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**Behavioural models of technological change**

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*Citation for published version (APA):*

Zeppini, P. (2011). Behavioural models of technological change Amsterdam: Thela Thesis

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# Chapter 1

## Introduction

### 1.1 Technological change

Technological change is an important driver of economic change which in turn affects human welfare. In addition, it can contribute to solving pressing environmental problems. This requires policies which are based in a good understanding of the mechanisms underlying technological change.

Early models of economic growth assumed that technological change occurs in a linear uni-directional way, from science to society, as in Solow (1956). Later studies recognized that technological innovation is often shaped by its users, be they consumers or suppliers of technological products (Dosi et al., 1988).

The recognition of the endogenous character of technological change gave place to two alternative streams of studies in economics: endogenous growth theory in neoclassical economics (Romer, 1990; Aghion and Howitt, 1992) and a class of models in evolutionary economics (Nelson and Winter, 1982; Dosi, 1988). The neoclassical approach of endogenous growth theory relies on the concept of the production function, while evolutionary economics describes a population of firms (and consumers) and stresses the heterogeneity of these. This thesis proposes a behavioural approach to technological change, focusing on technological competition and the non-linear dynamics that stems from the endogenous

interplay of heterogeneous actors and technological diversity. In this sense it links up with the evolutionary economics approach.

In both neoclassical and evolutionary economics as well as in the field of innovation studies, there are two rather distinct typologies of models of technological change. First, one class of models deals with the *diffusion* of innovation (Mansfield, 1961; Bass, 1969; Geroski, 2000) or with technology competition (David, 1985; Katz and Shapiro, 1985; Arthur, 1989). Here a fixed set of technologies is assumed, which do not change during the time horizon considered. A second class of models addresses technological *innovation* (including invention), either as expanding variety and horizontal differentiation (Romer, 1990; Aghion et al., 2001) or as an improvement of the profitability of an existing technology (Iwai, 1984; Romer, 1986). Relatively few models consider both processes, that is technology diffusion together with technological progress, although in the economy these two processes are strongly interactive. One example is Soete and Turner (1995).

The main focus of this thesis is the study of technology innovation and diffusion in the context of technology competition, when more than one technology or technological choice is available to decision makers (firms). This is done within a behavioural approach, with models that describe the agents' decision processes and the emergent pattern of technologies. The double perspective of technology diffusion and technological progress is important especially in the context of "environmental innovation policy". The role of technological innovation in environmental economics and policy has been addressed only recently. From an evolutionary perspective, examples are van den Bergh (2007) and Faber and Frenken (2009), while in neoclassical economics we find a computational general equilibrium approach, as in Bosetti et al. (2009) and the recent theoretical contribution of Acemoglu et al. (2009). Two out of four chapters in the present dissertation model explicitly an environmental policy, and propose a behavioural approach to the interplay of technological change and environmental policy.

## 1.2 Thesis outline

Chapter 2 of this thesis addresses technological diversification in the presence of recombinant technological innovation. Assuming that two (or more) technologies can “recombine”, giving birth to a third innovative technology, a firm’s investment decision is affected by the trade-off between the advantages of specialization (increasing returns) and the benefits from recombinant innovation. The chapter proposes a theoretical cost-benefit analysis of this investment decision problem, deriving conditions for optimal diversity under different regimes of returns to scale. Threshold values of returns to scale and the recombination probability define regions where either specialization or diversity is the best choice. When the investment time horizon is beyond a threshold value, a diversified investment strategy is the best choice. This threshold will be larger for higher returns to scale.

Chapter 3 extends the previous model to a dynamic framework, addressing the competition of possibly recombining technologies. The *R&D* investment decision takes place in a sequential manner, allowing to study stylised facts such as path dependence of technological trajectories and lock-in into one of multiple equilibria. The sequential decisions are described by an urn model based on Polya processes (a type of Markov process) as in Arthur et al. (1987). The innovative contribution of this chapter is to extend Arthur’s model of competing technologies with the concept of “recombinant innovation” (van den Bergh, 2008). The probability of recombinant innovation enters the mechanism of endogenous competition and counterbalances the positive externality of increasing returns to investment. A second extension is the introduction of pollution intensities for the competing technologies, and an environmental policy that charges a price for polluting. The costs of the environmental policy are also considered, with a growth-depressing factor. Numerical implementations of the model allow to study a number of different scenarios with a Monte Carlo approach, by looking at the distribution of final outcomes. In particular, one can thus evaluate the combination of environmental regulation and recombinant

innovation.

In Chapter 4, firms' behavioural heterogeneity is addressed with an analytically tractable model of the competition between a superior but costly technology and an inferior free technology. This model is inspired by the Schumpeterian dynamics model of Iwai (1984) and by the model of costly optimizers versus cheap imitators of Conlisk (1980). The theoretical strategy-switching framework is the discrete choice model of Brock and Hommes (1997). Adopters of the superior technology (innovators) pay a price to reduce their production cost, while the others (imitators) maintain the production cost level of the inferior technology. The basic idea is that imitation works better the more innovators are around, with a trade-off between the advantages of the two strategies. Asynchronous updating reproduces the more realistic scenario where agents only gradually change their strategy. The model is upgraded with a mechanism of knowledge cumulation, which describes the advancement of the technological frontier resulting endogenously from agents' innovation decisions in each time period. Put differently, Chapter 4 proposes a behavioural approach to model endogenous technological progress.

Chapter 5 consists of a discrete choice model of technology competition in line with Brock and Durlauf (2001). The model builds on the interaction of three factors: technological and social externalities, technological progress and environmental policy. A basic version of the model serves to study the equilibrium structure of technology competition. Technological progress and environmental policy are introduced separately and then brought together in the final version of the model. Environmental policy concerns cases where a "clean" and a "dirty" technology compete for adoption and investment. In this case the main interest is in the conditions that enable the market to escape a locked-in dirty technology by tipping the system from the "bad" to the "good" equilibrium where the clean technology is dominant. In this sense, the model provides insights into how decision externalities, technological progress and policy stringency interact and affect the path towards this target.

Technology competition is tackled from different angles in different chapters. Chapter 2 and Chapter 3 focus on the concept of recombinant innovation, the first being a cost-benefit analysis in a static environment, while the second extending the decision framework to many time periods, with a sequential decision framework. Chapters 4 and 5 study the dynamics of technology decisions in a discrete choice setting, and look at technological progress as cost reduction or profitability improvement. Put differently, chapters 2 and 3 address horizontal innovation, with the advent of a third technology, while chapters 4 and 5 deal with vertical innovation, which is about performance improvements of given technologies. Finally, chapters 3 and 5 introduce an environmental economic analysis, taking into consideration the role of an environmental policy that affects technology choices. Table 1.1 summarizes the type of technological progress considered in each chapter, and whether environmental economics issues are addressed.

	Horizontal technical progress	Vertical technical progress	Environmental policy
Chapter 2	yes	no	no
Chapter 3	yes	no	yes
Chapter 4	no	yes	no
Chapter 5	no	yes	yes

Table 1.1: Main themes of the thesis chapters.

### 1.3 A behavioural approach to technological change

This thesis is about the decision making process that underlies technology competition and its dynamics, and the main actor in such decision process is the firm. The focus on agency and dynamics is an important departure from neoclassical models of endogenous technical change, as Romer (1990) and Aghion and Howitt (1992). Aggregation of individual decisions turns into technology competition and, possibly, technological progress, at the macro-level. This way to describe technological change as an emergent property of dynamically interacting agents is inspired by behavioural models of financial markets seen

as complex evolutionary systems. For a survey of such models see Hommes and Wagener (2009) and Hens and Schenk-Hoppé (2009).

The focus on decision making and agency leads to dynamic models, apart from the case of Chapter 2. In this chapter time only plays the role of a parameter indicating the time horizon of the investment. All other chapters present a dynamic setting, where agents make decisions in each time step, be this in a sequential manner as in Chapter 3 or at the same time in each period, as in the discrete choice models of chapters 4 and 5. The application of a discrete choice framework and a logit dynamics to technology competition is one of the contributions of these two chapters. A second contribution of these two chapters is to introduce technological progress in the process of technology competition. Technological progress arises endogenously through a knowledge cumulation process. The latter depends on the time pattern of agents' technology choices. This allows one to model endogenously vertical technological progress, because agents choose between lower or higher production costs (Chapter 4), and lower or higher profitability (Chapter 5). Horizontal differentiation of intermediate goods is not invoked to trigger the endogenous mechanism of technical progress, as it is the case in Romer (1990) and Aghion and Howitt (1992). This is a second difference with respect to these models.

A recent stream of literature studies the effects of social interactions on the process of innovation adoption and consequently on the diffusion pattern of innovation. Examples are Manski (2006), Young (2009) and Brock and Durlauf (2010). In Manski (2006) there is a focus on dynamics, which is studied with a computational approach. The main research question is the role of cohorts in innovation diffusion. Young (2009) studies the effect of different typologies of social effects on the adoption time curve, namely contagion, social influence and social learning. Adoption curves are studied also in Brock and Durlauf (2010), with a focus on expectations consistency and equilibrium, instead of dynamics. In all these models there is one technological innovation under study, and the main issue is the timing of its adoption. The present dissertation addresses technological change in

a more complex setting, first by enlarging the set of technologies available for adoption, with technology competition, and second by introducing technological progress.

Another challenge of the discrete choice models in chapters 4 and 5 is to reproduce the variability of technology markets with simple deterministic models, through the occurrence of chaotic dynamics. Irregular technology fluctuations then have an endogenous explanation. In chapters 2 and 3 instead, the notion of uncertainty of the innovation event is present, with the probability of recombinant innovation. In Chapter 2, this probability is endogenously dictated by agents' choices, so that it turns out to be a deterministic factor. In Chapter 3, agents choices follow a stochastic process, which renders the probability of innovation a stochastic factor.

The dynamic models of chapters 3, 4 and 5 all adopt a bounded rationality approach. A survey of bounded rationality is found in Conlisk (1996). The idea of bounded rationality is present in two ways. First, agents may make decisions only based on past experience. Second, agents' vision or ability to choose the option that performed better in the past is limited. In the discrete choice models of chapters 4 and 5 the last concept is expressed by the *intensity of choice* parameter (Hommes, 2006), measuring how easily agents switch to the best performing strategy. This parameter has a counterpart in a parameter of the urn model of Chapter 3, so that a link is found between the discrete choice models à la Brock and Hommes (1997) and the urn models of Arthur et al. (1987).

## 1.4 Positive and negative feedback

A number of stylised facts of technology dynamics, such as path dependence, lock-in, multiple equilibria, critical transitions, learning curves, can be explained with the endogenous mechanisms of the agents' decision process. More specifically, such stylised facts arise as emergent properties of decision feedback loops. Decision feedbacks can be negative or positive, depending on whether the marginal effect of one agent choosing one option gives a positive or a negative contribution to the utility of agents choosing the same option,



respectively. For this reason, the feedback takes the form of an externality in one agent's decision.

The literature on technological change and technology competition has addressed different sources of positive feedback, as for instance economies of scale (Mansfield, 1988), network externalities (Arthur, 1989) and learning-by-doing (Arrow, 1962). A comprehensive study of positive externalities in the economy is done by Arthur (1994). Whenever technology decisions are affected by motives and incentives other than technological performance, there can be also negative feedbacks. One example is when technologies have an impact on the environment. Polluting technologies are characterized by a negative externality (Stern, 2007). An environmental policy internalizes the negative externality of pollution with a tax on pollution or with a subsidy for clean technologies, giving place to a negative feedback in agents' decision about polluting technologies.

A different perspective on positive and negative feedbacks in the economy is offered by the concept of super-modularity (positive feedback) and sub-modularity (negative feedback). These concepts have been proposed in models that describe firms' output decisions in a strategic environment (see for instance Milgrom and Roberts (1990)). This thesis does not deal with strategic behaviour, because of two major assumptions: first, agents only consider past experience in making a decision; second, the economic systems addressed always present a large number of agents, and the marginal effect of an individual decision is negligible.

Decision feedbacks inhabit all dynamic models in this thesis, namely the models of chapters 3, 4 and 5. Positive feedback is modelled explicitly in chapters 3 and 5, with its effect being proportional to the share of one technology in the market. The rationale for this feedback is that a technology becomes more attractive as more firms implement it, cutting down costs (economies of scale), as more agents use it, because of technology standards and infrastructures (network externalities), and as it becomes more efficient due to its application (learning by doing). A further source of positive externality that is invoked

in Chapter 4 are social interactions (Manski, 2006; Young, 2009; Brock and Durlauf, 2010). These can give place to positive feedback whenever the technology adoption decision is driven also by “word of mouth” via a contagion effect or by a recruitment process (Kirman, 1993), or as conformity effects and habit formation (Alessie and Kapteyn, 1991). Social interactions by no means lead always to positive feedback: conspicuous consumption gives place to a snob effect (Frank, 2005), where an increasing number of adopters becomes a reason not to adopt, instead of to adopt. For technology choices this is not likely to be the case, and the models of chapters 3 and 5 assume that also social interactions lead to positive feedback.

Chapters 3 and 5 consider also a source of negative feedback with the introduction of an environmental policy that internalizes the negative externality from pollution of technologies. This is done with a tax on pollution (Chapter 3) or with a subsidy for the clean technology (Chapter 5). The introduction of the negative feedback of an environmental policy beside the positive feedback of technology decisions explained above give place to a complex system of decision feedbacks in the models of chapters 3 and 5.

The model of Chapter 3 presents a further decision feedback from the probability of recombinant innovation. This feedback may be either positive or negative depending on the diversity of the technology market, that is on the distribution of the market shares of competing technology. The probability of recombinant innovation is assumed to depend positively on the diversity of the market, being maximum for equal technology shares. Whenever one technology becomes dominant, the probability of recombinant innovation decreases. This represents an incentive to re-balance the market, choosing the technology with lower market share.

Technology decisions may also be characterized by a negative feedback from the price reduction effect of technological innovation. This is the fundamental idea of the model of Chapter 4. Here the endogenous market dynamics of supply and demand is modelled, so that also the market price affects agents’ decision. In particular, as more agents

choose the superior technology (more innovators), the price falls due to cost reduction, and so do profits from sales, which depend positively on the price. Lower profits hurt more innovators than imitators, because of the fixed cost of innovation. This mechanism translates into a negative feedback, where the utility from innovation decreases as more agents innovate.

Table 1.2 summarizes the arguments above, reporting the type of decision feedback in the dynamic models proposed in the thesis (Chapter 2 is not considered because it contains a static model).

	feedback
Chapter 3	positive and negative
Chapter 4	negative
Chapter 5	positive and negative

Table 1.2: Different types of decision feedbacks in the chapters with a dynamic model.