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Technology for Sustainable Development[1]

Debate continues on the question of whether or not it is possible to foster productivity that contributes to economic growth and a rise in income, while at the same time decreasing emissions down to the level that makes it possible to maintain availability of the environmental qualities for future generations. In this chapter, we discuss if it is possible to decouple economic growth and material use (so-called dematerialization) and whether it is possible to steer technologies towards less material use and emissions per unit of produced value (so-called ecoefficiency). A final answer cannot yet be delivered, but the arguments are discussed to pursue more balanced decision making in environmental policies and management.

2.1 Sustainable Development

The debate about dematerialization has been going on for the last few decades. However, the focus has changed. In the 1960s and 1970s, after a few decades of exceptionally high economic growth in Europe, Japan and North America, attention was given to the negative side effects of growth such as fuel and mineral exhaustion, extinction of species, health impacts, and fragmentation of land and so on. It is argued that the materials used in production and consumption disperse as emissions after some time and that the mass-conservation principle (the amount of emissions equals the extracted material and fuel resources) implies dispersion of the materials during and after use. However, the qualities of the dispersed materials change and degrade and the materials cause negative effects on environmental qualities (Kneese et al., 1970; Ayres, 1978). Some environmental economists argue that economic growth and the availability of environmental qualities are

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fundamentally incompatible. Many others assume that environmental qualities can only be sustained under far-reaching income distribution and radical technological changes in favor of environmental qualities. They point out that the degradation of environmental qualities causes welfare and productivity losses that should be incorporated in economic indicators like prices and income as this provides a more realistic view on welfare development in national accounts (Leipert 1985; Daly and Cobb, 1989; Hueting, 1990).

Contrary to environmental economic views, the mainstream (neoclassical) scholars expect that, in theory, the economic structure does change. More specifically, it is thought that, in theory, the non-reproducible factors (environmental qualities) can be substituted by the reproducible ones (labor and capital). Following this, it is underscored that global welfare can grow without depleting environmental qualities if the changes in economic structure proceed faster than the use of the non-reproducible resources (Kuipers and Nentjes, 1973; Solow 1974, 1977). The process of substitution can go on forever due to unlimited knowledge and can be directed towards the technologies that are based on non-scarce and renewable resources, recycling and the creation of new resources. In theory, the only physical limitation is the influx of solar energy that is so large that it is almost unlimited for human development (Weitzman, 1977; Gregori, 1987). It is stressed that the reservation with respect to the substitution of the non-reproducible by reproducible inputs is not so much availability of natural resources but rather emissions that cause pollution. This is because pollution damages environmental qualities, in particular biological processes like biodiversity, health and so on. In a precautionary mainstream view it is accepted that technological progress can create value at decreasing emissions and it is underlined that far-reaching emissions reduction is the prerequisite for welfare growth. In this view, emissions must be decreased to the level that does not distort availability of environmental qualities. That means a reduction by a factor of ten or more in 20 years in Europe and North America in order to balance the growth of materials in use (Perrings, 1991; Nentjes, 1990, Klaassen and Opschoor, 1991; Weterings and Opschoor 1992).

In the 1980s and 1990s, it was widely acknowledged that maintaining good environmental qualities was a precondition for welfare growth. This view was rooted in the political debate occurring under the term "sustainable development". This term, introduced into international politics by the World Commission on Environment and Development, is defined as: "development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs" (WCED, 1987, p. 43). The stewardship of economic development became the focal point of attention. The idea of stewardship through co-operation between market interests and public decision makers addressed the need of technological change towards low-emission methods, renewable resources, resource saving, durable products, low-input production and consumption, non-toxic means, effective space use, and so on. Stewardship in entrepreneurship is underlined with biological metaphors such as sustainable metabolism, tree-like companies, industrial metabolism, green business and industrial ecology. These ideas are translated into a metaphor known as "triple bottom line" (profit, people, planet) that balances income growth, distribution of wealth and environmental qualities (Reijnders, 1984; Winter, 1987; Ayres, 1989; Elkington and Burke, 1990; Graedel and Allenby, 1995). Economic models have also been developed to emphasize the possibility of sustainable development under the assumption of progress in dematerialization and the rapid increase of ecoefficiency among technologies (Hartog and Maas, 1990; Meadows et al., 1991; Duchin and de Lange, 1994).

The empirical findings gained from 1970 to 1990 do not support overly optimistic views. The positive trend is a growing share of labor-intensive services despite increasing labor costs. In addition, there is a trend towards increasing value added in the manufacturing process in many industrialized countries. This trend causes reduction of energy and material use and emissions per unit of output in several countries including Germany, Japan and Sweden. The trend cannot be explained solely by the export of the most resource-intensive and polluting manufacturing processes from industrialized countries to developing ones. The main factors are changes in the manufacturing towards products with high value added and the use of environmental technologies that reduce material uses and emissions (Jänicke et al., 1986, 1997). Another positive sign of the decoupling between economic growth and the degradation of environmental qualities is a significantly negative correlation between the emissions connected with combustion—CO and NO_x—and the countries' Gross National Products. This trend suggests that there is a global shift towards less energy-intensive economies that is explained by the diminishing share of manufacturing in the global economy (Selden and Song, 1994). The findings on changes towards more services and high-value manufacturing that contribute to dematerialization invoked the view of an autonomous, long-term, global trend from the less-developed economies that are largely based on material-intensive manufacturing towards the more-developed economies that are largely service based. A hypothesis is put forward of the so-called "Green Kuznets-curve" that advocates a relation between income and pressure on environmental qualities. The relation is expressed by an inverse U curve. This suggests low pressure at the low-income level due to little manufacturing found in low-income countries, growing pressure to increase income because of more manufacturing in medium-income countries and less pressure in the highest-income economies because of the presence of more services. The message is that the autonomous trend towards higher income stabilizes and ultimately reduces the pressure on environmental qualities. This view is scrutinized in view of poor data on material use and pollution in most of the world's countries and failure to accommodate international material flows in the statistical accounts (Ayres, 1997; Bruijn and Heintz, 1999). Studies examining international material flows support the criticism. Per capita material use and emission, including the trade with materials, shows an increasing trend in Germany, Japan and the Netherlands, and stabilization in the United States but at a much higher level than in Europe and Japan (Bringezu, 1997; CE 2002). At best, it can be argued that the pressure of emissions on environmental qualities does not increase as fast as economic growth, but that does not mean that the impacts do not increase as fast or even faster, because growing pollution can cause fast deterioration of some qualities, such as biodiversity or atmospheric structure.

The discrepancy in findings about the positive changes in economic structure due to more service and the sluggish decrease of emissions pressure on environmental qualities can be explained by complementation in consumption. Complementation in consumption means that people tend to add various uses to products and services as their income grows instead of substituting one product for another. As a result, product consumption decreases very slowly. There are many examples of complementary uses as a function of income growth, including radio and television, paper and computers, telephones and e-mail, and so on. During the upswing, people spend on various uses that are only apparently substitutes for each other, for example people spend more on architects' services for new houses as well as more on professional maintenance of old houses and they buy more products to maintain houses by themselves, albeit the growth rates on the uses differ. Consumptive uses can rarely substitute for each other, but some uses grow faster than others as a function of income growth. Differences in the rate of growth cause the consumption patterns to change. Mobility is illustrative; mileage data for the last century show that the share of old transportation methods (ship and rail) decreased in favor of the new modes (road and air), but all transportation modes grew, albeit some faster than others (Nakicenovic, 1991). The complementation can be explained by the fact that product use is closely linked to the uses of many services and products in a product–service combination, for example, car use calls for roads (products) and regulators (services), and the use of televisions requires electricity and broadcasting. Therefore, it is difficult to substitute a product or a service because it entails a chain of changes in use. In addition, the positive effects that more services in an economy have on dematerialization are counteracted by gradual materialization of services. This means that the share of labor involved in the use of a service at a given income level is gradually substituted by capital and materials (Uusitalo, 1983; Krozer et al., 1996; Gatersleben and Vlek, 1998).

Dematerialization of the economy due to increased services in economies is an important trend for environmental qualities. It progresses due to changing consumers' preferences almost independent of companies' decisions and policy making. However, the growing share of services alone is not enough to limit the growth of emissions as they expand despite an increasing share of service, let alone a reduction in emissions by a factor of ten to twenty in the next few decades. In addition, an increasing ecoefficiency in production and consumption is needed at a rate that is much higher than production growth to compensate for pollution's negative effects on environmental qualities. The key factor for ecoefficiency in consumption is the fast development and diffusion of environmental technologies over a broad range of activities in production and in many types of consumptive uses. The issue becomes whether it is possible to foster technological development towards low-emission patterns at a much faster rate than the economic growth. This issue is discussed in view of economic theories: the neoclassical, the evolutionary and the behavioral theory.

2.2 Theories on Environmental Technological Progress

The economic theories on technology development provide different answers on the possibilities to foster changes towards environmental technologies. The differences are connected with diverse points of view on technology development: scarcity and prices in the neoclassical theory, policy decisions in the evolutionary theory and companies' organization in the behavioral theory. The neoclassical theory is so preoccupied with prices that other factors, including possibly even the main factors that influence technological development are less elaborated. Other factors are more explicitly considered in the other two theories. The evolutionary theory focuses on the positive external effects of technologies (spin-off). The means of productivity increase in many sectors due to the application of some closely related technologies (called a technology path or a *filiére*), thus suggesting that cleaner technology in a sector can provide spin-off to many other sectors. The behavioral theory addresses the internal organization that decides upon risk avoidance instead of output maximization. This theory suggests that innovation is an anomaly. These views partly exclude and partly supplement each other. After the review of these theories, we will enrich mainstream environmental economics based on the neoclassical economic theory with views from the other two theories. We discuss the theories primarily from the perspective of decision makers contemplating what guidance they offer in the quest for progress in ecoefficiency. The behavioral view has been largely neglected in the literature on environmental innovation and it is extensively covered here because it offers a fruitful approach to understand companies' decision making about environmental innovation, in particular on how incentives affect firms' innovation decisions.

2.3 Neoclassical Theory

The neoclassical theory concludes that welfare losses from pollution are unintended consequences of failures in market organization and in public sector performance. Market failure appears where property rights regarding environmental goods, like the right to use the environment as a sink for pollutants, have been imperfectly defined. Consequently, parties that suffer from pollution cannot develop trade with parties who benefit. Since a market for scarce environmental goods does not emerge spontaneously, scarcity remains under-priced suggesting to polluters that there is no scarcity at all. One option for the victims of pollution is to try to make polluters liable for environmental damage. Such lawsuits clarify the rights of respective parties, laying the basis for negotiations and the elimination of market failure. However, if the sources and the victims of pollution are many, remedial action through private law breaks down. In such circumstances, which are typical in high-income and developing countries, control of pollution is a public good and a task for national government (Angel, 2000). Public-sector failure occurs when governments fail to take appropriate action. In the neoclassical view, the consequence of such failures is that the environmental scarcities are not signaled, either in price of pollution or in any other restrictions on pollution that can be imposed by regulations. If pollution is free then the economic incentive to contain emissions is lacking. In addition, so is the incentive to invest in research and development of environmental technology that would provide the means to reduce or prevent pollution. As a result, the costs of development and procurement of environmental technologies are higher than the benefit of less damage due to lower emissions that could be achieved by the installation and use of the technologies. The argumentation follows that if the market mechanism does not specify the liabilities for the external effects sufficiently, then the policy makers should avoid pollution by emissions reduction. Policy makers can use various instruments that trigger companies to reduce emissions. Basically, policy makers can put a price on emissions or restrict emissions by standards with a maximum emissions allowance. The price and the standards invoke the use of environmental technologies to reduce the polluting activities, because it becomes beneficial, or in the second case to reduce emissions. In its policy advice, neoclassical economics has a clear preference for instruments that mimic a market, which is setting a price on pollution. Placing a price on pollution has two effects on polluters: it signals environmental scarcity and it provides polluters with an incentive to take action, while leaving them flexibility in their search for the best approach, including the search for and the development of new more effective technologies (e.g. Baumol and Oates, 1975; Pearce and Turner, 1990, Tietenberg, 1994). Following the neoclassical view, production for valuable markets as a function of inputs and production to prevent damage as a function of emissions reduction are differentiated (so-called joint production functions), which implies that companies confronted with environmental regulations must deliberate between use of additional environmental technologies and limitation of the most polluting activities (e.g. Duchin and Steenge, 1999).

This exposé of environmental economics is an application of the neoclassical theory on induced technological development. In this theory, perfect substitution between inputs is assumed in the long run. The substitution enables one to maximize output at the lowest input prices, whereas the prices are determined by scarcity of inputs. In this way; companies develop and apply technologies as a result of an exogenous set of input prices as opposed to autonomous technological development driven by the progress of knowledge that is an endogenous factor (Heertje, 1973; Stoneman, 1983; Grilliches, 1996). The theory on induced technological development is supported by many empirical studies among others in agriculture. The studies show that the high prices of inputs (measured by the relative price of agricultural inputs) invoke efforts in research and development (R&D) to develop technologies (measured by patents) that in turn, reduce the use of the most costly input (Ruttan, 1971, 1982). This train of actions is less clear in the case of environmental technologies. The poor responsiveness of environmental technologies with respect to resource and emission prices is explained by various imperfections, dominance of public interventions such as subsidies for natural resources and polluting products that undermine the positive effects of the prices on the use of environmental technologies, low-resource productivity that limits expenditures on R&D and protectionist measures like patents and import restrictions that create barriers to the entry of new technologies. As stated in the theory, the imperfections limit prices' positive effects on use and development of environmental technology. These imperfections are reflected by low elasticity of emissions reduction with respect to prices (Dasgupta and Heal, 1979).

Despite the recognition that price effects on environmental technology are far from perfect, the theory on induced technological change is widely applied in environmental policy. The theory is instrumental in practice because it relates the effects of policy instruments like emission standards or emission charges with the development and use of environmental technologies. The theory suggests a causal relation between scarcity, price and technological change. However, the theory's empirical foundation is weak. Based on the theory, it should be expected that the lower resource prices increase the use of material in products. In reality, the share of material measured by mass and value actually decreased as did resource prices during the past two centuries. In the 19th century, the prices of natural resources were already so low that the cost of resource use was considered hardly relevant for companies' decisions. In 1848, Mill remarked: "But the crude material generally forms so small a portion of the total cost, that any tendency which may exist to a progressive increase in that single item, is much over-balanced by the diminution continually taking place in all the other elements; to which diminution it is impossible at present to assign any limit" (Mill, 1985, p. 64). Ever since, the real prices of resources has steadily decreased albeit with some fluctuations (Rosenberg, 1975b, p. 229–248; Dasgupta and Heal 1979, p. 439–470), as well as the share of materials per unit of product, measured by real value and by weight, which is found on the national and sector level, as well as being illustrated by product cases (Larson, 1986; Herman, et al. 1989; Tilton, 1991; Wright, 1997). Similar trends should be expected for emissions. It seems that the price of natural resources, or emissions is not the only, and maybe not even the main, determinant of the changes towards environmental technologies.

The theory on induced technological change is criticized within the neoclassical theory. Scholars on the history of technological change have argued that the development of a new technology usually takes so many years that it is impossible to foresee the resource prices at the moment of sales of the technology, because the resource prices fluctuate. Hence, the demand factors, such as prices, are mainly relevant for the improvements of the available technologies (adaptations) because adaptations are less time consuming and the results of adaptations are more predictable than the development of new technologies (innovations). Studies on trends in technology development argue that the relation that is suggested in the neoclassical theory should be reversed. It has been put forward that technological development is largely driven by the cumulative increase of know-how. It boosts productivity that reduces the use of the costly inputs. The decreased use of the costly inputs, in turn, causes downward pressure on resource prices. Technological development thus explained by generated know-how is triggered by dramatic events like overexploitation of natural resources, population changes, wars and so on (Lilley, 1980; David, 1975; Rosenberg, 1977, 1982a). Therefore, distinction between autonomous (endogenous) and induced (exogenous) technological change should be made, although it is not clear why endogenous development is strong in the case of environmental qualities. It is rather odd in view of much higher and increasing labor and capital relative prices. An explanation is needed.

2.4 Evolutionary Theory

The observation of changes in economic structures irrespective of the relative input prices invoked another interpretation of technological development. In the argumentation that is usually called evolutionary theory, the technological development is viewed as the search and selection processes within socio-cultural and administrative frameworks that are determined by prevailing norms. In the search process, various options are presented to solve a problem, for example, to overcome resource scarcity. The selection process includes choosing the most suitable option for a firm or an institution in its specific situation. The final decision is rarely based on thorough economic calculations like cost benefit assessments. Instead it is based on the decision maker's expectation based on prevailing norms that the selected technology can perform well. In this train of thought, it is expected that input-prices have minor influence on technological change in comparison with generated know-how, socio-cultural conditions, quality of management, policy making and so on (Nelson and Winter, 1982; Dosi and Orsenigo, 1988).

Following this argumentation, it is pointed out that a new technology invokes development and use of other related technologies in various sectors, so-called spin-off. For example, development of computers invokes software that triggers investments in the software industry that in turn invokes development of the Internet and so on. The result is that many linked technologies form a pattern, called a path. The related technologies, becoming path dependent, entail many improvements that raise productivity. A positive effect of path dependency on economic development is an increasing return to scale in many sectors. A negative effect is that once an inefficient technology is established, it is difficult to substitute it with a potentially superior technology because of interrelated, past investments. The established technologies have a character of sink costs; so the technology path becomes a pervasive system. Only large investments in a new technology can break down the superior pattern and establish a new one (Arthur et al., 1987; Arthur, 1989; Arthur, 1990). This causes regional and structural repercussions, because many companies depend on each other in clusters. Even partial replacement is difficult because the activities linked with the established technology do not fit with the new technology and consequently the whole system of businesses collapses. Forceful policy interventions are needed to introduce a new pattern or cluster, like subsidies for co-operation between companies, new stringent regulations and public investment (Malecki, 1991). An illustration of the problem is the idea of substituting a hydrogen-based energy system for the present fossil-fuel-based energy system that would require huge capital investments in a new energy infrastructure to replace the present infrastructure that would have to be dismantled. Technology is locked in because the huge capital investments made in the past for the infrastructure and organizations crafted on the established technology are sunk costs.

The evolutionary theory presents a convincing image of technological development, but it does not explain the relations between socio-cultural factors and technological change, nor does it provide arguments on how to assess the changes in technological patterns beforehand. Some call it "theorizing" because causal relations are absent (Nelson, 1995). The pros and cons of the neoclassical and evolutionary theories are not discussed further as they are lively debated in literature (Stoneman and Diederen, 1994; Metcalfe, 1994; Balman et al., 1996; Ruttan, 1997; Dosi, 1997). We focus on the application of the evolutionary theory in environmental technology.

Advocates of evolutionary theory on environmental technologies make a distinction between two development patterns. The cornerstone is the dichotomy between treatment technologies and process-integrated technologies that make the pattern with the technologies for emissions treatment that are called add-on or end-of-pipe technologies and the pattern of technologies for emissions prevention that are called cleaner technologies. In decision making, emissions treatment is called a curative approach as opposed to the preventive approach offered by cleaner technologies. The difficulties involved in reducing emissions are primarily explained by the dominance of technological patterns from the past that comprise emissions treatment. It is assumed that the technologies have been selected without adequate, overall consideration of environmental issues and that the substitution of the treatment technologies by the process-integrated technologies is imperfect. These scholars even suggest that environmental policy can be a major cause of the imperfections because it enforces far-reaching pollution reduction in the short-term that promotes emissions treatment instead of longer-term policies that can invoke cleaner technologies. Along these lines, various socio-cultural factors are presented to explain why companies favor treatment technologies instead of process-integrated technologies. These factors include: poor awareness and information about environmental qualities, imperfect selection of solutions by management as well as policy focus on standards in licenses that prescribe treatment instead of process integration (Quakernaat et al., 1987; Mensink, et al., 1988; Schot, 1988; Christensen, 1991; Saviotti, 2005).

Forceful policy interventions are argued to introduce environmental innovations. The State of California's regulation in the US on electric cars, so-called zero-emission vehicles regulation, is used to illustrate the fact that policies can trigger clean-technology development. It is argued that the regulation can force the environmental innovations that, in turn, provide competitive advantage to US car manufacturers. This occurs because they gain experience in the state on how to sell electric cars in other parts of the world (Kemp, 1995, p. 262–282). However, this example also illustrates that predictions are risky and fail. The case shows how non-compliance with the regulations has invoked several successive policy amendments that weaken its stringency and that discouraged the innovative spur and delayed implementation. Nevertheless, it is suggested that time and again decisive policy makers and managers can change the pattern in environmental technologies from the curative approach (emissions treatment) to the preventive approach (using integrated technologies). Breakthrough innovations are advocated that would provide positive effects on the economy and the environment (Weizsäcker, 1998, Weaver et al., 2000). Various policy interventions in R&D, intermediary organizations and implementation of environmental policies are encouraged to reach breakthrough innovations, such as: assistance with initiatives, funding of the development of cleaner technologies and strict regulations (Arentsen et al., 2001; Kemp and Moors, 2003).

Evolutionary theory as applied to environmental technologies argues that there are choices in patterns of technological development and the metaphor of cleaner technology paths as a result of decision making is appealing. The theory is attractive because it suggests managerial capability to steer technologies towards sustainable development, but it does not outline which mechanisms cause shifts towards cleaner technologies and why present decision makers can make better choices than decision makers in the past. Moreover, the dichotomy between "good" and "bad" innovations is dubious because it cannot be predicted whether a "clean" technology becomes "dirty" during use and vice versa. It is uncertain beforehand if the potentially cleaner technology actually contributes to emissions reduction or vice versa, if a dirty technology can become a cleaner one due to additional actions. Experience shows many unfortunate decisions and changes in mindset in decision making. For example, trains were the example of "dirty" technology in the 1920s. However, nowadays they are considered to be the clean transport system. Nuclear power plants that were expected to provide unlimited, clean energy in the 1950s were found unacceptable in the 1980s. And recently, return packaging has been assumed to be environmentally sound, but assessments and experiences in many countries undermine this perception. The advocacy of the breakthrough towards clean patterns is also disputable because dissemination of incremental changes can be very effective. For example, a 10% annual rate of technological progress towards more effective technologies reduces emissions by a factor of five in 15 years and by a factor of 10 to 20 in 20 to 25 years. The rate is realistic regarding the experiences with technological development that indicate progress in effectiveness during many decades, like in shipping (Rosenberg 1982a). Such a high rate of the effect-increasing technological progress without breakthrough technology is also found in environmental technology. For instance, the tenfold higher energy performance of locomotives in the 20th century measured by the pulling power per unit of mileage (Heel and Jansen, 1999), or in the air fleet that on average reduced fuel use per passenger kilometer by half during the period 1970 to 1990 (Flemming, 1996). Moreover, treatment technologies became very effective. In the last few decades, treatment technologies have reduced many emissions by a factor of 4 to 10 at similar or even lower costs through an innovation with subsequent adaptations such as the almost 90% reduction of biological matter due to improvements at wastewater treatment plants and more than 95% SO_2 emission reduction through better ventgas treatment.

Far-reaching emissions reduction can be achieved through innovations and adaptations of available technologies, both by treatment technologies and by process-integrated technologies. These patterns can be seen as competitive technologies at the moment of decision making, but all of them can be equally good. If policy makers, following the evolutionary view, decide to subsidize heavily process-integrated technology because they need a breakthrough with an uncertain effect of the subsidy on environmental performance this then contradicts the rule that rivaling technologies should compete on a level playing field. As a result, breakthrough technology may emerge as the competition's winner, even though it is not actually the most environmentally benign solution. At the same time, adaptations of the available treatment technologies could be triggered by regulations with hardly any subsidies. The need for environmental innovation can be motivated by high costs and poor effectiveness of environmental technologies available at the moment of decision making. However, decision makers must also consider that it is uncertain whether a new technology becomes superior after installation and if it performs well during use (Rothwell, 1992). Doubts about the necessity of breakthrough from treatment technology to the process-integrated technology path should not be considered a plea against environmental innovations, but rather as a way to foster innovations in areas that lack effective and efficient environmental technologies.

2.5 Behavioral Theory

The behavioral theory provides a convincing presentation of companies' decision making on the development of new technologies by addressing firms' organization. In the exposition of the theory, the work of Cyert and March (1968) on the organisation of firms is linked with decision making on environmental technology. In their seminal work *A behavioural theory of the firm* Cyert and March from 1963 criticise neoclassical economics for modeling the firm as a single-minded profit maximizer, possessing all relevant information on the options from which it can freely choose, and acting without internal co-ordination problems, as if it were one person. In contrast with the holistic conception of the firm of neoclassical economics, the behavioral theory has a pluralistic view. It sees the firm with its different functions at different levels as a conglomerate of interest groups, each with its own specific objectives imperfectly coordinated by the firm's top management, because of incomplete information and control. We shall clarify this view, using three key concepts: satisfying behavior, organizational slack and conflict resolution.

Satisfying behavior means that a department's objectives are set as aspiration levels, mainly determined by extrapolation of past achieved results. It can be, for example, that the target for marketing department's sales volume is increased once sales targets of the last period have been met. If an objective is not achieved, options to solve the problem are considered one by one starting with the least incisive option and within the department where the problem emerged. For example, a drop in sales has to be solved in the first instance by the marketing department. The search for options stops if an option that promises to meet the aspiration has been found. When circumstances become even more difficult and the search for alternative options has to be widened, solutions requiring more drastic changes and involving higher risks are taken into consideration. Conflicts between the potentially competing objectives of different departments in a firm, for example, aspired sales level and profit aspiration, can be avoided because each group does not go for the unknown best but rather for a satisfactory outcome, given its aspiration level, and because organizational slack, also known under the name X-inefficiency, offers a buffer. Slack is expenditure that is not really necessary. It is a form of waste that tends to rise in good times when a firm's management units achieve their aspiration targets. The search for better options, which starts when aspiration levels are not achieved, will result in detection and reduction of X-inefficiency or absorption of slack as Cyert and March (1968) call it. A third element that helps to avoid outright confrontation is the established internal procedure for decision making. In particular, this is the guideline that if an aspiration level is not achieved the unit whose objective is not achieved must come up with a solution. For example, a drop in sales below the aspiration level can be countered by the marketing department through slack reduction. This means a more effective marketing effort with an unchanged budget. Other groups come in when the problem cannot be fixed locally, for instance, production is adjusted when stocks increase due to lower sales. The company's top management acts when problems at lower decision levels accumulate and its major objective—the aspired profit level—is not achieved. The selected solution, if adequate for the objective, is then internalized in management procedures such as internal quality assurance. The solution becomes the preference routine in management of the company.

From the behavioral theory emerges a picture of the firm as a plural organization that relies on conventional solutions and is sluggish in adjusting to changing external circumstances. Actions do not automatically lead to the optimal solutions predicted by neoclassical economics. In short, firms decide under bounded rationality.

March (1989) has investigated the implications of the behavioral theory for innovation. In line with his notion of the firm's behavior as satisfying aspiration levels preferably by conventional actions and considering a restricted number of options for solutions in a hierarchical order, he argues that innovations are not the result of spontaneous, voluntary actions. On the contrary, the established positions of management units in decision making form large barriers to change because innovations are perceived as a risk to the unit. The conventional mechanisms for problem solving dominate, thus avoiding the risks involved in exploring new ways. Innovations come into sight when several possible solutions are considered and are expected to fail. In his view, innovations need organizational changes that enable pop-up, new views such as specialized development units to generate new ideas and invoke changes. He calls for the functions that develop a playful process in decision making to invoke innovations ("foolishness"). Studies into innovation processes confirm that risk taking is rarely spontaneous or directed by management or by calculations. Instead it is a necessity in view of resource scarcity, strict regulations or tough competition. Innovations are rarely deduced from technological patterns in the past and the innovators often act apparently irrationally, driven by self-fulfillment ("with guts"). This view suggests that companies' decisions to innovate are driven by entrepreneurial initiatives that cannot be derived from the past because they distort the existing patterns. Hence, an innovation is uncertain and rarely predictable by policy makers, though clear aims and the expectation of rigorous enforcement are favorable conditions for innovation. Thereafter, numerous adaptations during decades and even centuries follow (Rosenberg and Birdzell, 1986; Coombs et al., 1987; Allen, 1988).

The argument of the neoclassical and the evolutionary theory against the view of trial and error in innovation processes presented in behavioral theory can be that more preparatory work reduces the uncertainties, although some expenditures are needed to generate information and to negotiate with the relevant internal and external interests (transaction costs). Hence, it is argued that more expenditure on transactions could provide an even larger benefit, because better solutions would be found. However, this view is challenged by studies on decision making processes. The studies show that decisions on controversial issues are often delayed to keep track of traditional patterns from the past. Higher expenditure on the deliberation about alternatives often does not help, because more deliberation increases companies' transaction costs, but cause an unanticipated effect: the demand for even more deliberation. This means that uncertainties encountered in decisions about innovations can only be reduced by more information or negotiations with various interests but they cannot be prevented (Colinsk, 1996). The acts of consultancy, brokerage and accountancy have only a limited contribution to risk reduction in decision making. Trial and error is unavoidable.

Building on earlier work (Klink et al., 1991), a view on innovation can be brought together and integrated into the framework of behavioral theory on the firm. Under the conventional policy, direct regulation with mandatory performance standards that can be met with technologies available from the past, the task of environmental management is to comply with the standard at the lowest cost. Environmental management is a technical routine task as the requirement and the technologies are largely preselected by policy makers. When it comes to acquiring the environmental license allowing operations to start, the task of installing the available technology does not affect the firm's profitability because the technologies are preselected that are expected to be affordable for the firm. Hence, the firm's decision is delegated to an environmental unit low in the management hierarchy, possibly a sub unit of the production department. The task can be left to the environmental unit. The firm's top management remains at a distance; it has no motive to interfere. It is not a climate favorable to environmental innovation because the environmental unit has no authority to make R&D decisions. In addition, if it considers proposals to do so, the units higher in the company's hierarchy will not be able to explain how that unconventional option, not belonging to the firm's core business, contributes to the firm's prime objectives. Once the license is acquired and the environmental technology operates, the solution is incorporated as a routine and management attention diminishes because the problem is assumed to be solved.

The position of environmental management would become different, however, if a drastic change in policy were to bring new and very strict regulation, demanding such high investment in the preselected available technology that the costs threaten to depress firm profits below top management's aspiration level. Even more threatening is the exceptional step of technology-forcing performance standards that must be achieved within a number of years with sanctions for non-compliance. A problem also occurs when competitors are expected to accrue a share of the market by provision of the products that comply with policy targets or satisfy customers' growing demands. The environmental unit is unable to fix the problem on its own and other departments must be involved. This is a task for top management to initiate and coordinate a search for options to address the problems. Among the first, least-costly options are lobbying for less-stringent regulations. Another can be postponement of the compliance date, criticizing competitors and taking legal action to delay compliance. When these options are not expected to deliver the aspired recovery of profits, a range of more incisive options has to be considered. These can include starting R&D on new, more effective environmental technology or participation in a joint innovation project. R&D necessarily involves the production department because new environmental technology may require adjustment of production methods. The procurement and sales departments have to participate if the input mix, in particular, raw materials and fuels must be changed and product characteristics and possibly even product image have to be modified. The more that different departments become stakeholders the more necessary it becomes to move the problem up the firm's hierarchy and to face and accept the risks related to unconventional solutions. Innovation is an option that is not chosen spontaneously because it is costly and risky. Only under circumstances of urgency and potential high rewards from a successful R&D investment can one expect a firm to accept the costs and risks inherent to such a strategy and innovate. The more the option means having to reduce or shift production as the way to meet environmental demands, the greater the probability that environmental innovation will be attempted. Depending on the perceived option, R&D may focus either on ambitious improvements in add-on technology, a total redesign of production, or an intermediary solution. In short, behavioral theory of the firm suggests that environmental innovations can only be expected if high-ranking management senses the urgency and anticipates tough environmental demands in the future with promising market conditions.

2.6 A Framework on Environmental Innovations

In light of these theories, the question is how to direct technology towards higher income at lower emissions levels in order to increase greatly the present ecoefficiency. All the theories suggest such a possibility. Analyses diverge with respect to the mechanisms that invoke technological changes and therefore policy recommendations differ. Neoclassical theory argues that technologies can flexibly be adapted to the changing input prices by input substitution. Neoclassical economists emphatically advocate a high price on emissions to reflect scarcity of good environmental qualities. This would invoke development of effective environmental technologies and reach the lowest-cost solutions through competition between the technologies. Evolutionary theory views technological development as a process of lock-in by the patterns created in the past. To force a break through of the existing patterns, policy makers have to choose for new, cleaner options and support technology development in that direction by using a full range of policy instruments such as subsidies, technology-forcing enforcement and so on. Behavioral theory describes technology as an entrepreneurial instrument embedded in the company's organization that essentially resists changes unless the available solutions are insufficient to attain the organization's objectives. Forceful, external demands for environmental qualities in combination with well-informed and creative internal management are necessary requisites to innovate. At first glance, the views seem to point in different directions for decision making. However, closer examination suggests that the neoclassical theory provides a good starting point for a theoretical framework on environmental innovation. The postulate that a price on pollution affects the perception of scarcity is not disputed but the causality that the price determines the development of environmental technology is arguable.

Neoclassical theory's argument that input substitution in the long run is supposed to be perfect is particularly unconvincing regarding the finding that material-intensity in economy decreases even under decreasing resource prices. The finding can be explained by the engineering theory on loss prevention. The theory explains inefficiencies in production by the occurrence of losses in production. A production is described by the output function of heterogeneous inputs to perform a demanded output (a product). On the assumptions that the goal of production is a qualified output goal and operations in the production are stochastic events created by human skills, the outputs are described by factorial inputs (Leeuwen, 1988). It is formally:

$$N_o = (N_i!+1) \tag{2.1}$$

with N_o outputs and N_i inputs.

The production function of three inputs ($N_i = 3$) can provide seven outputs ($N_o = 3!+1 = 3*2*1+1 = 7$). Out of seven outputs only one is the qualified output (product), whereas all the others are side products that can be waste. For product maximization, six out of the seven outputs must be prevented. The production with four inputs can provide 25 outputs with only one product and 24 outputs must be prevented, and so on. The theory postulates that the number of inputs determines, *ceteris paribus*, the probability of loss and efforts to prevent it. This illustrates how complex any manufacturing process is because even a limited number of inputs provide so many outputs to prevent that 100% valuable output is only attainable through endless experimentation and operational adaptations in production. Scholars on technology change confirm the complexity of manufacturing entailing imperfections in operations that invoke endless engineering experiments to improve complex capital goods such as ships and planes (Rosenberg, 1982b) as well as daily-life utensils such as knives and forks (Petrovsky, 1994). The necessity of experimenting explains autonomous technological change towards lower use of materials by the necessity of loss prevention. Technological change can go forever, irrespective of prices, because any change of inputs in the production brings an exponential increase of outputs that must be prevented.

The engineering theory can be related to the neoclassical economic theory. Input substitution is essentially an innovation. It entails costly adaptations to prevent losses. It implies that those inputs are substituted that pose the risk of the most costly adaptations. The inputs that are difficult to adapt are not necessarily the highest price inputs as neoclassical theory suggests. If input price is high and an even higher price is expected in the future, for example because of emerging scarcity, it can be worthwhile to change the input despite the high additional efforts. The input substitutions or innovations need subsequent adaptations that go on during decades or even centuries to reduce the losses. However, if the price is moderate or no price increase is expected then the costs of input substitution can be perceived as too high. Adaptations of the available technologies follow to reduce wasteful outputs. This process of innovation entailing many adaptations explains endogenous technological progress in environmental affairs that is underlined by the evolutionary theory. This implies that technologies become less wasteful per unit of product as they mature.

The decision making on environmental innovations faces uncertainties. The neoclassical theory and the behavioral theory applied to environmental innovations underline the importance of the demand for environmental qualities that maintain upward pressure on emission prices. The demands, however, are also uncertain because ownership of environmental qualities is imperfectly distributed. Even under the heroic assumption of lasting upward pressure on emission prices there are persisting uncertainties in the decision making. Innovators and users of innovations are confronted with uncertainties. The innovators that supply new technologies are uncertain about the result of effort in technology development and about the sales because the innovations can be wasteful for the users. The users of new technologies are uncertain about the costs and benefits of environmental innovations during the life cycle in comparison to the adaptations of available technology with less uncertainty due to experiences in use. Environmental innovations can be expected in cases where the innovators expect high profits after realization of the innovations and the users expect lower costs or a benefit regarding environmental demands and risks during the life cycle of product in comparison with the available technologies. The sum of the expected innovators' profitability plus the expected savings or revenues, usually called innovation rent, must cover all user costs and risks of environmental innovation. All three factors: companies' expectations about future demand for environmental qualities, the risk perceptions of potential users of innovations and the credibility of innovators, influence progress in the ecoefficiency. The path dependency on the treatment (end-of-pipe) technologies that is supposed to be inferior to the integrated (cleaner) technologies in the argumentation of the evolutionary theory can be explained by high risks changing inputs.

2.7 Conclusion

The presented theories on technology development do not exclude but rather supplement each other. Price signals (neoclassical theory) are important because they co-ordinate decisions, but the effect of prices on environmental innovations depends on policies. If a price is put on emissions, for example, by an emissions charge and effective technologies are already available, then fast dissemination of the effective available technologies should be expected, although it might have little impact on the development of new ones. Subsidies, networks and infrastructure (evolutionary theory) contribute to innovations if the results of interventions are predictable, that is, in cases where there are clear objectives and a few interests that determine progress. Above all, management must sense urgency to innovate despite high costs and uncertainties connected with technology development (behavioral theory). The sense of urgency can be invoked by environmental authorities, liabilities for damage imposed by social groups and exceptionally favorable sales opportunities of environmentally benign products. Policy can create sound conditions for innovation by translating the sustainability perspective into the mid-term objectives that must be attained, but with freedom to act and support technology development.