Financing Green Innovation

Public Finance and Eco-innovation Diffusion: An Evolutionary Modelling Approach

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Public Finance and Eco-innovation Diffusion: An Evolutionary Modelling Approach

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Preface

Ithaka

As you set out for Ithaka
hope your road is a long one,
full of adventure, full of discovery.
. . .
and may you visit many Egyptian cities
to learn and go on learning from their scholars.
. . .
Ithaka gave you the marvelous journey.
Without her you wouldn't have set out.
. . .
Wise as you will have become, so full of experience,
you'll have understood by then what these Ithakas mean.

C.P Cavafy

This thesis concludes my two-year journey as a student at TU Delft's Engineering and Policy Analysis master's program. I choose to start this preface with a few lines of one of my favorite poems, Cavafy's Ithaka, to highlight that both the two years as an EPA student and my thesis project have been beautiful and educational journeys, demanding at times but nevertheless rewarding both at a personal and academic level. As with most journeys, it is the fellow travellers who make the experience meaningful, and who provide support to overcome barriers. I would like to thank the following people, who supported me greatly throughout the thesis project and the past two years.

First, I would like to thank my thesis supervisors, Martijn Warnier and Servaas Storm, for your understanding, for providing guidance, and for the insightful comments. I would like to thank you for supporting me and providing clarity and direction at crucial moments of this thesis. Additionally, I would like to thank all the professors at TPM and EPA for sharing their knowledge and expertise, and opening up new avenues of thinking.

I would like to thank Anja for supporting me throughout this journey both personally and academically, and making the past demanding months a beautiful experience. I would also like to thank all my EPA friends who are one of the main reasons for those two great years and I hope that we made some friendships that will last through time. Finally, I would like to thank my family for always supporting and believing in me.

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Executive Summary

The window of opportunity for achieving the Paris COP21 goal of limiting mean global temperature increase to well below 2 °C compared to the pre-industrial mean is closing (UNEP, 2019). In order to achieve this goal, it is urgent to decarbonize societies in historically unprecedented levels (IEA, 2020).

Decarbonization, as many sociotechnical transitions, can benefit from directed innovation diffusion, in this case directed eco-innovation diffusion (Geels, Sovacool, Schwanen, & Sorrell, 2017). An important determinant of innovation diffusion is the availability of finance (Pacheco, Caten, Jung, Navas, & Cruz-Machado, 2018) which in the case of eco-innovation is inadequate (Monasterolo, Roventini, & Foxon, 2019). This finance gap has been attributed to the reluctance of private sector to direct funds towards sustainable technologies (Monasterolo et al., 2019; Mazzucato & Tancioni, 2012) and has resulted in many scholars suggesting more active involvement of public entities in financing innovation (Lamperti, Mazzucato, Roventini, & Semieniuk, 2017; Mazzucato & Semieniuk, 2017; Mazzucato et al., 2015).

Innovation diffusion is characterized by path-dependency (Stirling, 2010; David, 1985), strong feedback loops (Arthur, 1989), non-linearities, and actor heterogeneity (Mazzucato & Semieniuk, 2018). To gain insights into the dynamics of systems with those characteristics and into the effectiveness of policy instruments, many scholars (Rennings, 2000; Nelson & Winter, 1982; Van Dam, Nikolic, & Lukszo, 2013; Farmer & Foley, 2009; Dosi, 1982) support that the evolutionary bottom-up paradigm is a suitable modelling approach.

Inspired by these streams of literature, this study contributes to the understanding of the impact of public finance on fostering the diffusion of eco-innovation. The main research question this study aims at answering is:

> **Main Research Question**
>
> "What can we learn from an evolutionary modelling approach about the effectiveness of public finance in supporting eco-innovation diffusion in SMEs?"

The literature review of evolutionary approaches studying the interaction of eco-innovation diffusion and finance revealed that no studies compare the effectiveness of different public finance tools in supporting eco-innovation diffusion. The focus of this study is on the effectiveness of loan guarantees and public procurement policies in supporting eco-innovation diffusion in markets consisting of small and medium sized firms.

In order to answer this research question, the model developed by D'Orazio and Valente (2019), the most relative encountered in the evolutionary economics literature, is conceptually extended and implemented in the Python programming language. The central agents in the model are: (1) firms producing products that are defined by three qualities: environmental performance, user quality, and cost-efficiency, (2) consumers purchasing this products based on their preferences, (3) a commercial bank providing loans to firms, and (4) a state investment bank providing loan guarantees.

Subsequently, the effectiveness of different public finance policies in fostering eco-innovation is simulated for a range of scenarios. The effectiveness is measured in terms of the market share weighted average value (MSWA) of the products' environmental performance. Other metrics of the policies performance include the final GDP of the market, the total cost of the implemented policies, the final MSWA of user quality, and the final MSWA of cost-efficiency . The policies include three different levels of public procurement (10%, 15%, and 20%) three different levels of loan guarantees (40%, 60%, and 80%), and three combined policies consisting of both loan guarantee and public procurement.

Table 1 summarizes the results for three of the best policies. The results for these policies suggest some important trade-offs for policy makers. Initially in terms of environmental performance, the best performing policies are the combined policies but at the cost of the least improvement in the other two product aspects , user quality and cost-efficiency, and important market disruption. The loan guarantee policies have satisfactory performance in all aspects except for final market GDP. Finally, the public procurement policies are the best performing policies in terms of GDP, but are the most market disruptive, the least effective in increasing the MSWA value of environmental performance ,and have a high implementation cost.

The market disruption aspect refers to the number of initial firms exiting the market due to poor financial health, a high market disruption could potentially deter the policymaker from applying the policy.

Table 1: Performance of selected policies, average over 100 simulations.

Metric	Loan 80%	PP 20 %	PP20 % Loan 80%
Env. Per. 2045	16.23	16.29	18.15
Env. Per. 2070	21.27	20.51	24.13
Qual. 2070	16.99	16.59	15.81
Effic. 2070	16.98	16.41	15.78
GDP 2070	7.02	8.92	8.24
Avg. Total F.	105.3	68.3	70.46
Old F. 2045	83.6	45.9	49.2
Costs PP	0	466	441
Cost LG	0.27	0	0.65

Therefore, it is evident that none of the public finance instruments can be applied without trade-offs. However, this study finds that all the studied instruments have a positive effect on eco-innovation diffusion. Thus, to foster the decarbonization of our economies there is a need to direct more public in support of eco-innovation diffusion by firms.

This study could be expanded in a multitude of ways. In the author's opinion some promising could be: (1) explore more in-depth the impact of market characteristics on the effectiveness of these policy tools, (2) further elaborate the model by making firms more responsive to their environment, and (3) explore the impact of demand shocks on the progress of eco-innovation diffusion and the effectiveness of the policies.

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Part I

Introduction

Chapter 1

Introduction

Climate change constitutes one of the greatest threats to modern societies and has the potential of creating natural, societal, and economic disruptions of great scale. Steffen et al. (2018) warn that a temperature increase of 2°C compared to the preindustrial mean can result in the planetary system engaging in an irreversible downward spiral towards hotter temperatures. Pre-coronavirus estimates based on each country's nationally determined contribution (NDC) placed the planetary system in a trajectory of limiting, with 66 % probability, the temperature increase by the end of the century to 3.2 °C (UNEP, 2019); it is clear that the current trajectory is far from the desired one. Therefore, mitigation, the attempt to minimize future climate change, and adaptation, the effort to minimize the impact of unavoidable climate change are of great importance.

An important climate change driver is the concentration of carbon and other greenhouse gases in the atmosphere. Decarbonization, the reduction of societies' dependence on CO2 producing activities, can be a useful tool for climate change mitigation. Decarbonization though, is a demanding challenge, as CO_2 is deeply embedded in the functioning of modern societies as the output of many industrial, transport, and domestic activities. Additionally, a multitude of different actors with vested and competing interests are involved in CO_2 producing activities further complicating the process of decarbonization. Finally, the scale of decarbonization needed further adds to the challenge, as in order to achieve the Paris COP21 agreement goal of limiting global warming to 1.5 °C, a yearly reduction of 7.6 % in the carbon emissions is needed (UNEP, 2019), which is equivalent to the reduction IEA (IEA, 2020) anticipates will happen due to the coronavirus-lockdown and recession.

Geels (2002) refers to sociotechnical configurations as combinations of regulations, infrastructures, user practices, maintenance networks and other elements aligned with a current technology and defines sociotechnical transition as the change from one sociotechnical configuration to another. The production of $CO2$ is embedded in many such sociotechnical configurations and reducing societies' dependence on $CO2$ activities is not only a matter of improving technology but switching from one sociotechnical configuration to another; or in other words achieving a sociotechnical transition. Sociotechnical transitions are complex and multifaceted challenges. According to Geels et al. (2017), for sociotechnical transitions to emerge, broad societal acceptance, a gradual decline of dominant industries, and niche innovations are needed. In their opinion, directed innovation can have a catalytic role in these processes, as the resulting synergy of multiple innovations, fostered by directed innovation, can lead to the emergence of new markets that can forge public, business, and political support, and finally disrupt existing industries. In the case of decarbonisation, directed green innovation, can lead the way in the sociotechnical transition towards carbon neutral, more sustainable societies.

In the case of green innovation though there is neither the direction nor the necessary scale needed to achieve the timely decarbonization of societies. As a result, many scholars (Lamperti et al., 2017; Mazzucato et al., 2015; Mazzucato & Semieniuk, 2017; Edler & Georghiou, 2007; Georghiou, Edler, Uyarra, & Yeow, 2014) envision an important role for public finance in providing clear market signals and laying the ground for large scale investments in sustainable technologies and thus direct innovative activities towards green innovations. Supporting green innovation is one of the goals of the European Green Deal (EGD), European Commission's ambitious plan of eliminating greenhouse emissions in the European Union by 2050. The European Commission, through the EGD, aspires to mobilize more than one trillion euros over the next decade towards sustainable ventures: 600 billion of own funds, 115 billion from national contributions, and 300 billion through private-sector crowding in (European Commission, 2020a). However, there is limited understanding of the effectiveness of public finance on the diffusion of green innovation.

1.1 Research Objective

The objective of this study is to provide insights into the impact of public finance on the diffusion of eco-innovation by private firms. To this end, this study uses an evolutionary modelling approach and simulates the effects of different public finance policies under different scenarios.

1.2 Research Scope

A number of decisions define the scope of this study; the most important ones are: (1) this study focuses on small and medium sized enterprises (SMEs), (2) this study focuses on firms that innovate through R&D, (3) this study focuses on bank-based systems, (4) focus on science based innovators. The scoping decisions are elaborated on in the next chapter.

1.3 Structure of the Study

The study is structured in four parts. The first part is introduction and consists of chapters 1 to 3. This section concludes chapter 1, introduction, where the general problem is introduced. In chapter 2 the relative literature on eco-innovation, climate finance, and modelling of eco-innovation diffusion is reviewed and based on the identified knowledge gaps the main research question is formulated. In chapter 3 the sub-research questions needed to answer the main research question are identified, and the research approach for answering the sub-research question and the main research question is outlined.

In the second part of this study the methods and tools used to answer the sub-research questions and the main question are presented. In chapter 4, model conceptualization, the agent-based model (ABM) used in this study is introduced. In chapter 5, model implementation, the process of creating a software representation of the agent-based model is described. Finally, in chapter 6, the research problem is structured according to the XLRM framework.

In the third part of this study the results of the simulation outcomes are presented. In chapter 7 the general behavior of the model is validated. In chapter 8 a higher level presentation of the simulation outcomes takes place. Finally, in chapter 9 a more in-depth analysis of the results is performed.

This study concludes with the discussion part. In chapter 10 the limitations of this study are explored and policy implications are inferred. In chapter 11, the sub-research questions and the main research questions are revisited, the scientific and societal contributions are discusses and finally further research avenues are explored.

Chapter 2

Literature Review

In this chapter a number of literature strands related to eco-innovations are reviewed and synthesized in order to identify the knowledge gaps that this study is based on. In section 2.1 eco-innovations are defined. In section 2.2 concepts from innovation economics relative for this study are discussed. In section 2.3 eco-innovation diffusion and the eco-innovation policies are discussed. In section 2.4 the topic of climate finance is introduced and the literature focused on the interaction of finance and innovation is reviewed. Next, in section 2.5 the evolutionary modelling paradigm is introduced, and evolutionary modelling attempts combining eco-innovation diffusion and finance are reviewed. Finally, in section 2.6 the knowledge gap that serves as the basis of this study is identified.

2.1 Eco-innovation

Rennings (2000), introduced the term eco-innovation to describe innovations that: "contribute to the reduction of environmental burdens or to ecologically specified sustainability targets". Kemp and Pearson (2007), based on the OECD (2005) innovation definition, extended Rennings definition, providing an all encompassing definition for eco-innovation:

Definition 1 - Eco-innovation

Eco-innovation is the production, assimilation, or exploitation of a product, production process, service or management or business method that is novel to the organization (developing or adopting it) and which results, throughout its life cycle, in a reduction of environmental risk, pollution and other negative impacts of resources use (including energy use) compared to relevant alternatives.

This definition conceptually, focused on the product aspect, fits the use of the term in this study.

The eco-innovation discipline was built on the foundation of three economic subdisciplines: environmental, ecological, and innovation economics. Environmental and ecological economics are both disciplines that focus on the interaction between economies ,economic policies, and the environment and their main difference lies in their underlying theoretical background: environmental economics is based on the neoclassical economics paradigm while ecological economics have a more pluralistic theoretical background (Tietenberg & Lewis, 2018). Innovation economics, a discipline built on the foundations laid by Schumpeter (Schumpeter, 1911, 1939, 1943), studies the impact of innovation and entrepreneurial activities in determining economic growth and technological progress.

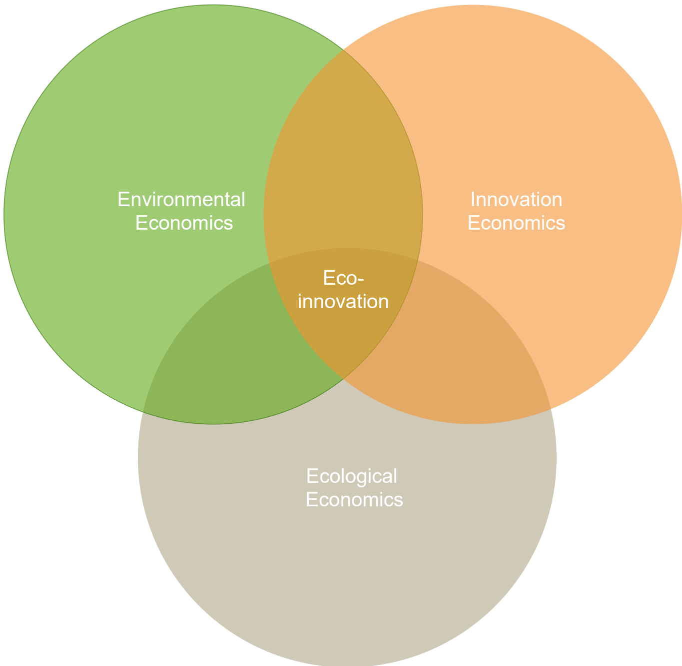


Figure 2.1: Theoretical foundations of eco-innovation, eco-innovation is a discipline built on the foundations of environmental, ecological, and innovation economics (Tietenberg & Lewis, 2018).

2.2 Topics on Innovation Economics

In this section a number of innovation economics topics relative for this study is discussed.

2.2.1 Innovation and Firm Size

An important dichotomy in the study of innovation economics exists regarding the size of the firms undertaking innovative activities. In literature firms of smaller and medium size are labeled as Small and Medium Size Enterprises (SMEs). [1] This is an important distinction in the study of innovation dynamics as firms of different size exhibit different behaviors (Klepper, 1997). An important difference between firms of different size is reflected in their R&D financing behavior. SMEs depend to great extend in external financing when pursuing R&D projects, and especially on banks (Popov & Udell, 2012). On the contrary, large firms, have other means of finance at their disposal: retained earnings, debt, or large institutional investors.

[1] In Europe this category includes firms with less than 250 employees and a turnover of less than 50 million euros (European Commission, 2020b)

Since this study is focused on the impact of public funding on the diffusion of eco-innovation, the focus will be on SMEs, which are more dependent in this source of financing.

Scoping Decision 1

This study will focus on Small and Medium Size Enterprises (SMEs)

2.2.2 Different Types of Innovation

Schumpeter (1911) identified two different types of innovations: process innovations and product innovations. Product innovations focus on increasing the quality and variety of goods and support firm's growth through higher output or prices. Process innovations on the other hand focus on improving the efficiency of production and reducing prices, supporting firms by making them more competitive. Based on this distinction Pianta and Vaona (2007) call firms focusing on process innovation as price competitive and firms that focus on product innovation as technological competitive. Eco-innovations, according to the definition provided in the previous subsection can be both product and process innovation.

Another important aspect in the study of innovation economics, is the division of innovative firms in different categories. A widely used taxonomy (Archibugi, 2001) is the one suggested by Pavitt (1984) according to which innovative firms are divided into four groups: (1) science based: firms that innovate through R&D and advances in science, (2) specialized supplier: producers of machinery and equipment that innovate through R&D and the knowledge embedded in the labor force, (3) scale intensive: firms for which economies of scale are relevant and innovate through process innovation and introduction of new products, and (4) supplier dominated: firms that do not focus in producing innovation and "import" it from their suppliers.[2] This study will focus on science based and specialized supplier innovative firms which are the ones most dependent on R&D. Regarding science based innovation, according to Auerswald and Branscomb (2003), the different innovation stages are: 1) research, 2) concept/invention, 3) early stage technology development (ESTD), 4) product development, and 5) production/marketing. It is common to refer to the first steps as upstream innovation while to the later steps as downstream innovation.

Scoping Decision 2

This study will focus on science based and specialized suppliers innovators.

2.2.3 Technological Change

Schumpeter (1943) conceptualized the process of technological change in three stages: (1) invention, the initial technical implementation of an idea, (2) innovation, the commercialization of this idea implementation through a product or a method,

[2]The taxonomy proposed by Pavitt has been criticized for neglecting the heterogeneity in the service sectors (Gallouj, 2002); (Bogliacino & Pianta, 2010) have extended this taxonomy and proposed the Revised Pavitt Classes by broadening the existing classes.

and (3) diffusion, the spread of this idea in other actors. Many scholars consider technological change a cumulative and path dependent process (Dosi, 1982; Nelson & Winter, 1982). For example, Pavitt (1984) argues that the knowledge used in innovative efforts is context specific and cannot be easily applied outside its original field; as a result, technical change tends to follow technological trajectories which depend to an important extend to what has been done in the past. This view of technological change according to (Rennings, 2000) can be useful in giving insights in the development of eco-innovations and is the one that will be adopted for this study.

2.3 Topics on Eco-innovation

In this section two important topics for this study are discussed: eco-innovation diffusion and eco-innovation policies.

2.3.1 Eco-innovation Diffusion

Innovation diffusion is a sub-discipline of innovation economics which aims at answering the questions of why, when and how innovations spread. The comprehensive study of innovation diffusion started in late 1950s. Rogers (1962), one of the founders of the field, defined diffusion of innovation as:

Definition 2 - Innovation Diffusion

The process by which an innovation is communicated through certain channels over time among the members of a social system.

Since late 1960s the literature on the diffusion of innovations has greatly expanded and many strands of literature have emerged. This study will focus on the diffusion of eco-innovations. Related to the determinants of eco-innovation diffusion in SMEs, Pacheco et al. (2018) in an extended meta-analysis of the literature found that the main ones are:

1. Resource constraints related to people, time and money.
2. Actions that promote the cooperation of SMEs with external stakeholders (other SMEs, universities, research institutes, government).
3. Cost reduction and risk management (avoidance of negative environmental impacts and compliance).
4. Strategic importance of eco-innovation to the sectors and the customers.

The importance of financial constraints as determinant of eco-innovation in SMEs has been further highlighted by Ghisetti et al. (2017) in an analysis of interviews covering 5222 managers of SMEs executed at 2011 in 27 EU member states which concluded that financial barriers hinder to a significant extent the eco-innovative capacity of european SMEs manufacturing.

2.3.2 Policies and Eco-innovation

Innovation policies are broadly divided into two categories: demand-pull and technology-push. Each policy category aims at solving one of the two externalities commonly associated with eco-innovations: environmental externalities and knowledge market failures (Popp, 2019).

The knowledge market failure of eco-innovation is a positive externality that refers to the knowledge spillovers during eco-innovations diffusion. This is a theory introduced to the eco-innovation discipline by the innovation economics and supports that once innovations diffuse, the knowledge embedded in it becomes partially or wholly public, and thus loses some of its value for the innovator. Technology-push policies aim at solving this positive externality by giving incentives for research.

A technology-push policy examined in this study is a credit guarantee scheme for loans directed towards sustainable investments. Credit guarantee schemes or simply loan guarantees provide guarantees on loans to borrowers by covering a share of the default risk of the loan. Credit guarantee schemes are commonly used to mitigate the constraints small and medium sized enterprises face in accessing financing (EBCI, 2014).[3]

The environmental externality refers to the lack of pricing mechanisms for the adverse environmental impacts some technologies have; this lack of pricing mechanism results in eco-innovation not being rewarded for their better environmental performance and thus less incentives exist for the development of more environmental friendly technologies. Demand-pull policies aim at solving the problem of negative environmental externalities by increasing the market for eco-innovations through emission taxes, fines, and public procurement amongst other tools. Demand-pull policies have been introduced to the eco-innovation by the environmental economics subdiscipline (Rennings, 2000).

One demand-pull policy that is going to be examined in this study is public procurement. Public procurement refers to the direct purchase of goods and services by public entities. Public procurement is policy that has been neglected before crisis by academics and policy makers, who were mostly focused on supply-side fixes or technology-push policies, assuming that innovative technologies will be absorbed by the market (Edler & Georghiou, 2007). The interest in public procurement policies in Europe has been renewed after the 2008 crisis which led in drops in aggregate demand and employment (Mazzucato et al., 2015; Georghiou et al., 2014). Crespi and Guarascio (2019) by analyzing data of 24 OECD countries for the years 1995-2012 found that public procurement was a strong innovation driver.

2.4 Climate Finance

Studies on climate finance synthesize insights from finance, economics, organizational strategy, and natural sciences with the aim of addressing the social and

[3]Overall the difficulty of SMEs accessing finance is empirically validated and well-documented; economic theory attempts to explain the financing gap SMEs experience through the credit rationing theory (Stiglitz & Weiss, 1981), a more detailed discussion of credit rationing follows in the next subsection on climate finance.

environmental risks associated with climate change (Linnenluecke, Smith, & McKnight, 2016). The climate finance literature includes topics related to: regulation, climate risks and assets impairment, adaptation to change, increased volatility management, and green assets evaluation amongst others. The strands of climate finance literature that are of interest for this study are the ones studying the interaction of finance and eco-innovation with a focus on SMEs.

2.4.1 Climate Finance and Innovation

Financial actors are broadly categorized into private and public and both play an important role in financing innovation. Public actors usually include governments, development financial institutions, and investment banks, while private actors include private equity, venture capital, commercial financial institutions, and household's investments among others.

Public actors play a crucial role in financing innovation throughout all of its stages (Mazzucato, 2013). As the examples of biotech, nanotech, and now greentech highlight, public financial actors tend to engage more than other financial actors in the riskier early development stages of new technologies (Mazzucato & Wray, 2015; Mazzucato & Semieniuk, 2018). Additionally, examples of the importance and potential of public finance in supporting innovation across all of its stages are the mission-oriented policies: systemic public policies that try to direct the frontiers of innovation towards a specific goal (Kattel & Mazzucato, 2018); those mission oriented policies are accompanied by extended public financing of innovative technologies directed towards this goal. Examples of impactful and successful mission oriented policies, include the efforts to bring a man to the moon, and a variety of military technologies (Mowery, 2010).

Private actors also play an instrumental role in financing innovation and the literature on their role and their importance is extended. This study though will focus on the inefficiencies of private capital in financing innovations in order to identify how public capital can act complementary to private capital in supporting eco-innovation diffusion. For instance Pisano (2006), giving biotechnology as an example argues that the venture capital financing model, the main way private capital supports innovation in early stages, is not suitable for science-based sectors characterized by complex and interdisciplinary knowledge. Additionally, Mazzucato and Tancioni (2012) provide evidence that in the case of green-innovation private financial actors have been reluctant to invest. This reluctance has been attributed to a multitude of reasons. At first, policy uncertainty related to climate change makes it difficult for private actors to anticipate the risk associated with sustainable technologies (Monasterolo et al., 2019). Furthermore, as Haldane (2011) points out, especially after the great financial crisis, private sector has been increasingly influenced by short-termism and combined with the inadequacy of markets in giving long-term signals, long-term sustainable investments are avoided. Finally, as evidence shows (Barbieri, Marzucchi, & Rizzo, 2020), eco-innovations are riskier and more uncertain, which could be another reason for the underfunding of sustainable technologies.

Apart from the aforementioned reluctance of private actors to invest in green technologies, there are more fundamental reasons that make private actors not suitable for financing innovative riskier technologies. In the case of commercial banks, Stiglitz and Weiss (1981) have proved that imperfect information in market can result in credit being rationed.[4] This credit rationing is an outcome of commercial banks' inability to assess the riskiness of different projects due asymmetry in information and results in supply constraints in the market. Information asymmetries tend to be more prevalent in SMEs as they are not publicly listed and their larger number makes their monitoring by commercial banks more difficult; thus, credit rationing is a bigger problem for SMEs than large firms (Wehinger, 2014). As discussed in previous section, one of the main determinants of eco-innovation in SMEs is the access to finance, as a result, this credit rationing can have detrimental effects in the diffusion of eco-innovation in SMEs. Finally, another fundamental problem related to private capital is that in the past decades it has diverted away from investments in real economy and innovative activities and has focused in value extraction through financial innovation and speculations (G. Epstein, 2018; Palley, 2007).

All these reasons contribute in the inadequacy of private capital in providing alone the necessary funds to eco-innovation, especially in the riskier early stages of their development. Thus, private capital without clear signals by governments and support in funding riskier ventures is not capable of leading the transition towards more sustainable investments. In this spirit, Mazzucato (2013) is calling for "enough patient, long-term, committed finance" by public entities in order to enhance the pace of green innovation by giving the opportunities to riskier ventures. For these reasons, Lamperti et al. (2017) see a clear role for directed and timely public investments, in providing clear market signal and laying the ground for large scale investments in sustainable technologies and green innovation. Thus, this study will focus on the impact of public financing in fostering eco-innovation diffusion.

Scoping Decision 3

This study will focus on the impact of public financing.

Public financing though does not have the same importance in all financial systems. Financial system are path dependent, and different historical contingencies resulted in significantly different financial systems (Fohlin, 2014). The last decades, due to globalization the different financial systems converged to some extent but still significant differences remain. Financial systems can vary in a multitude of ways, for this study though, the common division of financial systems in market-based and bank-based would suffice. Bank-based systems are the ones where the majority of corporate finance is allocated through banks, while in market-based ones securities market has that role. This study, inspired by the european green deal and focused on the impact of public-financing in the diffusion of eco-innovation, is more relevant to a bank-based financial system, like the european one (Langfield & Pagano, 2016).

[4]Credit rationing occurs when in a group of loan applicants with identical characteristics some receive and some don't receive loans and the applicants rejected would not be able to receive a loan even if they bid up the interest rate or provide more collateral.

Scoping Decision 4

This study will focus on bank-based financial system.

2.5 Modelling and Innovation Diffusion

2.5.1 ABM Modelling and Innovation Diffusion

The last decades, evolutionary economic approaches are gaining attention and a growing community of researchers support that this paradigm can give novel insights into the functioning of the economy. The major methodological difference of evolutionary approaches compared to mainstream approaches is the bottom up approach: agent behaviour is not imposed exogenously through aggregate equations; instead, every agent behaviour is described and an aggregate behavior emerges (Dosi, 1991; M. J. Epstein, 1999). This bottom up approach is valuable and allows to capture important dynamics of systems characterized by strong feedback loops, non-linear behavior, and path-dependency (Nelson & Winter, 1982; Van Dam et al., 2013; Farmer & Foley, 2009).

Rennings (2000) argues that the evolutionary economics paradigm can be useful for the eco-innovation discipline by introducing concepts like irreversibility, path-dependency, feedback loops, and technological trajectories. The phenomenons described by the aforementioned concepts have been empirically encountered in the innovation systems. As mentioned in the subsection discussing technical change many scholars consider technological change a cumulative and path dependent process (Dosi, 1982; Nelson & Winter, 1982; Pavitt, 1984). Additionally, the existence of feedback loops between downstream and upstream innovation that can result in technology lock-ins is highlighted by Arthur (1989)[5]. David (1985) studied the existence of path-dependency in the trajectory of innovation and Stirling (2010) calls for more attention by policy makers in recognizing the multitude of pathways and directions innovation can take. Thus, it is argued that the evolutionary economics paradigm has the potential of providing insights into the dynamics of eco-innovation as many of the evolutionary concepts have been empirically encountered in the behavior of innovative systems.

As the eco-innovation discipline is a relatively new field and the evolutionary modelling approaches are gaining traction only recently, the literature review revealed that only a few models following the evolutionary economics paradigm study the interaction between innovation, finance and growth. Vitali, Tedeschi, and Gallegati (2013) developed an agent-based model which studies the interaction between a commercial banking sector and three classes of innovators: single innovators, collaborative innovators, and imitators; by allowing firms to choose in which class of innovators they will belong they study the impact that different types of innovators have in micro, meso and macro aggregates. Their results suggest that collaborative innovators have the greatest impact on growth and that the inclusion of banking system introduces a trade-off between short term profitability and long-term effi-

[5]Downstream innovation refers to the later stages of innovation like product development and production/marketing while upstream to the initial stages of innovation like research and invention.

ciency. Caiani, Godin, and Lucarelli (2014) developed an agent based model that studies the structural change triggered by innovation and its interaction with finance. Their model consists of two household sectors, a banking sector, and two industrial sectors, one for consumption and one for capital goods. Their results suggest that the interaction of finance and innovation shape to great extend the long-term business cycle. Fagiolo and Roventini (2017) developed an ABM model with firms that produce homogenous goods, perform R&D research, and imitate the most productive practices. Both imitation and exploration activities are dependent on bank financing. Their results suggests that banks are conductive to growth up to a point, after that, excessive financing could hamper growth. Finally, D'Orazio and Valente (2019), developed an agent based model consisting of heterogenous consumers, heterogenous firms, and a financial sector composed of a standard commercial bank and a public investment bank. Their results suggest that the market diffusion of eco-innovation is enhanced when public investment banks support for eco-innovation is combined with strong consumer preferences. Table 2.1 presents a review of the different models.

Table 2.1: Modelling Attempts

	Vitali et al.	**Caiani et al.**	**Fagiolo and Roventini**	**D'Orazio and Valente**
Demand Preferences Role	No	No	No	Yes
Public Financial Entity	No	No	No	Yes
Stock Market	No	Yes	No	No
Heterogenous Products	No	No	No	Yes
Imitation Module	Yes	No	Yes	Yes
Consumption and Capital Sectors	No	Yes	No	No
Different Innovator Classes	Yes	No	No	No
Labor Market	Implicit	Yes	No	No

The model chosen as the basis of this study is the one developed by D'Orazio and Valente. A number of reasons contributed to this decision. Initially the model by Vitali et al., is narrowly focused on the impact of different classes of innovators and underrepresents the other aspects of the finance, diffusion, and growth nexus. The model developed by Caiani et al., is comprehensive and interesting, but focuses more on the macroeconomic impacts of the innovation diffusion, and is a rather complex and extended model, which does go beyond the scope of a MSc thesis. The model developed by Fagiolo and Roventini, is conceptually an interesting model, but is also heavily focused on macroeconomic growth. Finally, the model developed by D'Orazio and Valente, has many interesting features ,unique in the literature, that make it a good candidate for studying the impacts of public funding on the diffusion of green innovation. This model has been developed with that purpose in mind, as it already accounts for the impact on eco-innovation of state investment banks. Additionally, by including heterogenous products and consumer preferences, it is the only model that can capture the effect of the consumer side on innovation diffusion. This is an important aspect, as the sustainability transition, is a multifaceted effort that tries to promote sustainable technologies through a variety of channels.

2.6 Knowledge Gap

Popp (2019) in an extensive review of the literature on environmental policy and innovation identifies knowledge gaps regarding the role of different policy instruments in supporting the innovation diffusion. The literature review of the available evolutionary models studying the interaction between innovation and finance also revealed that none of the studies explored the relationship between different financial tools and innovation diffusion and that all the studies focused only on loans given either by commercial or state investment banks. This study aims at contributing in this topic by exploring the impact of two different public financing tools, loan guarantees and public procurement.

The overarching question summarizing these knowledge gaps is:

> **Main Research Question**
>
> "What can we learn from an evolutionary modelling approach about the effectiveness of public finance in supporting eco-innovation diffusion in SMEs?"

Chapter 3

Research Methodology

This chapter introduces the research methodology used to answer the main research question of this study:

> **Main Research Question**
>
> "What can we learn from an evolutionary modelling approach about the effectiveness of public finance in supporting eco-innovation diffusion in SMEs?"

In section 3.1 innovation systems are examined though the lens of complex adaptive systems and the concepts of adaptivity, complexity, and path-dependency are discussed. Section 3.2 describes the necessary steps needed to carry out a modelling study of a complex adaptive system. Finally, in section 3.3 the necessary sub-research questions for answering the main research question are identified.

3.1 Innovation Systems as Complex Adaptive Systems

Kline and Rosenberg (1986) define innovations systems as the set of actors who directly or indirectly contribute to the production of scientific and technical knowledge. Innovation systems are embedded in sociotechnical systems composed of interwoven networks of technical artifacts and social entities. Van Dam et al. (2013) view those interwoven networks of technical artifacts and social entities as complex adaptive systems and provide a framework for developing an agent-based model of those. The research methodology applied for this study is based to an important extent to their proposed framework. In the following subsections, some important concepts related to complex adaptive systems are presented: adaptivity, path-dependency, and complexity.

3.1.1 Adaptivity

An important concept related to complex adaptive systems is adaptivity. Adaptivity refers to the ability of a system to become better suited to its environment over time. Adaptivity is not to be confused with evolution, which is the mechanism through which adaptivity takes place. In order for evolution to occur three conditions are necessary: the existence of variation in the system, a replication mechanism or some form of inheritance, and finally some determinant of which variations are better. (Darwin, 1859) The final condition is also called selection pressure, describing the force in the environment that determines the suitability of a particular variation over the others for that environment defining in the same time the direction of adaptation. The innovation system also presents adaptive behaviors to its environment; for example policies (Costantini, Crespi, & Palma, 2017; Stucki, Woerter, Arvanitis, Peneder, & Rammer, 2018) or financial incentives (Mazzucato & Semieniuk, 2018) amongst other factors can influence the evolution of innovation systems.

3.1.2 Path-dependency

Another important characteristic of complex adaptive systems, closely related to adaptivity, is path dependency. Many of the steps in complex adaptive systems are irreversible, the entities cannot return to their former state or there are high costs in returning to those states. Additionally, at every step, both the environment and the system change and co-evolve based on their characteristics in the previous step. Thus, history matters, and the combination of irreversibility and an evolving landscape can lead to diverging unique pathways. In the case of innovation, technical change, the outcome of innovation is perceived by many scholars as a path-dependent and cumulative process (Dosi, 1982; Nelson & Winter, 1982). For example, Pavitt (1984) supports that most of the knowledge directed towards innovative activities is not general purpose and its usefulness if repurposed and concludes that technological trajectories will heavily depend by their past. An example of strong path dependency is given by the QWERTY keyboards, which despite not being the most efficient keyboard configuration came to dominate the market through a combination of historical contingencies (David, 1985).

3.1.3 Complexity

The next important aspect related to complex adaptive systems, is complexity. Complexity is a concept difficult to define that is often defined as the opposite of simplicity. Mikulecky (2001) approximates a definition through the following statement:

> Complexity is the property of a real world system that is manifested in the inability of any one formalism being adequate to capture all its properties. It requires that we find distinctly different ways of interacting with systems. Distinctly in the sense that when we make successful models, the formal systems needed to describe each distinct aspect are not derivable from each other.

Complexity in the case of innovation systems is manifested through the multitude of disciplines that study the it, ranging from theoretical ones like legal and cultural studies to more technical ones like computational economics and network theories.

3.2 Modelling Complex Adaptive Systems

Van Dam et al. suggest that every model of a complex adaptive system, in order to be useful for gaining insights into to the functioning of the real system and informing decision-making, should contain three characteristics: (1) multi-domain knowledge, (2) generative bottom up capacity, and (3) adaptivity. Multi-domain knowledge allows for the model to integrate multiple formalisms that will increase the validity of the model. Van Dam et al. define formalisms as " formal systems of capturing statements, consequences and rules, that are not derivable from each other, such as mathematics and psychology...". The integration of multiple formalisms increases the model's validity -representation of reality- as it incorporates more aspects of the real system. [1] The generative bottom up capacity refers to the capability of a model to describe macroscopic phenomena through networks of simple interacting agents with well defined behavioral rules (M. J. Epstein, 1999). Finally adaptivity refers to the potential of the model to exhibit the evolutionary mechanisms described in section 3.1 and consequently adaptivity. Van Dam et al. argue that the agent-based modelling paradigm, the paradigm used in this study, has all the characteristics needed to facilitate this bottom up perspective.

For developing agent based models of complex adaptive systems Van Dam et al. suggest the following ten steps:

1. Problem formulation and actor identification: in this step the problem to be solved and the actors involved in the problem are identified.
2. System identification and decomposition: in this step the physical and social entities of the system, their behaviors, and their interaction are identified.
3. Concept formalization: in this step the concepts identified in the previous steps are transformed in a computer understandable format (e.g. code).
4. Model formalization: in this step the model narrative is developed, the sequence of events and interactions between the agents is established.
5. Software implementation: in this step the model is implemented in the chosen software environment.
6. Model verification: in this step it is ensured that the model built is the one intended to.
7. Experimentation: in this step the experiments that will provide insights in the research questions are designed and executed.
8. Data analysis: in this step the outputs of the experiments are analyzed.
9. Model validation: this step ensures that the model creates a reliable representation of the aspect of reality that we want to capture.
10. Model use.

[1]Complexity, the inability of any single formalism to fully describe the system, is one of the characteristics of complex adaptive systems; thus, the more formalisms are included in the model conceptualization the closer the model resemblance to reality, the higher the model's validity.

3.3 Sub-research questions

Based on the main research question, the literature review, and the steps proposed by Van Dam et al. for developing agent-based models of complex socio-technical systems, the following sub-research questions are formulated:

1. How can the model developed by D'Orazio and Valente be expanded to account for: (a) diverse initial market conditions, and (b) for public procurement policies?
2. How can the extended model be implemented in Python using the MESA framework?
3. How can the model be validated?
4. Based on the model and using the XLRM framework, what are the effects of different financial tools on the diffusion of eco-innovation?

3.3.1 SQ1 Model Expansion

This study explores the effectiveness of loan guarantee and public procurement policies in promoting eco-innovation diffusion using the evolutionary modelling paradigm. To achieve this goal, the most relative evolutionary economics model identified in the literature (D'Orazio & Valente, 2019) is critically evaluated and expanded to account for different initial market conditions and for public procurement policy

This research question covers the second and third steps suggested by Van Dam et al.: (2) system identification and decomposition, and (3) concept formalization, as the first step -problem formulation and actor identification- has already been covered in the introduction and in the literature review. The concept formalization in this step is covered only partially by presenting the model equations, which is a step towards having a computer understandable model but not the final one. The final step of concept formalization is covered in the next research question.

3.3.2 SQ2 Model Development

This research question covers the third, fourth, fifth, and sixth step of the taxonomy proposed by Van Dam et al. In concept formalization the various concepts are translated into machine readable format. In model formalization the narrative of actions that takes place in the model is explained. In implementation the model is developed in Python using the MESA agent based modelling library. Finally in verification the question whether the model built is the one which the modeler intended to construct is answered. Model verification is carried out by ensuring that the model behaves in the way described in concept and model formalization.

3.3.3 SQ3 Model Validation

This research question covers the 9th step proposed by Van Dam et al., model validation. In this step the behavior of the model is validated by testing whether it replicates empirically encountered market behaviors.

3.3.4 SQ4 XLRM Framework, Experimentation and Data Analysis

This research question covers the rest of the steps proposed by Van Dam et al.. The experiments will be designed based on the adaptation of XLRM framework used by Kwakkel (2017). According to this framework X represents external factors, L policy levers, R Relationships, in this case the model, and M the performance metrics. Finally, based on the model developed in the first three research questions, and the XLRM framework, experiments will be performed for a number of market scenarios and the results will be analyzed.

Part II

Methods

Chapter 4

Conceptualization

In this chapter the model used in this study is discussed. In sections 4.1 to 4.2 the original model developed by D'Orazio and Valente is presented. In section 4.1, the entities, the environment, and their relationships are identified and the model narrative, the story of when and how the agents interact, is developed. In section 4.2, the model equations are presented. Finally, in section 4.3 the problems encountered in the main equations proposed by D'Orazio and Valente are explained and ways to overcome them are suggested.

4.1 System Identification

The model by D'Orazio and Valente focuses on the interaction of consumers' demand preferences, public and private finance, and firms' innovative activities and explores the impact of public financing in the diffusion of eco-innovation. The model is focused on markets populated by Small and Medium Sized Enterprises (SMEs) as they are the ones most dependent on external finance. The model consists of three sectors: household, finance, and production, and is populated by four main entities:

- A State Investment Bank (SIB).
- An aggregate commercial bank.
- Innovative firms.
- Consumers.

All the system components that are not influenced by other system components are included in the environment; these are also called exogenous variables and in this study they include the government and the overall economy. [1] Additionally, the assumption is made that the markets under study are not big enough so that they can influence the total economy; thus, the conditions in the economy within which the market operates are considered exogenous.

[1]The SIB is part of the government as it manages public funds and gets its mandate from the government, but there are other parts in the government not influenced by the SIB and are the parts that are considered exogenous.

4.1.1 Agent Properties

Firms

Firms are the central agents of this model. Firms manufacture products that have three characteristics: environmental quality, user quality, and efficiency. Environmental quality is a measure of product's eco-friendliness and is negatively associated with the environmental impact of the product. Efficiency is a measure of the cost-efficiency or price competitiveness of the product and is a function of the product's price. User quality is a broad measure of the overall user experience related to the product.

An essential aspect related to the conceptualization of the firms populating this model is their research activity. Firms undertake innovative research projects, based on their investment strategy, which upon success improve one of their three product characteristics. Investment strategy refers to the priorities each firm has regarding innovative research. Finally, firms have a number of properties related to their accounts which are introduced in the following section [2].

Firms' Basic Properties

```
– User quality
– Environmental performance
– Cost efficiency
– Investment strategy
– Wealth account properties
```

As mentioned in literature review in section 2.1 innovative activities are divided into product and process innovations (Schumpeter, 1911). In this model conceptualization investments in user quality produce product innovations while investments in efficiency produce process innovations; finally, investments in environmental performance can produce both product and process innovations. Pianta and Vaona (2007) identify firms with a focus on product innovations as having a strategy of technological competitiveness while those focused on process innovations as having a strategy of price competitiveness. This distinction will be used and for this study.

Consumers

As mentioned in section 2.5, one novelty of the model created by D'Orazio and Valente is the inclusion of the impact consumers' preferences have in the market diffusion. Consumer preferences are expressed as weights for the different aspects of the products.

The main properties of consumers in this model are:

Consumer Properties

```
– User quality weight
– Environmental performance weight
– Cost efficiency weight
```

[2] sales, revenue, fixed costs, price, costs, profits, and wealth.

Commercial Banks

Commercial banks are one of the two model entities that can provide loans to firms wishing to perform research to improve their products characteristics. Commercial banks take a number of factors in consideration when making the decision to finance an innovative project:

- The type of the project (environmental, user quality, or efficiency).
- The financial health of the firm requesting the loan.
- The economic conditions at the time of request.

The main properties of commercial banks in this model are:

Commercial Bank Properties

```
– Propensity to give loan for user quality research
  project
– Propensity to give loan for environmental
  performance research project
– Propensity to give loan for cost-efficiency
  research project
– Impact of economic cycle conditions in bank’s
  loan propensity
– Impact of firm’s economic health in bank’s
  propensity to provide loan for the firm
```

State Investment Bank

The state investment bank included in the model is the other model entity that provides loans to firms. State investment banks, contrary to commercial banks are public financing entities. The state investment bank in this model is a green state investment bank, with the goal of supporting research activities which aim at improving the environmental quality of the product. The state investment bank can promote green investments through two tools:

- Pubic procurement: increase the demand for environmental friendly products.
- Provide loan guarantees for loans given from commercial banks to sustainable research projects.

State Investment Bank Properties

```
– Scale of loan guarantees
– Size of public procurement
```

Model Interactions

A model interaction takes place when two or more model entities exchange information that affects their behaviors. The most important interactions of the agents are:

- Commercial bank provides loans to firms that want to undertake research projects aimed at improving one of their product aspects. This decision is based on the financial health of the applying firm, on the commercial bank's propensity to provide loans for the product aspect the firm wants to invest, and in the general macroeconomic conditions.

- If the loan guarantee policy is active, the SIB supports loans to firms that want to undertake research projects aimed at improving their sustainability.
- Consumers based on their preferences consume firms' products.
- The government through public procurement can increase the demand for products with higher environmental performance.
- The government can control SIB's loan guarantee scale.
- The economy is influencing through business cycles the propensity of commercial banks to provide loans to firms; during recessions commercial banks provide fewer loans compared to expansionary periods.

The agents, the environment and their main interactions are illustrated in fig. 4.1

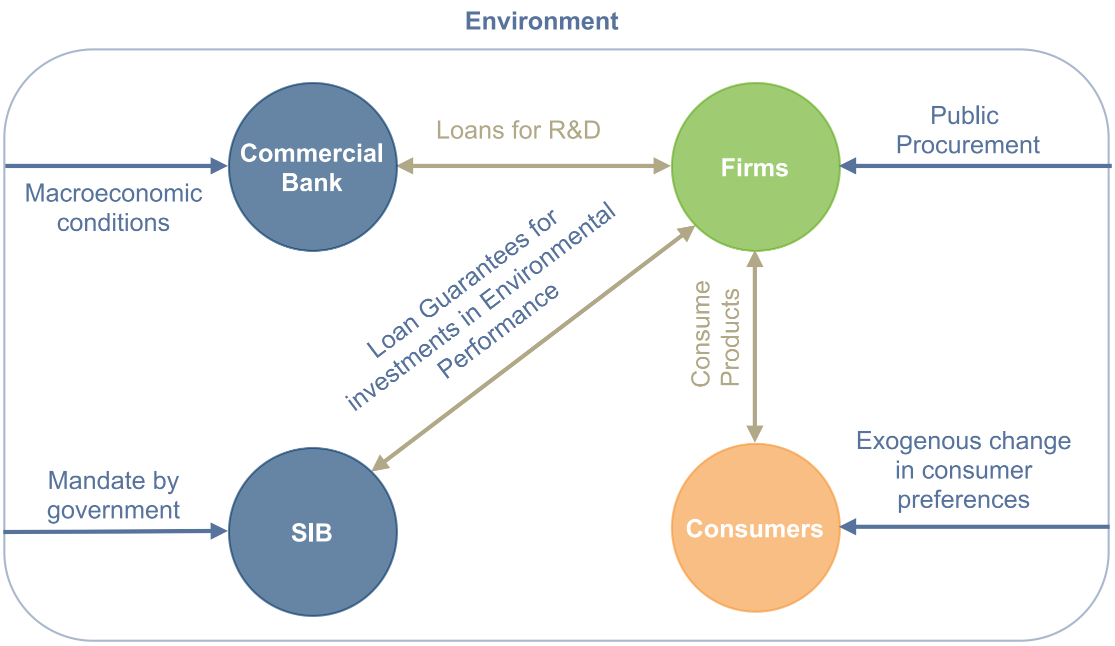


Figure 4.1: High level representation of the main model entities, the environment, and their interactions. The four main entities are: a State Investment Bank(SIB), a Commercial Bank, Firms, and Consumers. The environment includes the government and the macroeconomy. The relationships between entities are depicted with brown arrows while the interactions with the environment with blue arrows.

4.1.2 Model Narrative

The model narrative takes place in four broad steps: market initialization and market shares calculation, wealth accounts update, market dynamics, and innovative project financing.

In the first step, the model is populated by a number of heterogenous firms, and a number of consumers. The firms differentiate in the three product characteristics: user quality (overall quality/performance of the product), environmental quality (how environmental friendly the products are), and efficiency (how efficiently the products are produced, how cheap they are) and in their investment strategy. The consumers, have preferences, expressed as weights for the product characteristics. The first step concludes by calculating the market share of each firm based on their unique characteristics, the consumer preferences, and a market concentration index. The first step is described by equations eqs. (4.1) to (4.3).

In the second step, based on firms' market shares: their sales, fixed costs, profits, and wealth are calculated. The second step is described by equations eqs. (4.4) to (4.8).

In the third step, firms that perform poorly exit the market, while new firms try to enter the market, by imitating successful firms. The third step is described by equations eqs. (4.8) to (4.9)

In the fourth and final step, firms attempt to start an innovation project to improve one of their three characteristics. The probability that a firm will succeed in getting a loan depends: on its financial health, on the commercial banks propensity to finance the specific type of project, on the overall economic conditions, and on whether the state investment bank provides loan guarantee for the specific project type. The innovation project that firms choose to invest upon is based on their innovation strategy, defined randomly during the firm's creation.

Aside from these steps, the model has an aggregate income module. The most important element of this module is the calculation of aggregate income growth. The growth fluctuates endogenously between two exogenous defined limits. The endogenous fluctuation is calculated based on the number of firms undertaking innovative projects at each step. Based on econometric data, innovative projects aiming at improving user quality or product innovations, correlate strongly positively with growth, projects aiming at improving green quality corelate slightly positive, and projects aiming at improving efficiency or process innovations slightly negative. The income module is described by eqs. (4.16) to (4.18).

4.2 Model

In this section the equations describing the model developed by D'Orazio and Valente are introduced. The first subsection describes the equations related to demand and supply interaction. The following subsection focuses on the equations related to the market dynamics: the conditions under which new firms enter the market and old firms exit the market. The next subsection cites the equations related to the financing of innovation, and the final subsection of this section is focused on the equations describing the aggregate income. The equations used in this section use a number of parameters, the default values used by D'Orazio and Valente can be found in appendix B.1.

4.2.1 Demand-Supply Interaction

The demand-supply interaction module of the model by D'Orazio and Valente is used in this study without major changes; changes in the values used in some parameters and the reasoning is presented in section 4.3 and the values chosen for the rest parameters are presented in chapter 6.

Market Shares Calculation

The production sector of the model is populated with firms producing products with three distinct characteristics: (1) user quality b_f, overall quality/performance of the product, (2) environmental quality g_f, environmental performance of the product, [3] and (3) efficiency e_f, cost efficiency of the product. Every firm is producing a single type of product described by those three characteristics[4].

Efficiency e_f as a function of price is shown in eq. (4.1). The price of the product is calculated based on its efficiency value by solving the inverse eq. (4.1).

$$e_f(t) = \frac{M_e}{1 + exp^{\gamma_e(p(t)-\hat{p}))}} \tag{4.1}$$

The parameters used in equation 4.1 are: (1) M_e, the maximum value of efficiency, (2) γ_e, slope of the efficiency curve, and (3) $\hat{p}$, mean product price.

A visualization of the efficiency curve can be found in appendix A.1. Efficiency is a negative function of the price and has diminishing returns: the further the price from the mean price, the less impact a price difference has. As a result of the diminishing returns, for extreme prices efficiency has an asymptotic behavior: as the price approaches zero the efficiency approaches its maximum value M_e and as the price increases the efficiency approaches the value of zero. For example given a mean value $\hat{p}$ of 250, a γ_e of 0.015, and M_e of 40, a product with a price of 250 has an efficiency of 20, a product with a price of 25 an efficiency of 39 and a product with a price of 500 an efficiency of 3.

[3]This feature is positively evaluated by consumers and negatively correlated with the environmental impact of the product.

[4]These values are defined during the initialization of the firms based on the different scenarios and change when firms successfully complete an innovation project related to this aspect. The innovation mechanism is described in more detail in section 4.2.3

Based on the three firm characteristics, their market share is calculated using equations 4.2 and 4.3.

$$I_f = e_f^{\lambda_e} \times b_f^{\lambda_b} \times g_f^{\lambda_g} \tag{4.2}$$

$$ms_f(t) = \frac{[I_f(t)]^a}{\Sigma_{j=1}^{F}[I_j(t)]^a} \tag{4.3}$$

It is important to note that in order to simplify the model, the authors instead of using multiple consumer agents, use a single aggregate consumer. The market shares then, can be calculated efficiently through eqs. (4.2) to (4.3). This simplified approach is adopted in this study as well and has the advantage of efficiency but does not account for the impact of consumer heterogeneity in the model.

In eqs. (4.2) to (4.3) parameters λ_e, λ_b, and λ_g add up to 1 and describe consumer preferences for efficiency, user quality, and green quality respectively. Parameter I_f is an indicator of firm's competitiveness and is calculated as the weighted geometric mean of the product aspects with weights the consumer preferences; the values it can take are bounded by the maximum and minimum value the three produce aspects have.[5] Parameter α defines the concentration of market shares and takes values greater than 1. Parameter α amplifies differences in firm's competitiveness; a visualization of the impact α has can be found in appendix A.1.

Evolutionary Perspective 1

As mentioned in section 3.1 the three conditions for evolution to exist are:

- Variation.
- A replication mechanism or some form of inheritance.
- A determinant of better variations or a selection pressure.

Two evolutionary elements are encountered in this subsection:

- Variation in the system is introduced by firms having different characteristics, and by having different investment priorities which result in increased future variation.
- Selection pressure is introduced by consumers who discipline the market by rewarding firms that are closer to their preferences with higher market shares and revenues, thus improving their probabilities of survival.

Firms' Accounts Update

Following market shares calculation, firms engage in sales and accounts update, the following set of equations describe these interactions, all the variables have real

[5]The calculation weighted geometric mean is part of the computationally efficient method D'Orazio and Valente (2019) use to calculate the market shares of each firm based on its product characteristics and the consumer preferences. An interesting property of the weighted geometric mean that make it usefull for some application is that it imposes a limiting factor: if the value of one of the three aspects is very small then the outcome will be affected stronger than a common weighted average; for example, for equal consumer preferences for a product with $e_f = 5$, $g_f = 27.5$, and $b_f = 27.5$ the weighted average is 20 while the geometric weighted average is 15.57.

values:

$$r_f(t) = ms_f(t) \times GDP(t-1) \tag{4.4}$$

$$c_f(t) = \frac{p_f(t)}{(1+\mu)} \tag{4.5}$$

$$fc_f(t) = \psi \times fc_f \times (t-1) + (1-\psi) \times \Phi \times r_f(t) \tag{4.6}$$

$$\pi(t) = (p_f(t) - c_f(t))\frac{r_f(t)}{p_f(t)} - fc_f(t) \tag{4.7}$$

$$s_f(t) = (1-\delta) \times s_f(t-1) + \pi_f(t) \tag{4.8}$$

Equation eq. (4.4) calculates firm's revenue as the product of firm's market share ms_f and the market's real GDP in the previous period. Equation eq. (4.5) calculates the unit variable costs for each product based on its price p_f and the price markup μ. Equation eq. (4.6) calculates the fixed costs as a percentage of revenue. The parameter ψ describes the adjustment speed of the current level of fixed costs to long-term level of fixed costs equal to $\Phi \times r_f(t)$. Equation eq. (4.7) calculates the profits of the firm at each step as the sum of sales minus variable costs minus fixed costs.[6] Finally, eq. (4.8) calculates the firms wealth[7] by adding to the previous' step wealth the profits minus the dividends retained from the firm's owners which are equal to $\delta \times s_f$.

This is a rather simplified model for the firms' accounts. The reason for using this simplified model is to allow firms compete only in their product aspects. The competition between firms is discussed in more depth in section 4.3.

4.2.2 Market Dynamics

The next part of the model focuses on market dynamics. Market dynamics describe the conditions under which firms enter and exit the market.

Firms enter the market through a process of imitation. The probability that an existing firm will be imitated at a given time step is a function of its market share and is calculated by equation 4.9 .

$$Pr_{imit} = \frac{ms_f^{\eta}}{\Sigma_j ms_j^{\eta}} \tag{4.9}$$

Parameter η can take values between 0 and 1 and adjusts the weight of market share in calculating a firm's probability to be imitated; the sum of the firms' η add up to 1. For η closer to 1 larger firms have higher chances to be imitated; a visualization of the impact η has can be found in appendix A.1

[6]The profits according to this model are $revenue - variable\ costs - fixed\ costs$, $revenue$ and $fixed\ costs$ are already calculated; the $variable\ costs$ can be calculated as the product of the number of products sold with the variable costs per unit c_f, the number of items sold is calculated by dividing the $revenue$ with the product price p_f. Thus the profits are calculated as $r_f - \frac{r_f}{p_f} \times c_f - fc_f$, which is eq. (4.5).

[7]Wealth refers to the firm's accumulated profits and not to its total capital stock.

Firms entering the market differentiate from the firms they imitate by a factor Ω, $0 < \Omega < 1$. Firms entering the markets can be environmental performance innovators, user quality innovators (product innovators), or efficiency innovators (process innovators). The value of their innovative aspect is calculated based on the values of the firm they imitate and the imitation factor Ω. Their innovative aspect is calculated by dividing the value in that aspect of the firm they imitate by Ω and their other two factors by multiplying the related aspect value of the firm they imitate with Ω. As a results innovative firms entering the market have a greater value for their innovative aspect than the firm they imitate and smaller for the other two aspects. In the following equations the values e_{new}, b_{new}, and g_{new} refer to the innovative firm entering the market and values e_i, b_i, and g_i to the firm that they imitate; equation set (a) calculates the product characteristics for an efficiency (process) innovator, equation set (b) for a user quality (product) innovator, and equation set (c) for a environmental innovator:

$$\begin{aligned} e_{new} &= \frac{e_i}{\Omega}, \quad b_{new} = b_i\Omega, \quad g_{new} = g_i\Omega \quad (a) \\ e_{new} &= e_i\Omega, \quad b_{new} = \frac{b_i}{\Omega}, \quad g_{new} = g_i\Omega \quad (b) \\ e_{new} &= e_i\Omega, \quad b_{new} = b_i\Omega, \quad g_{new} = \frac{g_i}{\Omega} \quad (c) \end{aligned} \tag{4.10}$$

Firms exit the market when their wealth gets negative.

if their market share is below a threshold defined by variable τ, their wealth negative, and they are older than an age threshold defined by variable $minAge$. Values for variables τ and $minAge$ are discussed in chapter 6.

Evolutionary Perspective 2

This subsection introduces two more evolutionary elements in the model:
- An imitation mechanism: firm's enter the market by imitating to an important extent an existing firm through eq. (4.10).
- A selection pressure in the form of financial disciplining of firms, as firms performing poorly are dropped of the market.
- An indirect form of selection pressure exists in the imitation module, as based on eq. (4.9) firms that are performing better in market have higher chances to be imitated. This way firm characteristics that result in higher market shares have higher chances of surviving in the market by being imitated.

4.2.3 Innovation and Finance

Commercial Bank

In order to improve their characteristics, firms engage in research by funding innovation projects. At each time step, firms without an ongoing innovative project, attempt to finance one through a loan from the commercial bank. The project, based on firm's innovation strategy, aims at improving one of the three firm characteristics. After a firm chooses an innovative project, the probability of successfully taking a loan for it, is defined by the equation:

$$P_i^x = \frac{S_i(t)}{r_i(t)} \times Pr_l^x \times I(t) \tag{4.11}$$

where:

- P_i^x: probability that the firm i will get a loan to finance an innovative project related to the aspect x.
- Pr_l^x: commercial bank's propensity to finance a project related to the aspect x.
- $\frac{s_i(t)}{r_i(t)}$: ratio of firms wealth to revenue, an estimator of firm's financial health.
- $I(t)$: proxy for the current economic conditions, calculated based on equations eq. (4.12) to eq. (4.14).

Index $I(t)$ is computed as the ratio of two tracking indexes: MA_y^L tracking the long-term nominal GDP level , and MA_y^S tracking short-term nominal GDP level.

$$MA_y^L(t) = MA_y^L(t-1) \times \delta^{Long} + Y(t) \times (1 - \delta^{Long}) \tag{4.12}$$

$$MA_y^S(t) = MA_y^S(t-1) \times \delta^{Short} + Y(t) \times (1 - \delta^{Short}) \tag{4.13}$$

$$I(t) = \frac{MA_y^L(t)}{MA_y^S(t)} \tag{4.14}$$

In equations eq. (4.12) and eq. (4.13) deltas represent the inertia of every index, with $\delta^{Long} > \delta^{short}$.

State Investment Bank

The impact of a state investment bank in supporting green investments, is captured by equation section 4.4.1.

$$Pr_{l,SIB}^g = Pr_l^g + \sigma \tag{4.15}$$

The parameter σ describes the increased probability for a firm to receive a loan aiming at improving the environmental aspect of the product.

Evolutionary Perspective 3

In this section two more evolutionary elements are added in the model both related to the third condition for evolution, selection pressure. The two added selection pressures are:

- The financial disciplining imposed by commercial banks: firms with better financial health have higher probabilities of receiving a loan and thus improving their aspects and surviving in the market.
- On the same time, another form of disciplining is imposed by the state investment bank: firms that try to receive a loan to fund research aiming at improving their environmental aspect have higher probability of receiving one and thus improving this aspect and becoming more competitive.

Innovation and Technical Change

Successful projects in environmental performance, user quality, and efficiency improve the relative characteristic by K_g, K_b, and K_c respectively. The values that these parameters can take are discussed in chapter 6.

4.2.4 Aggregate Income

The aggregate nominal income at each time step is calculated eq. (4.16).

$$Y(t) = \zeta Y(t-1) + (1-\zeta)Y^T(t) \tag{4.16}$$

Parameter ζ describes the inertia of GDP to changes and $Y^T(t)$ represents the economy's potential income.

Potential income is calculated based on equation:

$$Y^T(t) = Y^T(t-1) \times G^T(t) \tag{4.17}$$

where G^T represents the potential growth rate. The potential growth rate is calculated based on equation:

$$G^T(t) = [\omega_g \Theta_g(t) + \omega_b \Theta_b(t) - \omega_c \Theta_c(t)] \frac{(G_{max} - G_{min})}{2} + G_{min} \tag{4.18}$$

where Θ_g, Θ_b, and Θ_c, represent the total market share of firms started investing in, environmental quality, product quality, and efficiency, respectively. Parameters ω_g, ω_b, and ω_c, define the weights of the three aspects in defining the potential growth rate. Parameters G_{max} and G_{min} define the exogenous extreme rates of growth.

Based on equation 4.18 firms investing in environmental quality and product quality contribute to potential income growth, while firms investing in efficiency hamper growth.

4.3 Model Critique

This section focuses on errors encountered in the model developed by D'Orazio and Valente and introduces ways to overcome the limitations imposed by these errors.

4.3.1 Firms' Sales, Costs, Profit, and Wealth

In section 4.2.2, following the market shares calculation, firms engage in sales and accounts update according to eqs. (4.4) to (4.8).

$$r_f(t) = ms_f(t) * GDP(t-1)$$

$$c_f(t) = \frac{p_f(t)}{(1+\mu)}$$

$$fc_f(t) = \psi \times fc_f \times (t-1) + (1-\psi) \times \Phi$$

$$\pi(t) = (p_f(t) - c_f(t))\frac{r_f(t)}{p_f(t)} - fc_f(t)$$

$$s_f(t) = (1-\delta) * s_f(t-1) + \pi_f(t)$$

Equation set 1: Reprint of eqs. (4.4) to (4.8), parameters $r_f(t)$, $p_f(t)$, $fc_f(t)$, $\pi_f(t)$, and $w_f(t)$ are firm's revenue, price, fixed costs, profits, and wealth respectively.

The parameters and in parenthesis the default values used by D'Orazio and Valente are:

- GDP: aggregate output in the market.
- μ: profit markups (0.01)
- ψ: adjustment speed of current level of fixed costs to long-term level (0.3)
- Φ: fixed costs as a percentage of total revenues (0.05)
- δ: dividends payed to company owners (0.3)

In order to explore some structural aspects of these equations, their convergence for constant revenues is calculated:

$$fc_f(t) \to \Phi \times r_f = 0.05 \times r_f$$

$$\pi_f \to (1 - \Phi - \frac{1}{1+\mu}) \times r_f = -0.0400 \times r_f$$

$$s_f(t) \to \frac{1}{\delta} \times \pi_f \;\; = -0.1333 \times r_f$$

Equation set 2: Convergence of eqs. (4.6) to (4.8) for constant firm revenues.

The fixed costs as expected converges to $0.05 \times revenue$ which is equal to its long term value. The profit converges to $-0.04 \times revenue$ a value always negative and wealth converges to the profits divided by the percentage of dividends, an always negative value as well. Thus, for constant revenue streams, the equation behavior, for default parameters, is not the desired one.

In order to explore the behavior of eqs. (4.4) to (4.8) under dynamic conditions, two random revenue scenarios are simulated in figs. 4.2 to 4.3. Figure 4.2 illustrates the revenue, fixed costs, profits, and wealth for a random steep expansionary scenario. It is evident that despite the very favorable revenue conditions the firm's profits and wealth just get more negative. In fig. 4.3, the same conclusion is established for a random revenue path with no expansionary or recessionary tendency. Thus regardless of the market conditions, for default parameters, firms´ wealth and profits will converge to negative values.

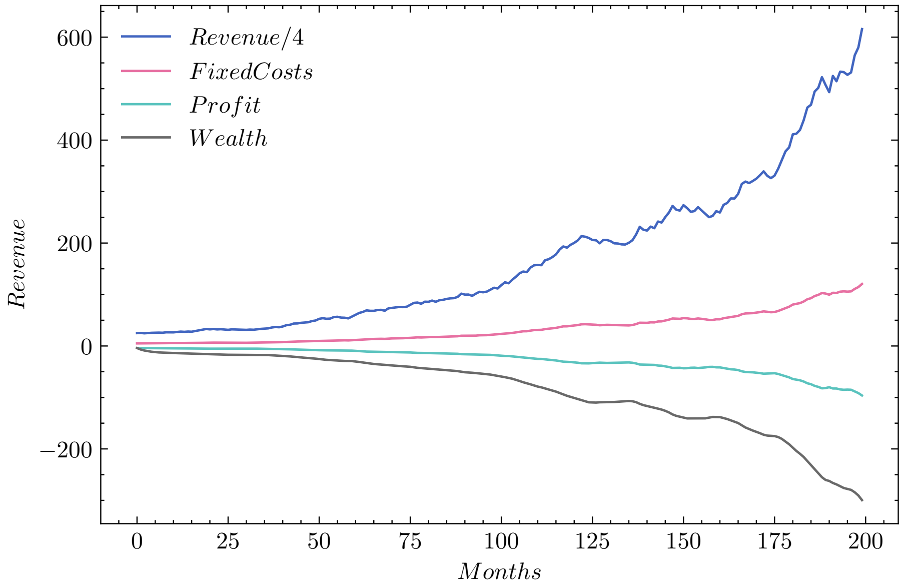


Figure 4.2: Visualization of equations 4 to 8. Revenue, fixed costs, profits, and wealth for default parameters and randomly increasing revenue. The revenue is imposed exogenously and the monthy revenue increase follows uniform distribution with interval -0.03 to 0.07. It is a rather unlikely scenario but aims at conveying the message that even in this unrealistically favorable market conditions, for default parameters, profits and wealth are negative.

Basic Model Problem 1

For the default values suggested by D'Orazio and Valente firms regardless of their market conditions and their market shares, will converge to negative profit and wealth values.

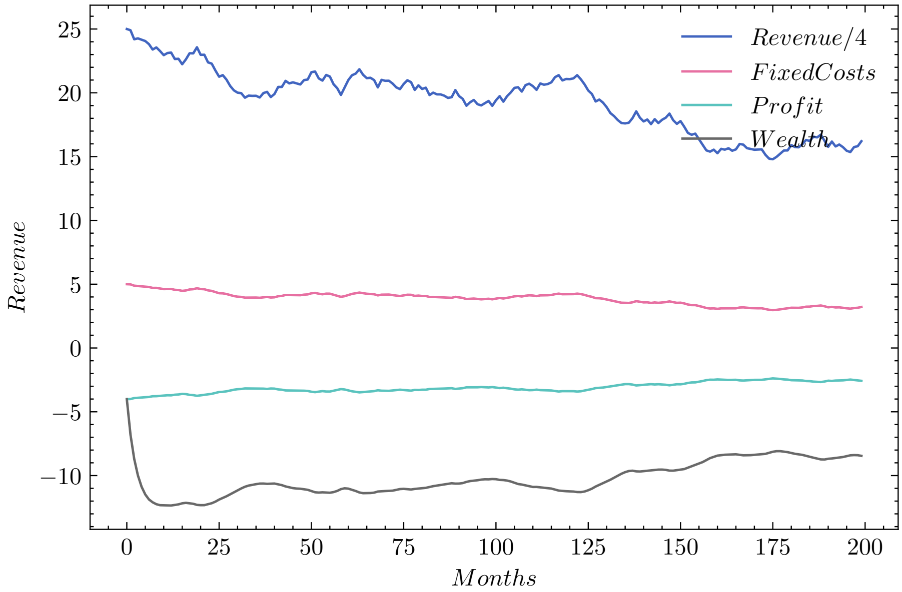


Figure 4.3: Visualization of equations 4 to 8. Revenue, fixed costs, profits, and wealth for default parameters and randomly revenue path. The revenue is imposed exogenously and the monthy revenue growth follows uniform distribution with interval -0.03 to 0.03.

Profit Markups

In order to have positive profit and wealth, solving the profit equation eq. (4.7), leads to the following inequality:

$$1 - \Phi - \frac{1}{1+\mu} > 0 \quad => \quad 1 - \Phi > \frac{1}{1+\mu}$$
$$1 + \mu > \frac{1}{1-\Phi} \quad => \quad \mu > \frac{1}{1-\Phi} - 1$$

Equation set 3: Condition for positive profit and wealth.

The above inequality, for default parameters, results in $\mu > 0.0526$, a value greater than the one used by the authors (0.01). As firms do not compete in markup prices, the chosen markup price does not have an important impact. For the simulations in this thesis an μ of 0.2 will be chosen, which is closer to the one used in the literature[8]

Modelling Decision 1

For this study a value for profit markup μ of 0.2 is used. As mentioned in section 4.3.1 a value for μ greater than 0.0526 results in profits and wealth being a positive fraction of revenues, which is the desired behavior. The choice of profit markup otherwise does not impact the results of the model as firms by having the same mark-up price, do not compete on this aspect.

[8]Dosi, Fagiolo, Napoletano, and Roventini uses a markup value of 0.2, Lamperti, Dosi, Napoletano, Roventini, and Sapio use a markup value of 0.28.

Long-term Costs Inertia

Figure 4.4 illustrates that choosing a mark-up price μ of 0.2 solves the problem of negative profits and wealth but it reveals another problem: despite the deep recession, the firm's profits and wealth do not get negative at any point.[9] This is to be expected as, according to the previous section, profit and wealth always converge to a fixed percentage of revenue; thus, since revenue streams are always positive, wealth and profit are also always positive.

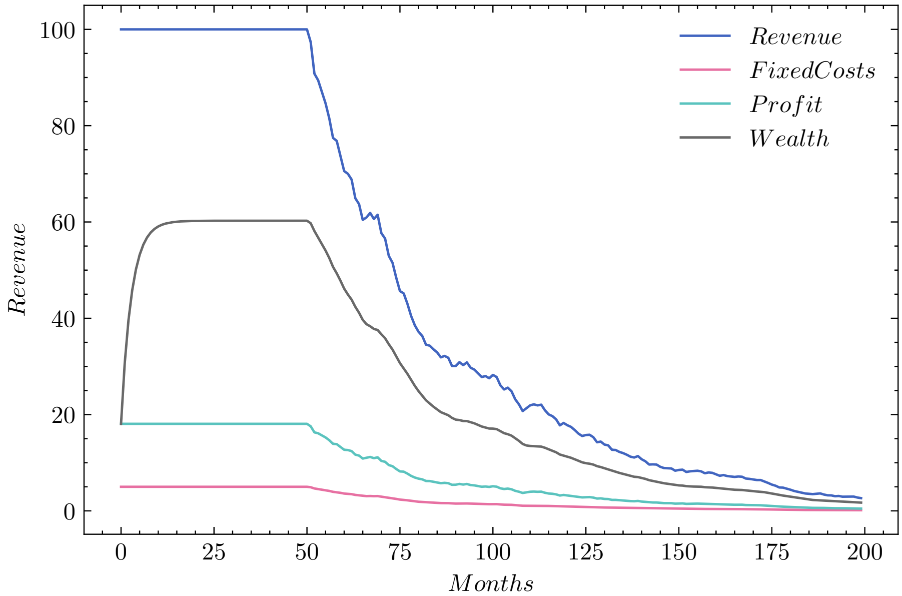


Figure 4.4: Visualization of equations 4 to 8. Revenue, fixed costs, profits, and wealth for default parameters, markup $\mu = 0.2$, and steep random recessionary path. The revenue is imposed exogenously and the monthy revenue increase follows uniform distribution with interval -0.07 to 0.03. It is a rather unlikely scenario, but aims at conveying the message that even in this unrealistically unfavorable market conditions, for default values and $\mu = 0.2$, profits and wealth do not become negative.

Basic Model Problem 2

The second problem in the model is that, for default values and $\mu = 0.2$, even under extreme recessionary conditions, firms do not incur loses. This is an important problem as negative wealth, a result of accumulated negative profit, is one of the exit conditions for firms.

This problem can be solved by making use of the inertia that characterizes the fixed costs. As mentioned in equation 4.6 fixed costs converge to $\Phi \times revenue$ with an inertia parameter ψ. The default ψ value is 0.3. For example, Figure 4.5 has the same revenue path as fig. 4.4 but with a ψ of 0.9 instead of 0.3 and Φ equal to 0.15. In this case, profit and wealth do get negative.

[9] As mentioned in section 4.2.2 negative wealth is one of the market exit conditions for a firms; thus, important to model functioning.

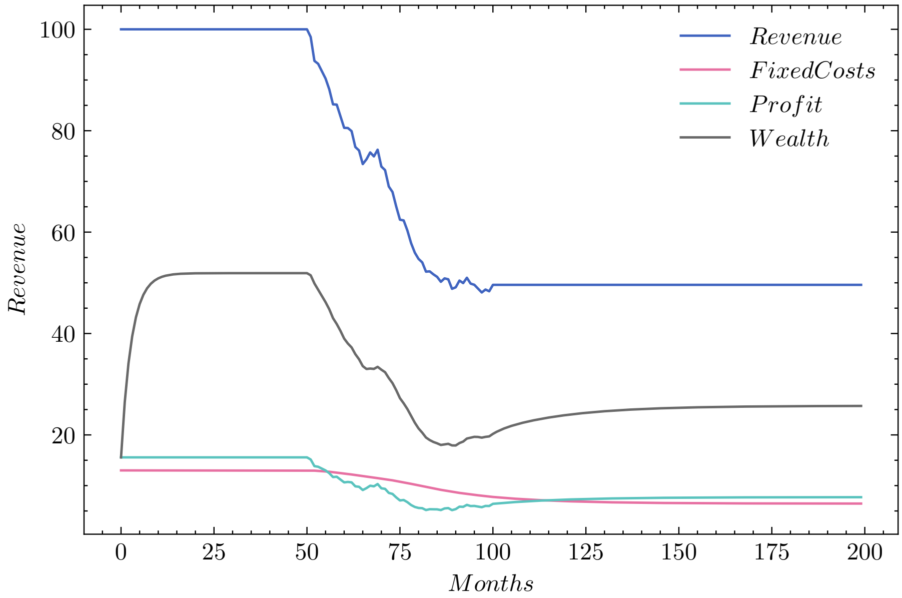


Figure 4.5: Visualization of equations 4 to 8. Revenue, fixed costs, profits and wealth for $\mu = 0.02$, $\psi = 0.9$, $\Phi = 0.15$, and steep random recessionary path. The revenue is imposed exogenously and the monthy revenue increase follows uniform distribution with interval -0.07 to 0.03. This graph illustrates that changing the ψ to 0.9 and Φ to 0.15 solves the problem of always positive profit by introducing inertia in the long-term costs.

Modelling Decision 2

The second problem identified in the basic model is that despite firms entering a deep recession the profits are not getting negative, they do not incur any loses. This is a result of the small inertia that firms' long-term fixed costs exhibit; as a consequence, when a firm loses market share the long-term costs adapt instantly and the firm becomes again profitable. For this reason the long-term fixed costs inertia parameter is increased from 0.3 to 0.9 and the fixed costs as a percentage of revenue are increased from 0.05 to 0.15. The choice of fixed costs' inertia and percentage does not otherwise impact the results of the model as firms by having the same values in those variables, do not compete in those aspects. This change serves only in making possible that the firms exhibit the desired behavior of getting negative wealth when losing rapidly market shares.

4.3.2 Loan Success

Another problem in the model developed by D'Orazio and Valente exists in eq. (4.11), which calculates the success probability of a loan:

$$P_i^x = \frac{S_i(t)}{r_i(t)} \times Pr_l^x \times I(t)$$

In the following subsections the values each term can take are explored.

Wealth Revenue Ratio

The first term of eq. (4.11) firm's wealth-revenue ratio for constant revenue streams converges to:

$$\frac{1}{\delta} \times (1 - \Phi - \frac{1}{1+\mu})$$

This is calculated based on the equation set 2.

For default model parameters, this term is equal to -0.1336. Substituting for the parameters used in this study, $\mu = 0.2$, $\Phi = 0.13$, and $\delta = 0.3$ it is equal to 0.0366. The only way that firms differentiate regarding this term is through the dynamic aspect of fixed costs. Figure 4.6 illustrates the wealth-revenue ratio of a firm under volatile market conditions with the monthly revenue growth following uniform distribution with interval -0.1 to 0.1. These extreme revenue conditions are used to explore the extreme values that this term can take. Figure 4.6 gives a good intuition about the value range of this ratio which gets its extreme values when sudden changes occur. The range of values this term takes are in the range of -0.015 to 0.015.

Cyclical Economic Conditions Index

The next term of equation eq. (4.11), $I(t)$, is calculated based on the equations eqs. (4.12) to (4.14):

$$MA_y^L(t) = MA_y^L(t-1) \times \delta^{Long} + Y(t) \times (1 - \delta^{Long})$$
$$MA_y^S(t) = MA_y^S(t-1) \times \delta^{Short} + Y(t) \times (1 - \delta^{Short})$$
$$I(t) = \frac{MA_y^L(t)}{MA_y^S(t)}$$

with $\delta^{Long} > \delta^{short}$.

This index is wrongly defined, as the author's intention, for the commercial sector, is a pro-cyclical investing behavior. In figure fig. 4.7, the counter-cyclical nature of the index can be inspected. The index is on average less than one during expansionary periods, and on average more than one during recessionary periods. The counter-cyclical behavior can also be confirmed by sole inspection of the equations. Default values for parameters δ^{Long} and δ^{short} are not mentioned by the authors. Higher differences between the two deltas, will result in greater value range for the index. The values used for figure fig. 4.7, are 0.95 and 0.5 for δ^{Long} and δ^{short} respectively. These are the values that are going to be used in this thesis. In figure fig. 4.7 it can be inspected that for these deltas, the ratio can during long expansionary or recessionary periods combined with sudden changes get values in the range of 0.7 to 1.4.

Basic Model Problem 3

The commercial bank has a counter-cyclical investing behavior while the authors' intention is a pro-cyclical one.

Modelling Decision 3

In order to convert the counter-cyclical behavior of the commercial bank into the intended pro-cyclical the inverted index $I(t) = \dfrac{MA_y^S(t)}{MA_y^L(t)}$ will be used in this study.

Loan Probability

The last term in the equation is the type specific loan probability of commercial bank financing an innovative project. The default author values for these probabilities are equal to 1, for all kinds of loans.

Conclusion

Bringing together the comments made on the previous subsections, it can be calculated that the probability for a firm to get a loan from a commercial bank to finance an innovative projects, based on the values used in this study, takes values in the range of $-0.15 \times 0.7 \times 1$ equals -0.105 and $0.15 \times 1.4 \times 1$ equals 0.21. This is conceptually wrong as: a probability gets negative values and the maximum probability that a firm can take a loan is 0.21 which is quite low.

Basic Model Problem 4

The equations calculating the probability that the commercial bank will fund certain types of innovative projects is a function of firm's financial heath, economic cycle conditions and commercial bank's propensity to finance the specific project type. Although this is conceptually correct the way the equation is expressed leads to the probability getting values in the range of -0.105 and 0.21 which creates the following two problems: the probability takes negative values, the maximum probability is rather small.

In order to solve these problems, firms that have negative wealth revenue ratio won't be considered for loans and a scaling factor f_a will be added in the equation which allows under optimal conditions the probability of getting a loan to become one. Thus eq. (4.11) becomes:

$$P_i^x = f_a \times \frac{S_i(t)}{r_i(t)} \times Pr_l^x \times I(t) \tag{4.19}$$

Modelling Decision 4

In order to solve the range problems related to eq. (4.11) a scaling factor is f_a is introduced and the assumption is made that firms with negative wealth won't be considered for loans.

4.3.3 Aggregate Income

Finally, some problems exist in the aggregate income growth equation.

$$G^T(t) = [\omega_g \Theta_g(t) + \omega_b \Theta_b(t) - \omega_c \Theta_c(t)] \frac{(G_{max} - G_{min})}{2} + G_{min}$$

The goal of this equation is to make growth fluctuate between the exogenously imposed G_{min} and G_{max} based on the number of innovation projects initiated at each time step.

Parameters Θ_g, Θ_b Θ_c represent the total market share of firms that started investing in environmental quality, product quality, and efficiency respectively, in the previous step. Parameters ω_g, ω_b ω_c, define the weights of the three aspects in defining the potential growth rate. Parameters G_{max} and G_{min} define the exogenous extreme rates of growth. Based on this equation firms investing in environmental quality and product quality contribute to potential income growth, while firms investing in efficiency hamper growth.

Table 4.1 contains the default values for the parameters of this equation.

Table 4.1: Aggregate Income Default Parameters

Parameter	Description	Value	Freedom
ω_g	Weight for green quality	0.1	Initially Fixed
ω_b	Weight for user quality	0.8	Initially Fixed
ω_c	Weight for cost	0.1	Initially Fixed
G_{min}	Increase of GDP	0.99	Initially Fixed
G_{max}	Decrease of GDP	1.015	Initially Fixed

Problems

The first part of the equation (the one in brackets), when all firms start investing at the same time in user quality will get its maximum value of 0.8; conversely, if all firms start investing in cost efficiency at the same time, it will get its minimum value of -0.1.[10] As a result G^T fluctuates between $-0.05 \times G_{max} + 0.95 \times G_{min} = 0.889$

[10] A high percentage of firms starting investing at the same time in the same project type is a highly unlikely event for two reasons: (1) an innovation project needs 4 time steps to be completed, thus it is very unlikely that all firms will by "synchronized" and start an innovation project at the same time as some will already have an active innovative projects and some won't be able to

and $0.4 \times G_{max} + 0.6 \times G_{min} = 1$, and that in the scenario all firms start investing at the same time. Thus even under the most favorable conditions the growth rate will be at maximum 1. Most commonly though, since an innovation project takes 4 time periods, even in the case that all project are approved for a loan, 20% of companies would start a project at a given time step. Limiting the range of growth rate to negative values.

Basic Model Problem 5

Using the definition of GDP growth of D'Orazio and Valente, we find that GDP growth is always negative or equal to zero and in the vast majority of time steps well below zero.

Another problem is the inclusion of the division by two in eq. (4.18) , since without it if the first part of equation fluctuate between 0 and 1, the growth would have the desired range. Taking into consideration the aforementioned comments, the following first part for eq. (4.18) is suggested in order to have a range of 0 to 1:

$$\frac{\omega_g \Theta_g(t) + \omega_b \Theta_b(t) - \omega_c \Theta_c(t) + \omega_c}{\omega_g + \omega_b}$$

Additionally, for this study Θ will represent the sum of the market share of companies investing at a specific aspect. Finally, since growth is updated every time step, for this study a month, it should be divided by 12 in order to get monthly rates. [11] Thus the final growth equation would be.

$$G^T(t) = \frac{\omega_g \Theta_g(t) + \omega_b \Theta_b(t) - \omega_c \Theta_c(t)}{\omega_b} \times \frac{(G_{max} - G_{min})}{2} + \frac{(G_{max} + G_{min})}{2} \tag{4.20}$$

Modelling Decision 5

In order to address the problems associated with eq. (4.18), eq. (4.20) is proposed which results in the intended behavior of GDP growth fluctuating between G_{min} and G_{max} based on the number and type of active innovation projects.

initiate one due to financial restrictions, (2) even in the extreme scenario that a high percentage of firms happen to initiate in the same time step a research project they will choose different projects based on their investment strategies.

[11] This is an approximation.

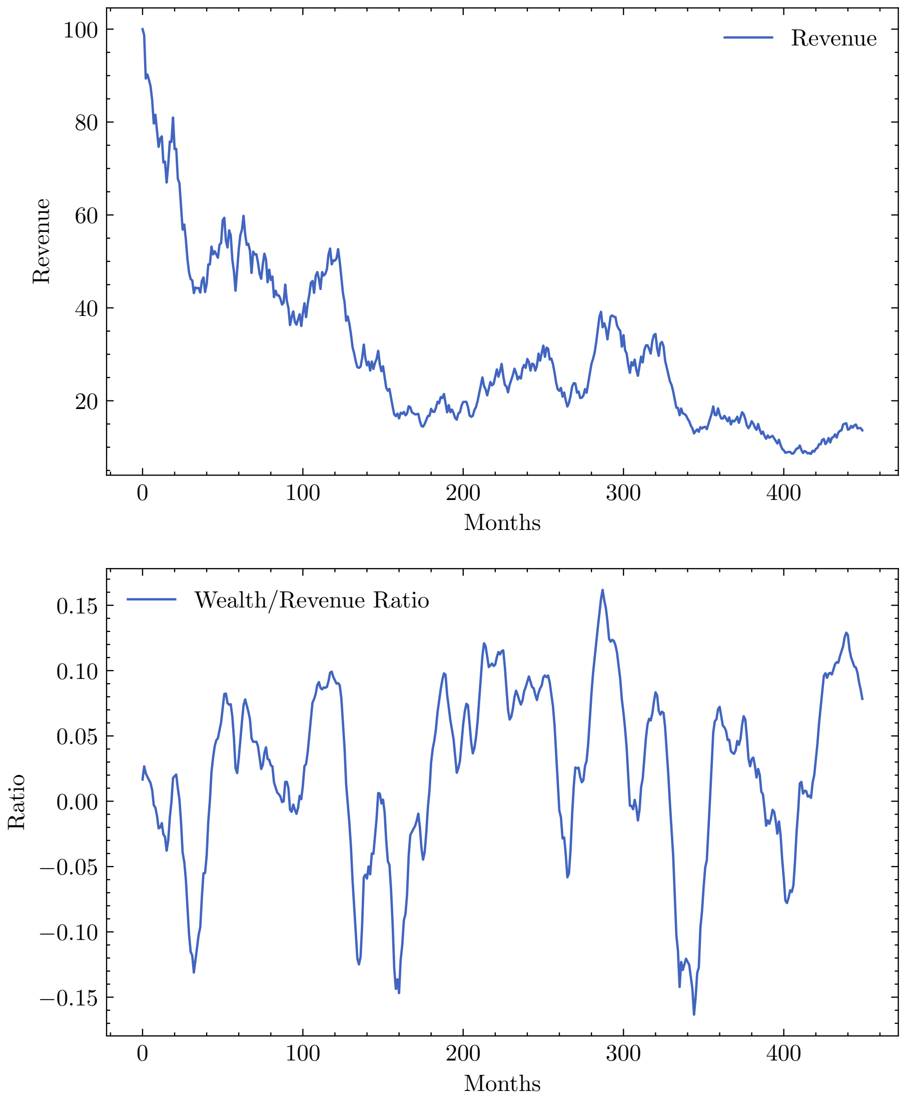


Figure 4.6: The top graph illustrates a volatile revenue scenario where the monthly revenue growth follows uniform distribution with interval -0.1 to 0.1. The bottom graph illustrates the wealth revenue ratio, based on equations 4 to 8, for a firm operating with the aforementioned revenue streams. The values this ratio can take are between -0.015 and 0.015. The values used for equations 4 to 8 are not the authors' default but the one used in this study, mentioned in the previous section.

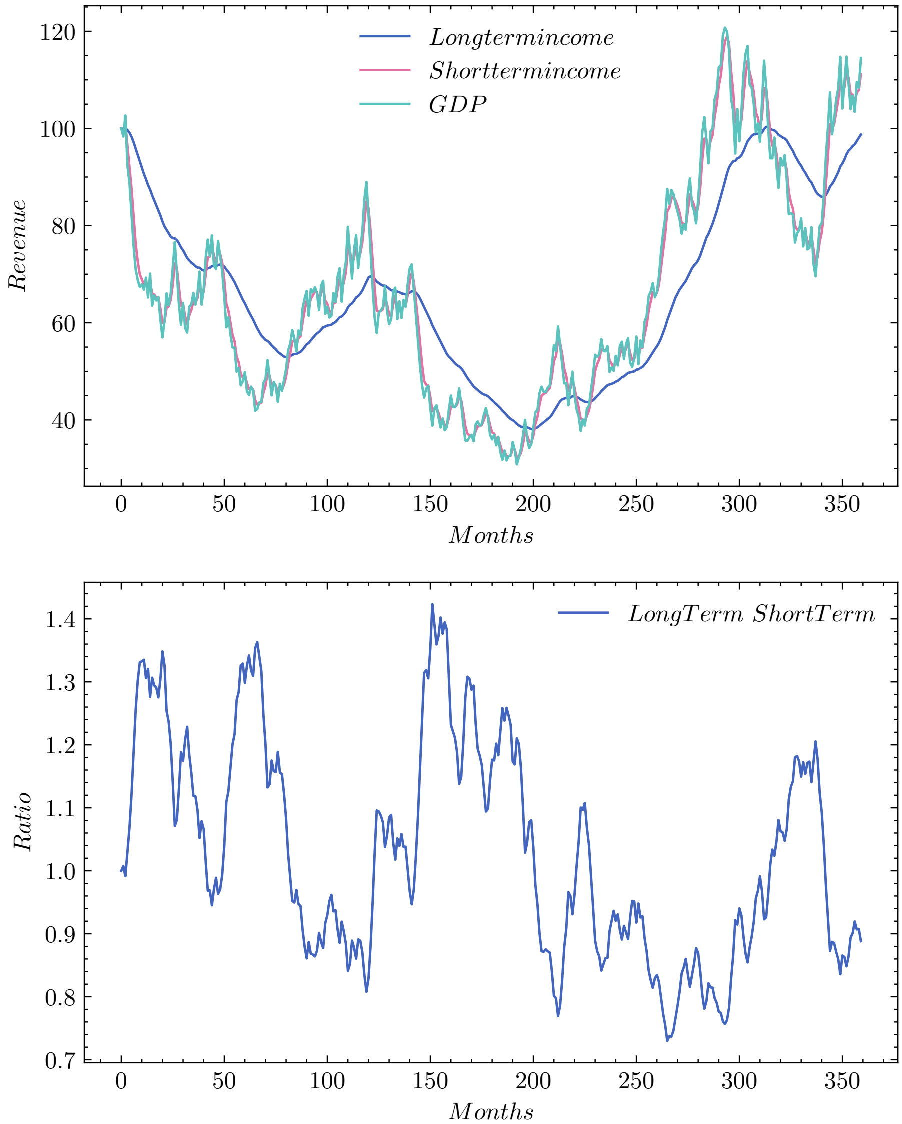


Figure 4.7: Visualization of equations 4.11 to 4.13. The top graph illustrates the GDP, the short term and the long-term income for a steep recessionary period followed by a steep expansionary period and the bottom graph illustrates the ration of long-term income over short-term. The revenue is imposed exogenously and the monthly revenue increase follows uniform distribution with interval -0.07 to 0.03 for the steep recessionary period and uniform distribution with interval -0.03 to 0.07 for the steep expansionary period.

4.4 Model Expansion

In section 4.1 the entities that will be considered for this study are identified, their properties and interactions are defined, and the overall model narrative is developed. In section 4.2 the model by D'Orazio and Valente is presented and in section 4.3 is critically examined while also some important problems and ways to overcome those are identified. In this section the updated model will be expanded so that it can be used for the purpose of this study.

4.4.1 Policies

As mentioned in literature review, policies related to innovation systems are often divided into demand-pull and technology-push; demand-pull policies, like public procurement, aim at fostering innovation diffusion by increasing the potential market size for eco-innovations, on the other hand, technology push policies, like loan-guarantees, aim at fostering innovation diffusion by addressing the knowledge market failures (Popp, 2019).[12] This study will consider one of each type: a demand pull policy, public procurement, and a demand push policy, loan guarantees for loans incurred by firms to invest in the environmental aspect of their products.

Loan Guarantee

The model by D'Orazio and Valente already accommodates for loan guarantee policies. According to their model conceptualization loan guarantee is expressed as an increase in the probability that a firm will receive a loan to finance a project aiming to improve environmental performance, this function is expressed in section 4.4.1. The loan guarantee levels that will be explored for this study are 40 %, 60 %, and 80 %.

$$Pr^g_{l,SIB} = Pr^g_l + \sigma$$

Public Procurement Policy

In this model public procurement will be expressed through the combination of: (1) an increase in the consumers' preference related to the environmental aspect λ_g, (2) a consequent decrease at λ_b and λ_e each equal to half the increase in λ_g as the lambdas must add up to 1, and (3) an increase in the total GDP in the market. It will be assumed that there is no crowding out of consumer demand due to the government expenditure.[13] The public procurement will be expressed as percentage of government expenditure over the total market revenue. The levels of public procurement that will be explored for this study are 10 %, 15 %, and 20 %.

[12]According to the knowledge market failure theory, the knowledge produced by the innovation once it becomes public produces benefits for the public but not to the innovator. Subsidizing knowledge creation "restores" part of this value lost due to knowledge spillovers.

[13]Guerzoni and Raiteri (2015) find evidence that indeed there is no crowding out due to innovative public procurement; their study on more than 5000 firms in EU, Norway and Switzerland suggest innovative public procurement stimulates private expenditure.

Chapter 5

Model Implementation

In the previous chapter the model used in this study was introduced. In this chapter the model implementation, the translation of the model in machine readable format, is described. Section 5.1 cites the softwares used for this study and section 5.2 explains the structure of the code and describes the classes used in the model. The verification process for this model can be found in appendix D.

5.1 Software Dependencies

The model is implemented using the Python programming language. For the model development, the MESA Python agent-based modelling library [1] was particularly useful as it contains a number of modules specifically developed for agent-based models.

The Python script containing the model is named `Model.py`. The Python script is complemented by four jupyter notebooks [2] which provide additional functionalities and facilitate the interaction with the model. The jupyter notebooks created are:

- `MainModel.ipynb`: this is the main notebook where interaction with the model takes place. In this notebook different scenarios can be defined and simulated and their outcomes visualized.
- `ModelValidation.ipynb`: in this notebook the model is validated based on the validation tests described in chapter 7.
- `ModelSensitivities.ipynb`: this notebook is used for the sensitivity analysis of the results.

5.2 Model Formalization

Figure 5.1 illustrates the structure of the computational model. The model starts with initialization where the appropriate scenario is loaded. Following model initialization the three main phases start. In phase 1 the aggregate income and the

[1] https://mesa.readthedocs.io/en/master/overview.html

[2] Jupyter notebooks are interactive online notebooks that combine code with enriched text and are helpful for code comprehension and interaction. https://jupyter.org/

firms´ characteristics are updated, these actions correspond to eqs. (4.1) to (4.8) of section 4.2. In phase 2 firms try to receive loans for financing innovative projects or continue with their existing innovative projects. A detailed flow diagram of the actions taking place at phase 2 is illustrated in fig. 5.2. In phase 3 the market dynamics are updated: under-performing firms exit the market and new firms attempt to enter the market by imitating existing ones. The datasets are updated in the end of phase 1, this choice is made so that new firms entering in phase 3 are included in the dataset with their accounts updated.

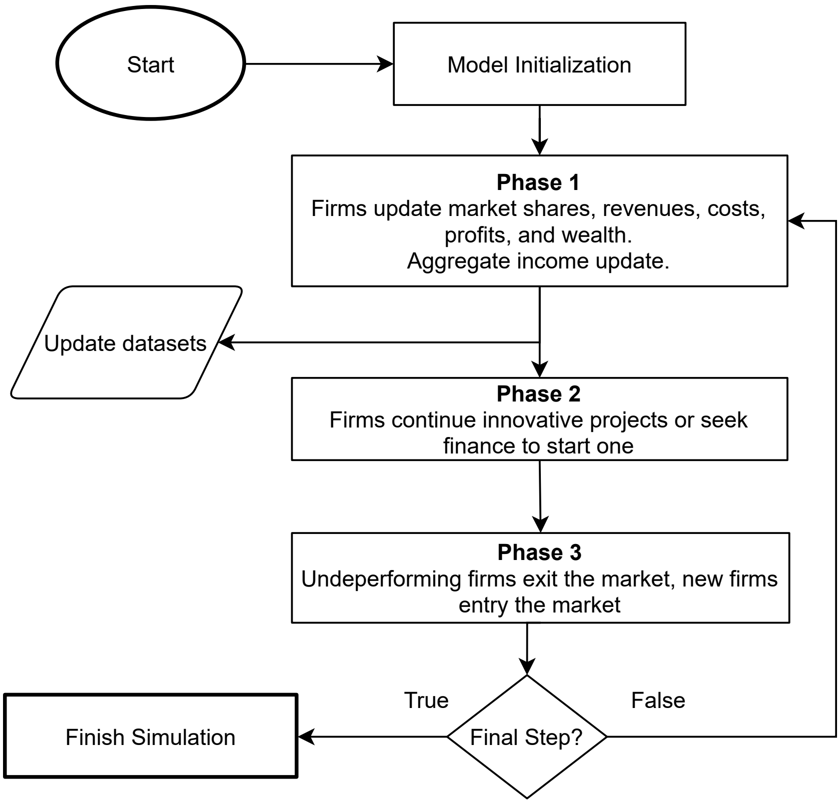


Figure 5.1: Flow diagram of computational model. The computational model consists of three phases; phase 1: the aggregate income and firm's characteristics are updated, phase 2: firms seek finance for their innovative activities, or continue their innovative projects, and phase 3: market dynamics are updated by dropping from the market under-performing firms and introducing to the market possible imitators.

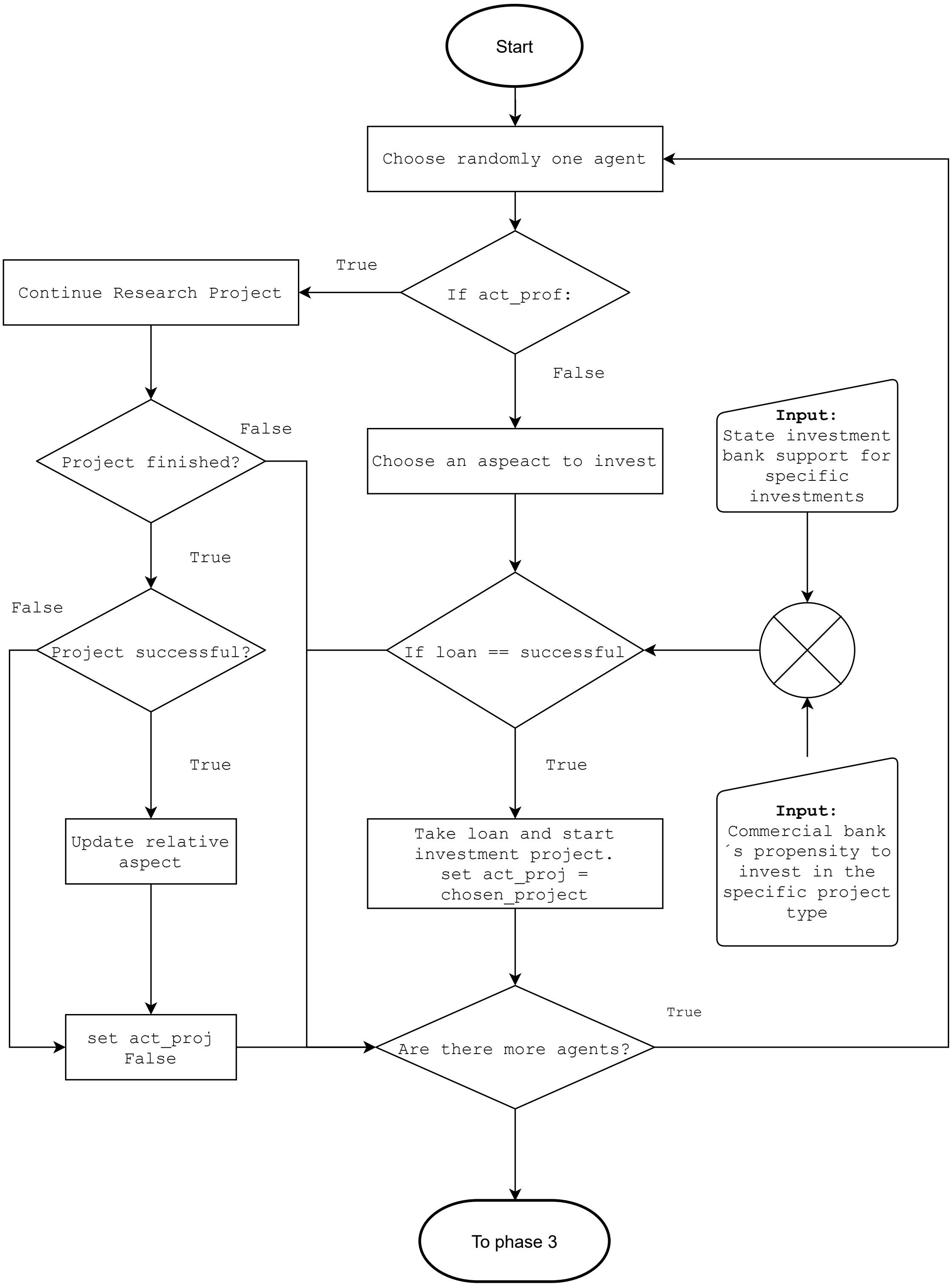


Figure 5.2: Phase two flow diagram. This diagram describes the process that firms undergo in order to receive a loan to invest in their desired project.

5.2.1 Class Diagrams

The model uses two classes:

- A Firm class, inherited from the `MESA Agent class`, representing the firms.
- An EconomyModel class, inherited from `MESA Model class`, representing the model environment.

The three other agents (consumers, commercial banks and public banks) that are active in the model's artificial economy do not have a separate class and due to their simple functioning and for model efficiency they are integrated in the EconomyModel class.

Figure 5.3 shows Firm's attributes and methods. The plus symbol in the start of each line denotes that all attributes and methods in this class are accessible by other entities. The Firm class has 20 attributes and 3 methods: (1) `update_agent_a` where firm's age and eqs. (4.4) to (4.8) referring to variable costs, fixed costs, profit, and wealth are updated for every firm, (2) `update_agent_b` which calculates the probability that every firm will be imitated based on eq. (4.4), and (3) `step` which calculates firm's competitiveness index.

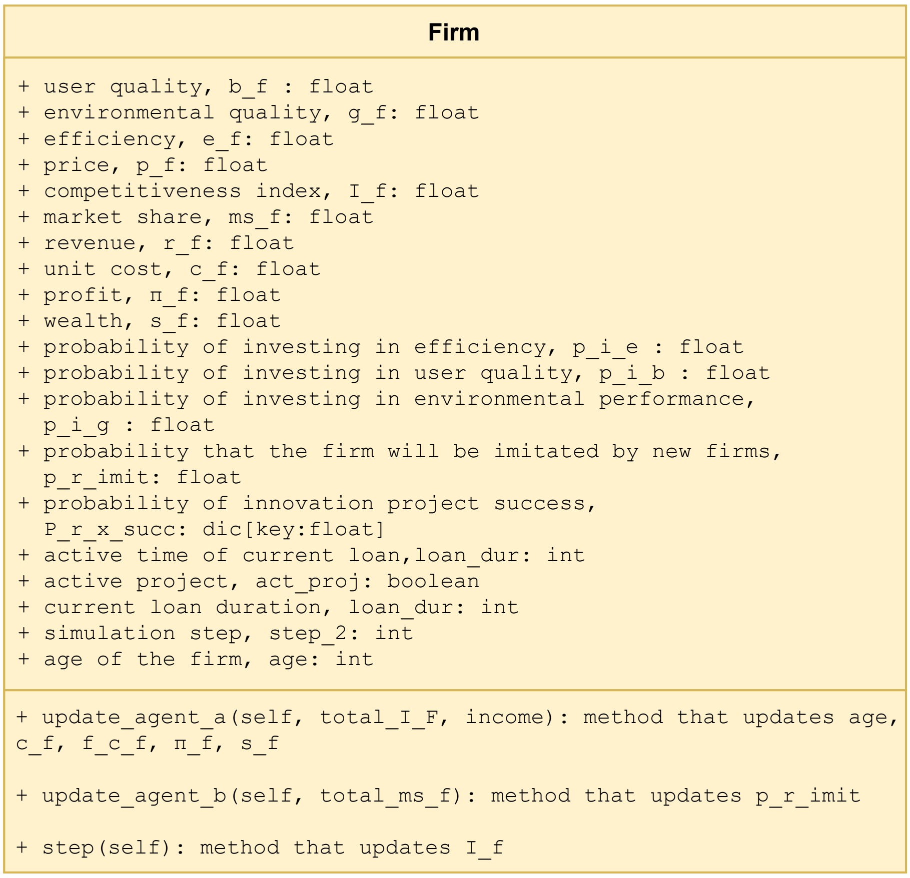


Figure 5.3: Firm class diagram

Figure 5.4 shows EconomyModel's attributes and methods. Again, the plus symbol in the start of each line denotes that all attributes and methods in this class are accessible by other entities. The EconomyModel class has 22 attributes and 2 methods: (1) the `agg_income` method where aggregate income growth and aggregate income are calculated based on the active investment projects, this method covers eqs. (4.12) to (4.14), eq. (4.18), and eq. (4.20), and (2) the `step` method which calls all the other methods and in which the 3 phases described in fig. 5.1 are embedded.

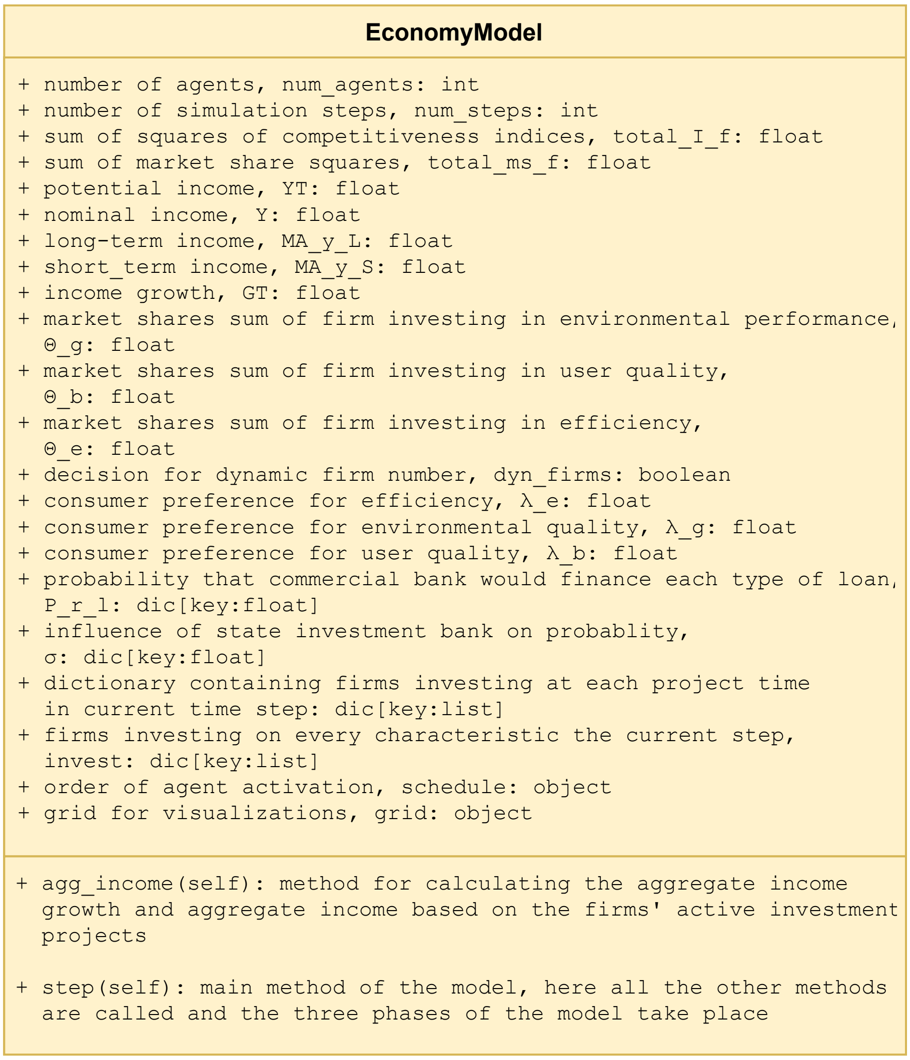


Figure 5.4: EconomyModel class diagram

The model parameters that do not change values during one or multiple runs, are, for simplicity, defined outside the class environment and are not mentioned here, these include the parameters discussed in chapter 6.

5.3 Model Interaction

The main model interaction takes place in the `ModelResults.ipynb` jupyter notebook. Figure 5.5 illustrates the module in which experiment and model parameters that vary amongst simulations are defined. In the first part of the module 5 variables are defined: (1) $seed1$, the seed that will be used in the simulation; defined for replicability of results, (2) d_steps, the number of simulation steps, (3) $d\_version$, a tag used in the name of the datasets produced by the simulation, (4) $dynamic\_firms$, a boolean variable that defines whether or not innovative firms

```
seed1 = 1
d_steps = 600
d_version = '26906a'
dynamic_firms = True
act_policies = 'base_scenario'

con_pref = {'increase':0.11666,   # 0.066666, 0.116666, 0.1666666
            'con_duration':360,
            'con_start':0 }

firm_scen0 =  [{"e_f_r": [7,13],"b_f_r": [7,13],"g_f_r": [7,13],
               "p_i_e": [0.2,0.4] , "p_i_g": [0.2,0.4] , "p_i_b": [0.2,0.4] ,
               "num": 100 }]
policies = {"base_scenario":{'λ_e' : 1/3, 'λ_b' : 1/3,'λ_g' : 1/3,
                             'pp' : 20, 'λ_start' : 1, 'λ_dur' : 1, 'λ_off': 358,
                             'σ_g' : 0, 'P_r_l_g' : 1 }}

model_params = {'ω_g' : 0.1, 'ω_b' : 0.8, 'ω_c' : 0.1,      # Impact of innovation on GDP Growth
               'G_min' : 0.985, 'G_max' : 1.015,            # Exogenous GDP growth
               'M_e' : 40, 'γ_e' : 0.015, 'p_hat' : 250,   # Efficiency curve parameters
               'α' : 20, 'μ' : 0.2, 'ψ' : 0.9, 'Φ' : 0.15, # Firms' accounts
               'δ' : 0.3,
               'Pr_new' : 1/12,                             # Market dynamics
               'η' : 0.85, 'Ω' : 0.85,
               'f_a' : 5}                 # Loans' correction factor
```

Figure 5.5: Module for model interaction in `ModelResults.ipynb` jupyter notebook. This module consists of five parts: (1) the first part in which values for the parameters controlling general simulation characteristics are defined, (2) the next part in which the scenario for consumer preferences is defined, (3) the third part, in which the characteristics of the firms that the model will be initialized with are specified, (4) the fourth part where the polices to be tested are defined, and the final (5) part in which the values of the model parameters are specified.

will attempt to enter in the market, and (5) *act_policies*, a variable that defines the active set of policies in the simulation.

In the following part of fig. 5.5 the scenario for consumer preferences is defined by specifying the increase, duration and start of the consumer preference change. In the next part the different firm scenarios used in the simulation are defined. A firm scenario consists of a finite number of firm groups where each firm group is defined by the following variables: (1) e_f_r, b_f_r, and g_f_r defining the ranges of the uniform distribution from which firms sample values for environmental performance, user quality, and efficiency respectively, (2) p_i_e, p_i_g, and p_i_b defining the ranges of the uniform distribution from which firms sample values for the three aspects of their investment strategy. [3]

In the third part of fig. 5.5 the policies tested in the simulation run are defined. The first three parameters λ_e, λ_b, and λ_g define the consumer preferences for efficiency, user quality, and environmental performance respectively. The parameter pp describes the scale of public procurement, the λ_start the time (in months) when the public procurement policy starts, λ_dur the duration of public procurement, and λ_off is used in case the public procurement is gradually withdrawn to to define the time duration (in months) of withdrawal[4]. Finally, the σ_g parameter controls the

[3] The actual probabilities are calculated by normalizing these three values; for example for a firm which during initialization samples an investment strategy with values 0.2 for efficiency, 0.25 for user quality and 0.35 for environmental performance, when normalized (divide by their sum) the corresponding probabilities become 0.25, 0.3125, and 0.4375.

[4] During the withdrawal time the public procurement level is linearly decreased from the pp level to zero.

loan guarantees scale and the parameter $P\_r\_l\_g$ controls the probability of success for an investment project aiming to improve environmental performance.

In the last part of the module illustrated in fig. 5.5 the values for a number of model parameters are defined. The model parameters are discussed in more detail in chapter 6.

Chapter 6

Design of Experiments

Chapter 5 focused on model implementation, the process of translating the equations described in chapter 4 into machine readable format. This chapter focuses on model usage and in particular on the design of experiments. In section 6.1 the parameters of the model are introduced and in section section 6.2 the parameters described in the previous section are structured according to the XLRM framework and the experiment's narrative is developed.

6.1 Model Parameters

6.1.1 Synopsis

The model in total uses 35 parameters: 6 for consumers, 9 for firms, 14 for financial aspects, and 6 for aggregate income interactions. Most parameters are used in the original model by (D'Orazio & Valente, 2019); the default parameter values D'Orazio and Valente use can be found in appendix B.1.

The tables that follow have a comments column where four different descriptive tags are used; the tags and their meaning are: (1) fixed: in the analysis the impact of alternative values for this parameter will not be explored, (2) market specific: these parameters describe an aspect of the model that may change from market to market, (3) uncertainty: general values about the future that cannot be anticipated[1][2], and (4) scenario dependent: these parameters will change values based on different scenarios[3] described later in this chapter.

6.1.2 Consumer Side Parameters

A synopsis of consumer side parameters is presented in table 6.1. Parameters λ_e, λ_b, and λ_g express the consumers' preference for the three different product aspects,

[1] The categories of market specific and uncertainties are overlapping to some extent their categorization is based on what the author of this study considers as their dominant aspect.

[2] The term uncertainty is used in the Knightian sense describing events with outcomes that cannot be tied to probabilities (Knight, 1921)

[3] These scenarios will represent different initial market conditions in the experiments.

initially they are equal to $\overline{3.3}$, but can change based on scenarios. Parameters M_e, γ_e, $\hat{p}$ control the efficiency curve defined by eq. (4.1).[4]

Table 6.1: Consumer side parameters

Parameter	Description	Value	Comments
λ_e	Consumer preference for efficiency	[0-1]	Scenario Dependent
λ_b	Consumer preference for user quality	[0-1]	Scenario Dependent
λ_g	Consumer preference for environmental performance	[0-1]	Scenario Dependent
M_e	Maximum value for efficiency	40	Fixed
γ_e	Slope of efficiency function	0.015	Fixed
$\hat{p}$	Parameter controlling the position of efficiency function	-	Fixed

6.1.3 Supply-side of the Model

A synopsis of the supply-side parameters is presented in table 6.2. F corresponds to the initial number of firms in the model; the choice for this model variable is related to an important trade-off for the experiments design, the higher the F the more computationally expensive [5] the model becomes, the smaller the F the higher the risk of losing some information due to inadequate agent interactions. For this study the experiments will be initialized with 100 firms. The reasoning behind values used for μ, ψ, and Φ is provided in section 4.3.1. Finally, for all the other parameters in this subsection default values are used.

[4] A visualization of the efficiency curve can be found in the appendix A.1. The parameter M_e defines the maximum value firm's efficiency product characteristic can have, as long as the other two firm characteristics, environmental quality and user quality have the same ranges, the actual value is not important; for this study, all three firm characteristics have ranges [0-40]. Parameter γ_e controls the slope around the mean price $\hat{p}$, the higher it is the more price sensitive the consumers are, for this study a value of 0.015 is used instead of the default 0.3 suggested by D'Orazio and Valente (2019). The reason for choosing a smaller value is in to make the curve smoother and consumers sensitive to wider range of prices.

[5] The computational costs grow exponentially.

Table 6.2: Supply side parameters

Parameter	Description	Value	Comments
F	Number of firms	100	Market Specific
Pr_{new}	Probability of new firm entrance at each step	$1 \setminus 12$	Market Specific
η	Parameter controlling the imitation	0.85	Market Specific
α	Market shares concentration parameter	20	Market Specific
μ	Price markup	0.2	Fixed
ψ	Adjustment speed of fixed costs	0.9	Fixed
Φ	Fixed costs as a percentage of revenue	0.15	Fixed
δ	Share of dividends	0.3	Fixed
Ω	Percentage the extent of imitation	0.90	Market Specific

6.1.4 Innovation, Finance and Aggregate Income

A synopsis of the aggregate income parameters is presented in table 6.3. For all the parameters in this table the default values suggested by D'Orazio and Valente are used.

Table 6.3: Aggregate income parameters

Parameter	Description	Value	Freedom
ζ	GDP adjustment speed	0.025	Fixed
ω_g	Weight for green quality	0.1	Market Specific
ω_b	Weight for user quality	0.8	Market Specific
ω_c	Weight for cost	0.1	Market Specific
G_{min}	Maximum market increase of total revenue in the market	1.015	Uncertainty
G_{max}	Maximum market decrease of total revenue in the market	0.985	Uncertainty

A synopsis of parameters related to innovation is presented in table table 6.4. For all the parameters in this table the default values suggested by D'Orazio and Valente are used.

Table 6.4: Finance of innovation parameters

Parameter	Description	Value	Freedom
L_e	Length of cost loan	4	Fixed
L_b	Length of user quality loan	4	Fixed
L_g	Length of green loan	4	Fixed
Pr_c^{succ}	Probability of success for cost loan	1	Uncertainty
Pr_b^{succ}	Probability of success for user quality loan	1	Uncertainty
Pr_g^{succ}	Probability of success for environmental performance loan	1	Uncertainty
K_g	Positive impact of innovation in green quality	0.2	Uncertainty
K_b	Positive impact of innovation in user quality	0.2	Uncertainty
K_c	Positive impact of innovation in cost	0.2	Uncertainty
Pr_l^c	Probability of getting loan for reduction	1	Fixed
Pr_l^b	Probability of getting loan for user quality improvement	1	Fixed
Pr_l^g	Probability to getting loan for environmental performance improvement	1	Fixed
f_a	Correction factor for loan probabilities	5	Fixed
σ	State investment bank parameter	[0-1]	Scenario Dependent

6.2 XLRM Framework

In the previous section out of the 35 model parameters 21 of special interest for the experiments design were identified:

- 9 categorized as market specific parameters.
- 8 categorized as uncertainties.
- 4 categorized as scenario dependent parameters.

These parameters create a vast parameter space which is computationally and conceptually demanding to explore in its entirety. For problems characterized by many uncertainties a useful conceptualization tool is the XLRM framework (Lempert, Groves, Popper, & Bankes, 2006). According to this framework X represents uncertainties outside of the control of the decision makers, L policy levers that decision makers can use to influence the system, R quantitative relationships usually represented by a simulation model, and M the performance metrics that decision makers use to evaluate the impact of the policy levers. A general visual representation of the XLRM framework is illustrated in figure fig. 6.1.

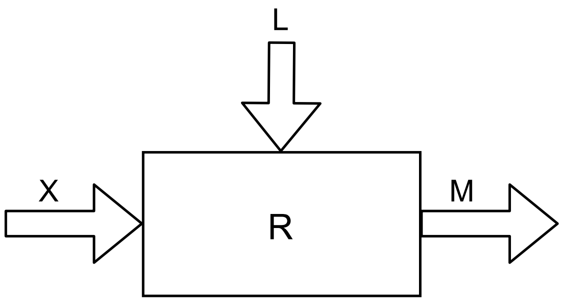


Figure 6.1: General representation of XLRM framework.

The following sections conceptualize the problem of this study according to the XLRM framework.

6.2.1 Uncertainties - X

According to the model conceptualization of this study there are three important uncertainties:

- The current and future probability of success of different investment projects.
- The positive impacts of successful investment projects in the researched aspect.
- The exogenous market conditions expressed by G_{min} and G_{max}.

These parameters are considered outside of the control of the decision makers and are included in this model as exogenous variables.[6] The success probability and the impact of successful projects will be included in the sensitivity analysis in chapter 9. The exogenous GDP growth limits will not be included in the sensitivity analysis as

[6]There could be some policies that could influence this parameters but are considered outside of the scope of this study.

due to the many parameters necessary for defining them increase significantly the computational complexity of the simulations.

6.2.2 Levers - L

As mentioned in section 2.1 the innovation policies are broadly divided into two categories: market pull and technology push. Market pull technologies aim at promoting innovation by increasing the potential market for specific innovations while technology push policies aim at promoting innovation by supporting the technology development in a specific field (Popp, 2019). For this study two policy levers are going to be explored, one market pull, public procurement and one technology push, credit guarantee schemes.

Public procurement refers to the direct purchase of goods and services by public entities. The levels of public procurement that will be explored for this study are 10 %, 15 %, and 20 %. The other policy that will be examined is a credit guarantee scheme for firms' loans used for investments in the environmental performance of their products. The loan guarantee levels that will be explored for this study are 40 %, 60 %, and 80 %. Finally, combined policies will be explored which consist of both loan guarantee policies and public procurement. Table 6.5 depicts the different policy levers that will be used for this study.

Table 6.5: Policy Levers.

Policy	Public Procurement	Loan Guarantee
LoanA	-	40%
LoanB	-	60%
LoanC	-	80%
PubProcA	10%	-
PubProcB	15%	-
PubProcC	20%	-
MixA	20%	80%
MixB	15%	80%
MixC	20%	60%

6.2.3 Model Relationships - R

Structural uncertainties are uncertainties related to the model's structure and parameters. For this study structural uncertainties are the parameters characterized as market specific in the previous subsection. These parameters can take different values for different markets but also for a given market it can be difficult to estimate an exact value. These uncertainties include the initial number of firms in the market, the impact of innovative research on GDP growth, the parameters defining the exact market dynamics[7], the market concentration parameter, and the slope of the consumers' sensitivity to prices. These market specific parameters are actually "secondary" uncertainties about the market, as the most important ones are included in the scenarios. These secondary market uncertainties could have an important impact on the robustness of the results and will be taken into consideration in the sensitivity analysis in chapter 9.

6.2.4 Metrics - M

The metrics of interest for this study are related to: (1) the evolution of the three product aspects over time and especially of environmental performance, (2) the GDP growth, and (3) the associated costs of each policy. Additionally, a number of secondary metrics are used in order to gain further insights into the impact the different policies have in the dynamics of the markets. In the following subsection the used metrics are discussed in more detail.

Diffusion of eco-innovation

In order to evaluate the effectiveness of each policy in promoting the diffusion of eco-innovation, the market share weighted average (MSWA) value of environmental performance will be inspected; in cases where descriptive metrics for each policy are provided the MSWA environmental performance will be provided for the year 2045, the midst of the simulation, and year 2070 the end of simulation. The MSWA for a product aspect of a firm is calculated as the sum of the products[8] of firm's market share[9] with the specific aspect of the firm's products at each time step. The MSWA has the advantage that takes into account each firm proportionally to its market share.

GDP Growth

In order to assess the impact of each policy in the actual GDP, the GDP at the end of the simulation run will be inspected. The market starts with an initial GDP equal to 1 million.

Policy Costs

For this metric the associated costs of each policy are calculated. The calculation of the public procurement costs are straightforward as at each time step the government contributes a certain percentage of the demand in the market. For the cost of loan guarantees a number of assumptions needs to be made in order to derive an estimation for the costs. The assumptions made are: (1) the average maturity of the loans is 3 year, (2) as a proxy for the size of the loans the short debt term ratio will be used[10] and it will be assumed that half of it is directed towards investments,

[7] The market specific structural uncertainties related to market dynamics are: the number of firms attempting to enter the market at each step, importance of market shares for the probability that a firm will be imitated, and extent to which new entrants can imitate old firms.

[8] Multiplication.

[9] Expressed as values between 0 to 1.

[10] Mc Namara, Murro, and O'Donohoe (2017) in an analysis of 34.559 european SMEs found an average ratio of short term debt obligations over total assets equal to 0.095.

(3) in order to estimate the total assets the average profitability[11] of european SMEs will be used, which is equally to 0.081 (Mc Namara et al., 2017). Based on these assumptions, the scale of the firms yearly debt obligations related to R&D can be approximated as $0.5 \times 0.095 \times revenue \setminus 0.081$.

Secondary Metrics

A useful index that will be used in this study to monitor the impact that the different policies have in the market dynamics is the Herfindahl and Hirschman Index (HHI). This market inequality index is attributed to Herfindahl and Hirschman (Hirschman, 1964), and is calculated as the sum of market share squares for firms participating in the market. For market shares expressed as percentage between 0-1, the HH index takes values from 0-1: values below 0.1 indicate an unconcentrated market, values above 0.1 and below 0.18 a moderately concentrated market, and values above 0.18 a highly concentrated market (Viscusi, Harrington, & Vernon, 2005). Another set of secondary metrics that will be monitored is the the number and percentages of loans given for environmental performance, user quality, and efficiency projects.

6.2.5 Scenarios

In order to study the effectiveness of the policies under different market conditions, a number of scenarios is developed based on the initial market characteristics. Those scenarios are created by randomly sampling the firms characteristics during initialization from uniform distributions. The firms sample values during initialization for the following characteristics:

- Environmental performance of the product.
- User quality of the product.
- Efficiency of the product.
- Parameters controlling the probability that the firm will invest in user quality, environmental performance, efficiency.

As mentioned in chapter 4 every time a firm needs to decide its next innovative project, it does so based on its investment strategy. The investment strategy of a firm is expressed as probabilities that the firm will invest on environmental performance, user quality or efficiency. The investment strategy of every firm is randomly defined during initialization by randomly sampling the three aforementioned parameters. [12]

For the base case scenario (the scenario for which validation and verification has been performed) firms during initialization sample for the three product aspects through uniform distributions with ranges (7-13) and for the parameters controlling the investment strategy from uniform distributions with ranges (0.2-0.4).

[11] Profitability is defined as earnings before interest and taxes over total assets.

[12] The actual probabilities are calculated by normalizing these three values for every firm; for example, for a firm which during initialization samples an investment strategy with parameter values of 0.2 for efficiency, 0.25 for user quality and 0.35 for environmental performance, when normalized (divide by their sum) the corresponding probabilities become 0.25, 0.3125, and 0.4375.

Part III

Results

Chapter 7

Model Validation

The model is validated based on the tests suggested by D'Orazio and Valente (2019). These validation tests aim at replicating three behaviors empirically encountered in innovative markets: pro-cyclical R&D investments, right skewed firms' size distribution, and fat tailed GDP growth distribution. The chapter starts with section 7.1 where the model configuration used in the tests is summarized and continuous with three validation sections, one for each test.

7.1 Model Configuration

In chapter 6 the model parameters and their values are introduced, for most parameters the default values suggested by D'Orazio and Valente are used (see appendix B.1); table 7.1 summarizes those with non-default values, their value, and the section where the reasoning behind the non-default value is developed.

Table 7.1: Validation Configuration: Parameters with different than default values.

Parameter	Value	Explanation
μ	0.20	section 4.3
Ψ	0.9	section 4.3
ϕ	0.15	section 4.3
δ_{long}	0.95	section 4.3
δ_{short}	0.5	section 4.3
$K_{g,b,c}$	0.1	section 6.1
M_e	40	section 6.1
γ_e	0.015	section 6.1
p_{hat}	-	section 6.1

The validation tests are executed for 600 monthly steps which correspond to the 50 year duration used by D'Orazio and Valente in their validation steps. The initial number of firms used in this validation tests is 100, the number of firms that will also be used in the simulations in the following chapters. The scenario used for this validation tests is the base case scenario, summarized in fig. 7.1.

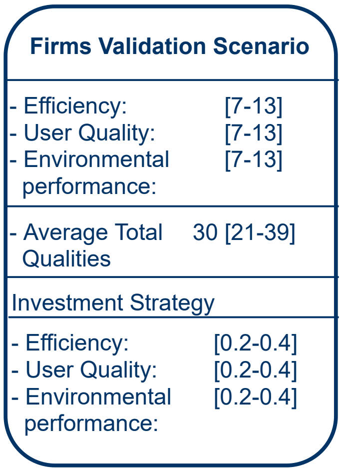


Figure 7.1: Validation Scenario - Base Case Scenario

Replicability of Results

For this section the seed used in the `numpy` random module is 1. All the results can be replicated using this seed, the `ModelValidation.ipynb` notebook, and the `Model.py` python script on `github`.

7.2 Pro-Cyclical Investments

Investment levels correlate positively with GDP growth (Wälde & Woitek, 2004; Aghion & Howitt, 2009); this positive correlation is validated in this step by plotting the graph of GDP growth rate versus investment growth rate. As a proxy for investment growth rate the change in the total market share of companies investing at each time step is used. The result for this simulation run is presented in fig. 7.2, while the ones from D'Orazio and Valente in fig. 7.3. The results replicate satisfactorily the results from the D'Orazio and Valente and especially the desired pro-cyclical investment behavior. On the other hand there are some differences in the spread and slope of the function that are possibly attributed to:

- The different metric used by D'Orazio and Valente. The metric used for this study, difference in the total market share of firms investing, can never be greater than 1 and mostly will be less than 0.3. The one used by D'Orazio and Valente has a different range as it can get values greater than 1, as seen in figure fig. 7.3.[1]
- The higher sample used by D'Orazio and Valente. D'Orazio and Valente use 2500 weekly steps to cover the 50 year gap while in this study 600 monthly steps are used. The higher number of steps results in more outliers.
- An altered growth equation is used for this study.

[1] D'Orazio and Valente do not provide information on the metric they use.

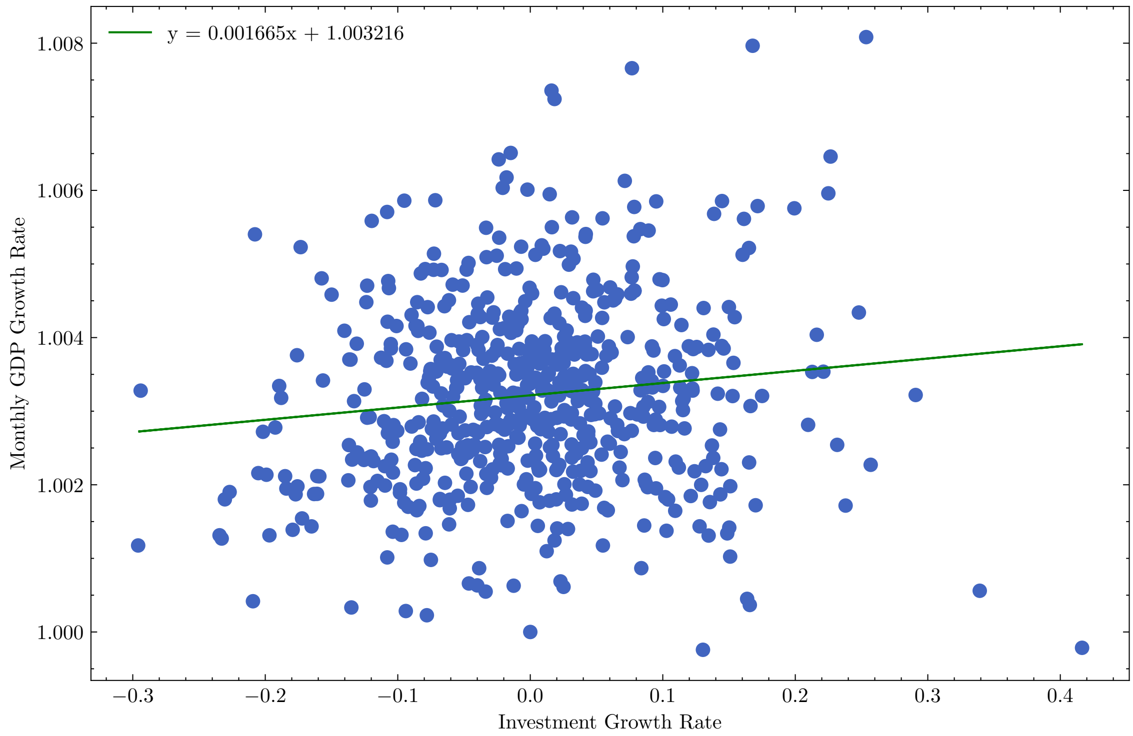


Figure 7.2: Scatter plot of investment growth rate versus GDP growth rate

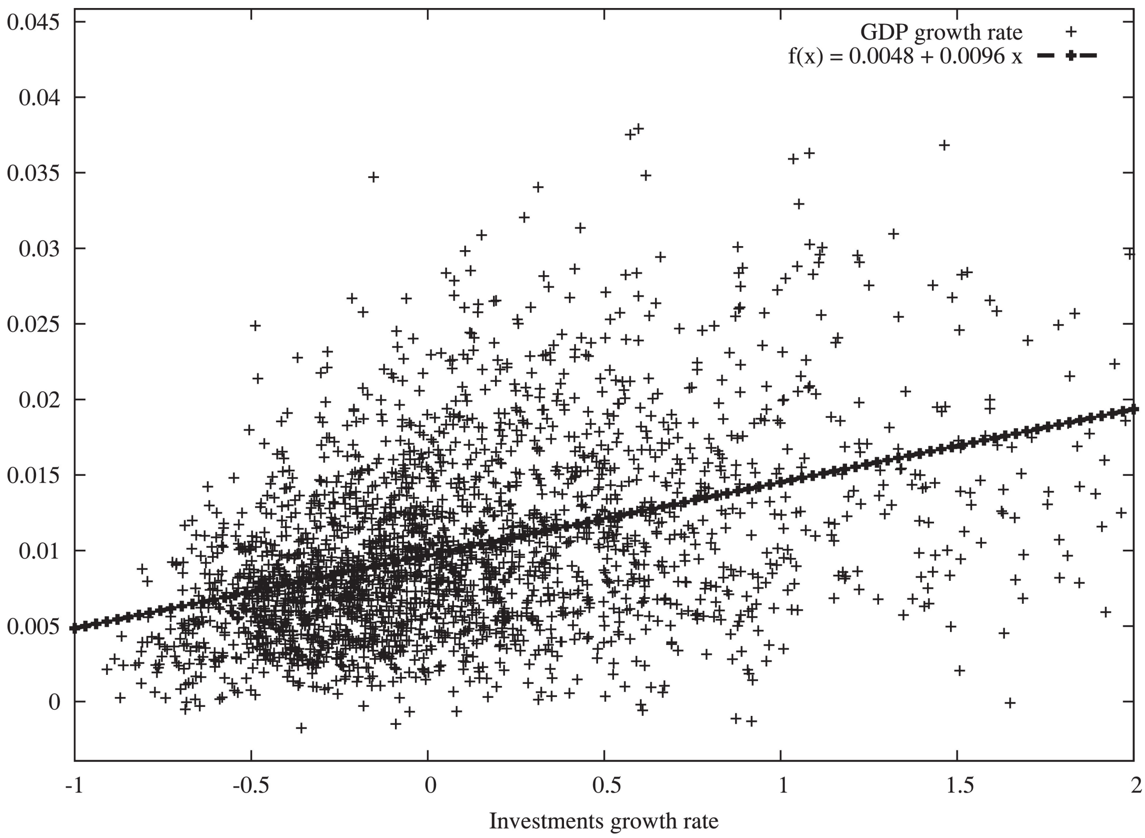


Figure 7.3: Original Scatter plot of investment growth rate versus GDP growth rate

7.3 Firms' Distribution

The second test performed by D'Orazio and Valente studies the firms' market share distribution. Right skewed distribution in firms' size is a well know empirical phenomenon that persists across economies and time (Gaffeo, Gallegati, & Palestrini, 2003). A variety of different explanations have been proposed about this phenomenon, for example Kwasnicki (1998) shows that innovation dynamics alone can lead to skewed firm's distribution. Innovation dynamics are the reason behind the skewed distribution in firms' size and for this study. Figure 7.5, where the results of D'Orazio and Valente are presented. In fig. 7.4 it can be seen that this study replicates satisfactorily the desired right skewed distribution.

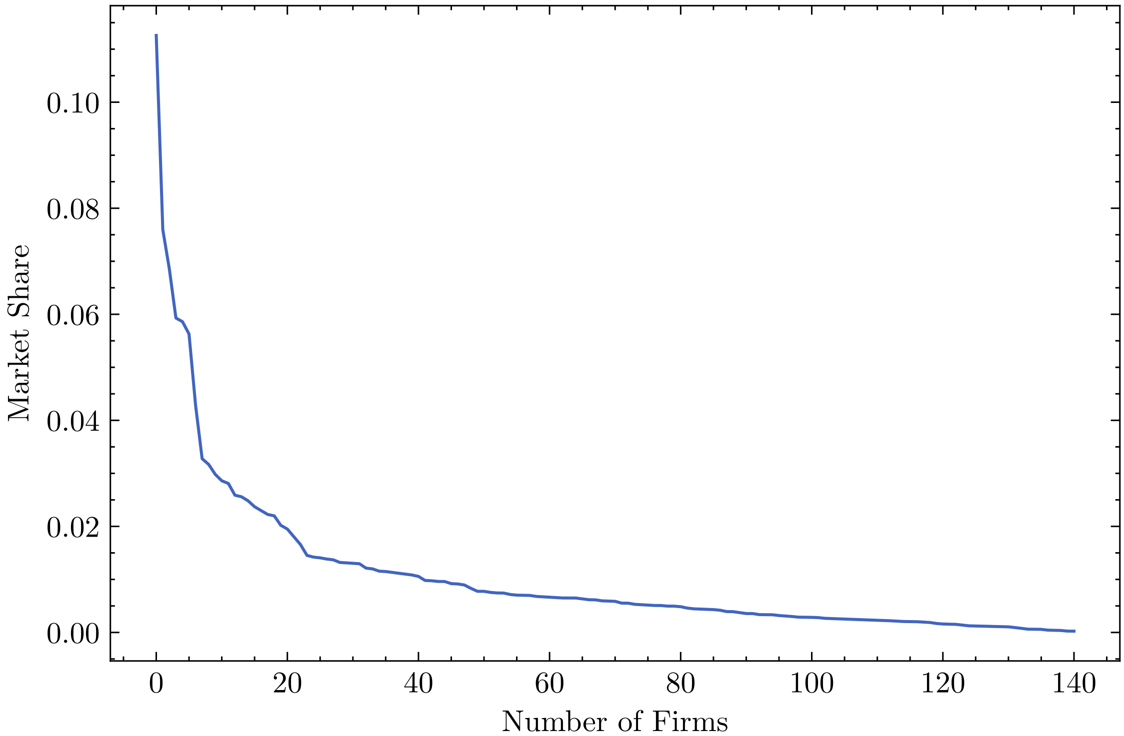


Figure 7.4: Distribution of firms market shares

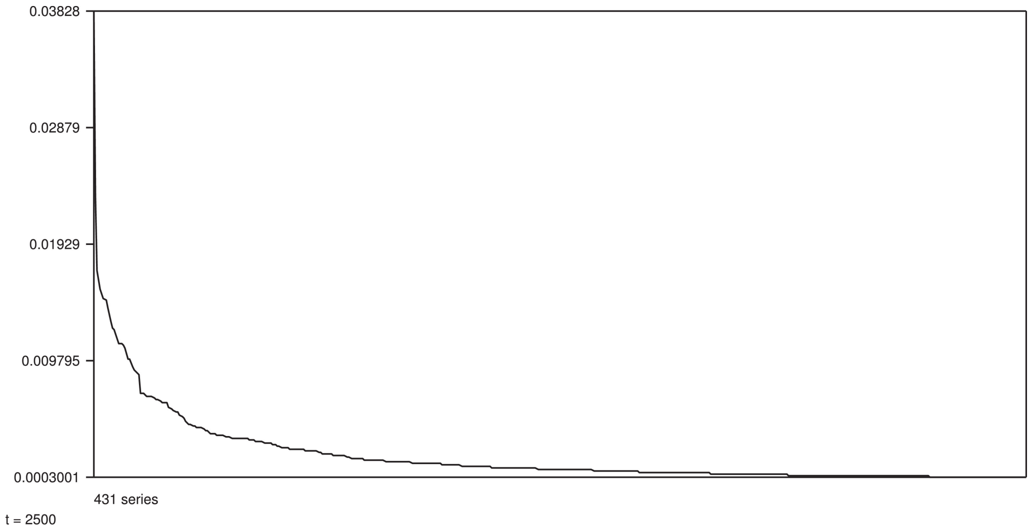


Figure 7.5: Original Distribution of firms market shares

7.4 GDP Growth Frequency

The last validation D'Orazio and Valente perform regards existence of fat tailed distribution for GDP growth. The existence of fat tails in GDP growth has been empirically confirmed by many researchers (for example Williams, Baek, Li, Park, and Zhao (2017)). The GDP growth distribution by D'Orazio and Valente is illustrated in fig. 7.7 while the one for this study in fig. 7.6. This study successfully successfully replicates the existence of fat tails in growth rate, as it can be seen in fig. 7.6.

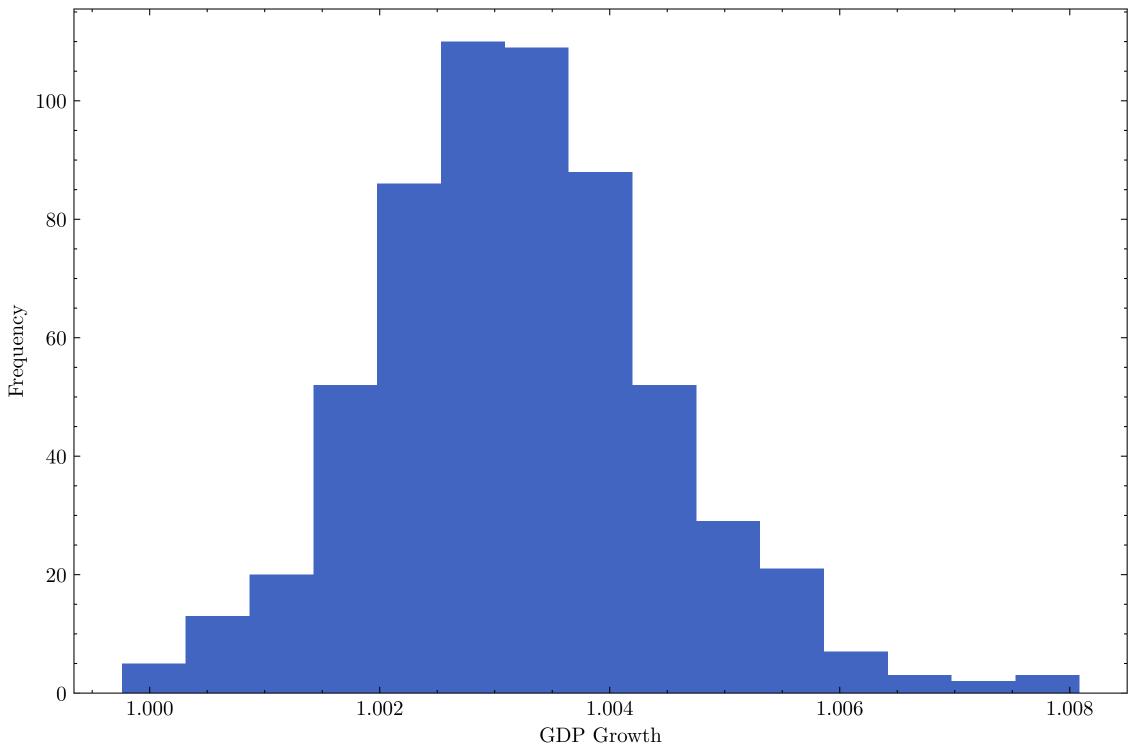


Figure 7.6: Validation test for fat-tailed distribution of GDP growth rate.

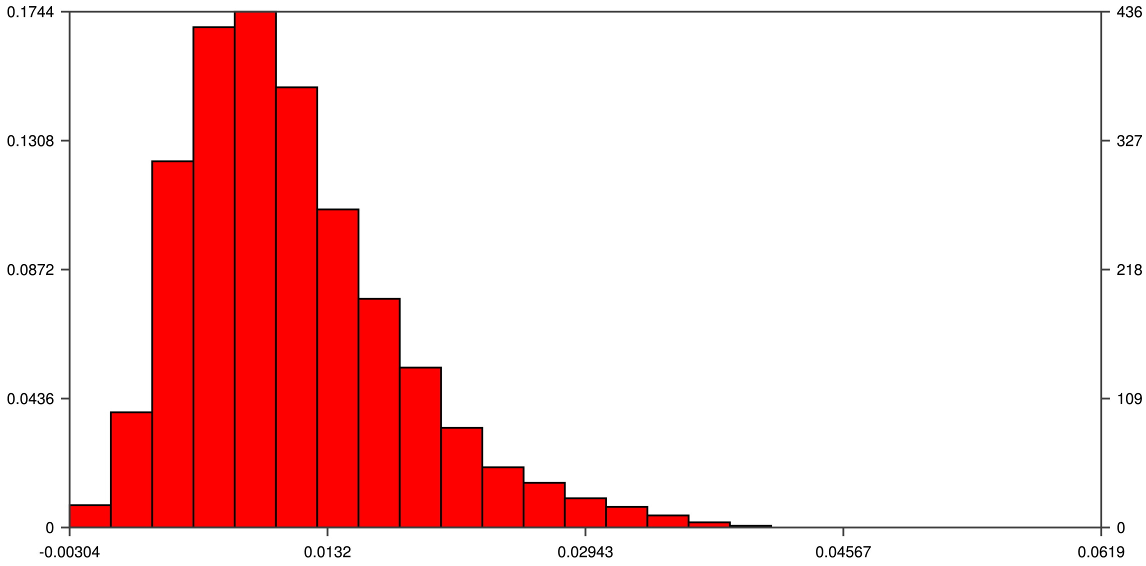


Figure 7.7: Original Frequency of GDP Growth Values

Chapter 8

Model Results

In this chapter, the outputs of simulations are presented. This chapter focuses on a high level interpretation of the results and aims at confirming some main hypothesis that both public procurement and loan guarantees foster the diffusion of eco-innovations.

8.1 Model Configuration

The model parameters during the simulation runs have the values mentioned in chapter 6, design of experiments. The simulations are executed for 600 monthly steps covering a period of 50 years. Table 8.1 illustrates the policy levers and their different levels. Parameter σ defines the level of loan guarantees provided by the State Investment Bank. The loan guarantee is active for loans provided to firms investing in their environmental performance. In the model it is implemented as an increase of value σ in the probability that the firm will get the loan from the commercial bank (see section 4.4.1). The other policy lever, λ_p corresponds to the public procurement policy. In the model it is expressed as an increase in the consumer preference related to environmental performance of λ_p and by a decrease of $\lambda_p/2$ for the consumer preferences related to efficiency and user quality. A value of 0.06 for λ_p corresponds to a government market participation of 10%, a value of 0.087 to a participation of 15%, and a value of 0.11 to a participation of 20%. The simulation runs start from the year 2020 while the public procurement policy starts from the year 2022.

Table 8.1: Policy levers.

Parameter	Value	Explanation
σ	[0.40,0.60,0.80]	Loan guarantee
λ_p	[0.06,0.087,0.11]	Procurement Parameter

Figure 8.1 depicts the firms' values during initialization. The three firms' characteristics, efficiency, user quality, and environmental performance are sampled from

uniform distributions with interval [9-11]. All the firms chose randomly at which product aspect to invest.

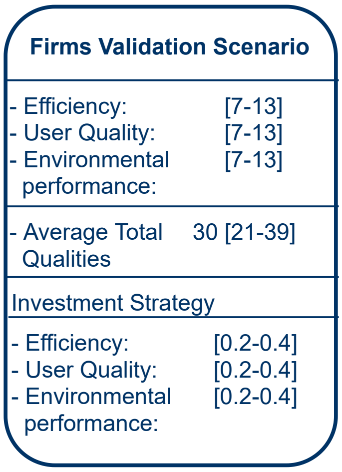


Figure 8.1: Firms' parameters for simulations.

Replicability of Results

For this section the seed used in the `numpy` random module is 1. All the results can be replicated by using this seed and the `ModelResults.ipynb` notebook and the `Model.py` python script on `github`.

8.2 Results

For each simulation in this section two main figures are presented: (1) a figure with a time-series for each firm's market share colored based on the firm's average environmental performance during the simulation run, (2) the evolution of market share weighted average for environmental performance, user quality and efficiency.

8.2.1 No Policy

Figure 8.2 illustrates the firms' market shares evolution and the market share weighted average for environmental quality, user quality, and efficiency for the base case scenario. Some remarks based on those two figures: (1) the market preserves the right skewed distribution in firms size[1], (2) despite preserving the right skewed distribution the market becomes more concentrated in terms of market shares over time, (3) regardless of the firm's size, firms can rapidly lose market share and as a results exit the market due to poor financial health[2], (4) the MSWA of the three characteristics increases by similar levels for the three product aspects: by around

[1] A small number of big firms and a big number of smaller ones. This is a commonly encountered behavior in markets (Gaffeo et al., 2003) which was also used as a validation test in chapter 7.

[2] This result although not surprising in real world in this simulation, without something changing in the environment, might seem surprising. There are two main reasons for this behavior: (1) this model is focused in small and medium sized enterprises and there is no mechanism for firms having greater market share gaining a competitive advantage and securing their market dominance, (2) there are feedback mechanisms that can lock a firm in a descending market share trajectory: for

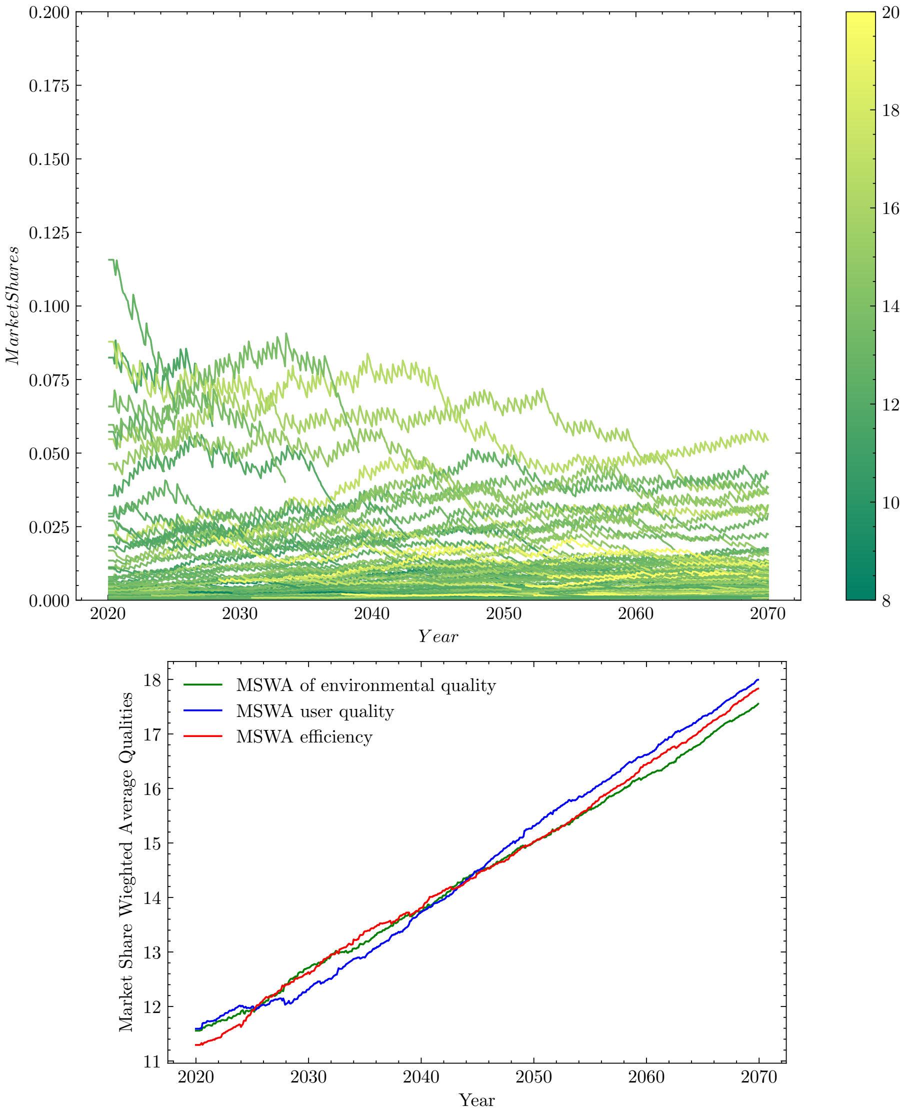


Figure 8.2: Simulation results for no policy scenario: top graph illustrates the evolution of firms' market shares, bottom graph the market share weighted average of environmental performance, user quality, and efficiency.

6 points for environmental performance from 11.5 to 17.5, by 6.5 for efficiency from 11.2 to almost 18, and by 6.5 for user quality from 11.5 to 18.

8.2.2 Public Procurement Policy

In fig. 8.3 the impact of a public procurement policy of 20 % starting at 2022 can be inspected. There is a number of remarks that can be made for this figure: (1) public procurement has a strong positive impact in the diffusion of environmental products, in particular the MSWA value of environmental performance reaches the value of 20 by the end of the simulation compared to 17.5 in the no policy scenario,

instance, once a firm starts losing market share, the inertia of the fixed long term costs compromises its profits and wealth and reduces its financial health, as a result the commercial banking sector becomes more reluctant in giving loans to those firms, which start becoming less competitive due to less research.

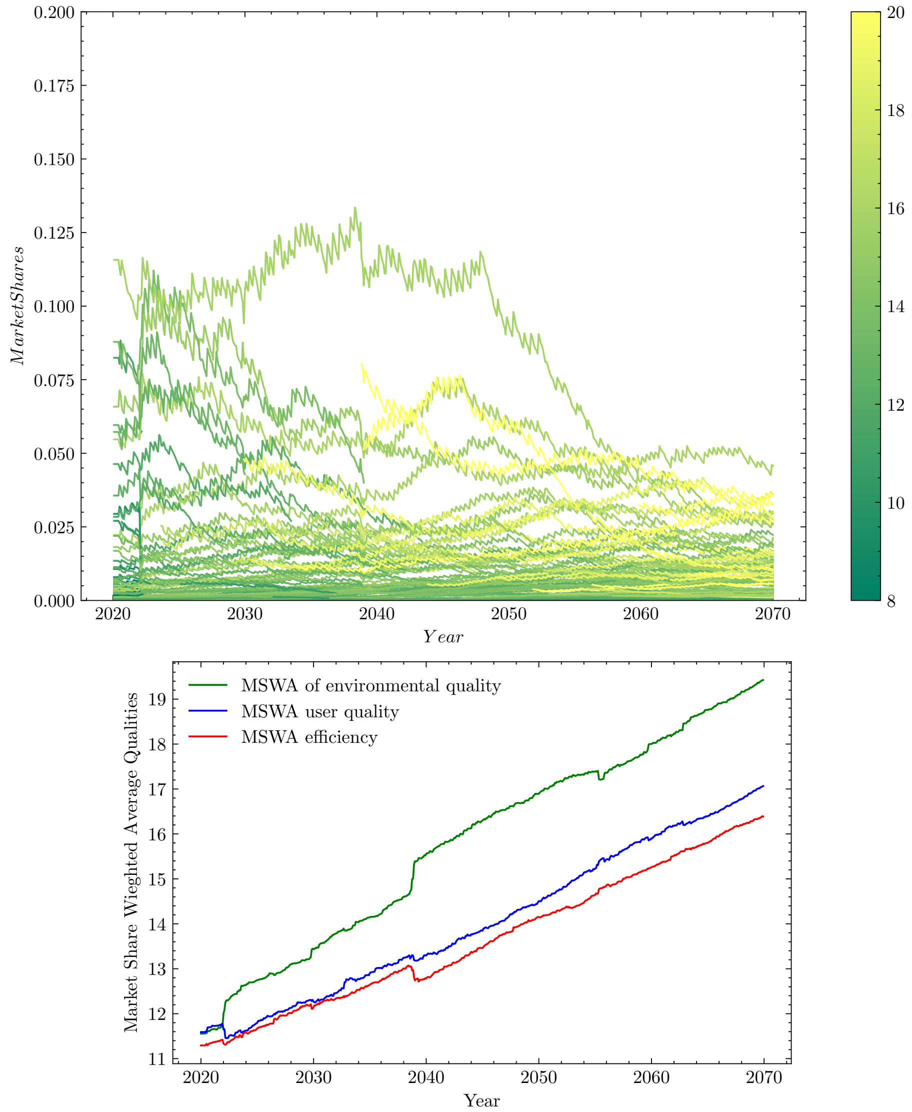


Figure 8.3: Simulation results for maximum public procurement of 20%: top graph illustrates the evolution of firms' market shares, bottom graph the market share weighted average of environmental performance, user quality, and efficiency.

(2) the other two product aspects are slightly underdeveloped compared to the no policy scenario, user quality reaches an average value of 17 compared to 18 in the no policy scenario, efficiency reaches a value slightly less than 16.5 compared to 18 in the no policy scenario, (3) the market preserves its skewed distribution in the firm size, (4) the market seems less concentrated compared to the no policy scenario.

8.2.3 Loan Guarantee Policy

In fig. 8.4 the impact of SIB providing a loan guarantee of 80 % can be inspected. There is a number of remarks that can be made for this figure: (1) the loan guarantee policy has a strong positive impact in the diffusion of products with better environmental performance, in particular the MSWA value of environmental performance reaches the value of 21 by the end of the simulation compared to 17.5 in the no policy scenario, (2) the other two product aspects are slightly underde-

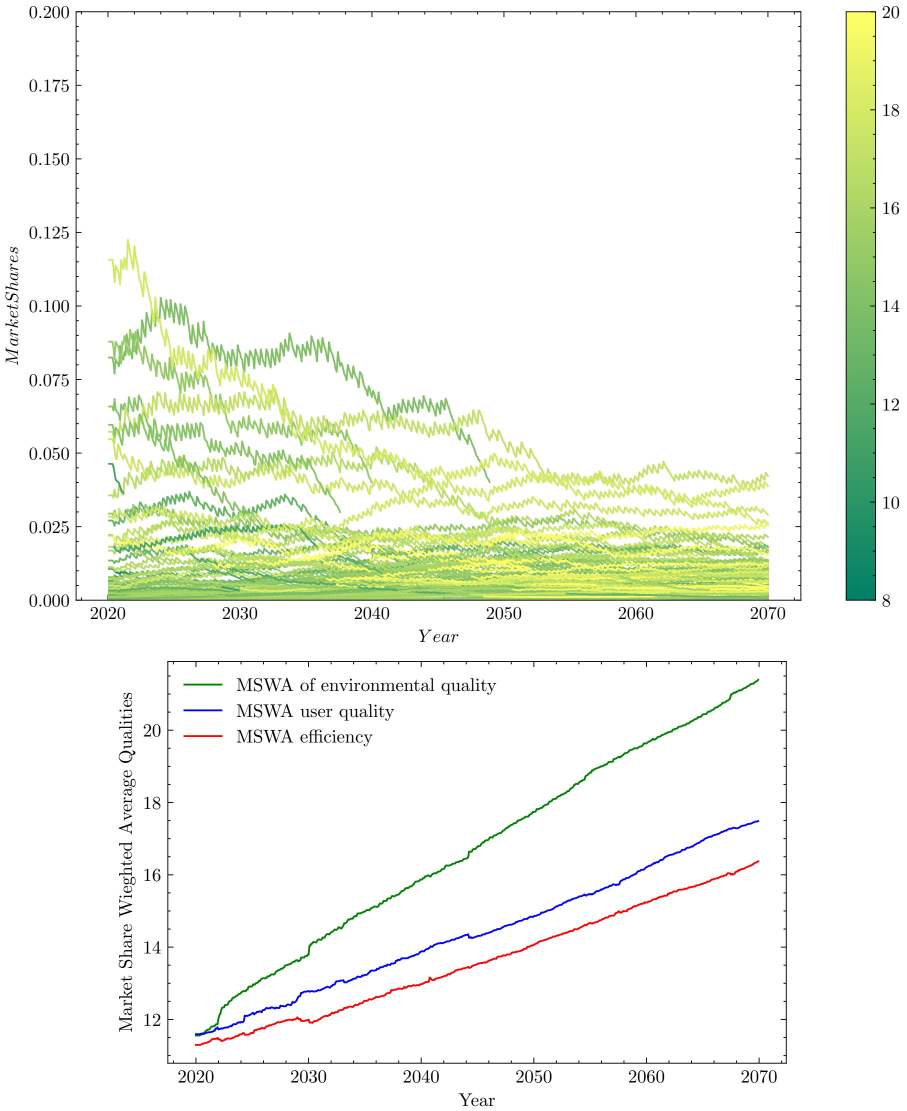
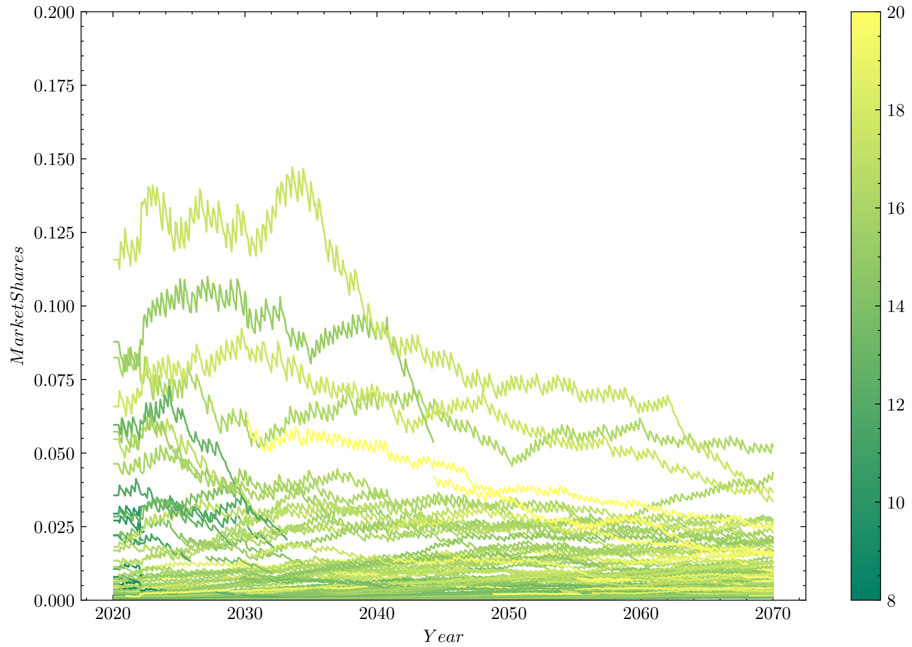


Figure 8.4: Simulation results for maximum loan guarantee policy of 80%: top graph illustrates the evolution of firms' market shares, bottom graph the market share weighted average of environmental performance, user quality, and efficiency.

veloped compared to the no policy scenario, user quality reaches an average value of 17.5 compared to 18 in the no policy scenario, efficiency reaches a value slightly less than 16.5 compared to 18 in the no policy scenario, (3) the market preserves its skewed distribution in the firm size, (4) the market seems more concentrated compared to the no policy scenario, (5) for the current simulation configuration the loan guarantee policy seems more effective than the public procurement policy.

8.2.4 Mixed Policy

In this subsection the impact of a combined policy will be explored, the combined policy consists of loan guarantees of 60% and public procurement of 10%. There is a number of remarks that can be made regarding this figure: (1) the mixed policy has a strong positive impact in the diffusion of products with better environmental performance, in particular the MSWA value of environmental performance reaches



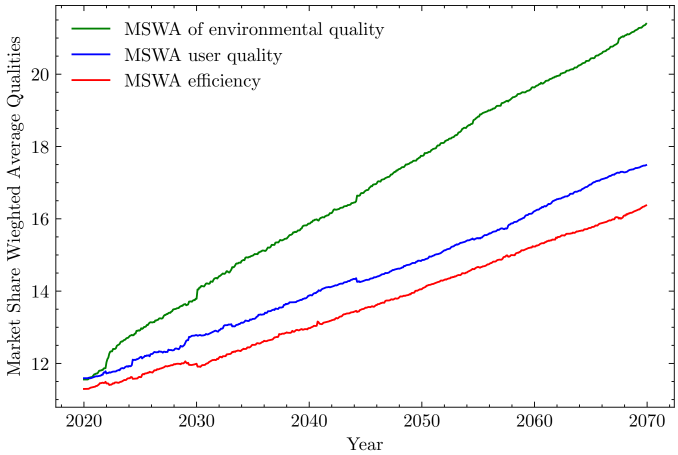


Figure 8.5: Simulation results for mixed policy consisting of loan guarantees of 60 % and public procurement policy of 10%.: top graph illustrates the evolution of firms' market shares, bottom graph the market share weighted average of environmental performance, user quality, and efficiency.

the value of 21.5 by the end of the simulation compared to 17.5 in the no policy scenario, (2) the other two product aspects are slightly underdeveloped compared to the no policy scenario, user quality reaches an average value of 17.5 compared to 18 in the no policy scenario, efficiency reaches a value slightly less than 16.5 compared to 18 in the no policy scenario, (3) the market preserves its skewed distribution in the firm size, (4) the market seems less concentrated compared to the no policy scenario, and (5) for the current simulation configuration it seems that substituting a part of the loan guarantees with public procurement increases the diffusion of products with improved environmental aspect.

8.2.5 Impact of Change in Consumer Preferences

In this subsection the impact changing consumer preferences is explored explored. In the previous simulations consumer had equal preference for the three product aspect equal to 1\3. In this simulation the impact of consumer preference for the environmental aspect of the products is increasing to 0.5, while for the other two product aspects, user quality and efficiency, is decreasing to 0.25, over the course of 30 years. The evolution of consumer preferences for this simulation scenario can be inspected in fig. 8.6.

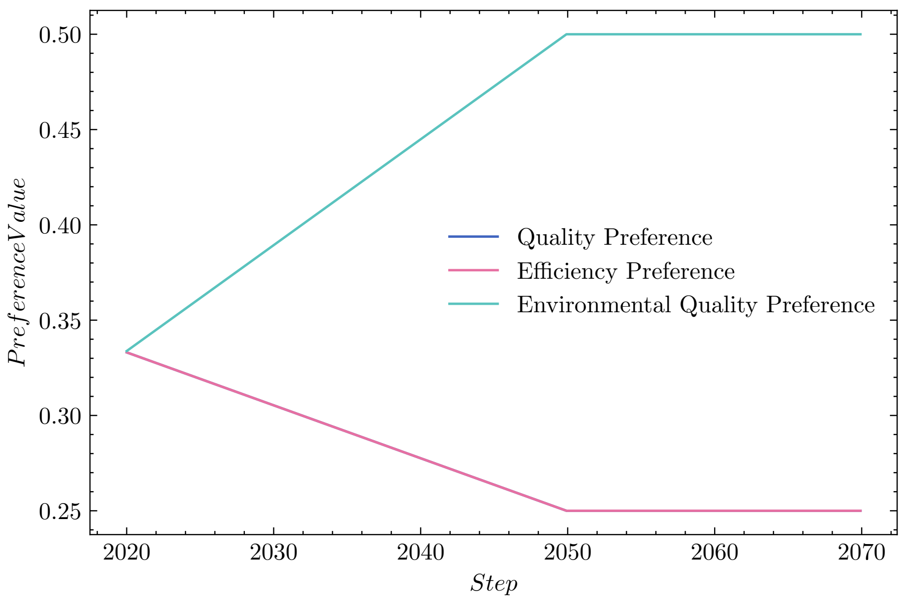


Figure 8.6:
Changing consumer preferences scenario: consumer preferences

The impact the change in consumer preferences has in the market and in the MSWA qualities of environmental performance, user quality, and efficiency can be inspected in fig. 8.7. There is a number of remarks that can be made regarding this figure: (1) the increase of consumer preference for the environmental aspect of products has a strong positive impact in the diffusion of products with better environmental performance, in particular the MSWA value of environmental performance reaches the value of 20.5 by the end of the simulation compared to 17.5 in the no policy scenario, (2) the other two product aspects are slightly underdeveloped compared to the no policy scenario, user quality reaches an average value of 16.5 compared to 18 in the no policy scenario, efficiency reaches a value slightly less than 16 compared to 18 in the no policy scenario, (3) the market preserves its skewed distribution in the firm size, and (4) the market seems less concentrated compared to the no policy scenario.

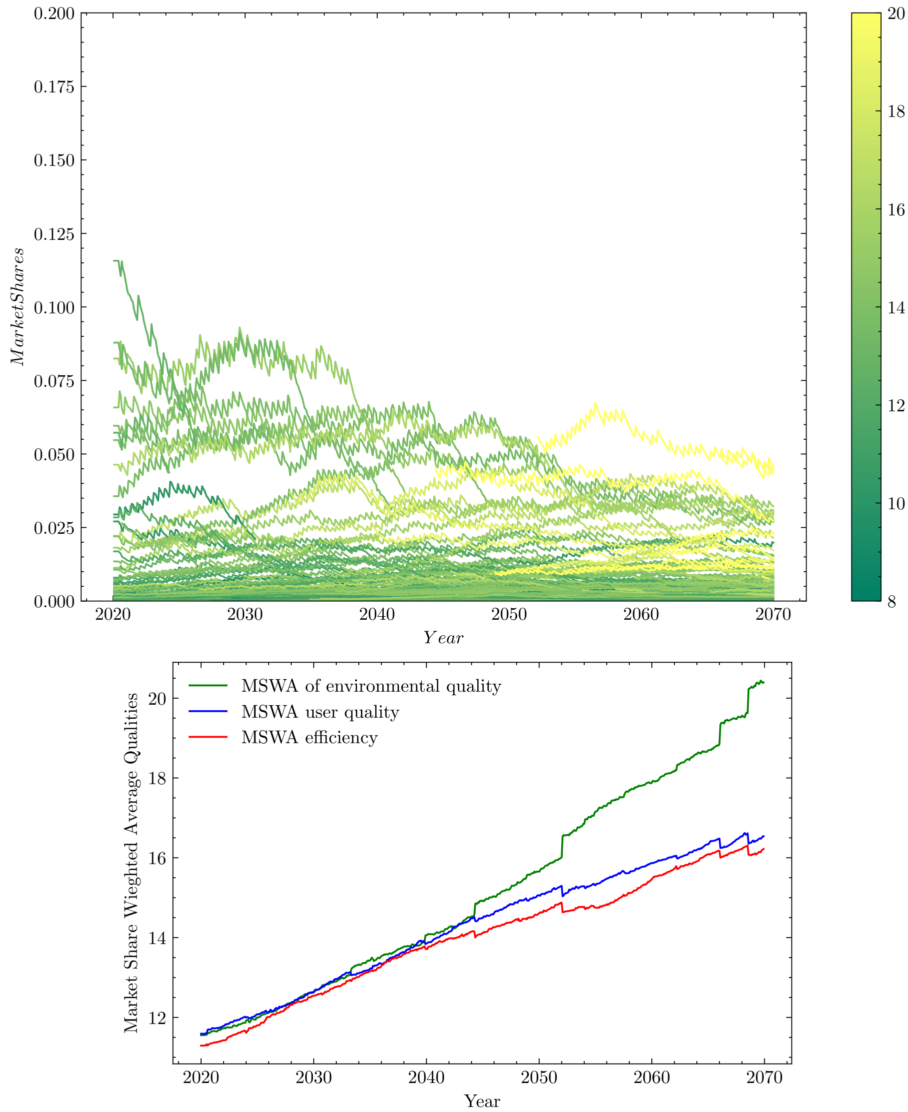


Figure 8.7: Simulation results for mixed policy consisting of loan guarantees of 60 % and public procurement policy of 10%.: top graph illustrates the evolution of firms' market shares, bottom graph the market share weighted average of environmental performance, user quality, and efficiency.

Chapter 9

Analysis

Chapter 8 focuses on a higher level presentation of the results and confirms the positive effect that both public procurement and loan guarantee policies have in promoting the diffusion of products with better environmental performance. This chapter focuses on a more in depth analysis of the results presented in chapter 8.

9.1 Introduction

In this chapter a number of different policies are evaluated. The policies consist of three loan guarantee policies (40%, 60%, and 80%), three public procurement policies (10%, 15%, and 20%[1]), and a combination of those policies.

The policies will be evaluated based on the metrics presented in chapter 6. The first set of metrics is related to the main KPIs of this study: diffusion of environmental performance, costs of implemented policies, real GDP growth, and are presented in table 9.1. A second set of metrics, not directly related to the KPIs of this study, but useful for gaining insights in the impact of policies on the market dynamics is also used; these secondary metrics are summarized in table 9.1.

Table 9.1: Metrics related to main KPIs

Metric	Explanation
GDP 2070	Real monthly GDP of the market in year 2070
Env. Per. 2045	MSWA of environmental per. in year 2045
Env. Per. 2070	MSWA of environmental per. in year 2070
Costs	Total costs of implemented policies

[1]Public expenditure as percentage of total market revenue

Table 9.2: Secondary Metrics

Metric	Explanation
HHI Max	Maximum of market inequality index HHI
HHI Mean	Mean of market inequality index HHI
HHI Min	Minimum of market inequality index HHI
Old F. 2045	Number of initial firms in the market by year 2045
Old F. 2070	Number of initial firms in the market by year 2070
New F. 2045	Number of new firms in the market in year 2045
New F. 2070	Number of new firms in the market in year 2070
Avg. Total F.	Average number of firms in the market during the simulation run
Green loans	Number of green loans given to firms
Green Loans %	Percentage of green loans over total loans given to firms
No Loans %	Percentage of time firms are not involved in innovative projects
Qual. 2070	MSWA of the user quality product aspect at they year 2070
Effic. 2070	MSWA of the efficiency product aspect at they year 2070

Replicability of Results

For this section the seed used in the `numpy` random module is 1. All the results can be replicated by using `ModelSensitivities.ipynb` and `ModelResults.ipynb` notebooks and the `Model.py` python script on `github` with this seed.

9.2 Results

The simulations that follow are performed for the base case scenario. Figure 9.1 depicts the firms' characteristics during initialization for this scenario. All firms are initialized by randomly sampling values for their three product aspects from uniform distributions with ranges [7-13]. Additionally, during initialization firms are randomly assigned an investment strategy (probability that they will invest in a given aspect when deciding the next innovative project) by randomly sampling values from uniform distributions with intervals [0.2-0.4].[2] Finally, all the simulations are executed for one hundred different runs in order to account for the inherent model uncertainty. This inherent model uncertainty is a result of: (1) the randomness in the firm initialization process, (2) the randomness incorporated in the firms' investment process, and (3) the randomness inherent to the imitation process.

[2]The actual probabilities are calculated by normalizing these three values for every firm; for example, for a firm which during initialization samples an investment strategy with values 0.2 for efficiency, 0.25 for user quality and 0.35 for environmental performance, when normalized (divide by their sum) the corresponding probabilities become 0.25, 0.3125, and 0.4375.

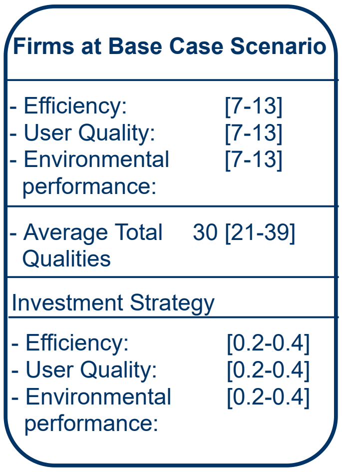


Figure 9.1: Base Case Scenario: All firms have average user quality, environmental performance, and efficiency of 10. Firm´s have an investment strategy that does not prioritize any of the product aspects.

9.2.1 No Policies

The results over the 100 runs for the no policy scenario are summarized in table 9.3. This is the reference scenario based on which the policies are evaluated. Some general findings for this scenario are: (1) the MSWA of user quality, environmental performance, and efficiency reach on average similar values by the end of the simulation, (2) the market remains unconcentrated for the vast majority of time as on average the maximum value of HH Index is equal to 0.072 and the HH Index mean on average is equal to 0.035, (3) the final GDP has a high standard deviation indicating that the different scenarios exhibit wide spread in terms of final GDP. Inspecting the data for the 5 worst and 5 best scenarios in terms of GDP can give insights in why this is happening. In particular the five worst performing GDP scenarios have: average GDP of 6.4 million, average MSWA of environmental performance at 2070 17.8, average MSWA of user quality at 2070 17.2, average MSWA of efficiency at 2070 18.15. On the other hand the five best performing GDP scenarios have: average GDP of 9.3 million, average MSWA of environmental performance at 2070 17.8, average MSWA of user quality at 2070 18.4, average MSWA of efficiency at 2070 17.69. These data indicate that in markets where firms are performing better on user quality the GDP growth is significantly stronger. This is a direct consequence of the assumption that user quality innovations contribute significantly to GDP growth.

9.2.2 Loan Guarantee Policies

In this section the impact of loan guarantee policies for the base case scenario is explored. The averages of 100 simulation outcomes for the different levels of guarantees are summarized in table 9.4.

The scale of loan guarantees correlates positively with: (1) the number and percentage of loans directed towards investments in environmental performance, (2) the MSWA value of environmental performance both in 2045 and 2070, (3) the total costs of the policy, (4) the average number of firms in the market during

Table 9.3: Base case no policy results

Metric	Mean	Standard Deviation	Metric	Mean	Standard Deviation
Env. Per. 2045	14.53	0.39	Old F. 2045	77.3	5.17
Env. Per. 2070	17.77	0.37	Old F. 2070	72.2	5.23
Qual. 2070	17.8	0.38	New F. 2045	19.3	4.31
Effic. 2070	17.7	0.34	New F. 2070	40.3	5.97
GDP 2070	7.29	0.736	Green Loans %	33.4	0.975
HHI Mean	0.035	0.008	No Loans %	29.35	0.007
HHI Max	0.072	0.026	Green loans	3520	220
HHI Min	0.018	0.03	Costs	0	0
Avg. Total F.	99.47	5.34			

the simulation, (5) the number of initial firms in the market both in 2045 and 2070. The positive impact on the number of environmental performance loans is to be expected as with the loan guarantee the commercial bank is willing to finance riskier firms who wish to invest in their environmental performance. The higher values for MSWA of environmental performance are a result of: (1) the higher number of loans directed towards environmental performance and (2) the increased probability innovative firms entering the market will try to imitate a firm with high environmental performance.[3] The positive correlation between the loan guarantee scale and the cost of the policy is the result of loan provision to riskier firms. The increase in the total number of firms in the market can be attributed to the increase in the number of initial firms that survive in the market, while the increase in the number of initial firms surviving in the market can be attributed to the help provided by the loan guarantees.

The scale of loan guarantees seems to correlate negatively with: (1) the percentage of time firms are not undertaking any innovative project, and (2) the final MSWA of user quality and efficiency. The percentage of time firms are not undertaking projects (Per. of no Loans) is decreasing because of the increased number of environmental performance loans. The final MSWA of user quality and environmental performance is decreasing because firms focused on those aspects are slowly losing market share.

9.2.3 Public Procurement Policies

In this section the impact of public procurement policies is explored. The averages of 100 simulation outcomes for the different levels of public procurement are summarized in table 9.5.

The level of public procurement seems to correlate positively with: (1) the min,

[3]The probability that a firm will be imitated by a firm entering the market is a function of its market share (see eq. (4.10)), as a result, firms with an environmental performance strategy are having easier access to finance for environmental performance investments, become more competitive, and finally increase their market shares.

Table 9.4: Loan guarantee policy performance, averages over 100 simulations.

Metric	Base Case	40 % Loan Guarantee	60 % Loan Guarantee	80 % Loan Guarantee
Env. Per. 2045	14.53	15.44	15.85	16.23
Env. Per. 2070	17.77	19.64	20.49	21.27
Qual. 2070	17.8	17.32	17.19	16.99
Effic. 2070	17.7	17.35	17.16	16.98
GDP 2070	7.29	7.34	7.23	7.02
HHI Mean	0.035	0.034	0.033	0.032
HHI Max	0.072	0.072	0.072	0.071
HHI Min	0.018	0.017	0.016	0.016
Avg. Total F.	99.47	102.9	103.9	105.3
Old F. 2045	77.3	80.8	82.2	83.6
Old F. 2070	72.2	76.2	77.9	79.9
New F. 2045	19.3	19.2	19.5	19.2
New F. 2070	40.3	41.4	41.4	42.1
Green Loans %	33.4	41.16	44.53	47.37
No Loans %	29.35	25.3	23.52	21.95
Green loans	3520	4746	5312	5844
Costs PP	0	0	0	0
Costs LG	0	0.12	0.2	0.27

mean and maximum HH index, (2) the real GDP at year 2070, (3) the MSWA value of environmental performance, both in 2045 and 2070, and, (4) the total cost of the policy. Public procurement policy seems to be more market disruptive than loan guarantee policies as less of the initial firms survive, compared to the base case, both by 2045 and by 2070, which results in all the metrics relative to HH market inequality index to increase. The positive impact of public procurement on the GDP can be attributed multiplicative effect of the initial positive contribution to the GDP. The positive impact on the MSWA of environmental performance can be attributed to the increased market share that firms which have products that perform well in environmental performance take. Finally, public procurement is a rather costly policy as contributing a certain percentage of the demand in the market every month is costly. On the other hand the induced increase in the overall GDP counterbalances that. More specifically, for the public procurement policy of 10% the overall costs are estimated to be 214 million euros while the total increase over those years in the GDP is estimated to be around 582 million. Furthermore, the costs associated with the 15% procurement policy are estimated to be 335 million while the overall increase in GDP is 804 million and finally the costs associated with the 20% procurement policy are 466 while the overall increase in GDP 978 million. In other words for every euro of public procurement spent the 10% policy produces 2.72, the 15% policy produces 2.4, and the 20 % policy produces 2.09 euros.

Table 9.5: Public procurement policy performance, averages over 100 simulations.

Metric	Base Case	10 % PP	15 % PP	20 % PP
Env. Per. 2045	14.53	15.57	16	16.29
Env. Per. 2070	17.77	19.17	19.9	20.51
Qual. 2070	17.8	17.20	16.86	16.59
Effic. 2070	17.7	17.08	16.77	16.41
GDP 2070	7.29	8.26	8.63	8.92
HHI Mean	0.035	0.040	0.043	0.045
HHI Max	0.072	0.081	0.085	0.085
HHI Min	0.018	0.022	0.025	0.027
Avg. Total F.	99.47	79.3	72.6	68.3
Old F. 2045	77.3	57.9	51.2	45.9
Old F. 2070	72.2	53.2	46.4	40.1
New F. 2045	19.3	18.3	18.2	19.0
New F. 2070	40.3	40.1	38.7	39.2
Green Loans %	33.4	33.65	33.92	34.26
No Loans %	29.35	30.05	30.47	30.96
Green loans	3520	2802	2566	2423
Costs	0	214.09	335.89	466

The level of public procurement seems to correlate negatively with: (1) the MSWA value of user quality and efficiency in year 2070, (2) the total number of firms in the market, (3) the number of firms initially in the market that survive by 2045, (4) the number of firms initially in the market that survive by 2070, and, (5) the number of green loans. The drop in the MSWA of user quality and efficiency is expected as firms that perform better in environmental performance are rewarded due to the increased demand for products with higher environmental performance. The drop in the number of firms takes place due to the market disruptiveness of the public procurement policy, which results in firms that don't have products that perform well in terms of environmental performance to lose significant market shares. Finally, the drop in the number of sustainability loans given is due to the fact that less firms exist in the market.

9.2.4 Combined Policies

In this section the impact of combined policies is explored. The averages of 100 simulation outcomes for the three combined policies, the maximum loan guarantee policy, and the maximum public procurement policy are illustrated in table 9.5. In terms of final MSWA value of environmental performance the best performing policy is the combined policy of a 20% public procurement with a loan guarantee of 80%. There are three important trade-offs related to this policy: (1) the maximum public procurement policy of 20% is more effective at increasing the GDP in the market and its cost performance is better (2.09 euros return for every euro spent) compared to that of the combined policy (1.29 euros return for every euro spent), (2) it is significantly more market disruptive than any other policy examined in this section, (3) it has the least positive impact on the final values of MSWA of user quality and efficiency than any other policy. Figure 9.2 illustrates the impact of the five examined policies in MSWA of environmental performance over the 100 scenarios.

Table 9.6: Performance of combined policies, average over 100 simulations.

Metric	Loan 80%	PP 20 %	PP20 % Loan 80%	PP15 % Loan 80%	PP20 % Loan 60%
Env. Per. 2045	16.23	16.29	18.15	17.86	17.8
Env. Per. 2070	21.27	20.51	24.13	23.59	23.48
Qual. 2070	16.99	16.59	15.81	16.07	15.85
Effic. 2070	16.98	16.41	15.78	15.96	15.93
GDP 2070	7.02	8.92	8.24	7.75	8.18
HHI Mean	0.032	0.045	0.043	0.041	0.043
HHI Max	0.071	0.085	0.086	0.085	0.085
HHI Min	0.016	0.027	0.024	0.022	0.025
Avg. Total F.	105.3	68.3	70.46	75.1	69.30
Old F. 2045	83.6	45.9	49.2	53.8	48.1
Old F. 2070	79.9	40.1	45.2	50.3	43.2
New F. 2045	19.2	19.0	18.2	18.5	18.1
New F. 2070	42.1	39.2	38	38.7	38.1
Green Loans %	47.37	34.26	48.3	48.1	45.6
No Loans %	21.95	30.96	22.94	22.78	24.9
Green loans	5844	2423	3937	4182	3561
Costs PP	0	466	441	313.5	441.6
Cost LG	0.27	0	0.65	0.51	0.46

9.2.5 Consumer Preferences

Consumer preferences and no policies

The previous simulations were performed under the assumption that consumer preference for the three different product aspects will remain constant and equal to $1 \setminus 3$. In this section the impact of changing consumer preferences will be explored. More specifically three different scenarios for the consumer preferences are simulated: (1) consumer preference for the environmental performance of the products increases to 0.4 by 2050 and for the other two product aspects reduces to 0.3, (2) consumer preference for environmental performance increases to 0.45 by 2050 and for the other two product aspects reduces to 0.275, and (3) consumer preference for environmental performance increases to 0.5 by 2050 and for the other two product aspects reduces to 0.25. The results of those three simulations are summarized in table 9.7.

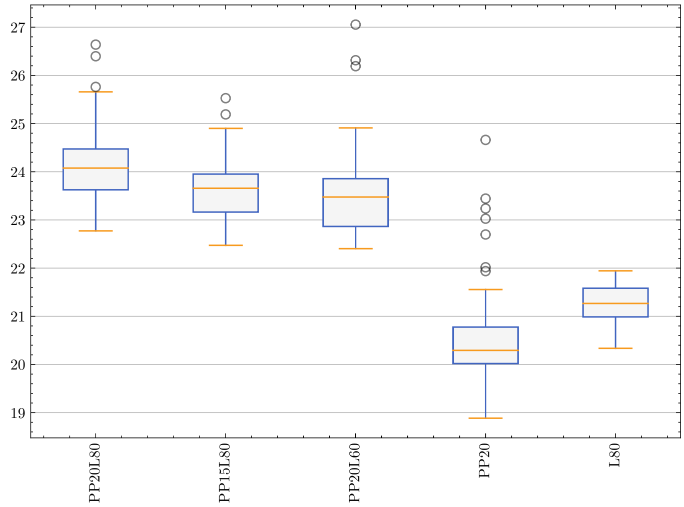


Figure 9.2: Impact of combined (PP20L80,PP15L80,PP20L60), maximum public procurement (PP20), and maximum loan guarantee (L80) policies on MSWA of environmental performance in the year 2070, PP stands for public procurement and L for loan guarantees. The box plots are created for 100 scenarios differentiating in the initial conditions.

A number of remarks can be made related to the impact of increased consumer preferences: (1) it does not seem to influence significantly the market concentration, the number of loans, and nor to be market disruptive, (2) it seems to affect slightly positively the real GDP by 2070, (3) it affects positively the MSWA value of environmental performance, (4) it affects negatively the MSWA values of user quality and efficiency. The absence of market disruption can be attributed to slow pace of change in consumer preferences. The increase in the MSWA of environmental performance can be attributed to the increased preference for environmental friendly products which result in environmental friendly firms to perform better, increase their market shares, and get imitated more by imitators thus affecting also innovators. The exact opposite dynamics are the reason for the decrease in the MSWA value of environmental performance and user quality.

Consumer Preferences and Combined Policies

In this section the impact of changes in consumer preferences on the effectiveness of different policies is explored. In the scenario that will be explored in this section consumer preference for environmental performance reach the value of 0.45 by the year 2050, while the other two preferences, for user quality and efficiency, reaches values of 0.275 by the year 2050. In this scenario an alternative public procurement policy is explored where the public procurement is in a sense complementary to the change in consumer preferences: it starts from 20 % at year 2020 and is gradually withdrawn until 0 % in year 2050. This scenario is explored for the three combined policies mentioned in the previous section but with the gradually withdrawn public procurement.

The results suggest that the three combined policies are equally effective in increasing the final environmental performance of the products in this scenario, as in the scenario without change in consumer preferences. On the other hand, one important drawback in this scenario is the significantly lower GDP reached in 2070;

Table 9.7: Changing Consumer Preferences, averages over 100 simulations.

Metric	Base Case	To 0.4 by 2050	To 0.45 by 2050	To 0.5 by 2050
Env. Per. 2045	14.53	14.63	14.74	14.94
Env. Per. 2070	17.77	18.08	18.51	19.26
Qual. 2070	17.8	17.6	17.43	17.02
Effic. 2070	17.7	17.63	17.29	16.97
GDP 2070	7.29	7.61	7.65	7.44
HHI Mean	0.035	0.035	0.035	0.037
HHI Max	0.072	0.072	0.072	0.073
HHI Min	0.018	0.019	0.019	0.022
Avg. Total F.	99.47	99.15	99	97.39
Old F. 2045	77.3	76.8	77	76.7
Old F. 2070	72.2	71.5	71	68.3
New F. 2045	19.3	19.2	19	18.6
New F. 2070	40.3	41	30.4	38.3
Green Loans %	33.4	33.5	33.71	33.73
No Loans %	29.35	29.53	29.64	29.91
Green loans	3520	3507	3521	3454
Costs	0	0	0	0

this decrease can be attributed to the negative of the gradually withdrawn public procurement which contributes a small decrease in the GDP of the market every month.

9.3 Sensitivity Analysis

In this section the sensitivity analysis for the base case no policy scenario is discussed. The impact that sensitivities have on MSWA of environmental performance in year 2070 are illustrated in fig. 9.3, and the impact they have on actual GDP in the year 2070 in fig. 9.4.

The one hundred simulation runs are performed for the following scenarios: (1) **lower success green**, in this scenario the success probability of environmental performance investment projects is reduced to 0.8 from 1, (2) **lower impact green**, in this scenario the positive impact of environmental performance projects in improving the same product aspect is reduced to 0.16 from 0.2, (3) **alpha 15** and **alpha 25**, in these scenarios values of 15 and 25 are used for the market share concentration parameter α instead of the default 20, (4) **lower init. ineq.**, firms are initialized by sampling their values for their three product aspects from uniform distributions with intervals of [8,12] instead of [7,13], (5) **higher init. ineq.**, firms are initialized by sampling their values for their three product aspects from uniform

Table 9.8: Combined policies performance and changing consumer preferences, average over 100 simulations

Metric	PPW20 % Loan 80%	PPW15 % Loan 80%	PPW20 % Loan 60%
Env. Per. 2045	18.23	18.13	17.79
Env. Per. 2070	24.33	24.41	23.51
Qual. 2070	15.67	15.62	15.79
Effic. 2070	15.54	15.67	15.75
GDP 2070	6.48	6.48	6.53
HHI Mean	0.047	0.049	0.047
HHI Max	0.087	0.086	0.086
HHI Min	0.026	0.026	0.027
Avg. Total F.	66.25	71.0	65.49
Old F. 2045	45.4	50.6	44.81
Old F. 2070	40.9	45.0	39.71
New F. 2045	16.9	17.3	16.62
New F. 2070	36.56	37.0	35.61
Green Loans %	48.4	48.5	45.8
No Loans %	23.62	23.3	25.2
Green loans	3677	3960	3363
Costs PP	61.0	44.5	61.0
Cost LG	0.73	0.63	0.49

distributions with intervals of [6,14] instead of [7,13], (6) **more innov. firms**, one innovative firm successfully enters the market every 6 weeks compared to the default every 12 weeks, and (7) **less innov. firms**, one innovative firm successfully enters the market every 24 weeks compared to the default 12 weeks.

The **lower success green** and **lower impact green** scenarios have the expected impact of significantly reducing the MSWA of environmental performance at year 2070 as a result of the decreased efficiency of innovative projects focused on environmental performance. These scenarios do not have an important impact on GDP as they only indirectly change the type and number of innovative projects performed. The scenarios that result in higher inequality in the market, **alpha 25** and **higher init. ineq.** improve on average all the product aspects by the year 2070. Their most important impact on GDP is that they increase significantly the range of possible outcomes. The scenarios that result in lower inequality in the market, **alpha 15** and **lower init. ineq.** have a negative impact on average on all the product aspects by the year 2070 and also they reduce the ranges. Their most important impact on GDP is that they decrease significantly the range of possible outcomes. Finally, changing the number of innovative firms does not influence significantly the two examined metrics. One important consequence of having less innovative firms is an increase in the number of outliers in terms of GDP growth. These are the cases where the market is initialized with firms having a good performance in environmental performance.

The impact the uncertainties have on the other main metrics and secondary metrics can be found in the appendix.

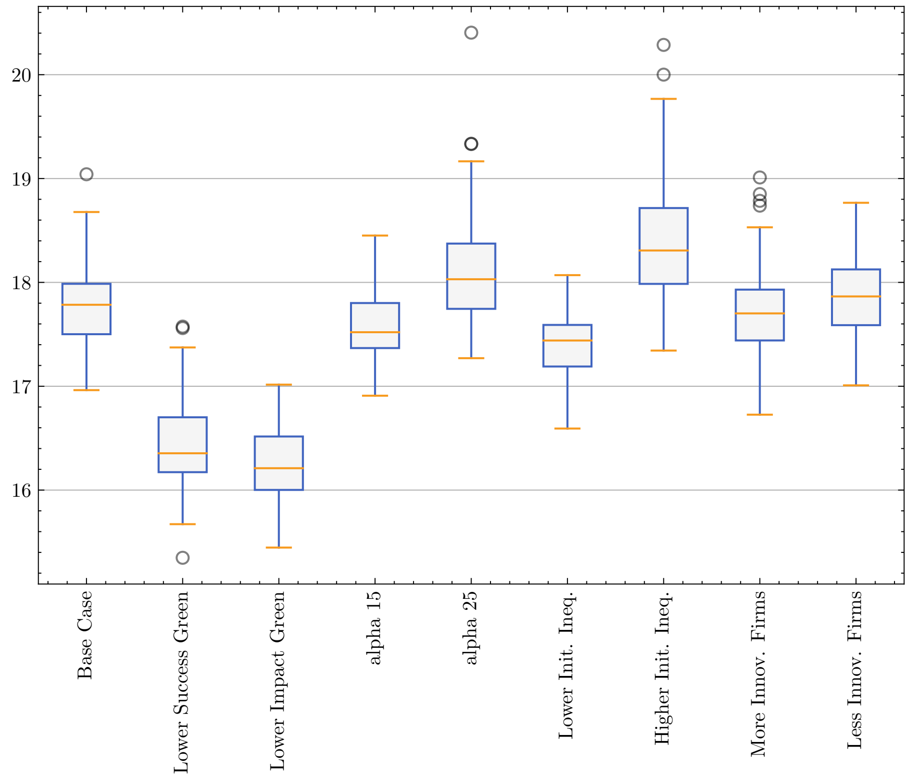


Figure 9.3: Impact of uncertainties on MSWA value of environmental performance in the year 2070 for the base case scenario. The box plots are created for 100 scenarios differentiating in the initial conditions.

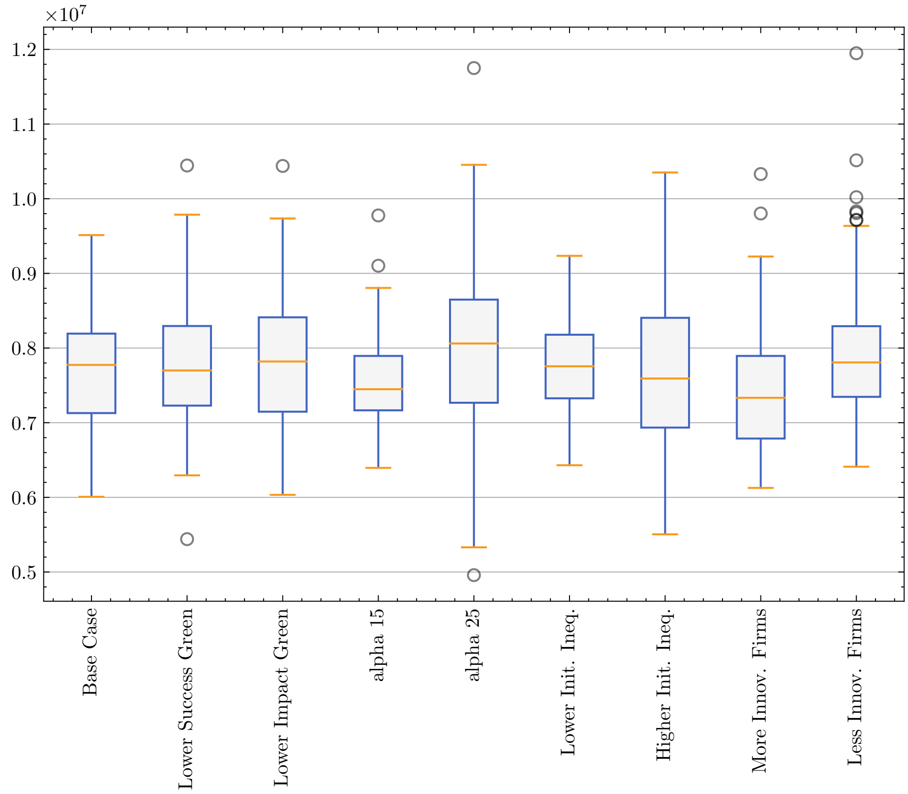


Figure 9.4: Impact of uncertainties on GDP in the year 2070 for the base case scenario. The box plots are created for 100 scenarios differentiating in the initial conditions.

Summarizing the findings

The main findings of this analysis are:

- The loan guarantee policies: (1) are effective at increasing the final MSWA value of environmental performance, (2) are the least market disruptive, (3) have the least negative impact on the other two product aspects, user quality and efficiency, (4) are cost-effective, but (5) are the least effective in increasing the final GDP of the market.
- The public procurement policies are: (1) slightly less effective than loan guarantee policies at increasing the final MSWA value of environmental performance, (2) have more negative impact in the MSWA value of the two other product aspects, (3) are more market disruptive, (4) are more costly, (5) significantly better at increasing the final market GDP to an extent that they counterbalance the total policy cost.
- Combining the two policies: (1) improves the effectiveness in increasing the MSWA value of environmental performance, (2) slightly increases the negative impact on the other two product aspects, (3) slightly improves the market disruptiveness compared to the public procurement policies, and (4) decreases the final GDP compared to the public procurement policies.
- Changes in consumer preferences especially combined with a public procurement and loan guarantees is very effective in increasing the MSWA value of environmental performance but decreases significantly the GDP.

Part IV

Discussion

Chapter 10

Discussion

In this chapter the research approach and the results of this study are examined. In section 10.1 the main study limitations are discussed focusing on the main scoping decisions, the study's critical assumptions, and limitations of the model validation. Section 10.2 focuses on the advantages and limitations of the used approach and finally, in section 10.3 the main implications of this study are discussed.

10.1 Study Limitations

10.1.1 Revisiting scoping decisions

In the literature review, four important scoping decisions are made: (1) focus on Small and Medium Sized Enterprises (SMEs), (2) focus on science based and specialized consumer firms, (3) focus on a bank-based system, and (4) focus on the impact of public finance. In the following section in the context of the aforementioned scoping decisions some critical assumptions are discussed.

10.1.2 Critical Assumptions

A number of assumptions are made in this study. These assumptions are made with the goal of providing a good approximation of reality inside the scope defined by the scoping decisions mentioned in the previous section. In the author's opinion this study uses four main critical assumptions: (1) firms have simplified account's and capital structure models, (2) firms do not act in response to environment developments and other firms' actions, (3) firms have a simple innovation model, and (4) GDP growth is defined according to a simplified model. These assumptions are discussed in the following section. Gradually relaxing those three critical assumptions can provide avenues for enriching this study. A list of all the other assumptions can be found in appendix C.

Isolated firms

Firms don't change any of their characteristics in response to developments in the environment or other firms' actions. This is a limiting assumption but a reasonable one considering the relatively high number of firms in the market (100 on average), and the non-oligopolistic nature of the market (the Herfindahl–Hirschman market concentration index HHI is in the vast majority of cases less than 1). The non-oligopolistic nature of the market allows to ignore the strategic behavior of firms and their reactions to other firms' actions. The high number of firms in the market makes it difficult for firms to track the actions of all the other agents and thus justifies the assumption that they do not respond to their actions.

Simplified accounts model

The simplified accounts and capital structure model used in this study is described in eqs. (4.4) to (4.8) in chapter 4. This model calculates the firms' revenues, variable costs, fixed costs, profits and wealth; in this model it is assumed that all firms have the same markup price, fixed costs ratio, fixed cost inertia parameter, and fixed dividends percentage. An important decision that leads to the adoption of this simplified model is the omission of economies of scale due the focus on SMEs; as a result, fixed costs and variable costs are not dependent on firms size. Instead, the price and thus the variable costs is assumed to change only through innovation projects. Finally, the decision not to focus on changing markup prices is in line with the previous assumption of "isolated firms"; as allowing firms to compete on markup price entails elements of firms' interaction and strategic behavior.

Nevertheless, this simplified model is adequate for this study as it accomplishes the two main functions defined during model conceptualization: (1) firms that suffer market share losses have poorer financial health (defined as the wealth to revenue ratio), (2) firms that suffer persistent and important market share losses get negative wealth and consequently exit the market.

Innovation dynamics

For this study it is assumed that all firms perform innovative projects with similar characteristics. Innovation projects have the same duration, the same success probability, and the same positive impact on the researched aspect. This assumption is made having in mind the focus on SMEs and the assumed homogeneity in firms. Additionally, allowing for heterogeneity in that model aspect would further complicate the model and shift the focus towards the impact of the different innovation project characteristics, which is considered outside of this study's scope.

GDP growth

According to the conceptualization of this study and based on the model by D'Orazio and Valente (2019), innovations in user quality correlate strongly positively with GDP growth, slightly positively with innovation in environmental performance, and slightly negatively with innovation in efficiency. Although there is significant empirical evidence on the sign of these impacts the exact weights of these correlations may change from market to market or throughout time. These changes can significantly affect the impact of different policies in increasing the GDP in the market.

10.1.3 Validation

The goal of validation is to ensure that the model replicates successfully behaviours encountered in the real-world counterpart of the model. Common validation techniques include historic replay, model replication, and literature comparison (Van Dam et al., 2013). The model is validated through literature comparison by replicating successfully three commonly encountered behaviors of innovative markets: (1) pro-cyclical investment behaviors, (2) right skewed firms distribution, and (3) fat-tailed distribution of GDP growth. Thus, this study does not perform a validation on historic data nor validation based on alternative models, which can limit the reliability of the quantitative results. However, this study has incorporated several aspects that are novel, such as combined public innovation policies, which makes it difficult to directly compare the results to other studies or find available data. Furthermore, the aim of this study is to provide insight in the qualitative effects of policies rather than into the exact quantitative scale of their impacts. Nevertheless, further validation based on historic data and alternative models would be beneficial to confirm the quantitative results but could not be performed in the scope of this study.

10.2 Reflections on the used Approach

This study uses an evolutionary agent-based modelling approach. This approach proves to be beneficial for the study of eco-innovation diffusion in a number of ways. At first, it allows to focus on the behavior of individual firms rather than on the aggregate system. The system behavior is emerging bottom-up from the various micro-level behaviors of individual firms. This bottom-up approach compared to other commonly used modelling techniques like system dynamics or equilibrium approaches provides the advantage of accounting for sources of heterogeneity of firms. Second, this evolutionary modelling approach gives insights in the path-dependency that exists in the eco-innovation diffusion process. Path-dependency arises through new firms that enter the market by imitating the product aspects of firms that are performing well. Finally, selection pressures in the form of financial disciplining of under-performing firms and rewards to firms investing in environmental performance of their products are considered.

On the other hand, using this modelling approach imposes a number of limitations to this study. At first, the vast parameter space of the disaggregate model makes it possible to generate a wide range of regularities on a macro level by changing the initial conditions and the parameter values. Therefore, values for the model parameters need to be selected carefully and the model behavior has to be carefully validated. In this study, the models' parameter space was explored extensively, and each module of the model carefully verified and validated. Additionally, sensitivity analysis was performed for a number of parameters to ensure the robustness of the model results. Furthermore, the quantitative model outcomes cannot be easily translated into future predictions due to the lack of data for validation purposes. This is a drawback compared to econometric modelling, which is a widely-used approach to determine the impact of policies.

Concluding, the agent-based modelling approach offers several advantages for this study, as it allows to model emergent system behavior, agent heterogeneity, path-dependency, and interactions between agents. The main drawbacks are the limited quantitative interpretability of the results and the vast parameter space which can create a wide range of different behaviors. However, as the aim of this study is to offer insights into the effectiveness of different public finance policies by focusing on individual firm behaviors and the path-dependency of eco-innovation, the agent-based modelling approach offers a useful alternative to overcome some of the pitfalls of conventional economic modelling approaches.

10.3 Implications of the Study

The model results suggest that all public finance policies tested in this study are effective in promoting eco-innovation diffusion in markets consisting of SMEs. All policies are robust and maintain their effectiveness for a broad range of initial conditions varying in terms of market inequality, average product characteristics in the market, and initial investment strategies of firms. Table 10.1 presents the main KPIs for three representative policies examined in this study. The results suggest that the combined policy performs significantly better than the other two in terms of final environmental performance of products, but at the cost of: (1) the least improvement in the other two product aspects , user quality and cost-efficiency, (2) important market disruption, and (3) smaller GDP increase than the public procurement policies. These results are in line with two econometric studies on the effectiveness of policy mix in fostering eco-innovation which provide evidence favoring a more balanced use of demand-pull (public procurement) and technology-push (loan guarantees) instruments (Costantini et al., 2017; Guerzoni & Raiteri, 2015). Finally an important aspect of the policies that include public procurement is the high policy costs, for example the combined policy of 20% public procurement and 80% loan guarantee has a cost of 441.65 million euros over the 50 year it is implemented. However, the induced benefits due to GDP growth account for a cumulative GDP over the 50 years of 570 million.

Table 10.1: Performance of selected policies, average over 100 simulations.

Metric	Loan 80%	PP 20 %	PP20 % Loan 80%
Env. Per. 2045	16.23	16.29	18.15
Env. Per. 2070	21.27	20.51	24.13
Qual. 2070	16.99	16.59	15.81
Effic. 2070	16.98	16.41	15.78
GDP 2070	7.02	8.92	8.24
Avg. Total F.	105.3	68.3	70.46
Old F. 2045	83.6	45.9	49.2
Costs PP	0	466	441
Cost LG	0.27	0	0.65

Nevertheless, a number of reasons could deter policymakers from making use of a combined policy.

Firstly, policies that include public procurement although they cause significant increase in the total GDP of the market seem to be more disruptive and result in a high percentage of the initial firms exiting the market due to poor financial health. The high market disruption can be problematic: (1) for political reasons, it might prove difficult to promote such a drastic market reform or "market intervention", (2) for societal reasons, as firms exiting the market are connected to people's livelihood and although it will increase the market GDP policy makers need to cater for people transitioning from one firm to another, and (3) such a disruption may have market Implications that cannot be captured by this study's model formalism (e.g. impacts on the confidence for the quality of the market that may discourage new innovative firms from entering which can have strong negative feedback effects in the market and similar qualitative impacts). In the case that the induced market disruption deters policymakers from using a combined policy they can: (1) either use a loan guarantee policy but at the cost of significantly less increase in GDP and smaller increase in final environmental performance of the products in the market, or (2) use a set of complementary policies that help labour exiting the market to easily reallocate, and highlight the advantage of an increased final GDP that this policy have.

Another reason that can deter policy makers from choosing this public procurement policy, from the policies examined, is that it leads to the least improvement over time for the other product characteristics. For some markets this might be important, as it can lead to a decrease in the overall market competitiveness which can result in shrinking revenues. In this case policy makers can: (1) either use loan guarantees but compromise in terms of market GDP increase and final environmental performance in the market, or (2) create complementary policies that could support the other product aspects to some extend.

Chapter 11

Conclusions

In this chapter the conclusions of this study are presented. In the first two sections the sub-research questions and the main research question are revisited. In the third and fourth section the societal and scientific contributions are discussed and in the fifth and final section, future research avenues are suggested.

11.1 Revisiting Sub-research Questions

The first sub-research question of this study is:

> **Sub-research Question 1**
>
> How can the model developed by D'Orazio and Valente (2019) be expanded to account for: (a) diverse initial conditions, and (b) for public procurement policies?

For the first sub-research question the model developed by D'Orazio and Valente is reviewed and modified so it can be used for gaining insights into the effectiveness of loan guarantees and public procurement policies in promoting the diffusion of more sustainable products in small and medium sized enterprises (SMEs). Initially, the model is critically evaluated and a number of deficiencies are identified. Then, an updated model that accommodates for those problems is proposed and finally, the updated model is expanded with: (1) a module for implementing public procurement policies, (2) a module for randomly initializing the market with the desired number of firms while also controlling for the initial market share spreads, and (3) a module for estimating the costs of implemented policies. This is answered in the fourth chapter of this study.

> **Sub-research Question 2**
>
> How can the extended model be implemented in Python using the MESA framework?

The second research question is focused on model implementation. The model is implemented using the Python programming language and the MESA Python agent-based modelling library which contains a number of modules specifically developed for agent-based models. The central agents in the model are: (1) firms that produce products defined by three qualities: environmental performance, user quality, and cost-efficiency, (2) consumers who purchase products based on their preferences, (3) a commercial bank providing loans to firms, and (4) a state investment bank providing loan guarantees. The model runs in discrete time step, which represent one month. The model and associate code are available on Github. Besides the model (`Model.py`) a number of jupyter notebooks are developed for different tasks performed in this study. The jupyter notebooks created are: (1) ModelResults.ipynb, in this notebook most of the analysis and the visualizations are performed, (2) ModelValidation.ipynb, in this notebook the updated and extended model is validated, and (3) ModelSensitivities.ipynb where the sensitivity analysis of the model results takes place. During and after the implementation, the model is verified to ensure it is implemented without erros. The sub-research question is answered in the fifth chapter of this study.

Sub-research Question 3

How can the model be validated?

The third sub-research question focuses on model validation. In model validation the modeller explores whether the model is able to reproduce real world behaviors. The model is successfully validated by replicating three empirically encountered behaviours of innovative markets: (1) pro-cyclical investment behavior, (2) fat-tailed GDP growth distribution, and (3) skewed market share distribution. Model validation takes place in chapter chapter 7.

Sub-research Question 4

Based on the model and using the XLRM framework, what are the effects of different financial tools on the diffusion of eco-innovation?

This is a broad research question addressed in a big part of this study consisting of chapters 6,8, and 10. In chapter 6 the problem is structured according to the XLRM framework and the experiments are designed. The policies consist of three loan guarantee policies (40%, 60%, and 80%), three public procurement policies (10%, 15%, and 20%)[1], and combination of those policies. A set of main metrics is defined related to the three main KPIs: (1) diffusion of eco-innovation, (2) cost of implemented policies, and (3) real GDP of the markets. Moreover, a set of secondary metrics is defined that helps to get further insights into the impact of policies on the market dynamics. In chapter 8 the big picture of the results is presented where the effectiveness of loan guarantees, public procurement, and combined policies in promoting the diffusion of eco-innovation is confirmed. In chapter 9 a more detailed analysis of the results takes place. The main conclusions of the analysis are: (1) all public financing policies examined are effective in promoting eco-innovation diffusion, (2) all policies are robust in respect to different initial market conditions,

[1] Public expenditure as percentage of total market revenue

(3) the most effective policies in fostering eco-innovation diffusion are the combined policies.

11.2 Revisiting the Main Research Question

The main research question that guided the development of this study is:

> **Main Research Question**
>
> "What can we learn from an evolutionary modelling approach about the effectiveness of public finance in supporting eco-innovation diffusion in SMEs?"

Most of the lessons learned from this study are covered in the answer to the previous research question and can be summarized in two points. The first point is that both public procurement policies and loan guarantee policies are effective in promoting eco-innovation diffusion. The second point is that the two policies achieve innovation diffusion through a qualitative different way: public procurement by creating a shock in the market which results in firms not competitive in environmental performance losing market share, getting into poor financial health, and eventually dropping out of the market, creating space for new entrants in the market, especially for innovative firms that are strong in the environmental aspect. On the other hand, loan guarantees bring a less disruptive and more gradual change by helping firms that are focused on investing in their environmental performance getting a competitive advantage by having easier access to loans.

11.3 Scientific Contributions

This study contributes to the scientific debate about the effectiveness of public financing tools in fostering eco-innovation diffusion in the following ways. Firstly it provides further evidence of the usefulness of public financing tools in fostering eco-innovation diffusion. Secondly, it offers insights into the qualitative different ways that loan guarantees and public procurement policies affect the market and how their effectiveness is impacted by different initial market conditions. Finally, it provides a new set of lenses for studying the impact of public finance policies have on the diffusion of eco-innovation in markets consisting of small and medium size firms.

11.4 Societal Contributions

This study aims at giving insights into ways of fighting climate change, a pressing modern societal problem, by focusing on climate change mitigation. Decarbonization is the most popular climate change mitigation approach and can benefit significantly by eco-innovation diffusion, the focus of this study. Additionally this study aims at contributing to the debate about societal justice and transition by raising awareness for the potential market disruptive impacts some public policies could have. As seen in some of the simulations, especially procurement policies can lead to the majority of firms initially in the market to exit the market due to poor financial health. It is important for policy makers to take into account that these firms are connected with the livelihood of many people and take measures to support those most vulnerable.

11.5 Further Research Avenues

Most aspects of this study can be refined through further research. At first, relaxing the critical assumptions mentioned in chapter 10 can provide useful avenues for enriching this study. Relaxing the first critical assumption about firms acting in isolation by adding responsive elements in firms' behavior could give insights into potential feedback mechanisms established amongst firms or between firms and environment, and how these interactions might affect the innovation diffusion. The second critical assumption refers to the simplified accounts model used in firms. Relaxing this assumption can improve the model, for example by incorporating economies of scale, a more detailed capital structure or by allowing firms to compete in mark-up prices. This update could provide a more realistic representation of the way bigger firms can affect the market, for example by impeding competition, or it could offer a more elaborate understanding on the impact loans have on firms' financial health. The third critical assumption relates to the simple innovation module used in firms. Relaxing this assumption by incorporating a more detailed innovative module could help to provide insights into how different aspects of firms' innovative activities interact with and affect the effectiveness of policies.

Apart from gradually relaxing the three critical assumptions this research can be expanded by further elaborating on its results. Initially, a more elaborate sensitivity analysis can be performed by including a wider set of model parameters than the ones tested in this study and by examining broader sensitivities for all the policies. This could reveal whether some of the model parameters are critical for the effectiveness of some policies and could, in turn be translated into insights for policymakers. Additionally, a more detailed analysis of the results can provide a more nuanced understanding of how market conditions affect the effectiveness of policies. This study confirms that the tested policies are robust for a wide range of initial market conditions but does not elaborate on which are the worst market conditions for each policy and what that implies for policy makers. Moreover, based on this analysis a more detailed exploration of the combined policies can be performed by simulating a higher number of policy combinations.

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Appendix A

Appendix A

A.1 Graphical Representation of Basic Equations

A.1.1 Efficiency Equation

Figure A.1 illustrates the efficiency as a function of the price based on eq. (4.1):

$$e_f(t) = \frac{M_e}{1 + exp^{\gamma_e(p(t)-\hat{p})}}$$

.

In eq. (4.1) parameter M_e defines the maximum efficiency, parameter γ_e controls the steepness of the curve, the higher the γ_e the steeper the curve, and p_{hat} defines the mean efficiency price.

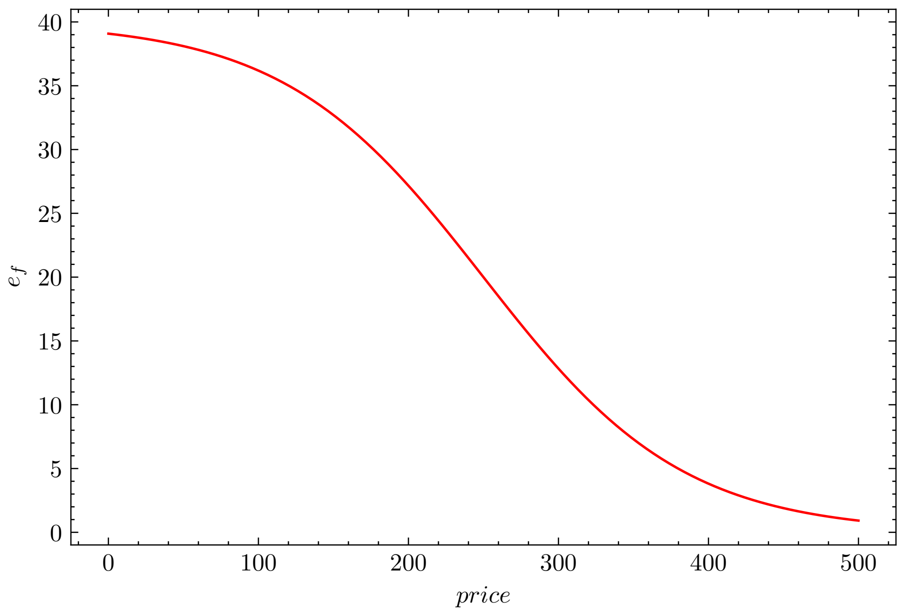

Figure A.1: Equation (4.1) for $M_e = 40$, $\gamma_e = 0.015$, and $p_{hat} = 250$.

A.1.2 Market shares equation

The market share for each company is calculated based on eq. (4.2) and eq. (4.3):

$$I_f = e_f^{\lambda_e} \times b_f^{\lambda_b} \times g_f^{\lambda_g}$$
$$ms_f(t) = \frac{[I_f(t)]^a}{\Sigma_{j=1}^{F}[I_j(t)]^a}$$

Parameters λ_e, λ_b, and λ_g add up to 1 describe the consumers preferences for efficiency, user quality, and green quality respectively. The parameter α defines the concentration of market shares. The impact of parameter α is illustrated in fig. A.2.

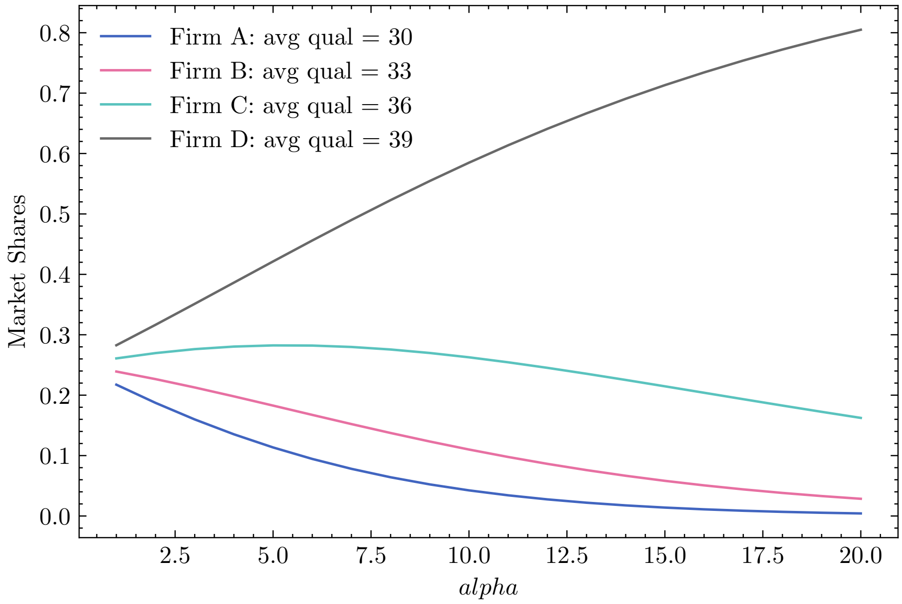

Figure A.2: Impact of α on market shares for consumer preferences all equal to 0.333. In the scenario illustrated in this figure: Firm's A products three product aspects take values of 10, Firm's B of 11, Firm's C of 12, and Firm's D of 13.

A.1.3 Supply side market dynamics

The **market dynamics** describe the conditions under which firms enter and exit the market. Firms enter the market through a process of imitation. At each time step - representing one week- on average Pr_{new} firms enter the market. The probability that an existing firm will be imitated by a new firm is a function of its market share and is given by the following equation:

$$Pr_{imit} = \frac{ms_f^{\eta}}{\Sigma_j ms_j^{\eta}}$$

In this equation ms represents the market shares and η is a parameter controlling the relative impact of different market shares. The impact that η has is illustrated in figure fig. A.3.

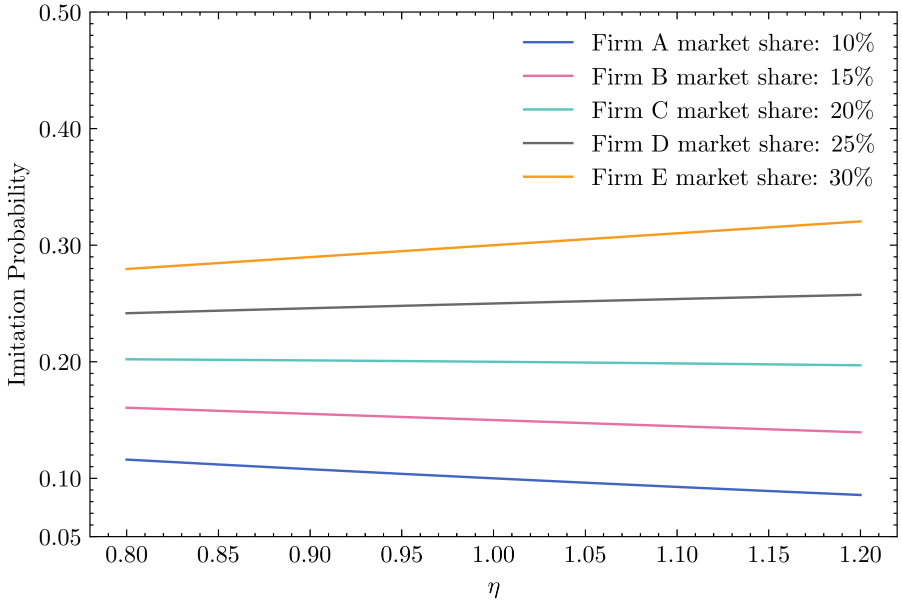

Figure A.3: Impact of η on probability that a firm will be imitated. In this scenario the market consists of 5 firms with market shares of 10%, 15%, 20%, 25%, and 30%. An η value of 1 results in the probability that a firm will be imitated being equal to its market share, η greater than 1 favor bigger firms and η smaller than 1 smaller firms.

Appendix B

Appendix B - Tables

B.1 Default Values for Model Parameters

Table B.1: Parameters used by D'Orazio and Valente in the original model

	Parameter	Description	Value
Initialization			
	H	Number of consumers	100.000
	F	Initial number of firms	10
Consumers			
	M_e	Maximum of efficiency function	200
	γ_e	Slope of efficiency function	0.03
	$p_h at$	Position of efficiency function	100
	λ_e	Weight of efficiency	0.333
	λ_g	Weight of green quality	0.333
	λ_b	Weight of user quality	0.333
Firms			
	α	Market shares concentration	20
	μ	Mark-up	0.01
	ψ	Speed of adjustment of fixed costs	0.3
	Φ	Share of revenues that determine fixed costs	0.05
	δ	Share of dividends	0.3
	τ	Threshold for firms' exit	0.3
	$minAge$	Minimum age for firms' exit	10
	Pr_{new}	Probability new firm entrance	0.5
	η	Imitation of existing firms	0.85
	Ω	Percentage of imitated firm's values	0.85
Finance			
	L_c	Length cost loan	4
	L_b	Length user quality loan	4
	L_g	Length green loan	4
	$Pr^s_c ucc$	Probability of success cost loan	1
	$Pr^s_b ucc$	Probability of success user quality loan	1
	$Pr^s_g ucc$	Probability of success green loan	1
	Pr^c_l	Probability to get loan for cost reduction	1
	Pr^b_l	Probability to get loan for user quality improvement	1
	Pr^g_l	Probability to get loan for green improvement	1
	σ	State investment bank parameter	0

	Parameter	Description	Value
Aggregate Income			
	ζ	GDP adjustment speed	0.025
	ω_g	Weight for green quality	0.1
	ω_b	Weight for user quality	0.8
	ω_c	Weight for cost	0.1
	G_{min}	Increase of GDP	1.015
	G_{max}	Decrease of GDP	0.99

Appendix C

Appendix C - Model Assumptions

The most important model **assumptions related to the firms and consumers** in this model are:

1. Consumers make buying decisions based on their preferences for the three product aspects: environmental performance, user quality and efficiency; there is no marketing, no brand loyalty or any other factors affecting their decision.
2. A complementary to the previous assumption is that firms produce goods that compete only on their environmental performance, their quality (user quality) and price (efficiency).
3. There are no elements of scale: firms of bigger size do not have any advantage over firms of smaller size.
4. There is one aggregate consumer instead of many heterogenous.
5. There is only a productive sector and not a manufacturing one.
6. A simplified accounts model and a simplified capital structure is used for the firms.
7. Firms do not interact with other firms, nor respond to the environment developments.
8. All firms have the same: markup price, percentage of fixed costs, percentage of dividends,
9. There is no labour market in the model.

The most important **assumptions related to market dynamics and innovation** are:

1. Firms undertake one innovative project per time.
2. All innovative projects are externally financed.
3. All innovative projects have the same probability of success.
4. All innovative projects have the same positive impact in the researched aspect.
5. All innovative projects have the same duration.
6. Innovative firms entering the market by imitating one existing firm.

7. Firms entering the market are better than the imitating firms in one product aspect and worse in the other two.
8. Firms can entering the market reach instantly the market share corresponding to the quality of their product.

The most important **assumptions related to commercial and state investment banks** are:

1. There is one aggregate commercial bank in the economy.
2. The aggregate commercial bank makes loan decisions based on: (1) the current cyclical economic conditions, (2) the firms financial health, and (3) the project type.
3. There is one aggregate state investment bank in the economy.
4. All loans have fixed duration and correspond to a fixed percentage of firms assets.
5. The loan guarantees are defined only by one variable, the level of loan guarantee.
6. Public procurement does not lead to a crowding out of other demand in the market.
7. Public procurement is defined by four numbers the starting time, the duration, the level, and the cut-off time.

The most important **assumptions relative to aggregate income** are:

1. Investments in user quality have strong positive impact on GDP growth.
2. Investments in environmental performance have slightly positive impact on GDP growth.
3. Investments in efficiency have slightly negative impact on GDP growth.
4. The aggregate income growth fluctuates between two exogenous demand limits.
5. The market conditions in the market under study do not influence the overall economy/economies where the market is active.

Appendix D

Appendix D - Model Verification

The verification process focuses on exploring whether the model behaves in the way described in chapter 4. In the following sections a number of modelling behaviors will be verified, at first for single agents and then for multiple agents.

Reproducibility of Results

For this section the seed used in the `numpy` random module is 1. All the results can be replicated by using this seed, the `ModelResults.ipynb` notebook, and the `Model.py` python script on `github`.

D.1 Market Dynamics Deactivated

In the first section the market-dynamics module will be deactivated; no firms will attempt to enter the market and no firms will exit the market.

Single Agent Verification

In this sub-section a single agent will "flow" through the model. The simulation steps are executed for 60 months or 5 years. The firm in this scenario is initialized with user quality, environmental performance, and efficiency equal to 10 and with a random investment strategy. Every innovation projects takes 4 steps. The firm in this simulation for the chosen seed performs innovation projects in the following order: efficiency, efficiency, quality, environmental performance, quality, quality, efficiency, environmental performance, efficiency, environmental performance, and on the last step starts an efficiency project.

Figure D.1 confirms that the GDP growth eq. (4.20) works as intended: when the firm is undergoing a cost efficiency project the monthly GDP growth rate is equal the $1 - 0.1 \div 0.8 * 0.015 = 0.998125$, for user quality it takes its maximum value of 1.015 and for environmental performance $1 + 0.1 \div 0.8 * 0.015 = 1.001875$. [1]

[1] These values can be obtained by substituting in eq. (4.20) the following default values: $\omega_b = 0.8$, $\omega_g = 0.1$, $\omega_c = 0.1$, $G_{max} = 1.015$, $G_{min} = 0.985$ and assuming that one of $\Theta_g, \Theta_b, \Theta_c$ is one and the other zero at each case.

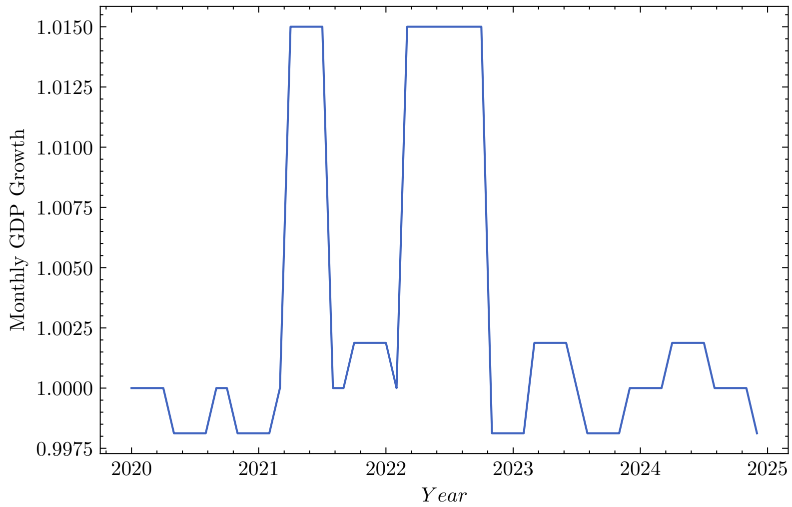

Figure D.1: Verification of monthly GDP growth without market dynamics; when the firm is investing in efficiency GDP growth is slighlty negative, when firm is investing in environmental performance slightly positive, and during periods it invests in user quality positive.

In fig. D.2 the various GDP curves can be inspected. It can be verified that the Potential GDP behaves according to the GDP growth depicted in fig. D.1. The Potential GDP and Actual GDP due to the small inertia value $\zeta = 0.025$ used by the authors, overlap to significant extend. The same $\zeta = 0.025$ value is used in this study.

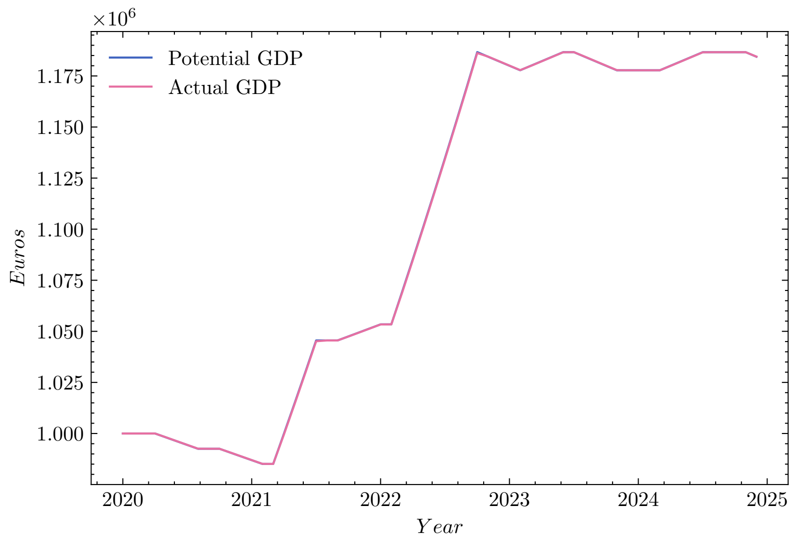

Figure D.2: Verification of GDP curves without market dynamics.

Figure D.3 confirms that the innovation projects have the expected impact: a successful innovation project improves the researched aspect by 0.2.

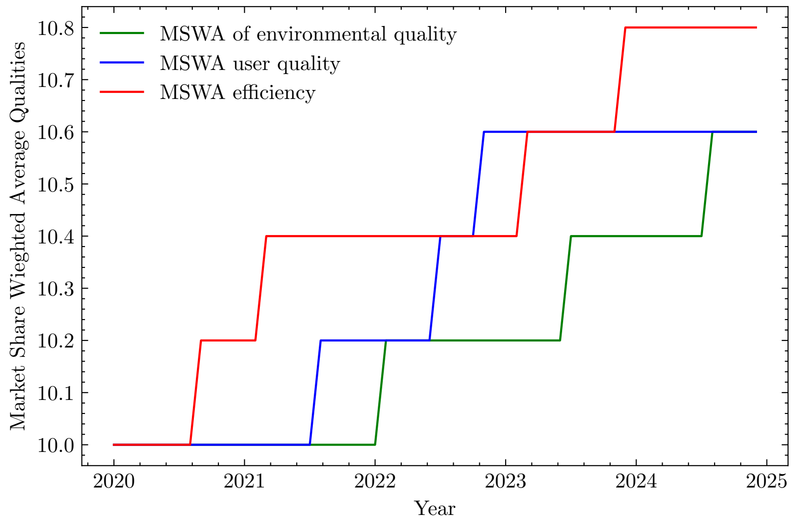

Figure D.3: Verification of innovation impact on firm characteristics without market dynamics. A successfull innovative project results in the researched aspect increasing by 0.2.

Multiple Agent Verification

In this section the model will be initialized with 6 agents and the simulation will have a duration of 10 years or 120 steps. The six agents sample values for their three characteristics randomly from a uniform distribution with intervals [9-11]. In fig. D.4 the GDP growth for this simulation is illustrated. The GDP growth fluctuates between the externally imposed limits 0.985 and 1.015, in the case of 6 agents though it is more difficult to reach extreme growth values, as it has to coincide that all firms invest at the same time in user quality(maximum growth) or efficiency (minimum growth).

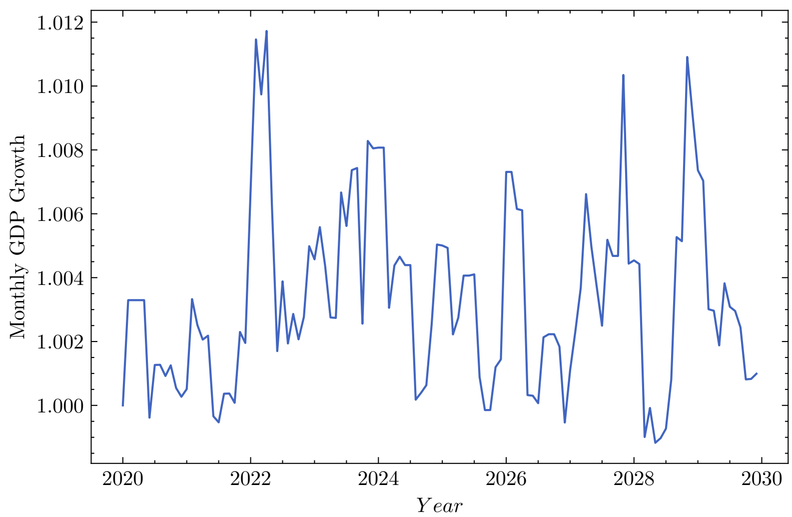

Figure D.4: Verification of monthly GDP growth for a market with 6 heterogenous agents, without market dynamics. The six agents sample values for their three characteristics randomly from a uniform distribution with intervals [9-11].

In fig. D.5 the market dynamics can be inspected, it can be seen that even without consumer preferences towards environmental performance and support from the SIB the initial market shares can change significantly through the years due to the innovation dynamics.

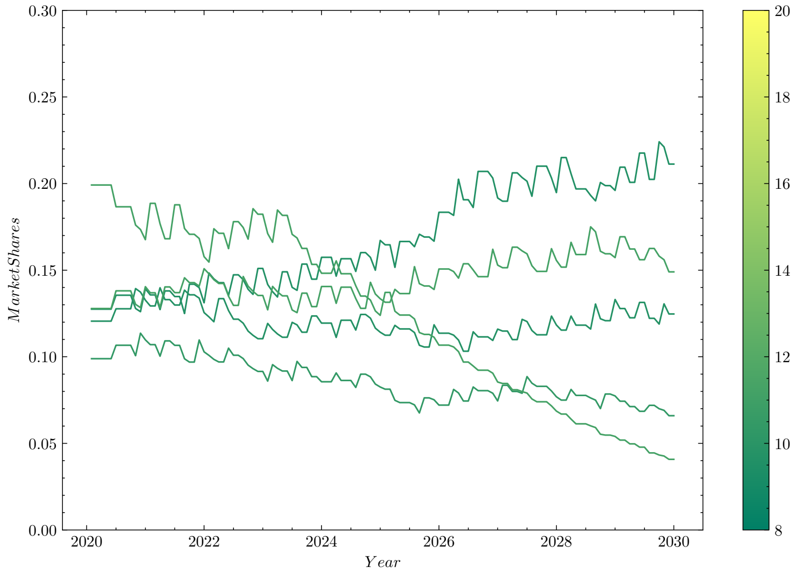

Figure D.5: Verification of market shares evolution for 6 heterogenous agents

D.2 Market Dynamics Activated

In this section the market dynamics are verified. Figure D.6 and figure D.7 illustrate the number of firms and their market shares for a market initialized with a single firm. At every step there is a probability of 1\12 than a new innovative firm will enter the market. Figure D.6 depicts that in the end there are 4 new firms in the market and that around 2021 the initial firm exits the market; this happens because the initial firm loses rapidly market share due the entrance of new firms in the market. In fig. D.7 it can be seen that in the tenth month a firm enters the market by imitating the existing one, the new entrant is less competent than the old firm and gets around 25% of the market share while the old firms maintains around 75%.

D.3 Impact of SIB and Consumers' Preferences

In this section the impact of an SIB providing guarantees for loans directed to investments in environmental performance, and of more environmental friendly consumer preferences is explored. The model is running for 240 steps or 20 years and is initiated with 10 firms that sample their environmental performance, user quality, and efficiency from uniform distribution with interval [9-11].

Figure D.8 illustrates the base case in which no loan guarantees exists and consumer preferences for environmental performance, user quality, and efficiency are equal to 1\3. The graph illustrates the market share weighted average (MSWA) values for environmental quality, user quality, and efficiency; in the end of the run MSWA for user quality is 13, for efficiency is 12.68 and for environmental performance is 12.26.

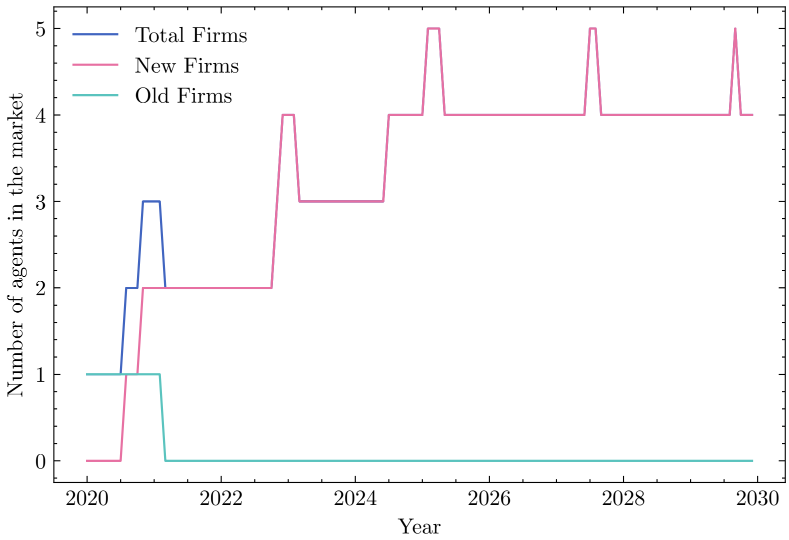

Figure D.6: Verification of market dynamics. Number of firms in a market initialized with a single firm, at every time step there is one sixth probability that an innovative firm will enter the market.

Figure D.9 illustrates the results for the same market and with an SIB active in providing guarantees 60% for loans directed in environmental performance. The final MSWA for efficiency 12.3 is , decreased by 0.38 compared with the base case ,for user quality is 12.59, decreased by 0.41 compared to the base case, and for environmental performance is 13.38, increased by 1.12 compared with the base case. Thus, an SIB providing loan guarantees can have significant positive impact in fostering higher environmental performance values in the market.

Finally, fig. D.10 illustrates the results in a market with the same characteristics as in previous two cases but with stronger consumer preference for the environmental aspect of the products; the weights of consumers for the three product aspects are: 0.5 for environmental performance, and 0.25 for user quality and efficiency. The results illustrate that consumer preferences can have significant positive impact in the MSWA of environmental performance; in particular environmental performance increases to 15.02 from 12.26 an 2.76 increase, user quality drops to 10.42 from 13 a 2.58 decrease, and efficiency drops to 11.71 from 12.68 a 0.97 decrease.

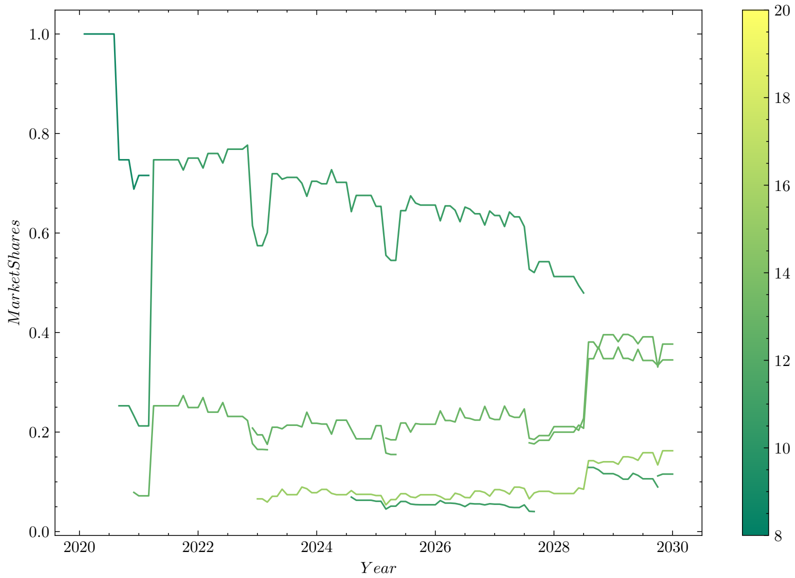

Figure D.7: Verification of market dynamics. Firms' market shares for market initialized with a single firm, at every time step there is one sixth probability that an innovative firm will enter the market.

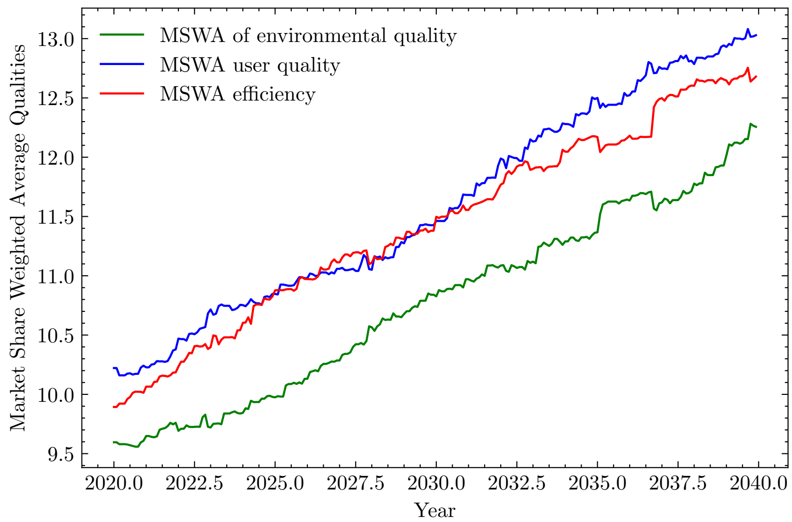

Figure D.8: Verification of SIB and consumer preferences impact. Base case, no loan guarantees by SIB and uniform consumer preferences. This run is initialized with 10 heterogenous firms sampling values for their three characteristics from uniform distribution with interval [9-11]

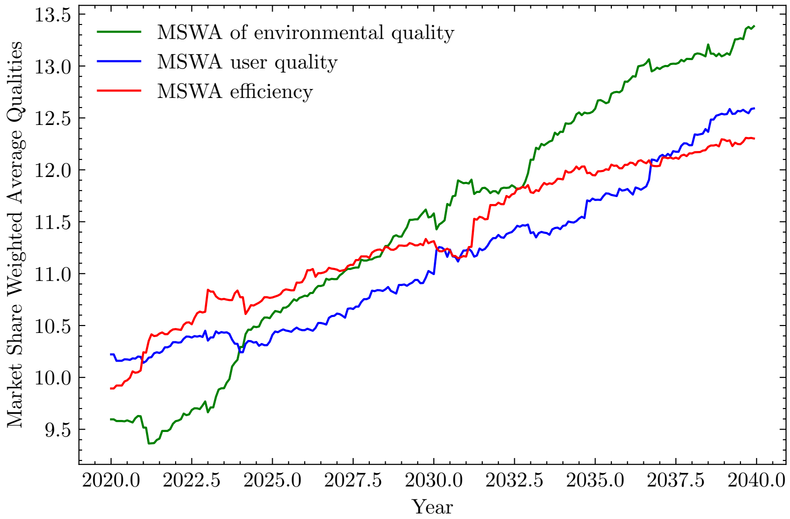

Figure D.9: Verification of SIB and consumer preferences impact. Scenario with SIB providing loan guarantees of 60% and uniform consumer preferences. This run is initialized with 10 heterogenous firms sampling values for their three characteristics from uniform distribution with interval [9-11]

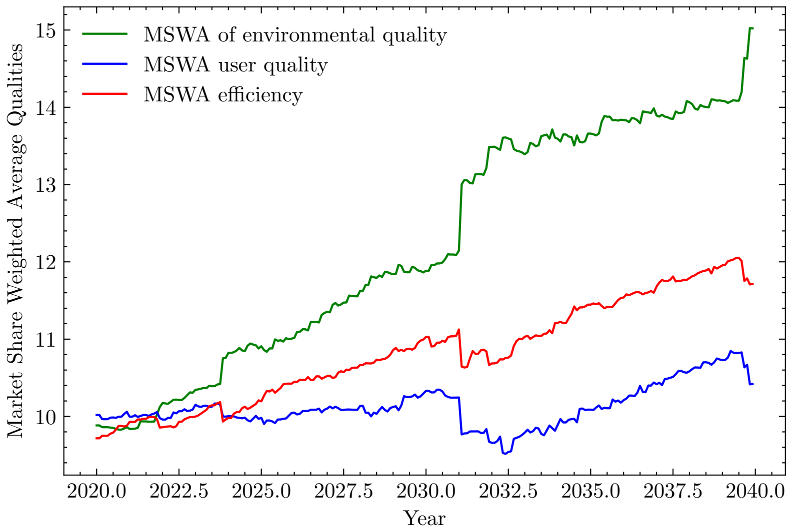

Figure D.10: Verification of SIB and consumer preferences impact. Scenario with consumers with stronger preferences for the environmental performance of the products: the weight for the environmental aspect of the products is 0.5, for the user quality 0.25 and for efficiency 0.25 and no loan guarantees by SIB. This run is initialized with 10 heterogenous firms sampling values for their three characteristics from uniform distribution with interval [9-11]

Appendix E

Appendix - E Sensitivity Analysis

E.1 No Policies

This section depicts the impact of the sensitivity parameters on the main and secondary metrics not included in chapter 9. Figure E.1 illustrates the impact of uncertainties on MSWA value of efficiency in the year 2070. Figure E.2 illustrates the impact of uncertainties on MSWA value of user quality in the year 2070. Figure E.3 illustrates the impact of uncertainties on the average value of HH market inequality index during the runs. Figure E.4 illustrates the impact of uncertainties on the average number of firms during the simulation run. Figure E.5 illustrates the impact of uncertainties on the number of initial firms surviving by the year 2070. Figure E.6 illustrates the impact of uncertainties on on the number of new firms in the market in the year 2070. The one hundred simulation runs are performed for the following scenarios: (1) **lower success green**, in this scenario the success probability of environmental performance investment projects is reduced to 0.8 from 1, (2) **lower impact green**, in this scenario the positive impact of environmental performance projects in improving the same product aspect is reduced to 0.16 from 0.2, (3) **alpha 15** and **alpha 25**, in these scenarios values of 15 and 25 are used for the market share concentration parameter α instead of the default 20, (4) **lower init. ineq.**, firms are initialized by sampling their values for their three product aspects from uniform distributions with intervals of [8,12] instead of [7,13], (5) **higher init. ineq.**, firms are initialized by sampling their values for their three product aspects from uniform distributions with intervals of [6,14] instead of [7,13], (6) **more innov. firms**, one innovative firm successfully enters the market every 6 weeks compared to the default every 12 weeks, and (7) **less innov. firms**, one innovative firm successfully enters the market every 24 weeks compared to the default 12 weeks.

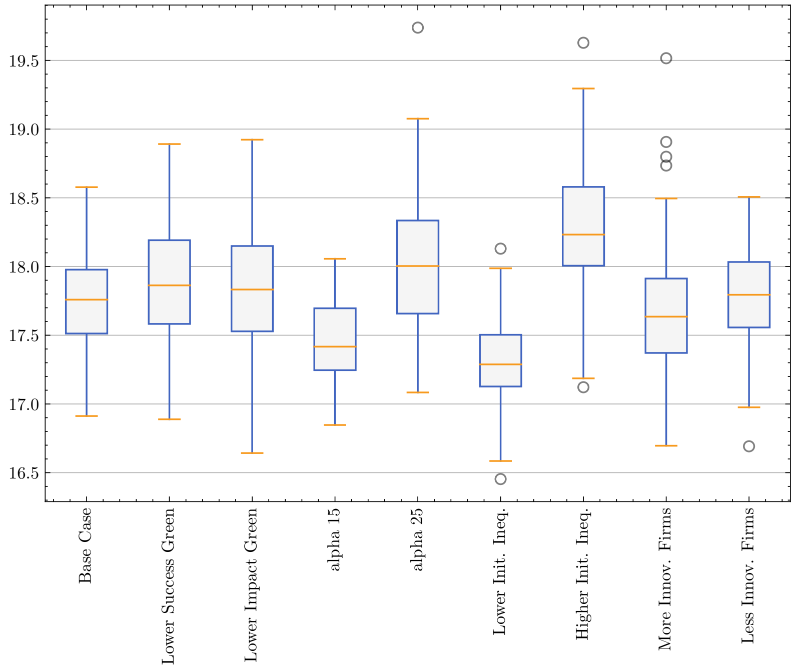

Figure E.1: Impact of uncertainties on MSWA value of efficiency at year 2070 for the base case scenario. The box plots are created for 100 scenarios differentiating in the initial conditions.

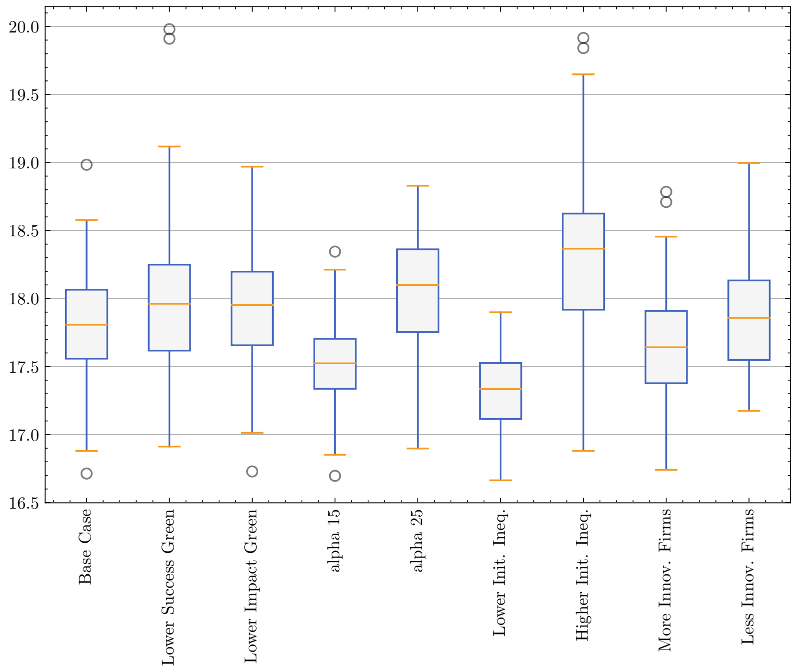

Figure E.2: Impact of uncertainties on MSWA value of user quality at year 2070 for the base case scenario.

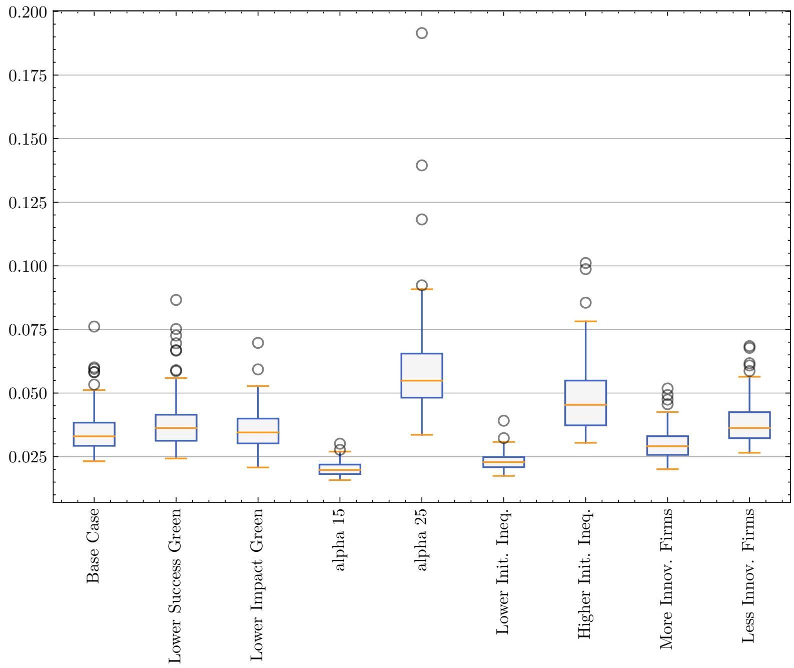

Figure E.3: Impact of uncertainties on average value of HH market inequality index. The box plots are created for 100 scenarios differentiating in the initial conditions.

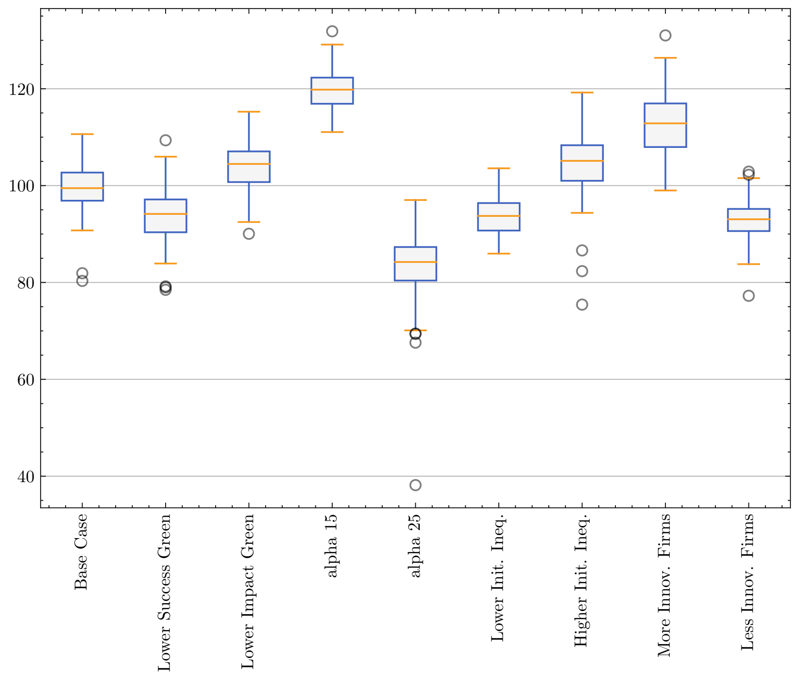

Figure E.4: Impact of uncertainties on average number of firms during the 100 simulation runs. The box plots are created for 100 scenarios differentiating in the initial conditions.

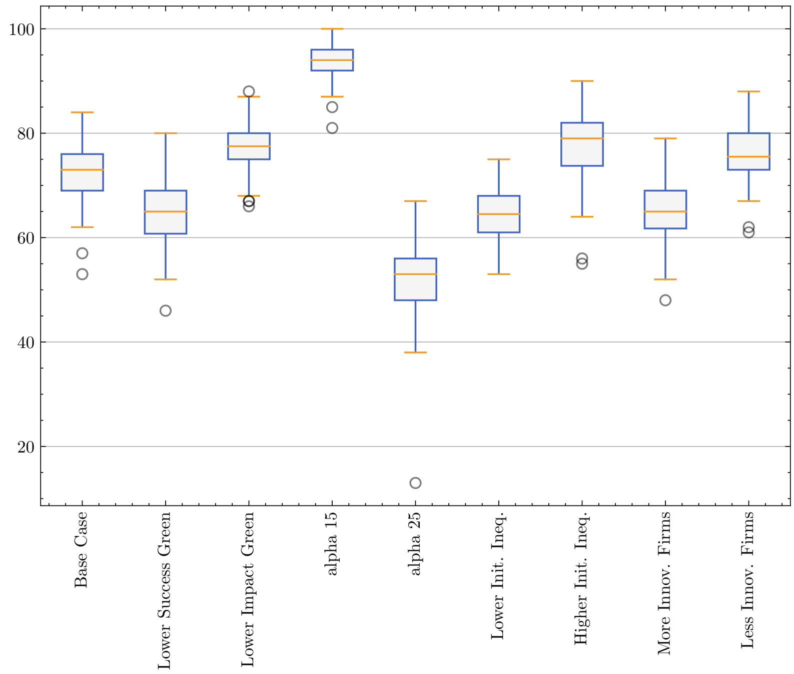

Figure E.5: Impact of uncertainties on the number of initial firms surviving by the year 2070. The box plots are created for 100 scenarios differentiating in the initial conditions.

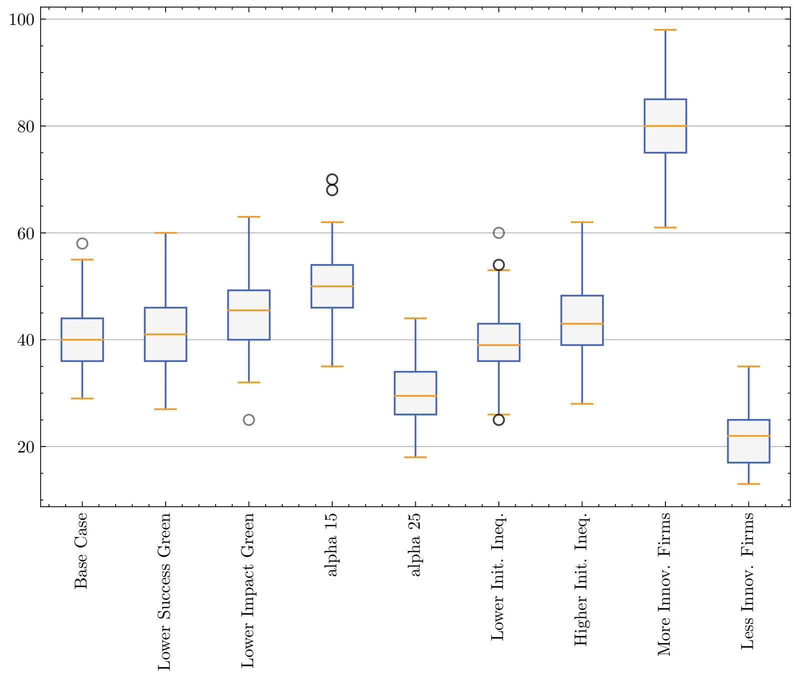

Figure E.6: Impact of uncertainties on the number of new firms in the market in the year 2070. The box plots are created for 100 scenarios differentiating in the initial conditions.