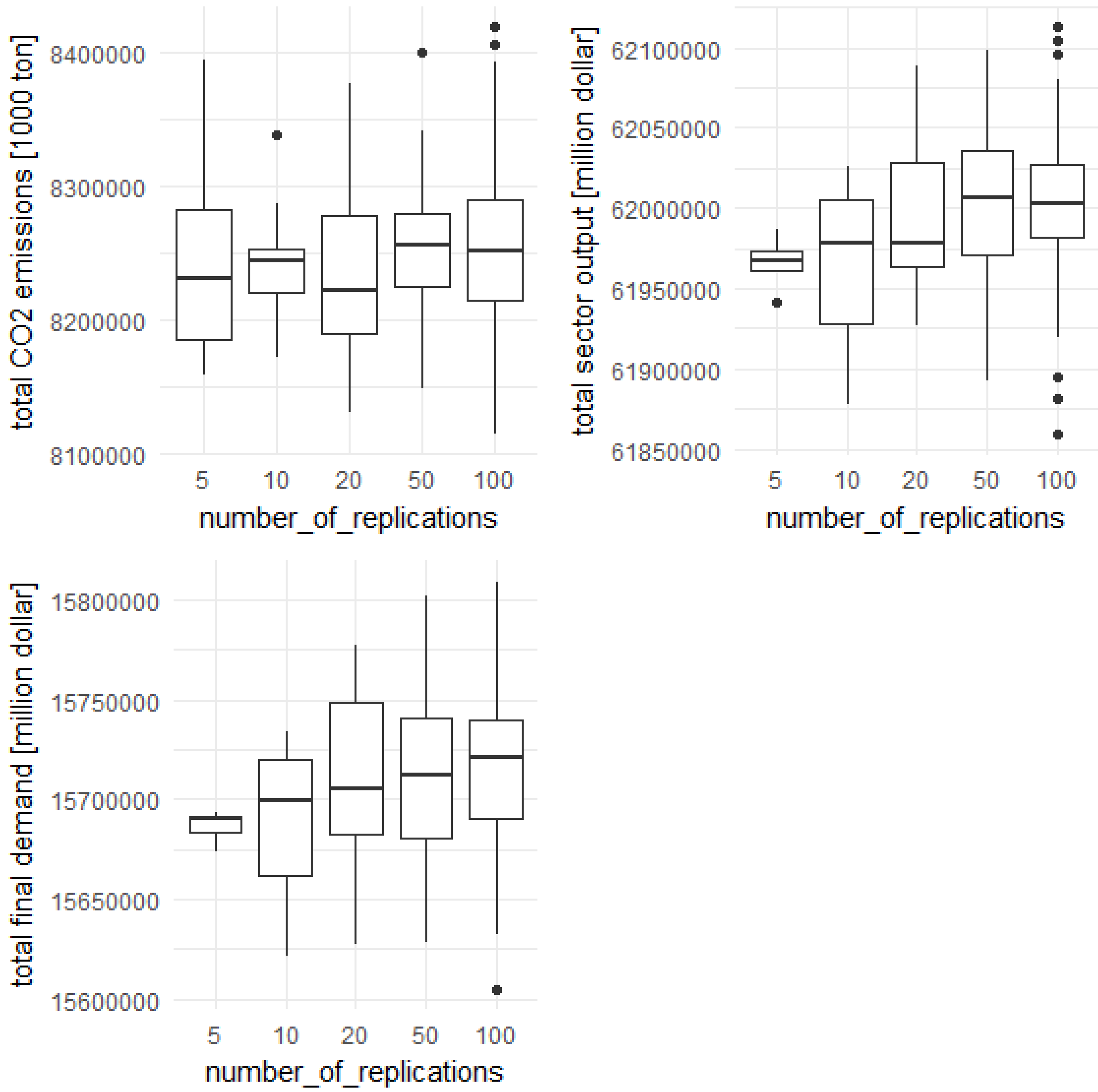

Figure C.2: Boxplots of CO2 emissions, total sector output and total final demand at the final time step for different number of replications

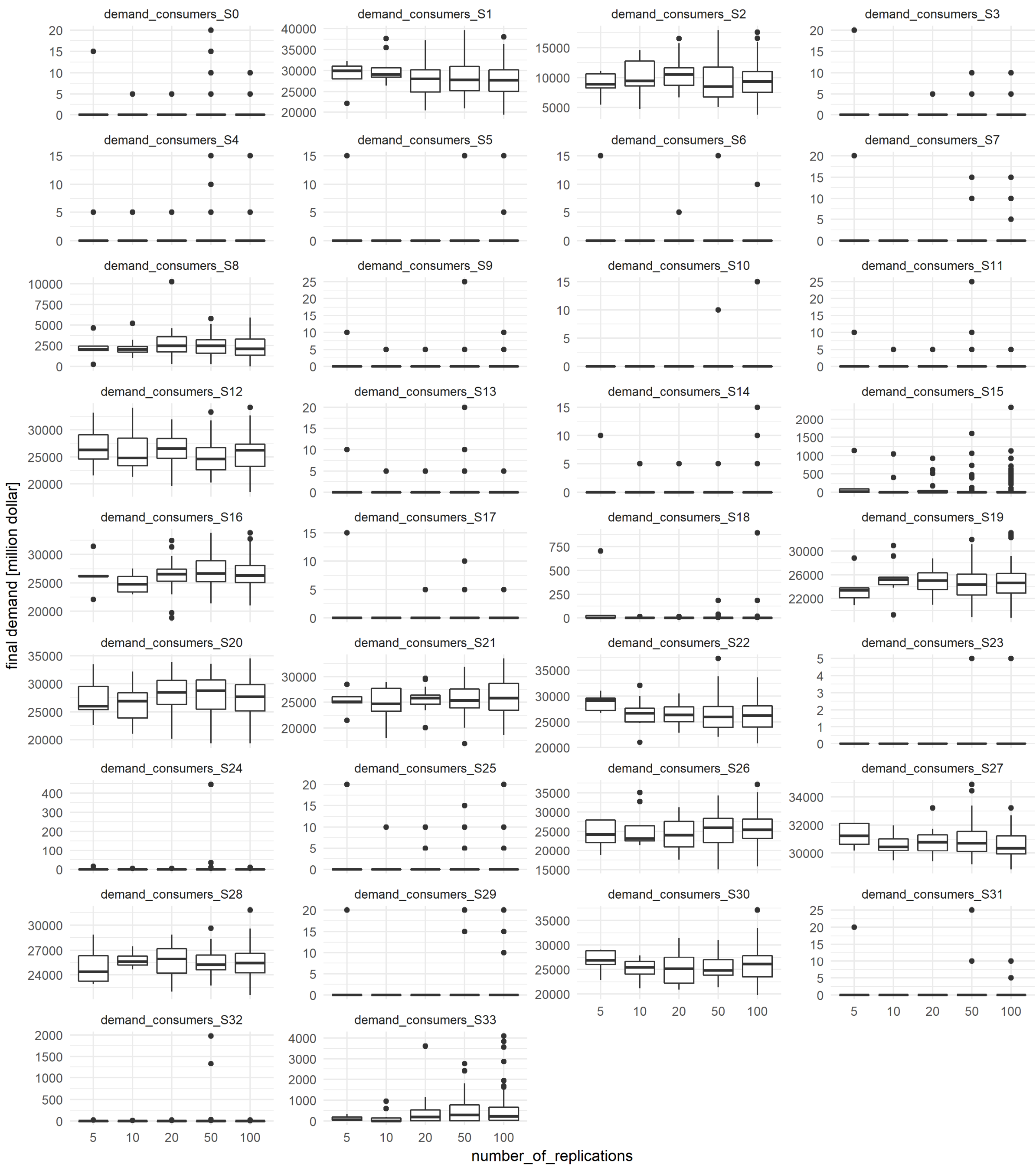

Figure C.3: Boxplots of final demand per sector at the final time step for different number of replications

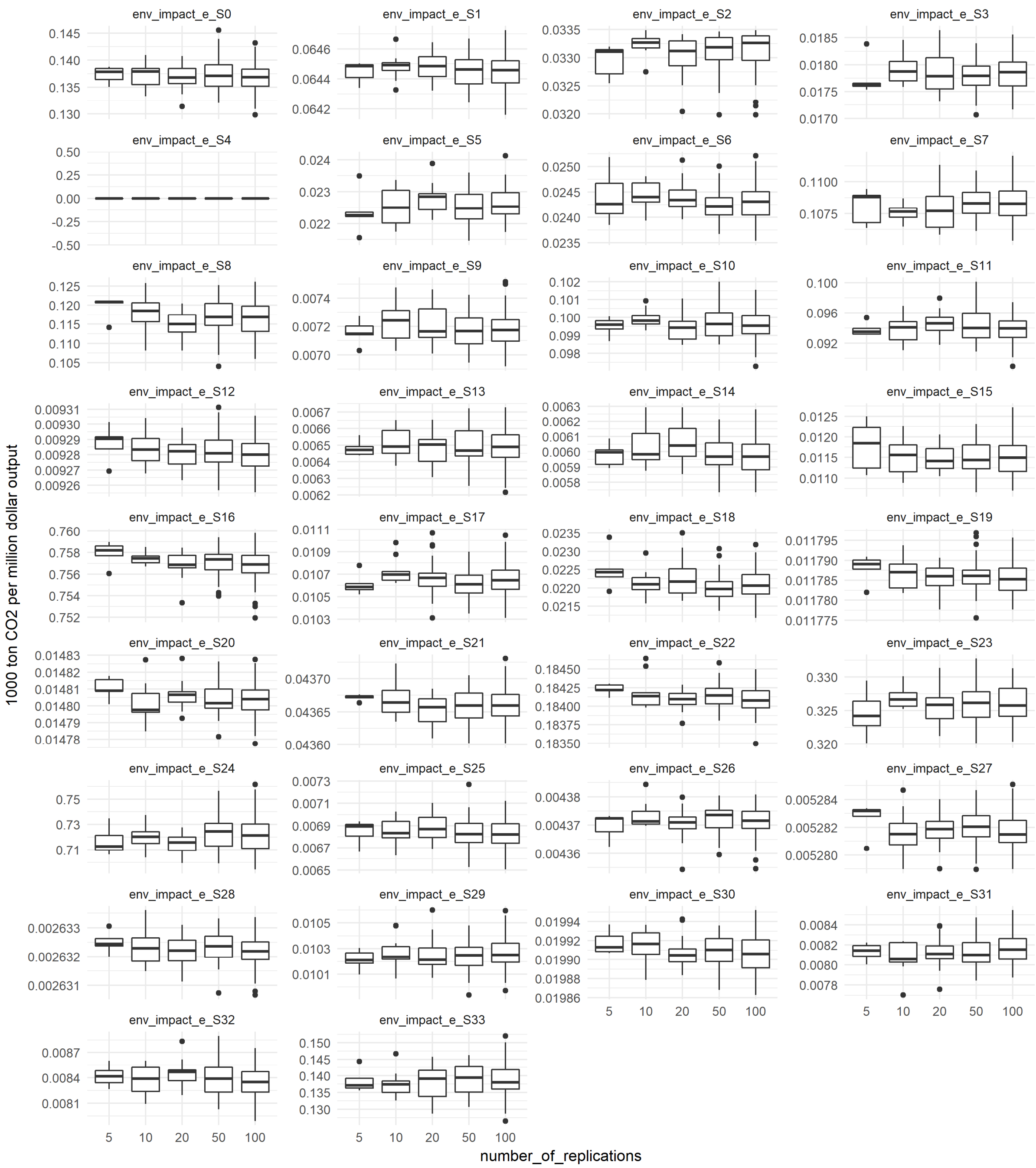

Figure C.4: Boxplots of environmental impact per sector at the final time step for different number of replications

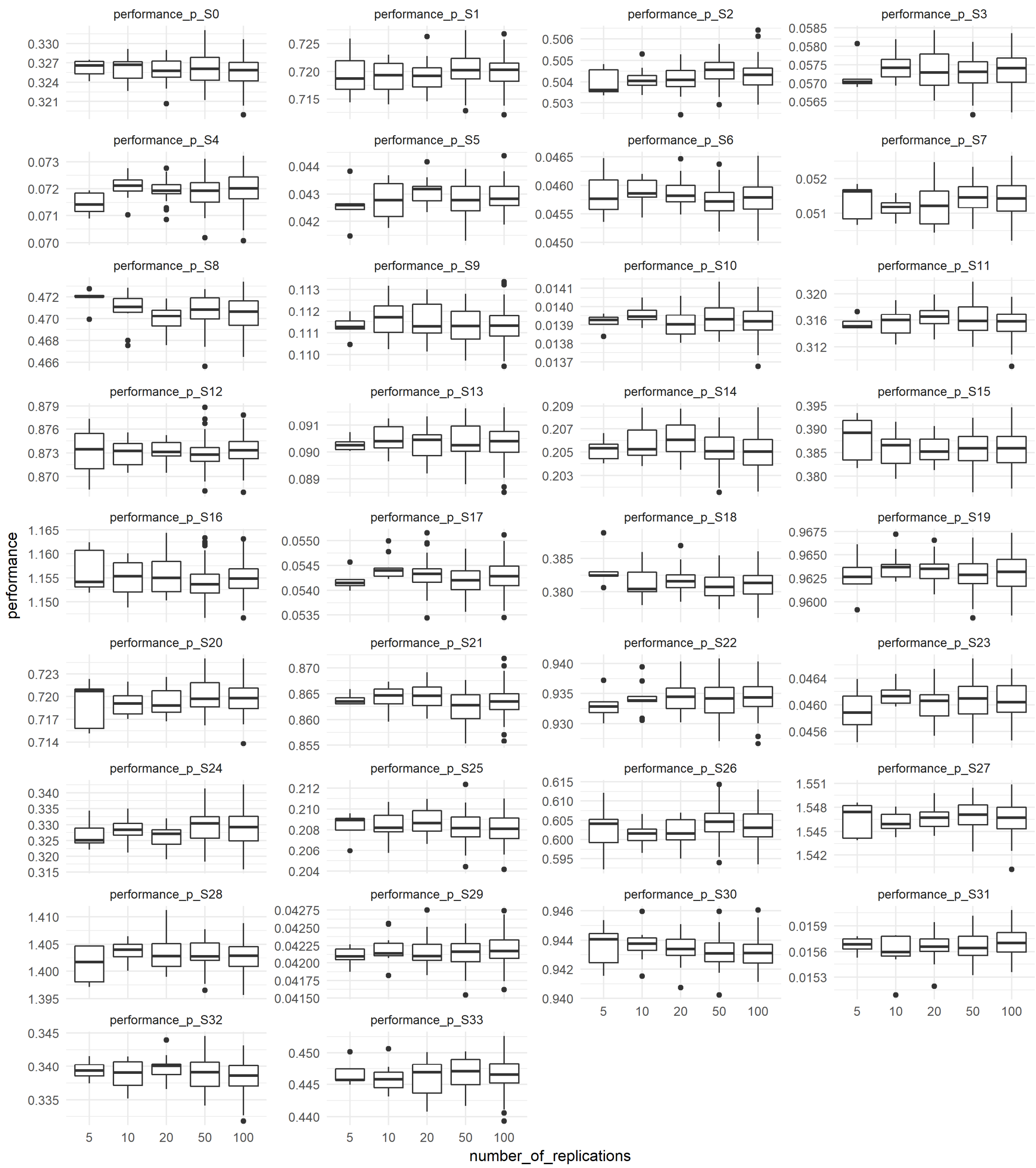

Figure C.5: Boxplots of performance per sector at the final time step for different number of replications

Appendix D: Verification of the proof of concept

This appendix describes the verification process of the proof of concept. The goal of the verification process is to test and prove that the code written for the proof of concepts works as intended. Per model procedure, experiments have been conducted to verify the functions work as intended. In the following table these experiments are described. In the model code of the proof of concept the verification code can be found to reproduce these verification experiments.

Table D.1: Verification experiments and results

Procedure	Function	Result
Input-output analysis matrix operations	Intermediate trade matrix is correctly loaded into a NetLogo matrix	Verified
	Technological coefficient matrix is correctly computed and stored	Verified
	Total sector output is correctly computed and stored	Verified
Assign budgets	Total wages are distributed correctly among the population according to an exponential distribution function	Verified
	Persons are re-trained if too few persons are available for labour with correct education level	Verified
	Persons are added to population if too few persons are available of any education level	Verified
Determine final demand	Cardinal utility function is correctly computed	Verified
	Difference weights are correctly computed	Verified
	The good of the highest utility per consumer per consumption iteration is purchased	Verified
Determine total output	Total sector output is correctly computed from all technologies within a sector	Verified
	Sector output is correctly stored	Verified
Update technologies	Technological coefficient vector of technologies is properly updated (according to Wright curve)	Verified
	Environmental impact per technology is properly updated according to	Verified

	progress direction, wright curve and inertia scalar	
	Performance per technology is properly updated according to progress direction, wright curve and inertia scalar	Verified
	Wage contribution high/med/low education is properly computed and stored	Verified
Update population	Population size is correctly set according to CBS long term projection	Verified

Appendix E: Analysis of the proof of concept data output

To assess the effects of the different dynamics that have been implemented into the model, the proof of concept model was used to simulate 50 years of production and consumption by the regional economy and the output data has been analysed. This appendix walks through the results of the experiment.

The experiment varied three settings of the model, corresponding to the three dynamics mechanisms that were either switched on or off; per setting ten replications were made. These switches were: Static technological coefficient to control the supply-side dynamics, Static final demand to control the demand-side dynamics, and difference weight disabled to switch between cardinal- and prospect theory based utility function. Static technological coefficient refers to the supply side dynamics model that has been proposed in chapter four; in the proof of concept model, the evolutionary algorithm imitating the appearance of novel innovations was not included. What the supply side model does do in the proof of concept is change the efficiency of technologies according to the Wright curve as a function of technologies' cumulative output. As a certain technology produces products, due to learning effects the efficiency increases. The properties of these different dynamics are discussed in more detail in appendix B, covering the pseudo code of the proof of concept model.

When these dynamics switches were turned off, the model took a single vector as input for every time step of that model element. If demand-side dynamics are disabled, the model took a fixed final demand vector for every consumer based on historic data for every time step. A single consumer's static final demand vector is a single consumer's proportion of the final demand of WIOD recorded for 2009, with a deviation drawn from a normal distribution. In this way, final demand was extrapolated by the number of consumers in the model. With demand-side dynamics enabled, consumers receive a budget as salary from firms and spend their budget on technologies' output based on their utility function.

With supply-side dynamics disabled, the technological coefficient of technologies does not change over time. The technological coefficient for a technology is based on WIOD data and computed following input-output analysis as described in subsection 3.1.1. With supply-side dynamics enabled, the technological coefficient changes along the Wright curve, decreasing the required amount of input for a unit of output as a function of cumulative output. Besides technological coefficient, two other attributes of technologies change over time along the Wright curve, these are the technology's performance (the single-parameter quality value of a technology) and environmental impact (in the proof of concept, only CO_2 emission is considered).

Finally, if the difference weight is disabled, the utility function of consumers did not consider previous purchases at all; final demand in model runs with demand-side dynamics disabled, are identical for difference weight disabled or enabled because with static final demand consumers do not use a utility function at all. When the difference weight is not used in the utility function of consumers, consumers base their purchasing decisions on the performance of technologies and partially on the environmental impact. If the difference weight enabled, the utility value per technology is multiplied with the difference weight to compute the difference-corrected utility. The difference weight is computed, per technology, as the difference between the current and the previous time periods quantity purchased for a sector, relative to the quantity purchased of a sector, added to a constant, with a lower-bound of zero.

The rest of this appendix contains an analysis of all results of the experiment. First, the demand side dynamics are discussed which generated the final demand by the consumer population. Second, the output of sectors throughout the model runs is analysed; the output is determined by the final demand of the demand-side dynamics model added to the non-consumers' final demand and exports; non-consumers' final demand and export is exogenous to the model, a single vector giving the level of consumption per sector was used. Third, the development of the supply side is discussed; how the technology's performance and environmental impact developed over time. Finally, the CO_2 emissions of the production system under the different model settings is reviewed. The only externality that was modelled is the CO_2 emission of technologies; with different model settings, different assumptions about modelling CO_2 emissions were used. The final part of this appendix shows how these assumptions affect the model outcomes.

The proof of concept model analyses behaviour on the national level, but also on individual sector level. The sector definition, or demarcation, is inherited from the input-output database WIOD. In table E.1, below, the sector labels are explained which are used to label the model output.

Table E.1: Sector label reference table

Sector label	Sector name
S0	agriculture hunting forestry and fishing
S1	mining and quarrying
S2	food, beverages and tobacco
S3	textiles and textile products
S4	leather and footwear
S5	wood and products of wood and cork
S6	pulp, paper, printing and publishing
S7	coke, refined petroleum and nuclear fuel
S8	chemicals and chemical products
S9	rubber and plastics
S10	other non-metallic mineral
S11	basic metals and fabricated metal
S12	machinery nec
S13	electrical and optical equipment
S14	transport equipment
S15	manufacturing nec; recycling
S16	electricity, gas and water supply
S17	construction
S18	sale, maintenance and repair of motor vehicles and motorcycles; retail sale of fuel
S19	wholesale trade and commission trade except of motor vehicles and motorcycles
S20	retail trade except of motor vehicles and motorcycles; repair of household goods
S21	hotels and restaurants
S22	inland transport
S23	water transport
S24	air transport
S25	other supporting and auxiliary transport activities; activities of travel agencies
S26	post and telecommunications
S27	financial intermediation
S28	real estate activities
S29	renting of m&eq and other business activities
S30	public admin and defence; compulsory social security
S31	education
S32	health and social work
S33	other community social and personal services

E.1 Analysing the final demand generated by the model's consumer population

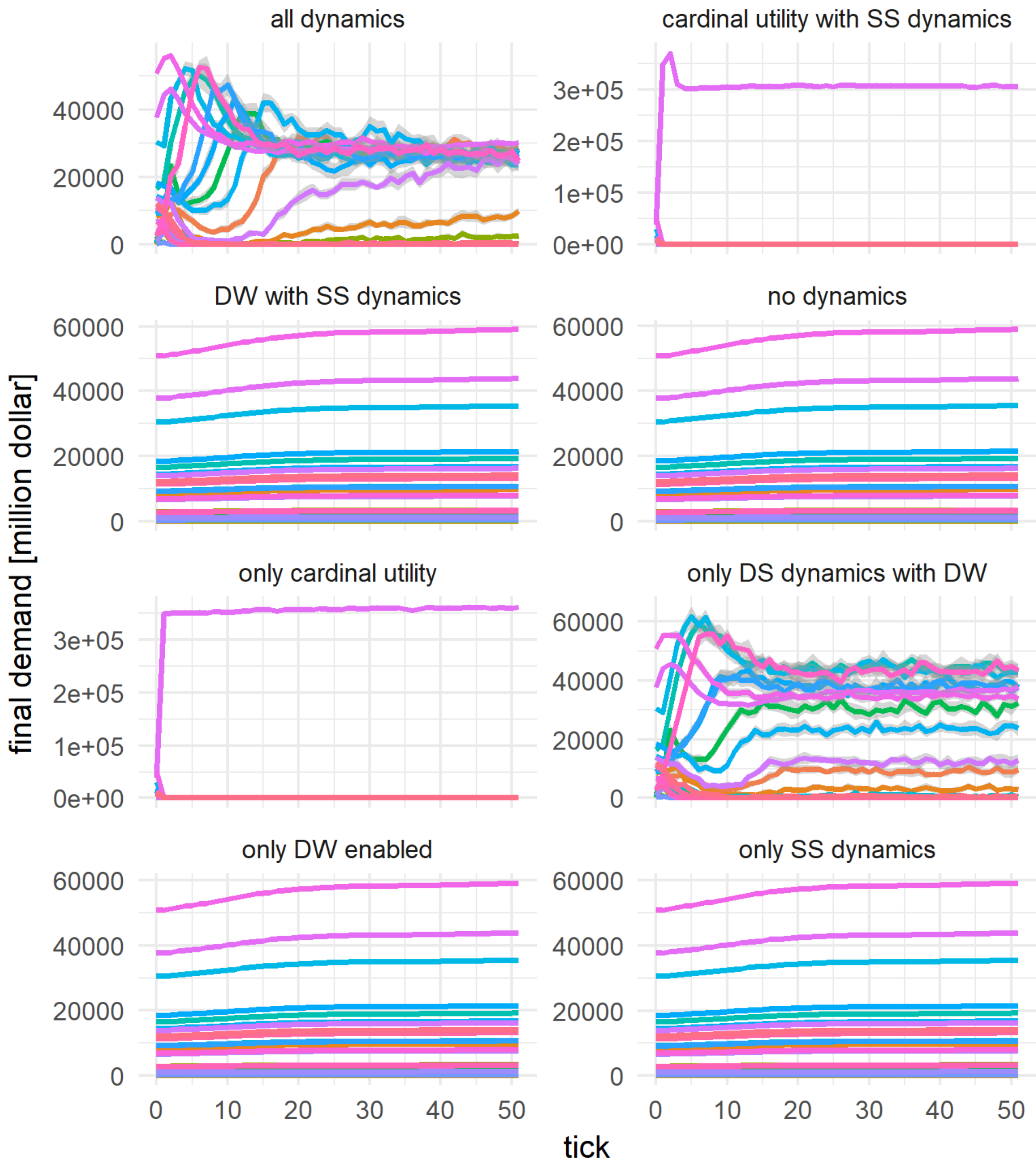

Figure E.1: Final demand by consumers of sectors over time for different dynamics settings

In figure E.1 above, the final demand per sector by consumer is shown. Each plot shows a line per sector which is that sector's mean along with a grey area around the mean which corresponds with the (bootstrapped-) 95% confidence interval. One observation that can be made for all plots where demand-side dynamics are enabled, is that the final demand changes drastically in the first few steps of the model. This is an artefact of the model, because the initial final demand is given by WIOD data. In the first time step, tick=0, the final demand is given in order to compute further final demand. With static final demand, the further final demand is extrapolated from this point. With demand-side dynamics enabled, to compute the difference weight an initial final demand vector is required. The difference weight requires some time steps to come to some sort of equilibrium final demand state, without the difference weight but with dynamic final demand the equilibrium final demand state is reached more rapidly.

Figure E.1 immediately makes clear that a standard, cardinal, utility function causes consumers to find the optimal sector to purchase and stick to that sector. The sector with maximum performance which has ‘acceptable’ environmental impact is chosen for the entire budget. In the model, this sector has a default performance of 0.98 (mean is 0.28) and environmental impact of 0.007 (mean is 0.18). While this model is abstracted far from reality, it is interesting to mention that this sector is ‘financial intermediation’. In the model runs which had difference weight switched off, consumers decided to spend their entire budget at their local financial mediator. The four settings-combinations which had static final demand merely extrapolated the demand per sector by the size of the population. Changes in the supply side did not change their consumption pattern at all and therefore all four plots with demand-side dynamics disabled are identical, labelled as "only SS dynamics", "DW with SS dynamics", "only DW enabled", and "no dynamics".

As one could expect, the interesting plots of final demand are the ones generated with demand-side dynamics enabled, and with the difference weight enabled. Figure E.2 below takes a closer look at the runs with these settings.

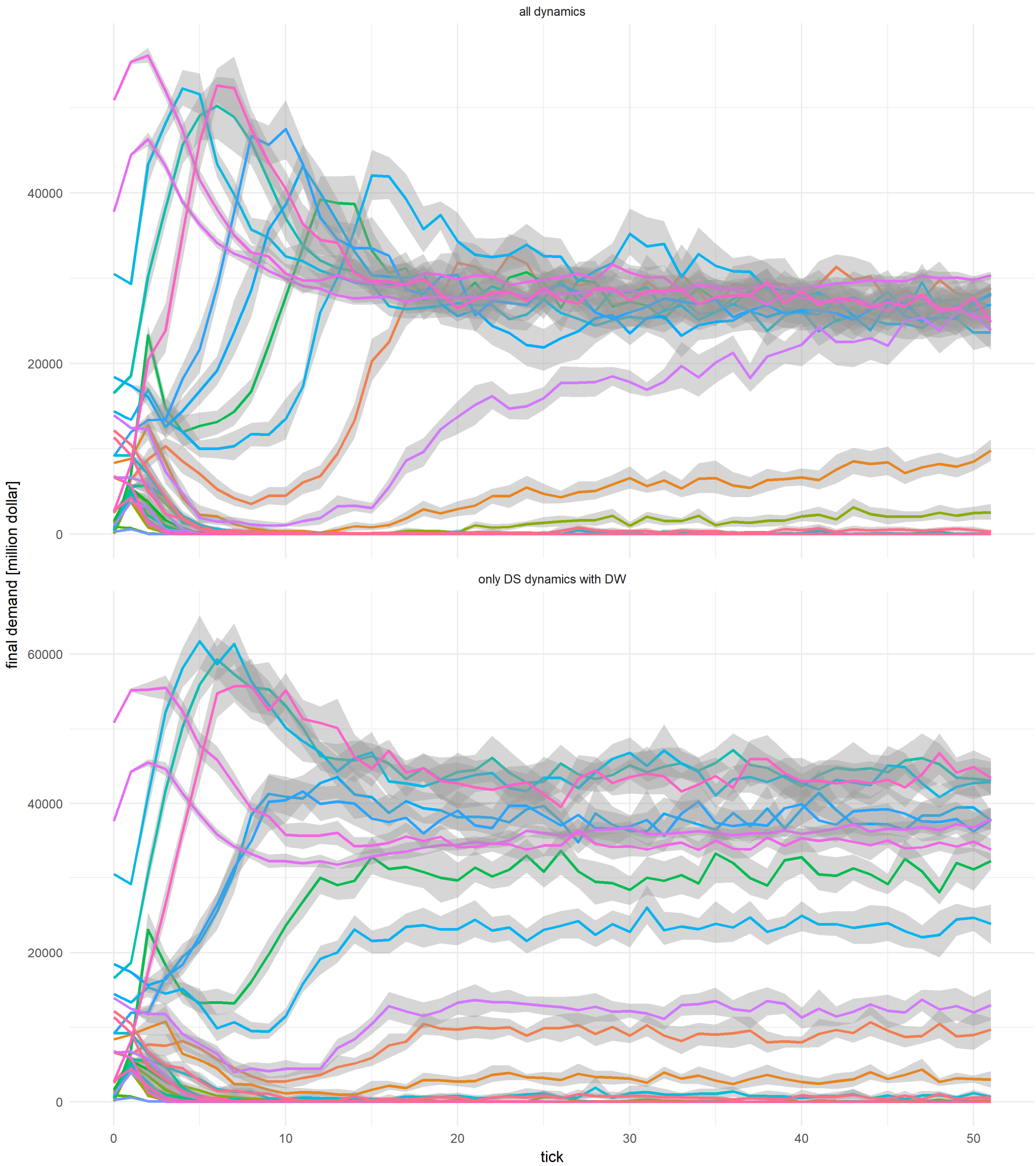

Figure E.2: Final demand of sectors over time with demand-side dynamics enabled, difference weight enabled for supply-side dynamics enabled and disabled

The difference between the runs with supply-side dynamics enabled and disabled is that with supply-side dynamics disabled, an equilibrium state is reached quicker and the final demand values of certain sectors seem to converge; in particular certain sectors become (more-) attractive to consumers due to learning effects if technological coefficient is dynamic. This is because technologies increase their cumulative output not only by supplying consumers but also by supplying intermediate goods, demand by non-consumers and exports. This increasing attractiveness is shown more explicitly when looking at final demand for individual sectors; figure E.3 below shows for all sectors the final demand over time. The mean final demand of the runs with technological coefficient dynamic is almost always higher than the runs with static technological coefficient; final demand of runs with static technological coefficient being higher than runs with dynamic technological final demand can be explained by consumers that consume from a certain sector until another sector becomes more attractive, if that sector might have had a steady higher output from exports.

The variance that can be observed in the plots is due to the heterogeneity that was incorporated into the consumer agents; consumers are heterogeneous in their available budget, their environmental impact utility weight and in their initial final demand vector. The environmental impact utility weight caused a minor portion of the variance in runs with the difference weight disabled, this can be observed when the sector demand is plotted for every switch setting; see figure E.4 below. The initial final demand influences the difference weight which causes the major part of the variance in the final demand for sectors; each consumer was assigned an initial final demand vector based on the total recorded final demand of 2009 divided by the amount of consumer agents with a deviation drawn from a normal distribution. That way every consumer had a unique final demand vector, but the total final demand of the population concurred with the recorded final demand. The final source of variance is the available budget of consumers; this is generated by sector activity which generates wages for the consumer population.

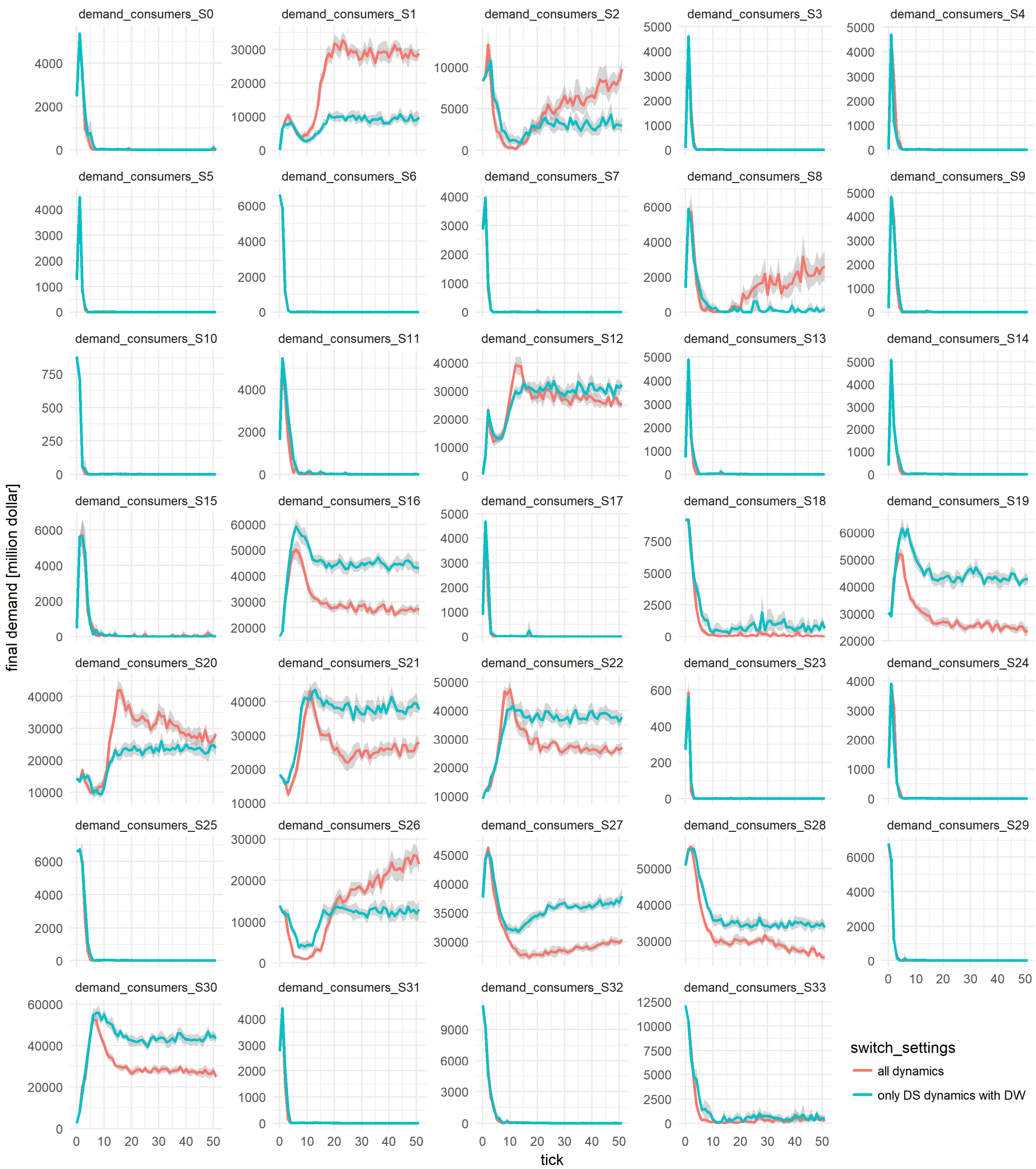

Figure E.3: final demand per sector with static and dynamic technological coefficient with dynamic demand and difference weight enabled

Another important observation that can be made is that many sectors are not popular at all among consumers; for instance, education is barely consumed. This can be explained by the quality conceptualisation in the proof of concept. Product quality is represented by a univariate parameter, performance, which was set in the calibration. When appreciating products in a single dimension, information is lost. Where a consumer might have several needs only two parameters were used by consumers to satisfy all their needs; performance and CO_2 emissions. When adding more decision criteria relating to the actual needs of consumers, such sectors would not die out. In reality consumers might prioritise food and shelter, after which secondary needs might be satisfied such as self-development and entertainment

Final demand for all sectors seems to, more or less, oscillate; this oscillation is caused by the difference weight in the utility function. As the difference weight is dependent on consumption in the current timestep, the utility function becomes recursive. However, the implementation of the proof of concept was done in a discrete model; the budget allocation function for consumers was divided into steps. Each step, the current time step's realised purchases were updated to incorporate the changing difference weight. To smoothen out these oscillations, an infinite amount of budget allocation steps have to be conducted. However, the computational requirements of the model were such that the model was parameterised to have each consumer make around 30 budget allocation steps, varying with their available budget. In figure E.5 below a heatmap is shown of the value of the difference weight for different values of the purchases made in the previous timestep and purchases already made in the current timestep. The vertical, grey, constant-lines represent a budget allocation increment. As can be seen, a single consumer tends to spread out its purchases; if a consumer reaches the amount purchased in the previous timestep, the utility becomes half of the original value. That way, other products become more attractive until quantities purchased in the previous timestep are reached in the current timestep, in this situation another product might become more attractive.

Figure E.4: Final demand for each sector per dynamics settings

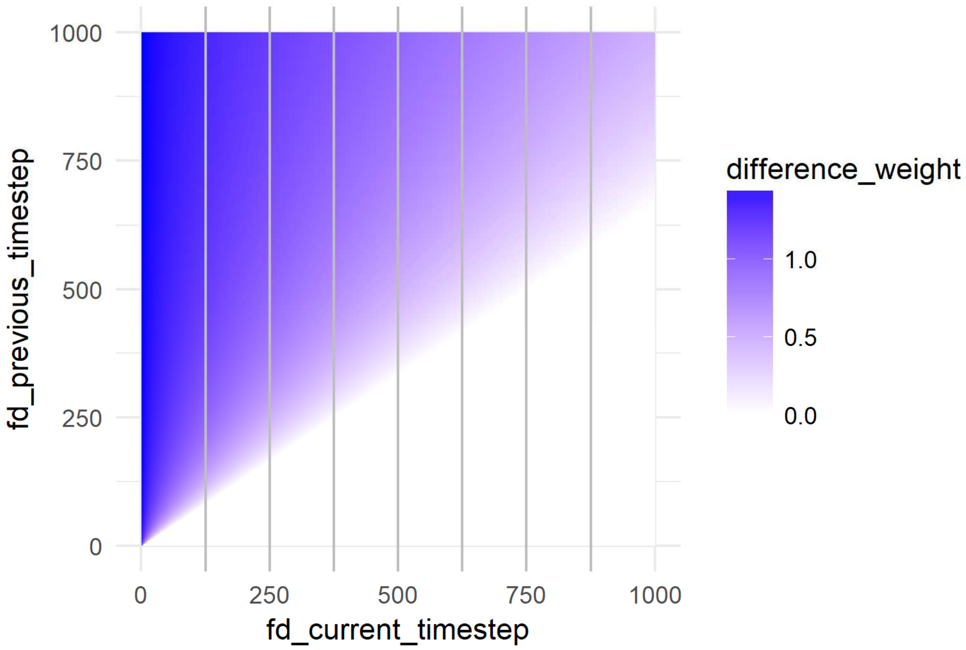

Figure E.5: Difference weight values for different consumption quantities

It is clear that all of the plots above display unrealistic behaviour; to support this statement below in figure E.6 the final demand that has been recorded in WIOD from 1995 up to 2011 is shown. No single sector dies out, obviously if a sector had died it would not have featured in the dataset as a separate sector (the data was compiled in 2013). Also, the final demand over time does not behave linearly, some sectors grow, some sectors jitter around a mean value, and few sectors remain small. A closer look at individual sectors is presented below in figure E.7 showing the recorded final demand per sector.

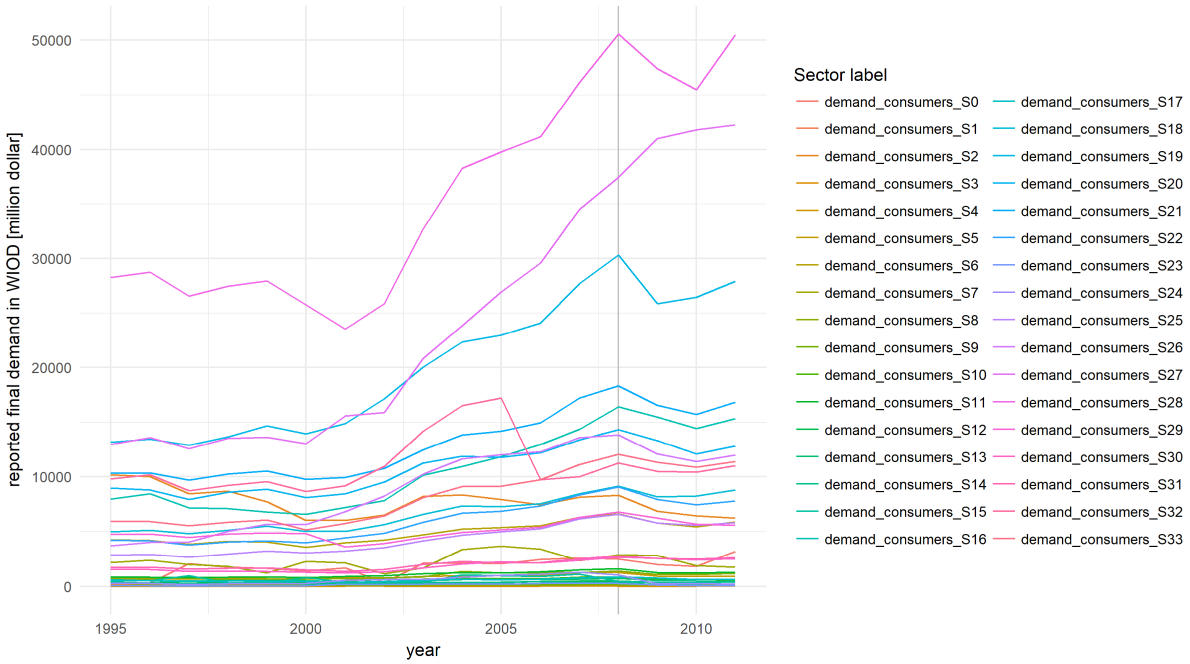

Figure E.6: Final demand between 1995 and 2011 recorded in WIOD

Figure E.7 below shows more clearly that among sectors generally three types of behaviour can be observed, growth, decline and jitter around a mean. The same behaviours observed for the three different dynamics settings. In figure E.7 a vertical line is drawn at the year 2008; this is done because after 2008 the final demand was heavily influenced by the financial crisis of 2007-2008. By far most sectors show growth over time, while the growth is not always smooth, but the growth jumps around. One thing to mention is that the final demand observations from historical data range for 16 years and the model results presented previously were from a simulation lasting 51 timestep, each representing one year. In figure E.8 below the historic final demand is shown along with the simulation results of the first 16 timesteps of the model with the three most distinct model settings: all dynamics enabled, all dynamics disabled and all dynamics, but difference weight enabled.

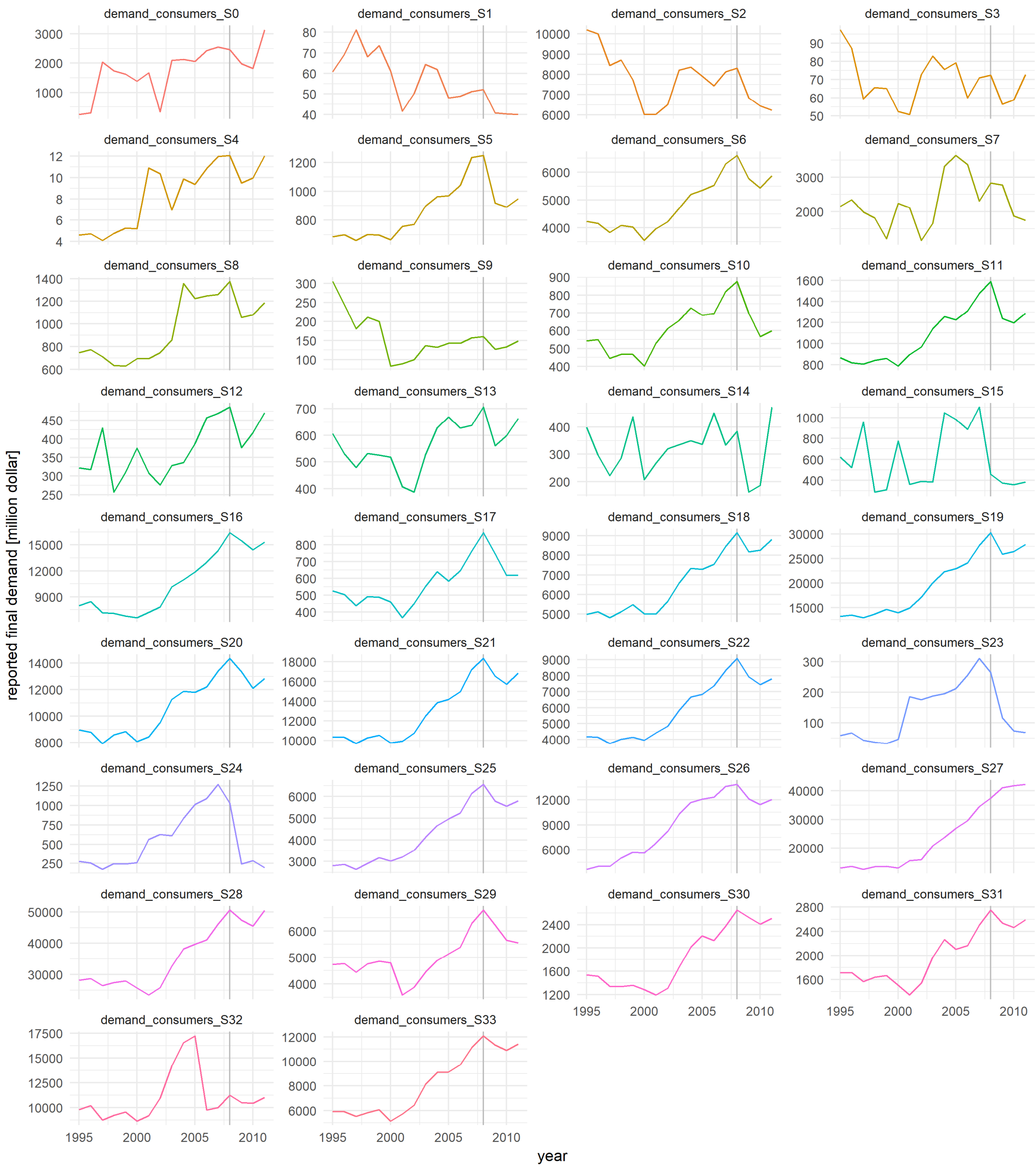

Figure E.7: Recorded final demand in WIOD per sector between 1995 and 2011

Figure E.8 below shows that some sectors in the model with all dynamics show similar behaviour to the historic data however, in figure E.8 it is difficult to see that many sectors die out in the model with all dynamics. As mentioned, this is due to the unidimensional performance parameter which does not consider the different needs of consumers to be satisfied.

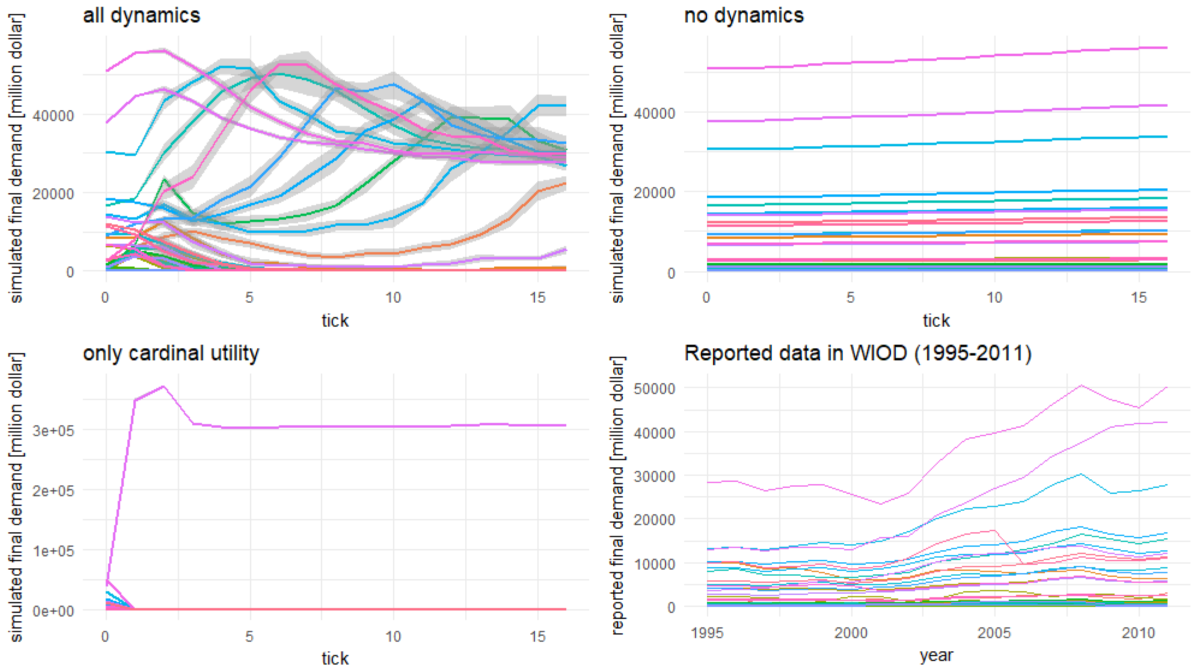

Figure E.8: Recorded final demand along with simulated final demand of distinct dynamics settings for the first 16 time steps of the model

In figure E.8, above, it is difficult to discern the individual sectors' behaviour, but figure E.8 makes clear that runs with "only cardinal utility" produce unrealistic behaviour. To inspect the individual sectors' behaviour with respect to real-world data, the individual sector's final demand has been plotted and is presented in figure E.9, below. In figure E.9, only the simulated final demand of the distinct switch settings is shown, as well as the recorded final demand between 1995 and 2011 in WIOD. It should be noted, again, that the model simulates the period between 2009 and 2025, while the historic data is recorded almost 20 years earlier. The model shows, for some sectors, similar behaviour as the recorded data but the behaviour per sector in the model output does not match the behaviour per sector in the historic data. This is due to the model's abstractions as well as the difference in time period.

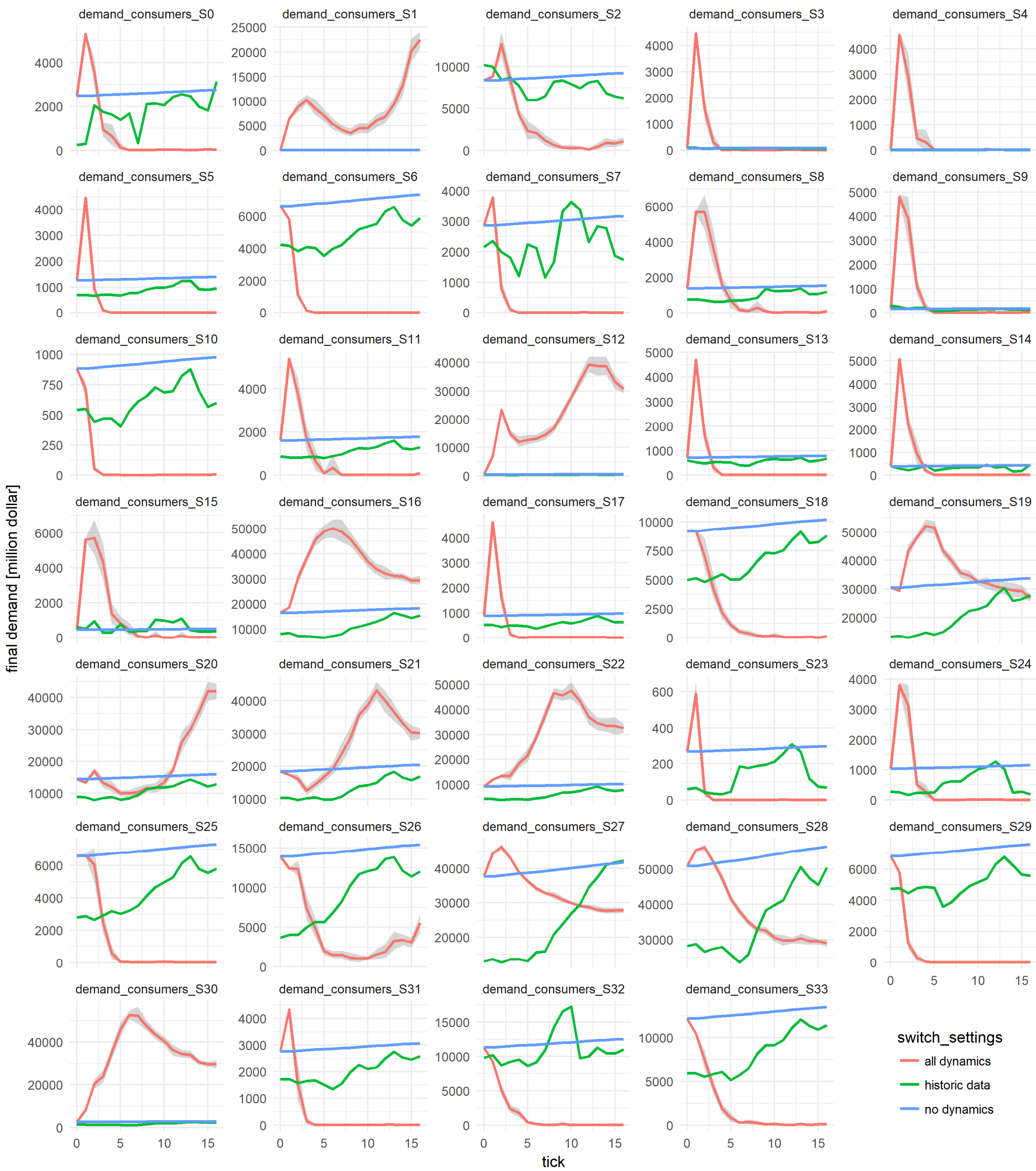

Figure E.9: Final demand observed between 1995 and 2011 and simulated final demand with all- and no dynamics

E.2 Analysing the output of sectors of the production system

The output of sectors is computed by taking the final demand of all sources and adding the demand of other sectors as intermediate products. The demand for intermediate products is determined by the technological coefficient matrix; a sector's technological coefficient vector gives the required output of other sectors to produce one unit of that sector's output. Final demand is composed of final demand by consumers, discussed in the previous section of this appendix, and export and final demand of non-consumers, which was endogenous to the model and assumed to be constant throughout the model run.

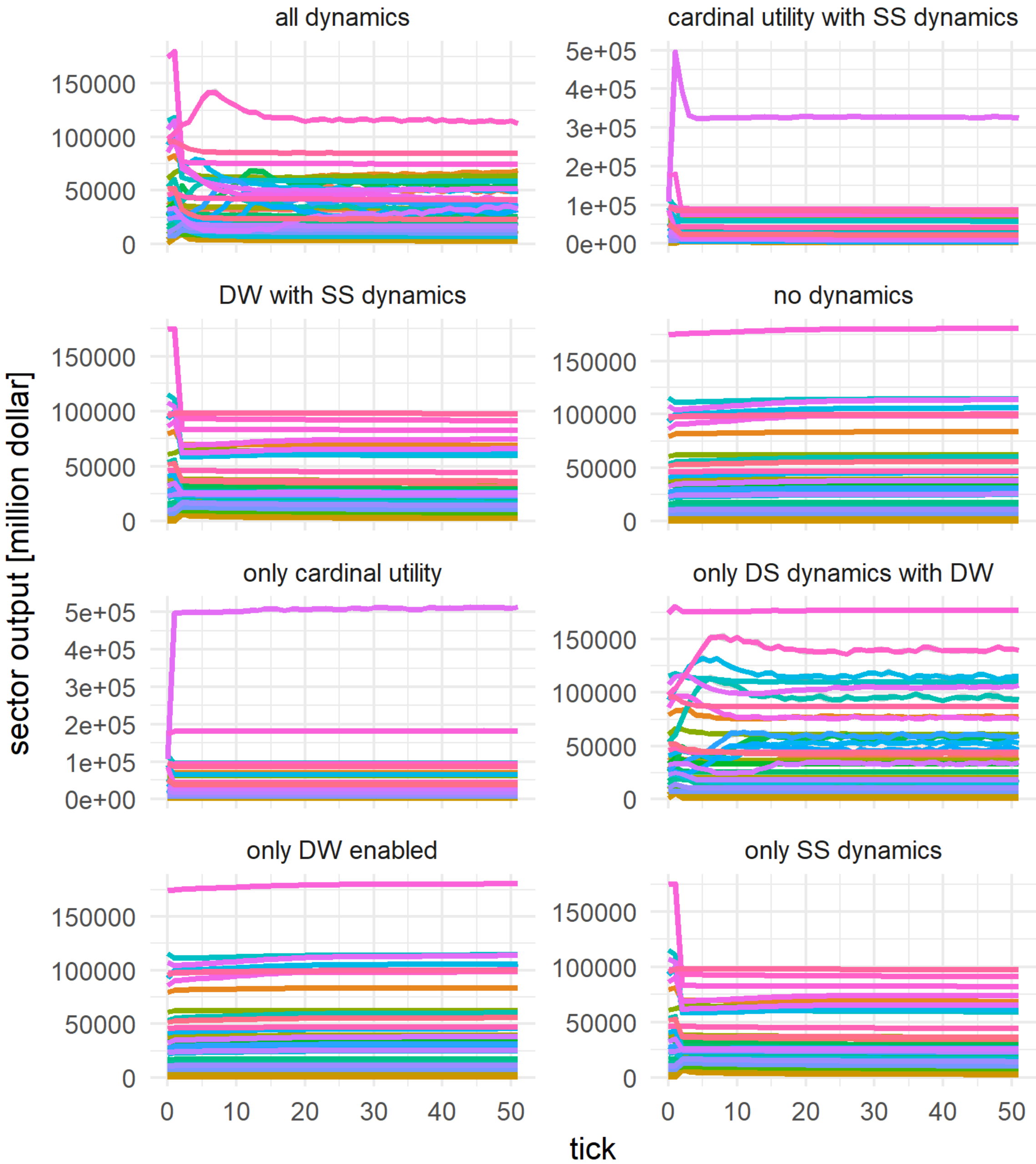

Figure E.10: Output of sectors for different dynamics settings

Figure E.10 above shows the output of all sectors for each of the settings of the dynamic features. The behaviour that can be observed is similar to the final demand plots discussed in the previous section, the relative deviation throughout the different replications is smaller because of the large portion of constant, exogenous, demand. Again, the runs without difference weight show rather constant lines for sector output, this can be observed more clearly when inspecting the output per sector; in figure E.11 below each sector is plotted individually.

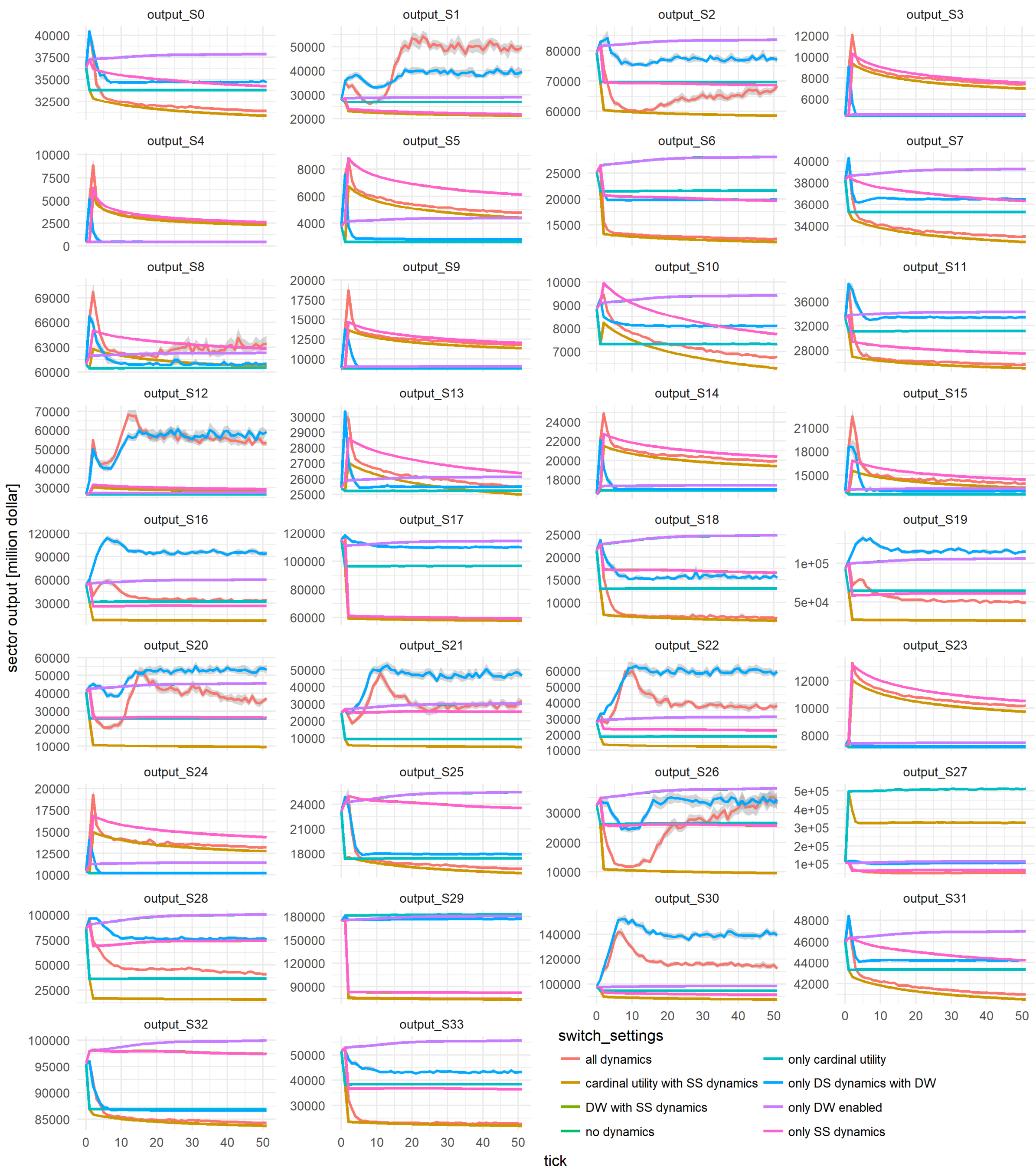

Figure E.11: Output per sector for different dynamics settings

The lower bound of figure E.11 is never zero because all sectors have at least some demand even if the consumer population does not purchase it; this becomes more explicitly visible when plotting the, constant, demand by non-consumers and export in the same figure. Figure E.12 below shows for four sectors, with distinct output behaviour, the non-consumer and export demand as well as the total output of sectors. In figure E.12 the level of export per sector is indicated by a horizontal black line, export is typically in the thousands, and the level of final demand by non-consumers, which is typically in the hundreds, is indicated by a horizontal grey line. As mentioned, the level of output never drops below these levels. In the plot for agriculture a steady decline of output can be observed, this is due to technological learning from sectors that use agriculture product as intermediate products. Due to learning effects these other sectors increase their efficiency and require less intermediate products (in monetary terms) to produce the same output. Having this steady demand from other sources than consumers makes the total output per sector much more stable than the final demand by consumers.

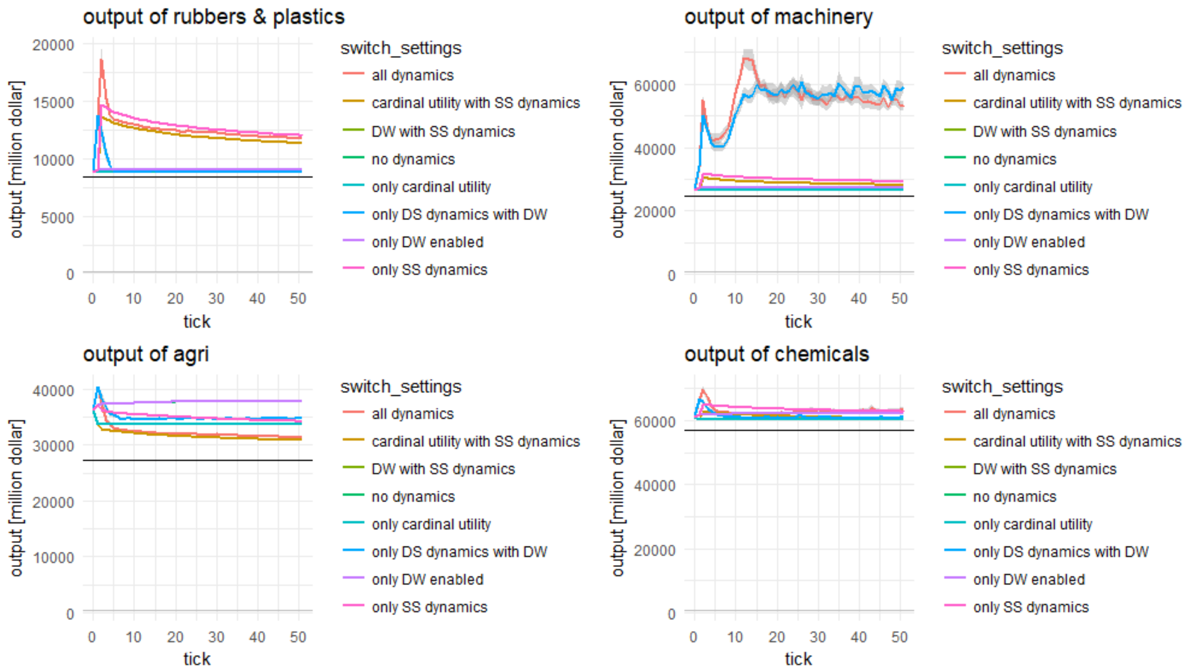

Figure E.12: Output of four sectors per switch settings along with the level of export and final demand by non-consumers.

E.3 Analysing the development of technologies of the supply side dynamics

The development of technologies over the course of a model run was reflected in the model in three ways, the technological coefficient decreased due to learning effects, as was observed in figure E.12, and the technologies improved either their performance or environmental impact. The assumption was made that a conflict exists between improving the performance or environmental impact; therefore, each sector was represented by two technologies, one focussing on reducing the environmental impact and one focussing on increasing the performance. The improvement of technologies is a function of the technologies' cumulative output. In this section, first the development of performance-minded technologies throughout the model runs is analysed by showing the performance of performance minded technologies over time. Second, the development of environment-minded technologies is shown by analysing the development of the environmental impact (per unit of output-) of technologies over time.

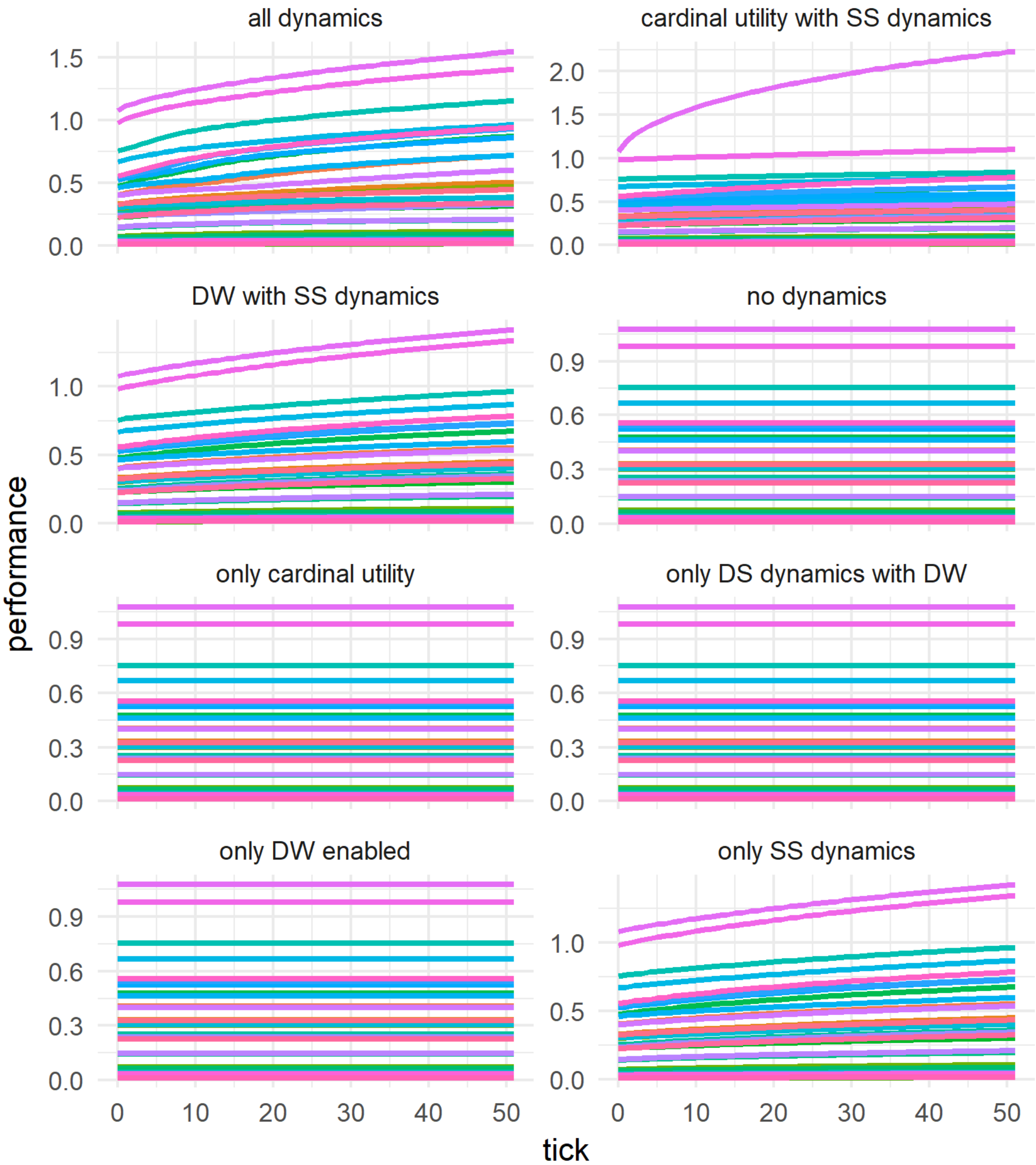

Figure E.13: Performance of performance-minded technologies over time per switch settings

Figure E.13 above shows how the performance of each sector's performance-minded technology changed over time. As expected, the runs with supply-side dynamics all show constant performance. In the runs with static final demand, all technologies move steadily along the wright curve with a somewhat constant slope of their cumulative output. The top two plots are interesting. In the plot labelled as "cardinal utility with SS dynamics", all dynamics are enabled but demand-side dynamics do not incorporate the difference weight. In these runs, all the consumers settle with a single technology; this technology's cumulative output rises rapidly, and large gains are made along the Wright curve with its diminishing returns. In figure E.13 it cannot be observed clearly, but the plot labelled as "all dynamics" shows behaviour that does not exactly follow the wright curve with linear cumulative output development. Because the final demand jumps around a lot, the cumulative output increase jumps around. In figure E.14 below the performance development over time is plotted per sector for a more detailed view.

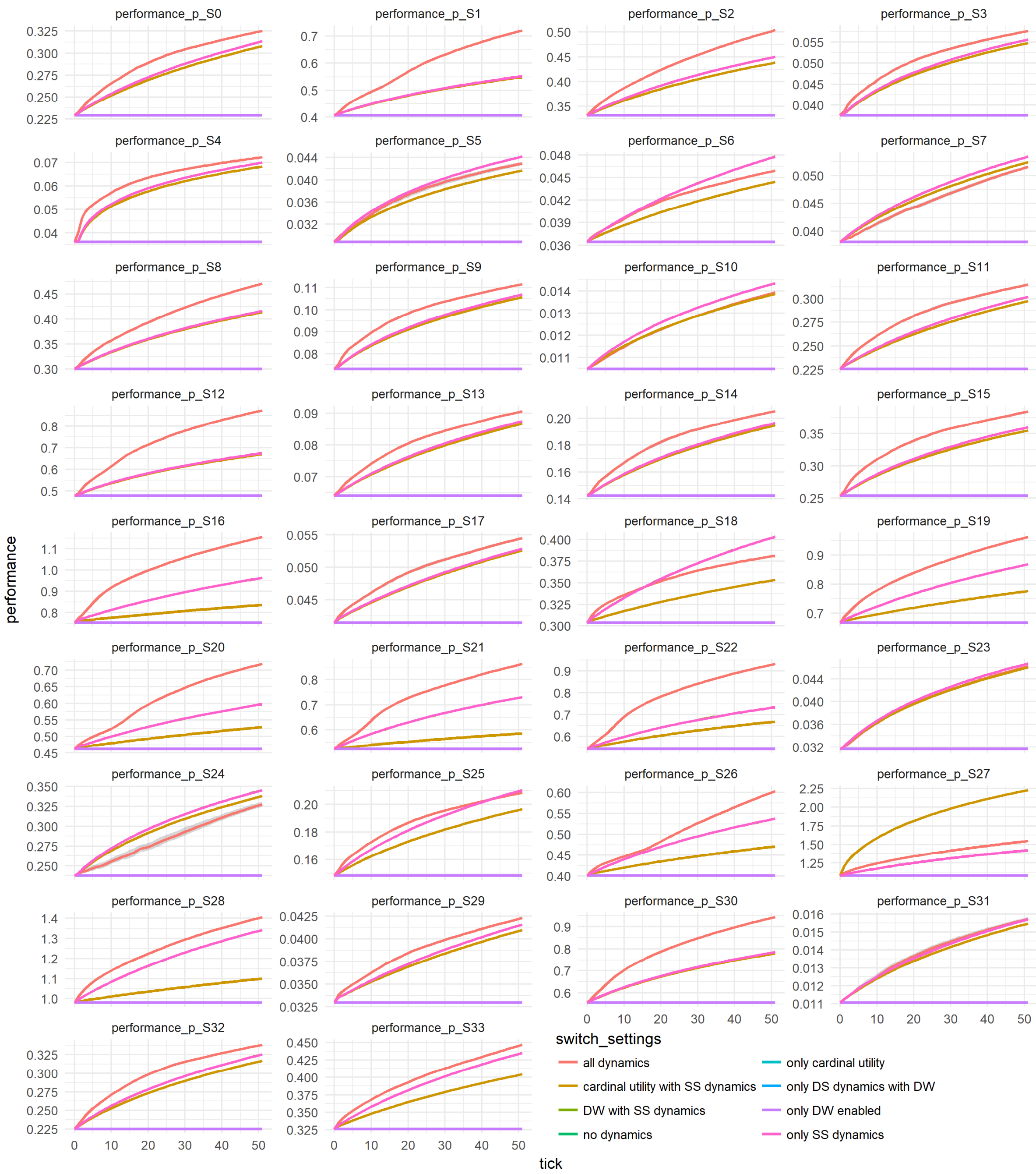

Figure E.14: Performance development over time per sector for different dynamics settings

Runs with switch settings labelled as "all dynamics" have some pivot points in their curves. As will be shown next, similar things happen with the environmental impact.

Figure E.15 below shows the environmental impact development of environment-minded technologies for the different dynamics settings. Figure E.15 shows that few technologies have a very high environmental impact; these technologies have the most evident development in this graph because of the scale of the y-axis. The sector with the highest environmental impact, the blue line in E.15 is S24, air transport. Air transport is not favourable for consumers at all, but because of the relatively low cumulative output and the steady final demand, but above all air transport supplies a large number of intermediate products. Especially the sector 'Renting of M&Eq and Other Business Activities' is an important customer of the air transport sector, requiring 0.05 units of Air Transport-output for one unit of 'Renting of M&Eq and Other Business Activities'-output. This explains why, although customers do not favour Air transport at all in dynamic model runs, this sector manages to produce a lot of output, and with this output reduce the emissions per unit of output as well. In order to look at individual sectors more closely, the emission development per sector is shown below in figure E.16.

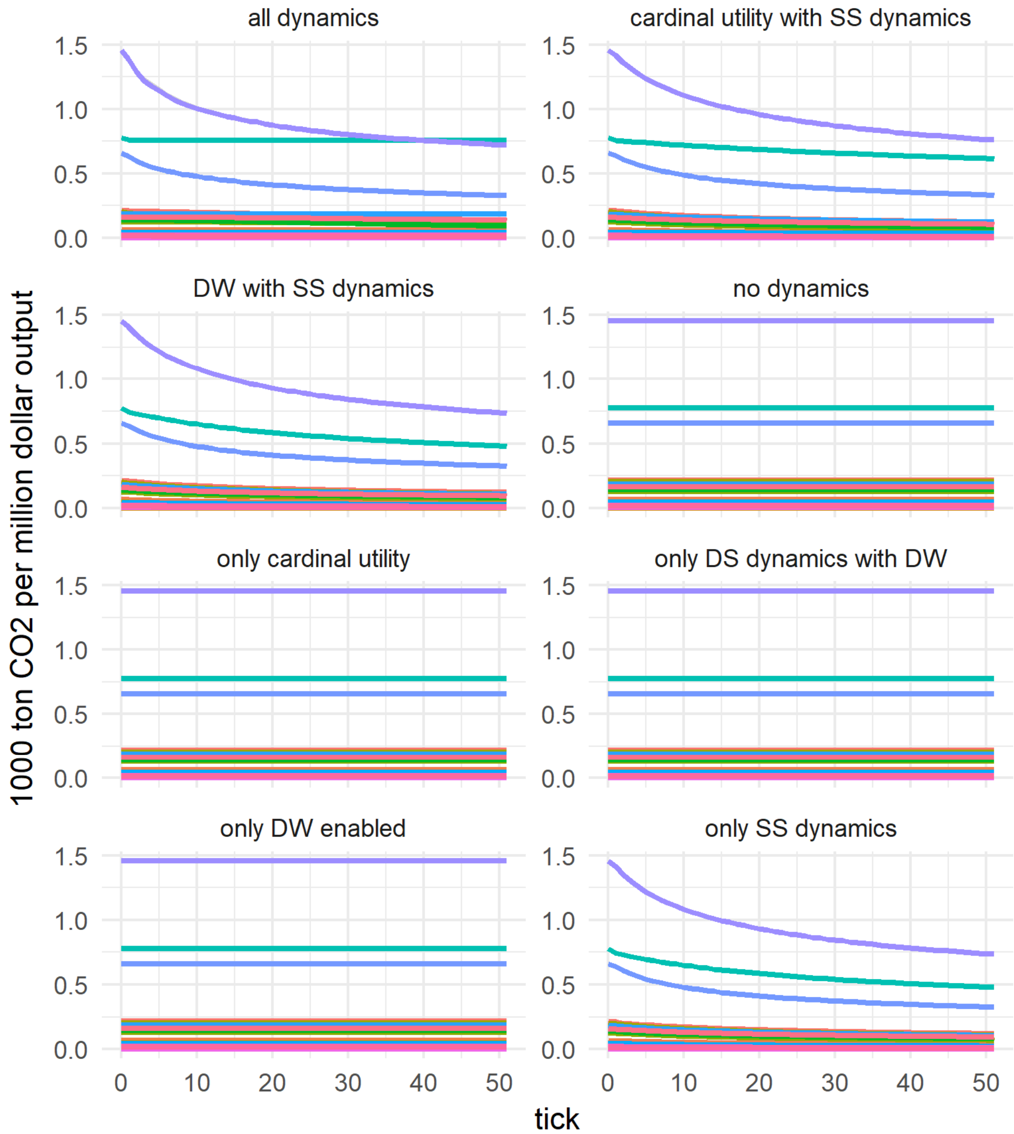

Figure E.15: Environmental impact of environment-minded technologies over time per switch settings

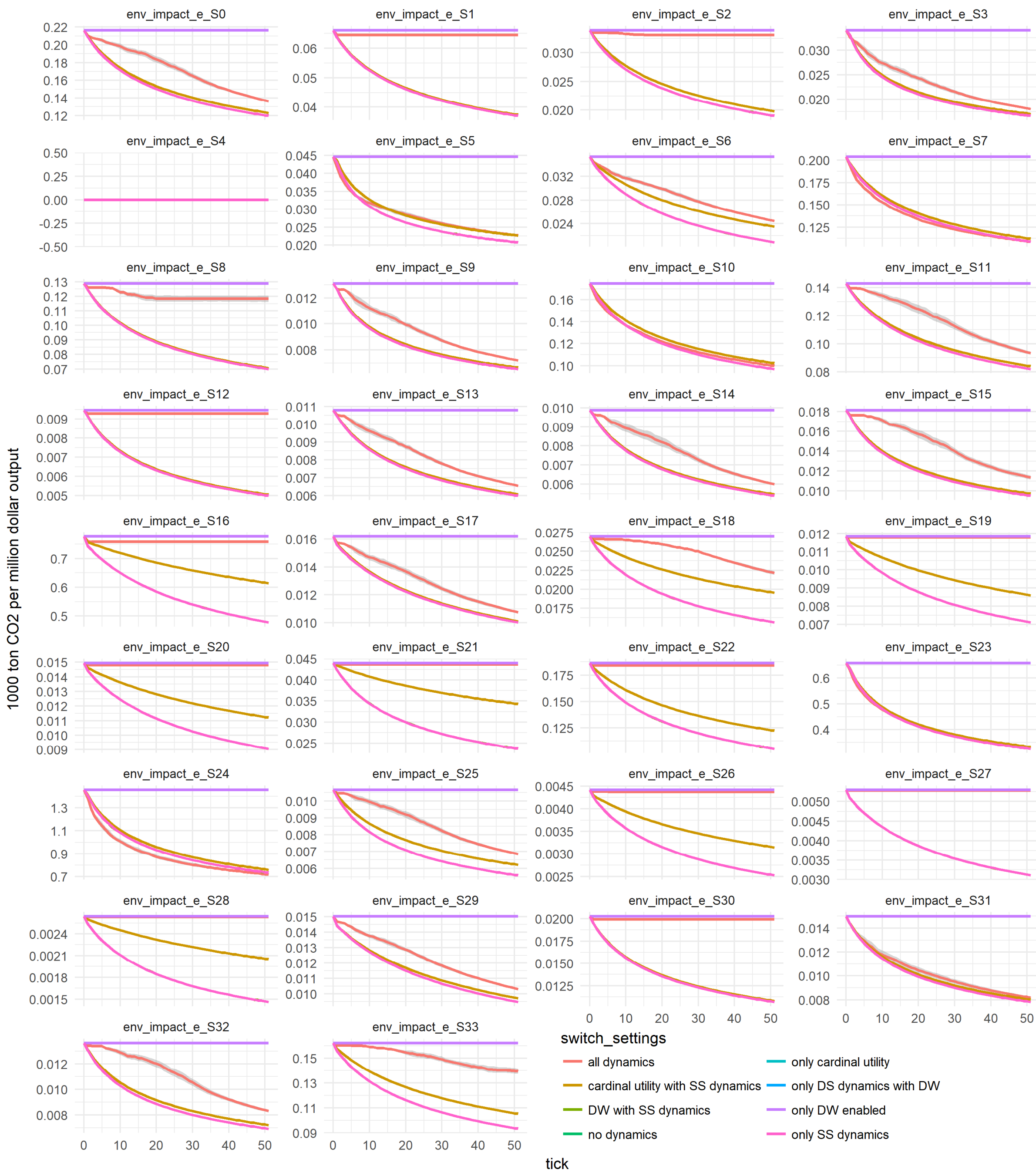

Figure E.16: Environmental impact per dynamics setting of all sectors

Figure E.16 shows, similar to performance, that when the supply side dynamics are disabled, the emissions per unit of output remain constant and that when the demand side dynamics are disabled, the emission per unit of output decreases according to the Wright curve. The behaviour of the runs with all dynamics enabled, coloured red, is the most remarkable. The behaviour does not follow the Wright curve because the sector output of these runs varies a lot. In order to illustrate the relation between output and incremental efficiency improvement, figure E.17 below shows a plot of a single sector, S9 or in reality the rubber and plastics sector, of its output and its environmental impact per unit of output, both over time. Rubber and plastics' products has a relatively high cumulative output, therefore the improvement from an absolute level of output in a certain timestep is relatively low. In the beginning of the simulation, there was an extreme peak in the output of the chemistry sector; this was accompanied by a sudden drop in environmental impact per unit of output. Subsequent output of the rubber and plastics sector was quite stable, which is reflected in its stable decline of environmental impact. Note that in the output plot in figure E.17 the lower bound of the y-axis is not zero but 60,000.

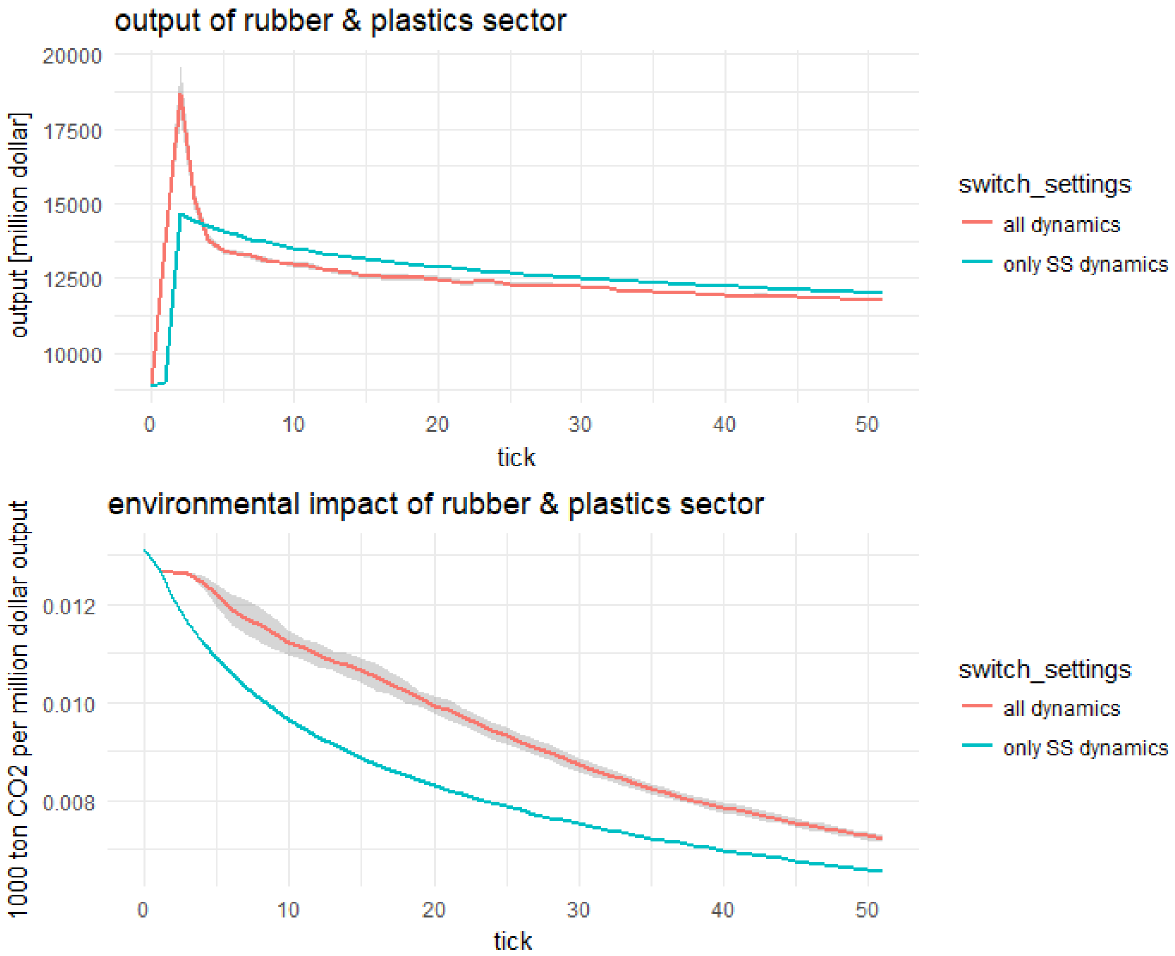

Figure E.17 Output and environmental impact per unit of output of the rubber & plastics sector

E.4 The CO_2 emissions of the model under different assumptions

There are different assumptions underlying the three dynamics models; all dynamics switched off applied the input-output analysis assumptions, that technological coefficient is static and final demand is exogenous. The exogenous final demand by consumers was represented by an extrapolation of demand following the consumer population size. The supply-side dynamics model is supported by the assumption that the Wright curve adequately predicts efficiency increases as a function of cumulative output; as technologies produce more products they gain efficiency by learning. The demand side dynamics are supported by the assumption that consumers allocate their budget by maximising utility of the budget; with two distinct sources of utility.

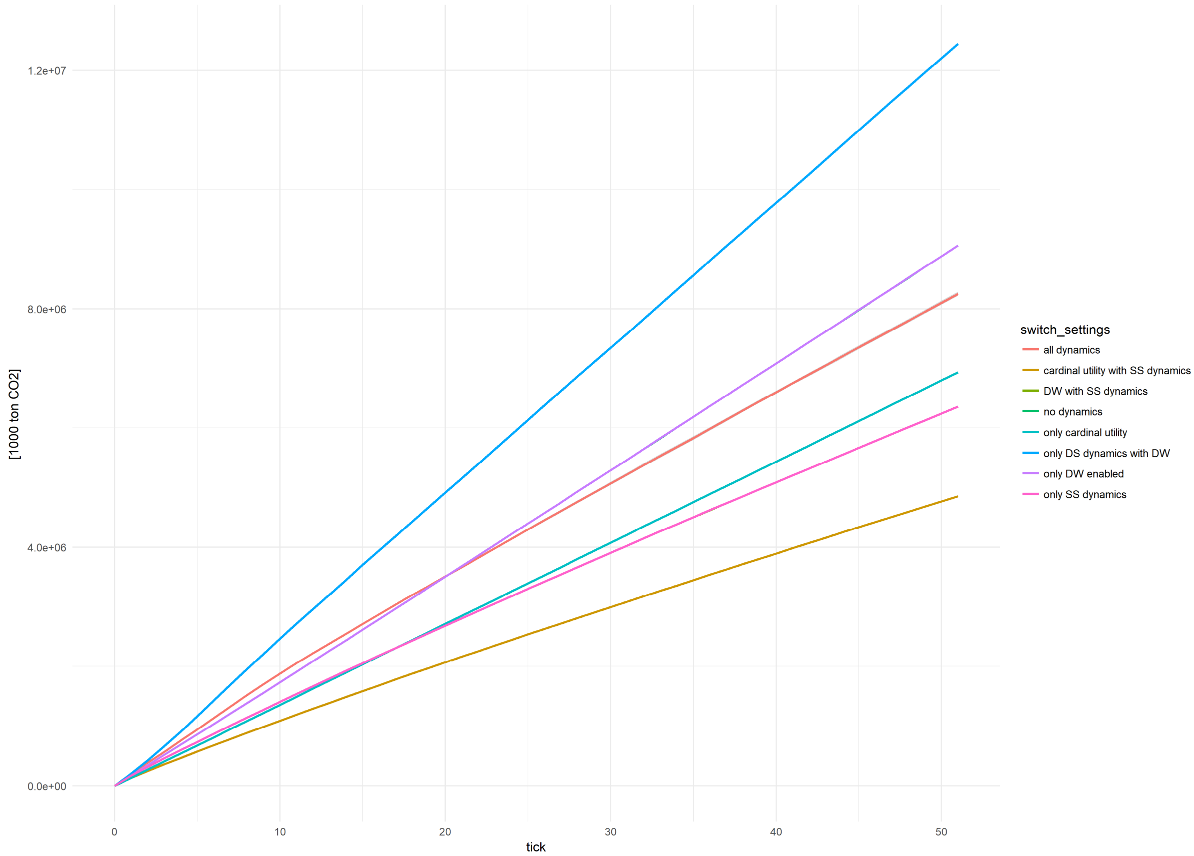

Figure E.18: Cumulative CO_2 emissions with different dynamics settings

Figure E.18 above shows the amount of CO_2 emitted by the production system for the different dynamics settings. The emissions for all dynamics settings follow, as far as can be observed from figure E.18, a linear curve; with a different slope per dynamics settings. This can be explained by two features; the fact that only consumers consider CO_2 emissions in their purchase decisions and the fact that air transport exists.

The fact that only consumers consider CO_2 emissions means that all other demand is not concerned with the development of emissions of technologies. In the model, in all settings, the major part of the output of sectors was not produced to supply consumer demand. Figure E.19 below breaks down the output per sector into the different demand sources, consumer demand, export, non-consumer demand and intermediate demand. The quantity of non-consumer demand and export is exogenous to the model; the values reported for the base year of the model (2009) are kept constant throughout the model runs.

Figure E.19: Output of sectors per demand source in a single run with all dynamics enabled

The statement in the previous paragraph that, because air transport exists the CO_2 emission curves of different dynamics settings are similar, is quite confusing and shall be elaborated on in more detail. Air transport has an extremely high CO_2 emission per unit of output: 1.94 [1000 ton CO_2 per million euro output]. While consumers consider CO_2 emission in their utility function, the relative CO_2 emission is used. That means that the part in the utility function that accounts for CO_2 emission for a given technology, equals that technology's CO_2 emission divided by air transport CO_2 emission. This caused the relative CO_2 emission of many technologies to be low while the absolute CO_2 emission was 'pretty' high. To support this argument, and to provide an improvement to the utility function, below in figure E.20 the absolute and relative CO_2 emissions per sector is plotted and sorted by size. In order to let the emissions weigh in more into the utility function two options are suggested, either increase the consumer's environmental impact utility weight or change the distribution of the relative environmental impact. To change the distribution of the relative environmental impact, the squared relative CO_2 emission could be used in the utility function. The absolute-, relative, and relative squared CO_2 emissions per sector have been plotted and are shown in figure E.20 below.

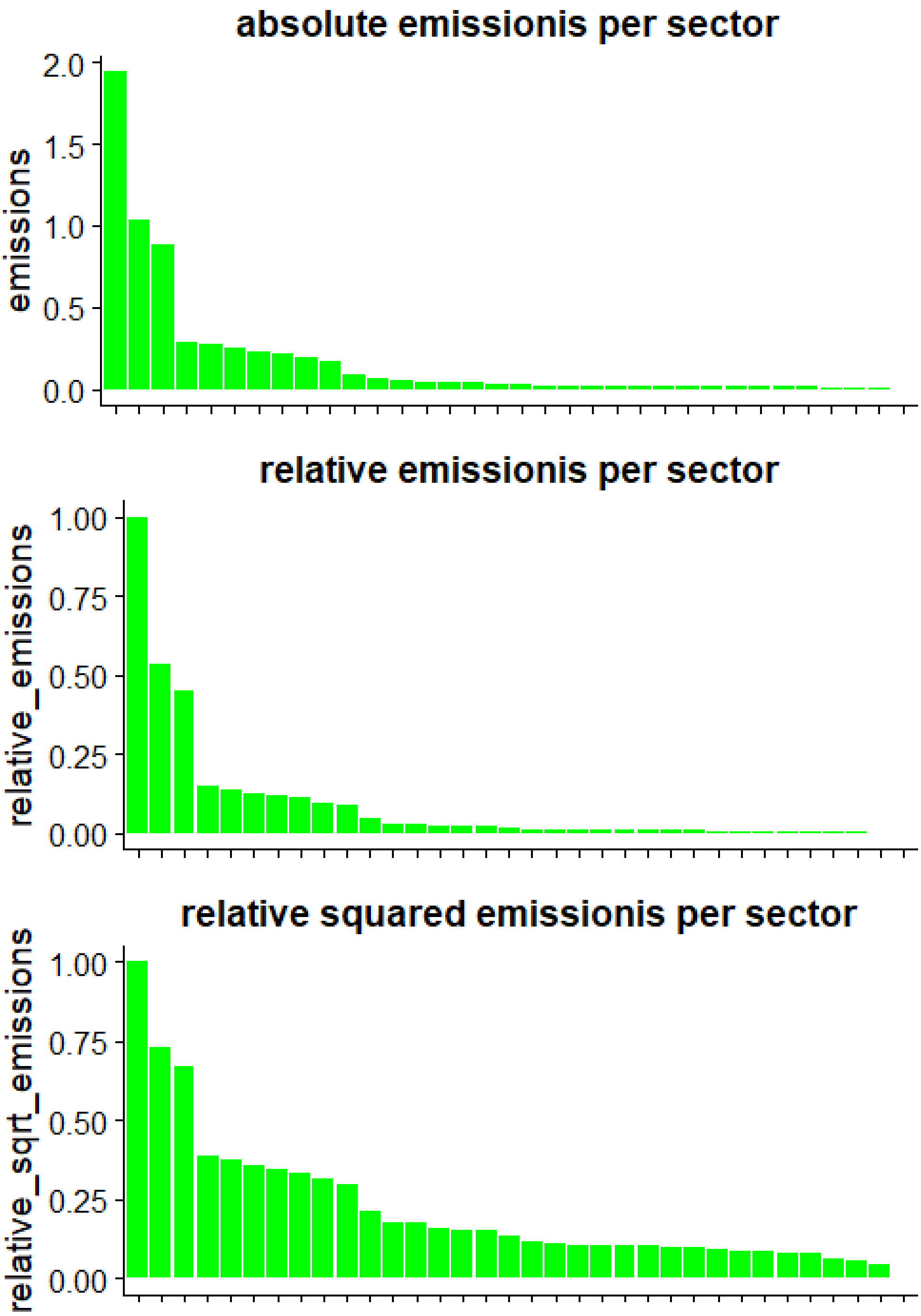

Figure E.20: Absolute-, relative-, and squared relative emissions per sector sorted by size

Appendix F: Scientific article

Integrating dynamic final demand into input-output analysis

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Abstract
One of the fundamental assumptions of input-output analysis is challenged in this paper. The assumption that final demand by consumers for future years is know is omitted from the model. Instead, a dynamic model is proposed to simulate consumer behaviour that results in a final demand vector. Consumers are modelled in an agent-based model; they make purchase decisions by optimising utility under a budget constraint. A utility function is proposed that results in a final demand vector with a resolution concurring with the sector-level decomposition of input-output analysis. A proof of concept has been developed and results show that for a number of sectors the generated final demand mimic the observed final demand levels. The proof of concept features the product quality as a one-dimensional, and two-dimensional attribute of sectors. However, some sectors are not consumed at all. This was attributed to a poor representation of product quality which relaxes the trade-offs that consumers make in their purchasing decisions. Future research should be dedicated to defining quality of sector-level products in more detail; this way the trade-offs of consumers become more explicit allowing the model to better represent final demand.

Keywords: Input-output analysis, agent-based modelling, consumer behaviour, utility theory, prospect theory

1. Introduction

Input-output analysis is a macro-economic planning framework that was first proposed by Wassily Leontief in the 1930's. The approach of input-output analysis is to decompose a regional economy into a set of trading sectors; each sector absorbs a specific set of inputs and generates a type of output (Leontief, 1986). The output of a sector serves either as input for another sector, or as a final product to be supplied to a consumer. By measuring and presenting the trade data in a matrix, with the sector delineations on both the rows and columns of the matrix, the trade flows between sectors is precisely mapped. Subsequent analysis assumes that the proportions of input requirements for one unit of output remains constant; by changing the required output for consumers, changed output down the supply-chain can be computed.

Nowadays, the input-output analysis framework is still in use and has been expanded by increasing the resolution, representing the economy in many different sectors. Besides trade flows, other impacts associated with a sector's production levels are mapped into the data. So called environmentally extended input-output databases exist which report associated environmental impact per unit of output per sector. An example of such a database is WIOD (Dietzenbacher et al., 2013). While the resolution of WIOD is 'only' 35 sectors, this resolution aligns with the resolution of many other Eurostat databases linking the economic data to social and environmental impacts. WIOD reports social impacts like the number of employees, and the labour compensation for three different skill levels associated to sector's levels of output. Environmental impacts associated with output levels of sectors are, for instance, energy use per carrier, CO_2 emission, and many more pollutants emitted to air. Using WIOD, analyses can be made of environmental impact with associated social- and economic impact.

While input-output analysis is under development for over 80 years, some of the fundamental supporting assumptions were left unchanged; one of these assumptions is that final demand is given. In input-output analysis, final demand is exogenous to the model, typically scenarios of demand levels are used to discern policy options. In this paper, this assumption is omitted. Rather than keeping final demand exogenous to the model, it is incorporated into the model by a modelled population of consumers. In this way, the assumption of 'predictable' final demand is replaced by the assumptions underlying the consumer model. To simulate the behaviour of consumers, agent-based models have been proven an adequate tool (Heckbert, Baynes & Reeson, 2010). Conceptually, both frameworks are compatible, the goal of input-output analysis aligns with the goal of agent-based models; to gain understanding of the structure of a system, not to predict exact levels of outcomes.

The remainder of this paper is structured as follows, first the advantages and challenges of integrating the input-output analysis- and the agent-based modelling perspective is given. Second, a brief overview of utility theory is presented on which the agent logic is founded. Third, the model that has been designed to be integrated with input-output analysis is presented and a proof of concept is given. Finally, the main conclusions are formulated and some suggestions for further research are proposed.

2. Advantages and challenges of integrating the two perspectives

Agent-based models are built by defining the low-level interactions and decision rules, system-level behaviour follows from these definitions. Input-output analysis takes the opposite approach, defining the highest system-levels and decomposing the system until the desired resolution is reached. Having both micro- and macro-levels represented in the model brings both advantages and challenges. In this paragraph, a summary of these main advantages and challenges is given.

2.1 Advantages of integrating ABM with I-O analysis

Both perspective can be mutually beneficial. One of the major issues with agent-based models is the validation of the models; mainly due to a lack of historical data combined with a large parameter space (Louie & Carley, 2008). This is where input-output analysis provides with a solution, because it contains a vast amount of historical data which is highly structured. Another quality of input-output analysis is that it provides simple but elegant solutions to handle the scale of the economic system. Fully modelling an economy by defining the smallest elements of the system, true to the agent-based formalism, would result is an extremely large model. Input-output analysis has devoted decades to refining a simple representation of the production system of economies.

For macro-economic models, like input-output analysis models, a common criticism is the lack of both technological detail and micro-economic realism. These aspects can be brought to the table by agent-based modelling. Combining micro-economic realism, technological detail and macro-economic completeness into a single model is what Hourcade et al. (2006) refer to as the 'holy grail' of economic modelling. This paper aims to account for more micro-economic realism by explicitly modelling consumer decisions; in this way, individuals' behaviour can be accounted for. Policies surrounding environmental impact often focus on technological efficiency, while the consumer is also an integral part of the economy with a (shared-) responsibility for the environmental impact associated with economic activity.

Integrating the two perspectives allows for more robust policymaking. A robust policy is a policy that performs well within the entire uncertainty space. It is known that input-output data contains a large degree of errors (Lenzen, 2001); however, most research utilising input-output analysis ignore this uncertainty. For agent-based modelling, and simulation modelling in general, highly sophisticated methods exist to explore these uncertainties. Readily available packages compatible with many different simulation environments exist which provide off-the-shelf uncertainty analysis methods, see for instance (Kwakkel, 2017).

2.1 Challenges in integrating ABM with I-O analysis

While the goals of input-output analysis and agent-based models align, to build understanding of a system, the approaches are fundamentally different. To align the perspectives is the major challenge in the integration. The approach taken by input-output analysis is to regard a regional economy as a set of sectors. The regional economy is broken down into a number of sectors and the inter-sectoral trade flows are reported. This decomposition is referred to as a top-down approach. Agent-based models are built in the opposite direction. In defining an agent-based model, the smallest relevant, functional and autonomous entity is programmed; this entity is referred to as an agent. For the agents, individual behavioural rules are defined as well as the agent's interaction rules. The model puts these agents into an environment; based on the agent's definitions and interactions, system level behaviour emerges.

When conceptualising the integration of these perspectives, this misalignment becomes evident. Input-output analysis requires a final demand vector in a sector-level format in order to compute the total output of sectors. However, sectors are assumed to produce homogeneous output. As an example, the Eurostat classification of economic activity discerns a large amount of different types of economic activity; however, even at the deepest level of decomposition these boundaries are still far away from individual choice options that are relevant for a consumer. For instance, the highest level of detail, representing the manufacturing of computers is enclosed in the sector *"Manufacture of computers and other information processing equipment"*; which includes laptops, desktops and server equipment. The agent population generating a final demand vector should result in a vector of the same resolution as the input-output data or some transformation is required. In this paper, a utility function is proposed that can produce this sector-level output vector.

3. A utility function for sector-level products

As the integrated model requires a vector for final demand on the aggregation level of sectors used in input-output analysis, this section is dedicated to formulating a utility function that can produce this vector. First, a brief literature overview is given on utility theory. Second, this paper's perspective on the utility function is formulated.

3.1 Overview of utility theory literature

A recent paper emphasises the validity of utility from a biological perspective; Levy and Glimcher (2012) provide a meta-analysis of different neuro-biological researches. All those researches showed that the human brain uses a common valuation path for different rewards, analogous to the concept of utility.

The concept of utility goes back a long way. The proposal of the utility-concept is often attributed to Bernoulli in the 18th century; the concept of utility as we know it now was formalised simultaneously by William Jevons, Carl Menger and Léon Walras in the 1870's (Stigler, 1950). Subsequent development of the utility concept can be divided into two streams, the ordinal utility theorist and the cardinal utility theorist. The main difference between the two lies in the structure of utility. Cardinal utility theory quantifies utility as a dimensionless value; ordinal utility theory rejects the quantification of utility but ranks different goods in order of preference. Modern day ordinal utility theory is founded by the works of Samuelson (1938) and Houthakker (1960); the ordinal approach to utility is therefore known as the Samuelson-Houthakker approach. Cardinal utility theory was formalised independently by Slutsky (1915) and Hicks (1956) and is now known as the Slutsky-Hicks framework.

While utility theory works well in theoretical, demarcated, situations, it does not always conform with empirical observations. Another framework concerned with consumer preferences is Prospect Theory (Kahneman & Tversky, 1979). In prospect theory, consumers are assumed to make imperfect decisions. A perfect decision accounts for all aspects, such a decision is called a reasoned decision. As prospect theory argues, reasoning is expensive in terms of time and mental computations. Therefore, humans replace reasoned decisions with intuitive decision-making. Intuitive decision-making is argued to be subject to a number of biases, one of those biases, which is applied in the utility function in this paper, is that utility is generated by changes of the state of wealth, rather than the state of wealth. In other words, the utility of a certain good is generated by gains and losses, not the absolute quantity obtained.

3.2 Generating a final demand vector by optimising-agents

For computational models, the cardinal utility function is attractive because it can be easily implemented. Prospect theory's approach of utility generation by changes in the state of wealth has proven to be able to account for empirically observed behaviour. For this paper, both cardinal utility and prospect theory approaches are incorporated. Utility is assumed to be quantifiable, and a function of the difference between the current time-period's, already realised, acquisitions and the previous time-periods realised acquisitions.

In every time-step of the model, a single consumer is presented with an optimisation problem, to maximise the utility under its budget-constraint. Because input-output data is presented in monetary units, one unit of output is equal to one monetary unit. Therefore, price can be left exogenous to the model. The different sectors of the input-output framework produce unique outputs, each sector has a unique utility value. Because consumers are modelled individually, their heterogeneity can be accounted for in individual preferences, reflected by individual utility-weights. The formulation of the optimisation problem of consumer i is presented in equation 1.

$$Maximise \sum_{0}^{j} U_{i,j} \ where \sum_{0}^{j} Q_{i,j,t} \leq budget_{i,t} \tag{1}$$

In this problem, $U_{i,j}$ is the utility of sector j for consumer i, $Q_{i,j,t}$ is the quantity purchased in time-step t of sector j by consumer i. A consumer maximises the utility of all sectors while not exceeding the budget that the consumer has available in the current time-step. The utility of a single sector is further defined in equation 2.

$$U_{i,j} = f(\mathbf{quality}_j, \mathbf{b}_i, Q_{i,j,t}, Q_{i,j,t-1}) \tag{2}$$

The utility of a sector j for consumer i is a function of a certain quality parameters contained in a vector. Vector $\mathbf{b}$ contains the utility-weights of consumer i per quality parameter, note that the utility weights are sector-independent; this way substitution effects can occur in the model. The quality vector should reflect the needs of individual consumers. The Hierarchy of Needs, by Maslow (1970) can be used as an initial guide to which needs a human being has that are to be fulfilled by the production system. Factor analysis can be applied on consumer choice experiments to quantify the utility-weights vector. Allowing a multi-dimensional quality parameter allows for a complex trade-off within consumers that can proxy the consumer's dilemma of its budget allocation. Finally, as utility is a function of the change in state of wealth, the realised purchases in the current- and the previous timestep also affect the utility.

4. An agent-based model with a sector-level utility function

The definition of the single agent's utility-optimisation problem is used to implement an agent-based model that was integrated with input-output analysis to provide proof of the concept. In this section, the formalisation of the utility function for the model is first described, along with an overview of the model that was developed as proof the concept. Second, an overview of the model results is given. The proof of concept was used to produce a final demand vector over a number of time steps. The results are compared with a simple, cardinal, utility function, a simple extrapolation of final demand and historic data of final demand. The input-output data used for the implementation was taken from the WIOD project; data for the Netherlands was used.

4.1 Implementation of the proof of concept

Parameterisation of the utility function defined in sub-section 3.2 proved to be a major difficulty. The proof of concept features a stylised implementation of the proposed utility function; a two- and three-dimensional quality vector modelled. Quality was decomposed into performance and the environmental impact of sectors. These two parameters reflect a consumer's trade-off in sustainable purchases. The three dimensional quality vector featured two performance term, one which was weighted 1.0 and the second was weighted 0.7 by all consumers. The formalisation of the utility function used in the proof of concept is shown in equation 3.

$$U_{i,j} = DW_{i,j} * \left(\frac{performance_j}{performance_{max}} - \frac{env.\,impact_j}{env.\,impact_{max}} * env.\,impact\ weight_i\right) \qquad (3)$$

Environmental impact per sector was taken from directly from WIOD data; the environmental impact weight of individual consumers was accepted as an uncertain factor. For the model results, consumers were given a utility-weight for environmental impact randomly varied between 0 and 0.5. The performance term groups together all other aspects of a products quality; for the proof of concept a black-box approach was used for the performance term. No utility weight was used for performance. The value of performance per sector was set using a calibration experiment. By implementing the model and randomly assigning performances per sector, the model was run for one time step of which historic data was available. The fitness of the set of performance variables was defined as difference with the final demand vector of the model and the observed final demand vector. Using simulated annealing, different performance values were set until the fitness converged to a final value. The best-fit performance values were assigned to each sector and used in the proof of concept. The term DW (difference weight) reflects the difference in realised purchases of the current and previous time-step. Because the proof of concept is a stylised version, a simple scalar was used. The difference weight in the proof of concept is defined as:

$$DW_{i,j} = MAX\left(0, base\ weight + \frac{Q_{i,j,t-1} - Q_{i,j,t}}{Q_{i,j,t-1}}\right) \qquad (4)$$

The base weight is the value of the difference weight when the current time-periods purchases equal the previous time-periods purchases. In the proof of concept, a base weight of 0.5 was used to reflect the tendency of loss-aversion by consumers. However, this parameter was also deemed to be an uncertain factor and accepted as such.

The number of consumers was equal to one agent per 10,000 persons aged above 20 in the Netherlands according to the statistics office's projection (CBS, 2018). Following that same projection, skill levels were assigned to these consumers along the same ratio of education levels projected for the Netherlands. The available budget per consumer was determined by the wage associated with the economic activity; WIOD provides data on wage compensation per skill level per unit of output of sectors.

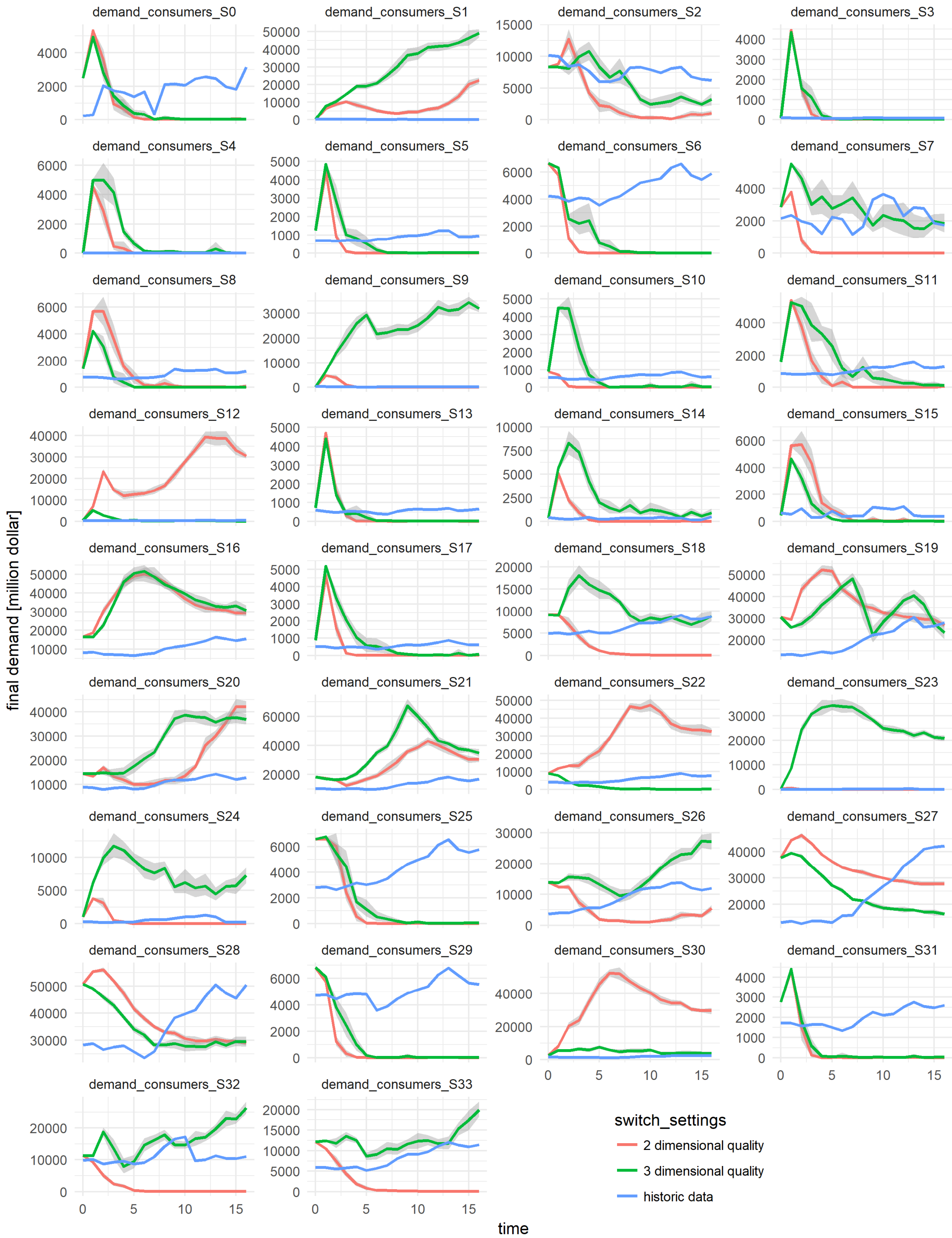

Figure 1: Final demand reported in WIOD (1995-2011) and simulated final demand (2009-2025) with a two- and three-dimensional quality parameter

The total wages per skill level were collected and distributed among the population of corresponding skill levels using an exponential distribution.

The production system in the proof of concept was represented by a simple model of technologies following the input-output analysis structure. Technologies improved their performance and environmental impact over time due to learning effects; the Wright curve was implemented to proxy these incremental improvements. Final demand in WIOD is composed of final demand by households, consumers in the model, exports, and non-consumers. As only consumers are endogenous to the model, these other final demand sources were taken from WIOD and kept constant throughout the model runs. The total sector output per sector was computed by multiplying the Leontief inverse matrix with this total final demand vector.

4.2 Results of the proof of concept model

The implementation described in the previous sub-section was done using NetLogo (Wilensky, 1999); NetLogo is a free, open-source, agent-based modelling tool. Both the agent-type operations and the required matrix-manipulations for input-output analysis are easily performed in NetLogo. The model was used to simulate fifteen years of economic activity, starting in 2009. In figure 1 above the final demand per sector is shown along with a plot of the reported final demand in WIOD from 1995 up to 2011. To account for stochastic uncertainty, figure 1 shows the mean of each sector with a coloured line over the different replications, the grey area around each line represents the 95% confidence interval. Observing figure 1, a caution should be made; the data contains the notorious financial crisis of 2007 where the production system started to show heavy distortions. The model shows for some sectors behaviour that looks like the behaviour observed in the historical data. However, many sectors seem to be not consumed at all. This can be explained by the fact that consumers only appreciate the quality of products in two- or three dimensions. Not all sectors are consumed by consumers, this violates the observed behaviour. However, the heterogeneity of sectors was very poorly represented in the proof of concept. The behaviour of the final demand for the sectors that are consumed, around 15-19 different sectors, does show similarity with the historic data. Explicitly modelling the consumers allows for properly accounting for the uncertainties in the model. Both the base weight and the environmental impact weight were tested.

5. Conclusions

This paper demonstrates that with a crude, stylised, model the behaviour of the historic final demand vector of some sectors can be mimicked. The proof of concept lacks in the representation of quality; increasing the quality term by adding more dimensions will create a more difficult trade-off for consumers' budget allocation problem. This will result in a more realistic modelled final demand vector.

This paper shows that formulating final demand vectors as scenario input is not the only way to represent consumer demand in input-output analysis. This paper showed that instead of ignoring all the works published in the field of behavioural economics, these works can be incorporated into the model. Having individual consumers explicitly modelled allows for policy design that is not only focussed on technological advancement but also on individuals' behaviour. However, the model is merely a proof of concept as was shown to be unable to fully mimic the observed behaviour. Another note to be made is that the validation of the proof of concept did not exceed observing patterns in the data. A more rigorous validation should be conducted before using the model for actual policy design

While the assumptions of input-output analysis clash with reality, these assumptions are still usable. Rather than making a radical change to the framework, a consolidated approach seems more reasonable. The dynamic demand model shows to be able to mimic the final demand of a number of sectors, other sectors are ignored by the consumers. A consolidation could be to have a baseline final demand; a final demand vector that is constant per consumer throughout the model run. This baseline demand vector is supplemented based on consumer agents' choices. Looking back at figure 1, this is what can be observed; a number of sectors' final demand seems to be small and constant while some other sectors show varying behaviour. This seems to be the most promising approach until the quality vector is better understood.

6. Further research

The most prudent topic for future research is to decompose the quality vector further. It was hypothesised that this will present the consumers with a more difficult trade-off in their budget allocation process. However, this statement should be further researched. Another point that deserves more research is the base weight of the difference weight function. In this paper, a value of 0.5 was used because it is not 1 and not 0. However, building understanding in the implications of the base weight will help to refine the model further. Lastly, as a consolidated option was labelled as the most promising near-future approach, this base-line final demand should be quantified. An option would be to look at the change in observed final demand of years when the available budget of consumers is known to have decreased. That way, the consumption patterns that supply the most prudent needs of consumers can be observed. In this way, a base-line final demand vector can be estimated. Using this base-line final demand; a new calibration experiment should be conducted to fit new quality parameters.

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