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Economic Analysis of Pharmaceutical Water Pollution Abatement in Nursing Home Effluents

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Abstract

Pharmaceuticals have been detected in surface and groundwater, and even in drinking water. Although concentrations are generally low, there are concerns about their impacts on aquatic organisms and human health. Risks are expected to increase due to rising pharmaceutical consumption and water reuse. From an economic point of view, pollution is an example of so-called market failure that can (and should) be corrected by means of government intervention, although pharmaceutical water pollution is a particularly difficult one to deal with in terms of regulation given that pharmaceutical consumption is critical to health outcomes. An alternative approach is to invest in end-of-pipe solutions which focus on reducing the impact of pharmaceutical consumption by removing harmful substances from wastewater before it is returned to the environment.

This work summarize knowledge on pharmaceutical water pollution and provides a cost-benefit analysis for two new kind of filters on a pilot scale, a solar pilot and a pilot combining a membrane bioreactor with photo-oxidation. The analysis is applied to nursing homes located in France, Spain and Portugal. The costs of both filters include investment costs (equipment and assembly) and operational costs (energy, chemicals, maintenance and equipment replacement) and the benefits based on shadow prices that differ depending on whether the residual water is discharged in a sensitive or non-sensitive destination. The net present value differs considerably across pilots, countries and the fact of the destination being sensitive or not.

Keywords: pharmaceutical water pollution, cost-benefit analysis, wastewater treatment, filter

JEL Classification: Q53; O22

Resumo

Os produtos farmacêuticos têm sido detetados em águas superficiais e subterrâneas, e mesmo até em água potável. Embora as concentrações detetadas sejam geralmente baixas, os impactos nos organismos aquáticos e na saúde humana constituem motivo de preocupação. Há uma tendência para estes riscos aumentarem devido ao uso crescente de medicamentos, assim como do reaproveitamento de água. De um ponto de vista económico, a poluição é um exemplo de uma falha de mercado que pode (e deve) ser corrigida através de intervenção governamental, contudo a poluição das águas com produtos farmacêuticos é particularmente difícil de regulamentar uma vez que o consumo de medicamentos é crucial em termos de saúde. Uma das alternativas é investir em soluções em que o foco é reduzir o impacto do consumo de medicamentos através da sua remoção das águas residuais antes da descarga no meio ambiente.

Este trabalho sintetiza o conhecimento acerca da poluição das águas com produtos farmacêuticos e apresenta uma análise custo-benefício de dois novos tipos de filtros numa escala piloto, um solar e outro que combina um biorreator de membrana com foto-oxidação. A análise é aplicada a lares de idosos em França, Espanha e Portugal. Os custos incluem o investimento (equipamento e montagem) e custos operacionais (energia, químicos, manutenção e substituição de equipamento), os benefícios baseiam-se no preço sombra que difere consoante as águas residuais são descarregadas em áreas sensíveis ou não sensíveis. O valor atual líquido varia consideravelmente consoante o filtro piloto, o país e o destino das águas residuais.

Palavras-Chave: poluição das águas, produtos farmacêuticos, análise custo-benefício, tratamento das águas residuais, filtro

Classificação JEL: Q53; O22

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1. Introduction

Every day, industries, agriculture and the general population are responsible for the emission of pollutants into water bodies. These discharges are placing pressures on the quality of those bodies, raising concerns about the impacts on ecosystems and human health (Deblonde et al., 2011). Emerging pollutants, which include pharmaceuticals, are increasingly noted as a potential hazard (US EPA, 2016). This group of contaminants is defined as "new products or chemicals without regulatory status and whose effects on environment and human health are unknown" (Deblonde et al., 2011, p. 442).

The presence of pharmaceuticals has been detected in surface and ground waters at low concentrations (WHO, 2012) and even in drinking water (Benotti et al., 2009). Although concentrations are considered low, there are concerns about their impacts on aquatic organisms and human health, e.g., Kidd et al. (2007) found negative effects from chronic exposure of wild fish to the main ingredient of the contraceptive pill, 17-alpha ethinylestradiol. The risks tend to increase for two reasons: (i) pharmaceutical consumption is rising due to the ageing of the population, the need to treat chronic diseases, and the changes in clinical practice (OECD, 2017); (ii) direct and indirect reuse of water is expected to continue to grow (Jones et al., 2005). The latter reason is justified by the increasing demands on freshwater supplies around the world due to population growth, climate change, depletion of groundwater resources, and impacts from salt (WateReuse, 2015). To address this concern, the European Union (EU) has included three pharmaceuticals in its first watch list published in 2015 (diclofenac, 17-Beta-estradiol (E2), and 17-Alpha-ethinylestradiol (EE2)). This is a dynamic list of substances, updated every two years, for which Union-wide monitoring data are to be collected with the aim of supporting future prioritization. Actually, according with the Commission Implementing Decision (EU) 2018/840 of 5 June 2018, an updated watch list includes E2, EE2, estrone (E1), macrolide antibiotics (erythromycin, clarithromycin, azithromycin), amoxicillin and ciprofloxacin). The other pharmaceuticals were removed because a risk-based assessment can be done without additional monitoring data.

From an economic point of view, pollution is an example of so-called market failure that can (and should) be corrected by means of government intervention, although pharmaceutical water pollution is a particularly difficult one to deal with in terms of regulation given that pharmaceutical consumption is critical to health outcomes. An alternative approach is to

invest in end-of-pipe solutions which focus on reducing the impact of pollution. Besides, most water resources have public-good characteristics, so people who extract and use water seldom pay its scarcity rent (they only pay the private extraction costs). This results in an inefficiently high extraction or pollution rate over time (Koundouri, 2000; Birol et al., 2006).

This work was developed within the project Innovec'EAU which is studying the problem of emerging pollutants in water pollution, in particular, pharmaceuticals and their metabolites. Our main goal is to analyze the economic feasibility of a new treatment to reduce pharmaceutical water pollution caused by nursing homes.

The remaining sections of this work will proceed as follows: the next chapter reviews the current state of pharmaceutical water pollution; in chapter 3, the project Innovec'EAU is described; then in chapter 4, a model is proposed to evaluate the economic feasibility of the solution developed in the scope of the project while chapter 5 discusses the proposed model in the light of a simulation; lastly, chapter 6 concludes with some final remarks.

2. Pharmaceutical Water Pollution

This literature review provides an overview on the current state of pharmaceutical water pollution. The first section discusses where emissions come from, what are the concentrations of pharmaceuticals in water bodies and what are the main pollutants. In the second section the impacts of pharmaceutical water pollution are presented, comprising an economic analysis of these impacts when available. In the last section the current methods to reduce pharmaceutical water pollution are described.

2.1. The Presence of Pharmaceuticals in the Environment

2.1.1. Emissions of Pharmaceuticals into the Environment

There are a large number of pharmaceuticals. For example in the European Union about 3000 different substances are used in human medicine (Fent et al., 2006). For this reason it is complex to select and investigate which pharmaceuticals can bring about harmful emissions. Furthermore, consumption of pharmaceuticals varies widely across countries, as well as through time, since some pharmaceuticals may be forbidden or replaced by related compounds (Fent et al., 2006; Kümmerer, 2008a). Globally, 631 different pharmaceutical substances have been detected above the detection limits of the analytical method in environmental water samples. The most common therapeutic groups are antibiotics, analgesics and hormones (aus der Beek et al., 2016).

The primary pathway of pharmaceuticals into the aquatic environment is through municipal wastewater (Winker et al., 2008), since the existing wastewater treatment technologies do not fully remove all pharmaceuticals (Fent et al., 2006). The main source of pharmaceuticals into municipal sewage is through excretion in urine (Winker et al., 2008). After a patient takes his medicine, only a fraction of the active compound is completely metabolized by the body. The rest is excreted as unmetabolized compound or processed metabolites in urine and feces (KNAPPE, 2008; Blair, 2016). Emissions from aquaculture, intensive livestock treatments and disposal of unused pharmaceuticals (see Kotchen et al., 2009) are another important source of pollution (EEA, 2010).

Other sources of pharmaceuticals are: (i) washed-off human topical treatments (BIO Intel-

ligence Service, 2013); (ii) veterinary use: excretion by animals in urine and feces, washed-off topical treatments (Boxall et al., 2003; KNAPPE, 2008); (iii) land application of manure and slurry (Boxall et al., 2003; KNAPPE, 2008); (iv) sewage sludge application (Fent et al., 2006); (v) leakages or manufacturing waste (Boxall et al., 2003).

The release from manufacturing processes is negligible in North America and the European Union due to regulatory controls (Boxall et al., 2003; Kümmerer, 2008a), although there are possible concerns in other regions, e.g., Larsson et al. (2007) analyzed a common effluent from about 90 bulk drug manufactures in south-central India and found high levels of pharmaceuticals. In this region, the top 11 active pharmaceutical ingredients were detected at levels >100 µg/L. Ciprofloxacin, an antibiotic, was the most detected with a range of concentration of 28,000-31,000 µg/L.

We are note aware of any studies about the contribution of nursing homes in the release of pharmaceuticals, although there is some discussion regarding hospitals and other health care institutions. Hospitals are important sources of microcontaminants from "active principles of drugs and their metabolites, chemicals, heavy metals, disinfectants and sterilizants, specific detergents for endoscopes and other instruments, radioactive markers and iodinated contrast media" (Verlicchi et al., 2010, p. 417). Some drugs are administered in out-patients which mean that pharmaceutical excretion will partially occur inside the hospital (Verlicchi et al., 2010). Usually hospital wastewater (HWW) is cotreated with urban wastewater (UWW) which is not a good practice given that it may reduce the removal efficiency (Verlicchi et al., 2010).

According to Santos et al. (2013), the contribution of hospitals varies according to their dimension, with bigger hospitals contributing more to the total mass load of pharmaceuticals. In their study, they found that NSAIDs, analgesics and antibiotics reach 50% of total mass load into wastewater treatment plants (WWTP). However, in general, the most of pharmaceutical load comes from urban wastewater and hospital contribution is less significant. Verlicchi et al. (2010) found that the average concentrations of micropollutants including pharmaceuticals in HWW are about 1 to 150 times the corresponding average concentrations in UWW: in the particular case of analgesics, concentrations are 8-15 times; for antibiotics 5-10 times, for β-blockers 1-4 times and for hormones 1-3 times. The authors also studied the case of cytostatic drugs for which the average concentration in HWW is about 4-10 times that in UWW.

On the other hand, Hermann et al. (2015) concluded that general hospitals, psychiatric hospitals, and nursing homes are, in general, insignificant emitters. Still, they recognize that specific pharmaceuticals are used to a great extent in specific health institutions, so in regions with a high density of medical facilities, the higher release to wastewater may pose an environmental treat. Kümmerer (2008b) also states that private households, not hospitals, are the most important source of the emission of pharmaceuticals into the aquatic environment.

Still, nursing homes can be considered a relevant point source of pharmaceutical pollution given that most of their residents are elderly and therefore consume a large amount of pharmaceuticals (Lacorte et al., 2017). In the U.S., the annual per capita retail prescription drugs filled at pharmacies in 2016 for people with 65 years or more was 23.9, almost double that for people between 19 and 64 years which had a value of 12.7 (The Henry J. Kaiser Family Foundation, 2016). Given the aging effect, there is a tendency for the number of nursing homes to grow which makes them even more important to study (Lacorte et al., 2017).

2.1.2. Concentrations of Pharmaceuticals in the Environment

Several studies have detected the presence of pharmaceuticals in water resources. Usually, reported concentrations in surface water, groundwater and partially treated water are below 0.1 µg/L; in treated water, the concentration is typically lower than 0.05 µg/L (WHO, 2012). Human exposure to pharmaceuticals from drinking water and/or fish consumption will mainly be in the nanograms per day range (PHARMAS, 2012). Although these concentrations are considered low, some compounds have been found at levels of concern in WWTP effluents (Verlicchi et al., 2012; Santos et al., 2013), rivers (Lacorte et al., 2017) and crops (Malchi et al., 2014).

Verlicchi et al. (2012) collected data from 78 peer-reviewed publications in books and international journals to study secondary biological effluents in terms of removal efficiencies, daily mass load and environmental risk. They found that 14 compounds pose a high risk: 7 antibiotics, 2 psychiatric drugs, 2 analgesics/anti-inflammatories and 3 lipid regulators. Also regarding WWTP effluents, Santos et al. (2013) studied the risk posed by pharmaceuticals at three different trophic levels: algae, daphnids and fish. The results have shown worrying concentrations in all three levels for different pharmaceuticals such as antibiotics, non-steroidal anti-inflammatory drugs (NSAIDs) and selective serotonin reuptake inhibitors (SSRI).

Pharmaceutical	Therapeutical group	Africa	Asia-Pacific	EEG	GRU-LAC	WEOG	Global
Diclofenac	Analgesics	3	8	13	3	23	**50**
Carbamazepine	Antiepileptics	3	6	13	2	24	**48**
Ibuprofen	Analgesics	3	8	10	2	24	**47**
Sulfamethoxazole	Antibiotics	5	9	10	2	21	**47**
Naproxen	Analgesics	2	8	10	2	23	**45**
Estrone	Estrogens	1	10	6	2	16	**35**
Estradiol	Estrogens	2	9	4	2	17	**34**
Ethinylestradiol	Estrogens	1	8	3	2	17	**31**
Trimethoprim	Antibiotics	2	9	3	2	13	**29**
Paracetamol	Analgesics	1	6	4	3	15	**29**
Clofibric acid	Lipid-lowering drug	1	3	5	2	12	**23**
Ciprofloxacin	Antibiotics	1	5	1	2	11	**20**
Ofloxacin	Antibiotics	1	4	1	1	9	**16**
Estriol	Estrogens	1	1	2	1	10	**15**
Norfloxacin	Antibiotics	1	4	1	2	7	**15**
Acetylsalicylic acid	Analgesics	1	4	1	2	7	**15**

Table 2.1. Number of countries with positive detection in surface, drinking, groundwater in each UN region
EEG (Eastern Europe Group); GRU-LAC (Group of Latin American and Caribbean States); WEOG (Western Europe and Other Industrialized Countries Group, including North America, Australia, and New Zealand)
(aus der Beek et al., 2016, p. 41)

The presence of pharmaceuticals in surface water and groundwater can be worrying since drinking water often comes from these water resources. For example in France, according to Vulliet and Cren-Olivé (2011), the percentage of drinking water coming from groundwater is 67% and water treatment is very limited. The authors investigated the presence of pharmaceuticals in surface and ground water intended for human consumption and found them in all water sources. The frequency and level of pharmaceuticals was globally lower in groundwater than surface water, with several pharmaceuticals not detected in groundwater at all. After comparing the daily drinking water intake of pharmaceuticals and the I70 values (based on a lifetime of 70 years and ingestion of 2 L/day of water) with the minimum daily therapeutic dose, the authors concluded that the presence of pharmaceuticals in drinking water appears to be a negligible risk for adult health, although the particular case of synthetic hormones may pose a risk. Regarding the specific case of rivers, Lacorte et al. (2017) studied pharmaceuticals released from nursing homes and found values that were higher than the limit proposed by the European Medicines Agency (concentration higher than 0.01 µg/L).

Benotti et al. (2009) reported the presence of pharmaceuticals and EDCs (endocrine disrupting compounds), some of which are pharmaceuticals (steroid hormone and synthetic steroid hormones), in drinking water. Their presence is more frequent in source water, which is collected by drinking-water treatment plants (DWTP), than in treated drinking water. They also found that concentrations in DWTP depend on the characteristics of the reservoirs, more precisely on whether reservoirs have a direct input of wastewater and/or recreational use. The lowest number of pharmaceuticals and EDCs were found in DWTP taking water from reservoirs with no direct input of wastewater and no recreational use.

Löffler et al. (2005) studied the persistence of 10 pharmaceuticals and pharmaceutical metabolites in water/sediment systems according to the dissipation time (DT50). The results showed that persistence varies widely according to pharmaceutical components exhibiting low to high persistence, where low persistent ranged between 3.1-7 days, moderate persistent ranged between 15-54 days and high persistent between 119-328 days. Moreover aus der Beek et al. (2016) refers that pharmaceuticals can be considered "pseudo-persistent" in the sense that they are continuously used and released to the environment.

Pharmaceuticals discharged into the environment can also show up in food sources, such as fish or vegetables. There is a possibility for aquatic organisms, particularly fish, to bioconcentrate pharmaceuticals and therefore create a route of exposure if these fish are eaten by people (KNAPPE, 2008). Malchi et al. (2014) studied the presence of pharmaceuticals

in carrots and sweet potatoes and some pharmaceuticals were found in roots and leaves, although most of them were not detected. The metabolites 10,11-epoxycarbamazepine and lamotrigine, which are potentially genotoxic, surpassed the TTC (threshold of toxicological concern) at an acceptable daily consumption.

It is important to note that a higher consumption of a specific pharmaceutical does not necessarily imply a higher risk for the environment and/or in a higher occurrence in water (Benotti et al., 2009; Verlicchi et al., 2012). What determines the environmental concern of a pharmaceutical is not high production volume per se, but also the environmental persistence and critical biological activity (Fent et al., 2006). Benotti et al. (2009) found that the most prescribed pharmaceutical in 2006 and 2007 was detected in only three sources water out of a considerable number of analyzed sources and was not detected in any finished or distribution water. Conversely, the most frequently detected prescription pharmaceuticals were not included in the top 200 prescribed pharmaceuticals for 2006 or 2007.

2.2. Impacts of Pharmaceutical Water Pollution

2.2.1. Environmental and Human Health Impacts

Most risk assessments have the limitation of analyzing a single pharmaceutical, which means that the probable synergic or additive effects of different pharmaceuticals, their metabolites and transformation products are not considered (Santos et al., 2013). Also, studies about the ecotoxiciy of pharmaceuticals are focused on short-term exposure of aquatic organisms, i.e., on acute effects in vivo in organisms of different trophic levels, and rarely consider chronic exposure. This focus is justified by the lack of data on chronic exposure and its toxicity (Fent et al., 2006).

Acute effects to aquatic organisms resulting from exposure to pharmaceuticals are unlikely, except for spills (Fent et al., 2006). Regarding the risks for human health, some studies likewise state that there are no acute risks given the low concentrations in drinking water (see WHO (2012), PHARMAS (2012)). In this studies, the usual way to proceed is to compare the maximum measured concentration in drinking water with some measures, such as the minimum daily therapeutic doses[1] or the acceptable daily intake[2].

[1] Lowest clinically active dosage.

[2] "Usually defined as the level of intake that should not result in any adverse human health effect even in particularly sensitive groups" (PHARMAS, 2012, p. 10).

Although these studies concluded that there are no acute risks for human health and aquatic ecosystems, PHARMAS (2012) point out some uncertainties: (i) exposure "hot-spots", such as locations with pharmaceutical manufacturing plants; (ii) sensitive subgroups of people, who that may react to lower concentrations of pharmaceuticals, namely the unborn fetus, elderly and/or infirm ; (iii) antibiotic resistance: this is of particular interest because it threatens our ability to treat common infectious diseases (WHO, 2017) (iv) effect of long-term exposure to low concentration; (v) combined effect of mixtures of pharmaceuticals.

Regarding chronic effects, Fent et al. (2006) compared the chronic lowest observed effect concentration (LOEC) with the maximal concentrations in WWTP effluents for different pharmaceuticals, and found that the chronic LOEC is generally about two orders of magnitude higher. However, there are some exceptions: diclofenac, for which the LOEC for fish toxicity is in the range of WWTP effluents; and propranolol and fluoxetine, for which the LOEC for zooplankton and benthic organisms is near to the maximal measured WWTP effluent concentrations. More research about potential long-term ecotoxicological effects is clearly needed.

Furthermore, the negative effects of some pharmaceuticals, such as estrogens and diclofenac, have been proven. Kidd et al. (2007) did a 7-year, whole-lake experiment and discovered that the presence of estrogens at low concentrations in freshwater can impact the sustainability of wild fish populations. The chronic exposure of fathead minnow to the ingredient of the contraceptive pill, 17-alpha ethinylestradiol, causes the feminization of males, impacts gonadal development and, ultimately, can cause near extinction. Regarding diclofenac, a NSAID, according to Oaks et al. (2004), this pharmaceutical was the cause of a considerable vulture population decline in Pakistan due to the ingestion of diclofenac-treated livestock carcasses, which are the primary food source of vultures. These authors found that diclofenac was directly correlated with renal failures which caused death, with positive concentrations of diclofenac residue in the kidneys. Nonetheless, the consumption of diclofenac through contaminated water sources is unlikely to cause toxicity given the very low concentrations.

There are some other studies focusing on the adverse effects of pharmaceuticals on non-target organisms in laboratory conditions, namely: fluoxetine (antidepressant) in leopard frog (Foster et al., 2010); oxazepam (anxiolytic) in european perch (Brodin et al., 2013); enrofloxacin and ciprofloxacin (antibiotics) in photoautotrophic aquatic organismss (cynobacterium and duckweed) (Ebert et al., 2011). Also, the effects of sulfonamides (antibiotic) were

studied in plants (willow and maize) (Michelini et al., 2012) and common hazel (Michelini et al., 2015) through a greenhouse experiment. Finally, Triebskorn et al. (2007) studied the effects of different pharmaceuticals (carbamazepine, clofibric acid, metoprolol, diclofenac) in fish (rainbow trout and common carp) through laboratory experiments.

Additionally, a small number of pharmaceuticals are designed to cause damage to living organisms, e.g. anti-cancer drugs (PHARMAS, 2012) and so might be expected to have negative impacts. Finally, in addition to pharmaceutical compounds themselves, it is important to study metabolites and transformation products related with pharmaceuticals (KNAPPE, 2008; Malchi et al., 2014)

2.2.2. Economic Analysis

A few studies have done an economic analysis of the environmental impacts of micropollutants, including pharmaceuticals. These economic analyses aim to measure the benefits of abatement options, and, ultimately, to compare these benefits with the costs in order to assess their feasibility. The abatement options can be analyzed through different methods: environmental benefit analysis (EBA), life cycle assessment (LCA) and cost-benefit analysis (CBA).

Kwak and Russell (1994) used a stated preference methodology to assess the environmental benefits of pharmaceutical removal. The authors did a contingent valuation survey to estimate the WTP for increasing the security of the drinking water system and ultimately to calculate the aggregate WTP. The contingent valuation was based on a person-to-person interview with an instrument modeled following the Mitchell-Carson "payment card" technique.

Logar et al. (2014) did a CBA of the Swiss National Policy on reducing micropollutants in treated wastewater. The authors used a choice experiment, another stated preference approach, to estimate the benefits of upgrading sewage treatment plants. In this study, the respondents' choices were analyzed using a mixed multinomial logit model with which they calculated the mean willingness-to-pay (WTP) of households for a specific policy alternative. The WTP for the upgrade of the sewage treatment plants would result in an increase in the annual water bill. The most conservative benefit estimate is defined as the reduction of the potential environmental risk of micropollutants to a low level for each canton. The mean WTP estimate for this policy scenario is CHF 100 annually per household, and the annual

costs of upgrading the 123 WWTP is CHF 86 per household. Given these results, an equipment life span of 33 years, and a discount rate of 2%, the CBA supports the implementation of this policy scenario with a benefit-cost ratio equal to 1.12. However, the limitation of this method is its hypothetical bias, i.e., there is a potential overestimation of stated preferences values compared to real market payments (List and Gallet, 2001).

Hernández-Sancho et al. (2010) used the output distance function to estimate the environmental benefit of removing five common pollutants in a treatment process. These were nitrogen, phosphorus, suspended solids, and organic matter that is measured as biological oxygen demand and chemical oxygen demand. They studied the shadow prices according to the destination and the potential users of the treated water, considering four destinations for the treated water: river, sea, wetlands and reuse. The greatest environmental benefit is associated with abatement of discharge in wetlands, because these areas are particularly sensitive to eutrophication. On the other hand, the lowest environmental benefit occurs when the destination is the sea because of the dilution and dispersion capacity.

Molinos-Senante et al. (2013) took a similar approach to estimate the economic value of the environmental benefits from avoiding the discharge of five pharmaceutical and personal care products (PPCPs) into water bodies. The environmental benefits were calculated by estimating the shadow price using the output distance function. This methodology estimates the shadow price by using information about the inputs and outputs (desirable and undesirable) of the technology process. The shadow price is defined as the "value of externalities that could produce environmental damage if inadequately managed" (Hernández-Sancho et al., 2010, p. 954), i.e., a proxy of the economic value of the environmental benefits gained by the application of an abatement process. These environmental benefits are quantified through the estimation of the avoided costs, and so they are at least as high as the costs required to prevent or compensate for environmental damage. A limitation of this approach is that avoided costs do not measure the total economic value which means that the environmental benefits are underestimated.

In Molinos-Senante et al. (2013), the estimated shadow prices are related to three pharmaceuticals (diclofenac, ethynilestradiol and sulfamethoxazole) and two musk fragances (tonalide and galaxolide) from treated effluent using a pilot-scale ozonation. The shadow prices of the undesirable outputs are negative since they are not marketable outputs that could generate an income. However, from an environmental point of view, these shadow prices represent the avoided cost. The authors compare two scenarios depending on the destination of treated

water: a sensitive area, where the damage avoided will be significantly higher, and a non-sensitive area. The two scenarios were defined through different prices for the treated water. For the non-sensitive area, the shadow prices of diclofenac, ethynilestradiol and sulfamethoxazole were -42.20; -73.73; and -34.95 respectively and expressed in €/kg. For sensitive areas, the values were -53.47; -93.76; and -44.46 respectively. The lowest shadow prices were obtained for both musk fragrances which were the most recalcitrant to ozone treatment.

Finally, this study calculates the total environmental benefit using the shadow prices (€/kg) of each compound and the volume of each pollutant removed (kg/m^3). Considering the sensitive area as destination, the largest environmental benefit is associated with the removal of diclofenac which represents 40.4% of the total benefit (741.6 €/year). Although ethynilestradiol has the highest shadow price, it has the lowest contribution to the total benefit (0.3% or 4.9€/year) due to its low concentration in effluents. The contribution of sulfamethoxazole is around 10% (216€/year). Although the values are not very high, only five PPCPs were assessed, which means that the total environmental benefit of avoiding pollutant discharges is underestimated.

As well as Molinos-Senante et al. (2013), Bellver-Domingo et al. (2017) estimated the shadow price of five pharmaceuticals (ibuprofen, carbamazepine, naproxen, acetaminophen, trimethoprim), according to three destinations: wetland, river and sea. The authors used data from 24 WWTP with the same wastewater treatment technology, activated sludge. The higher shadow prices were obtained for wetlands, followed by river and sea; such findings are consistent with Hernández-Sancho et al. (2010). The authors prioritized the remotion of pharmaceuticals according to shadow prices and they have reached conclusions similar to 82 articles that performed toxicological risk analysis. Their priorization was the following: acetaminophen > ibuprofen > naproxen > carbamazepine > trimethoprim.

Wenzel et al. (2008) used LCA to evaluate the environmental impact of advanced wastewater treatment of 9 micropollutants: organic hazardous substances (PAH, DEHP, nonylphenol and LAS), heavy metals (cadmium, lead and nickel), and estrogens (17-alpha ethynylestradiol and 17-beta estradiol). Three advanced treatment technologies were evaluated: sand filtration, ozonation and membrane bioreactor (MBR). The authors compared the environmental benefits gained from the removal of micro-pollutants and the reduction in (eco-) toxicity with the increased resource and energy consumption. In the studied scenarios, only sand filtration proved to have a positive outcome.

2.3. Policies to Reduce Pharmaceutical Water Pollution

Even though the environmental benefits assessed in the studies presented in the previous section are not very high, policies to reduce pharmaceutical pollution can be based on the precautionary principle, given the uncertainty of the risks. This implies that an action is taken to avoid potentially serious or irreversible threats before there is strong proof of harm (EEA, 2001). In the case of pharmaceuticals, the first measure is often to monitor relevant substances. Actual reduction options range from source-directed approaches to end-of-pipe approaches, as discussed below.

2.3.1. Economic Instruments

Pharmaceutical water pollution is a clear example of a negative externality since it is not taken into account by economic agents when deciding levels of consumption or prescription. Hence, there is a market failure, which might be corrected through government intervention aimed at pollution reduction. This type of pollution is particularly thorny given that pharmaceutical consumption is critical to health outcomes and thus cannot be easily reduced.

Regarding economic instruments, it is important to consider raising revenues to pay, e.g., for research and treatment of poor water quality. However, it is necessary clearly to define who will cover the costs of providing water quality management. The polluter-pays principle is widely used across Europe in the field of water protection and the same logic may be applied in pharmaceutical water pollution, which is considered a societal problem (KNAPPE, 2008). One possibility could be the application of a wastewater charge that could be additional to existing ones. Another one would be to charge pharmaceutical companies based on the environmental toxicity of their products. Nonetheless, it is difficult to define who are the relevant polluters, i.e., should we consider pharmaceutical companies, prescribing doctors and/or patients?

2.3.2. Regulation

In 2013, Directive 2013/39/EU of the European Parliament and of the Council as regards priority substances in the field of water policy defines diclofenac (anti-inflammatory), 17-beta estradiol (sex hormone) and 17-alpha ethinylestradiol (contraceptive pill ingredient) as priority substances, to be included in the first watch list. Still at the European level, marketing authorization of human and veterinary pharmaceuticals is regulated. Directive 2008/27/EC

requires an environmental risk assessment of human pharmaceuticals for all new authorization applications, although this authorization cannot be denied based on the environment risk assessment. In the case of veterinary medicine, there is Directive 2004/28/EC where contrary to the human pharmaceuticals, marketing authorization can be denied using the environmental impact as a criterion. The risk assessments done to gather the marketing authorization can be used to improve scientific evidence about the risks of pharmaceuticals (KNAPPE, 2008).

2.3.3. Source-Direct Approaches

One source-direct approach is to provide incentives to the development of green pharmaceuticals, i.e., compounds that are less harmful to the environment, although the cost associated with their development can turn this option into the least feasible (Blair, 2016). EEA (2010) raises the possibility of a reduction in health innovation due to any mechanism to promote greener pharmaceuticals that imposes costs or constraints. Solutions to avoid such a reduction could be to extend patents or to stimulate a behavioral change. Sweden, for instance, has developed an environmental classification of pharmaceuticals, the Swedish Environmental Classification and Information System, which aims to do a risk assessment of pharmaceuticals by combining two kinds of information: their hazardous properties and estimated environment concentrations (Ågerstrand et al., 2009).

2.3.4. End-of-Pipe Approaches

One available option to reduce pharmaceutical release in toilets or drains is to create take-back programs for the disposal of unused or outdated pharmaceuticals (Blair, 2016). At the European level, take-back schemes were introduced in Directive 2004/27/EC, so most European countries have this disposal options (see MEDSdisposal, 2017). Also, there should be specific policies or regulations for disposal practices at point sources of pharmaceutical pollution such as health-care institutions and veterinary facilities (WHO, 2012).

It is also possible to reduce pharmaceutical pollution by treating wastewater. In this approach, the percentage of removed pharmaceuticals will depend on the treatment process. New treatment technologies to remove the most environmentally significant pharmaceuticals can be applied. Possible improved technologies are: (i) chemical methods, such as advanced oxidation processes and selective oxidation reagents; (ii) the use of physical methods, such as different kinds of filters (sand filters, disc filters, membrane, micro and ultra filters); (iii)

improved biological methods (EEA, 2010).

Advanced wastewater treatment processes such as ozonation, reverse osmosis and advanced oxidation technologies have better removal rates for pharmaceuticals than conventional wastewater treatment, achieving almost 99% for some pharmaceuticals (WHO, 2012). As noted, Wenzel et al. (2008) studied the environmental advantages and disadvantages of advanced wastewater treatment of micro-pollutants using environmental LCA. In some scenarios, they found that more environmental impact may be induced than removed by advanced treatment. Zakkour et al. (2002) states that large-scale investments to improve water quality may not be environmentally sustainable because the benefits of the improvement can be outweighed by the negative effects on the wider environment caused by energy intensive WWTP producing greater amounts of sludge. It is therefore necessary to have an approach that includes the key factors involved in water pollution control: effluent quality, sludge production and energy use.

Given the costs of advanced treatment plants, it is important to consider other alternatives. One possibility is technology controls, e.g. a filter. Another possibility is the treatment of urine, an important resource of pharmaceuticals, by urine separating toilets (Blair, 2016) or urine source separation (NoMix technology) (Verlicchi et al., 2010).

2.3.5. Development of Social Responsibility

One final option to reduce pharmaceutical pollution is to educate and train doctors, pharmacists and patients regarding this problem and, as a consequence, to increase, e.g., the success of take-back programs or the use of green pharmaceuticals (Kümmerer, 2008b). Also, it is possible to promote eco-directed sustainable prescribing meaning to reduce the dose or usage of certain pharmaceuticals or prescribing according to the excretion profile and pharmacokinetics (Blair, 2016). Ecolabels could be important for OTC (over-the-counter) drugs where the consumer chooses between different pharmaceuticals (KNAPPE, 2008).

3. Project Description

The Innovec'EAU project has three main objectives: (i) characterize and compare effluents from establishments and nursing homes in France, Spain and Portugal; (ii) develop an efficient and sustainable effluent treatment to monitor and reduce pharmaceutical water pollution; (iii) analyze the perception of the populations and raise awareness of this problem.

3.1. Nursing Homes

Although there are different sources of pharmaceutical emissions into the environment, this study will focus on nursing home effluents. The selected case studies are from six nursing homes with a high number of beds (>50), located in urban areas from three different countries (France, Spain and Portugal) (see table 3.1). The residences include both housing and day care for independent individuals that do not require assistance, and also general impairment.

Nursing Home	Size		Country	Drainage System
	Beds	Day Center		
F1	75	6	France	Discharge to public sewage grid
F2	74	6	France	Discharge to public sewage grid
S1	130	40	Spain	Discharge to public sewage grid
S2	130	30	Spain	Discharge to public sewage grid
P1	60	0	Portugal	Discharge to public sewage grid
P2	52	0	Portugal	Discharge to public sewage grid

Table 3.1. Nursing home description (Innovec'EAU)

In all six nursing homes, metformin (antidiabetic), levetiracetam (anticonvulsant) and paracetamol (analgesic) were found in the top 10 of predicted environmental concentration (PEC) calculated. From the six nursing homes, Furosemide (diuretic) was found in 5 of them; macrogol (laxative) in 4 of them; amoxicillin (antibiotic) and acetyl salicylic acid (analgesic) in 3 of them. As can been seen in Table 3.2, S1 and F2 have the biggest total PEC, while S2, F1, P1 and P2 have a similar total PEC.

In order to perform a risk assessment, Lacorte et al. (2017) studied the aquatic toxicity

[1] 50% of residents wearing diapers.

Nursing Home	Water consumption (m^3/year)	Water consumption (m^3/days)	Total number of molecules	Total PEC (mg/L)[1]	Total Flux (g/day)
F1	4560	12.49	141	0.77	9.6173
F2	4574	12.53	161	30.30	379.659
S1	8687	23.8	192	30.95	736.610
S2	8687	23.8	146	1.67	39.746
P1	5230	14.3	139	0.60	8.580
P2	4859	13.3	180	1.11	14.763

Table 3.2. Pharmaceuticals description in each nursing home (Innovec'EAU)

of the pharmaceuticals with predicted environmental concentration in rivers (PECriv) higher than 0.01 µg/L and, also, of common pharmaceuticals in the three countries wich had levels higher than 0.001 µg/L. After estimating the aquatic toxicity using different organisms, the authors concluded that the toxicity is low. However, this risk assessment does not take into consideration long-term effects given the lack of information about chronic toxicity of pharmaceuticals. Also, it does not assess the probable synergic or additive effects of mixing of different pharmaceuticals, their metabolites and transformation products.

3.2. Description of the Filter

Project Innovec'EAU is developing two onsite filters on a pilot scale to reduce the concentration of pharmaceuticals in nursing home effluents, which aims to reduce pharmaceutical emissions into the sewage system, and consequently to reduce emissions into the environment. One of the filters will incorporate two kinds of processes: a membrane bioreactor (MBR) and a photo oxidation process for biorecalcitrant pharmaceuticals. The other one is a solar pilot. Its installation in nursing homes will have costs and benefits, both of which comprise environmental impacts. Their correct assessment is an important part of the project.

4. Project Appraisal

The evaluation of projects related to new environmental or technological risk must take into account the following aspects: long time horizon, stock externalities, possible irreversibilities (physical and socio-economic), large uncertainties and future scientific progress (Gollier and Treich, 2003). Molinos-Senante et al. (2010, 2012) discuss how to study the economic feasibility of wastewater treatment and also of improving drinking water quality (Molinos-Senante et al., 2014).

Pharmaceutical water pollution creates a set of complicated issues for the decision maker: a considerable number of remaining uncertainties (scientific and economic), time lag between emissions and effects, the need to consider multiple pharmaceuticals, and finally wide regional variation on pharmaceutical consumption.

- *Large uncertainties about the impacts*: only a few studies have addressed the environmental and human health impacts of specific pharmaceuticals. Most of them concluded that there are no acute effects, although there are considerable unknowns.
- *Time lags between emissions and effects*: the impacts of pharmaceutical water pollution are likely to show up more clearly in the long term.
- *Multiple pharmaceuticals of interest*: in a literature review of 1016 original publications and 150 review articles, 631 different pharmaceuticals, including veterinary drugs, have been found in 71 countries above the detection limits of the analytical methods employed in surface water, groundwater, tap/drinking water, manure, soil, and other environmental matrices. Occurrences in surface waters, groundwater, tap/drinking water exceed 100 different pharmaceutical substances in several European countries and the USA (aus der Beek et al., 2016). This raises questions about the relative importance of different pharmaceuticals and possible interactions among them.
- *Regional variation*: the scale of the problem is global, as pharmaceuticals have been detected in all continents (aus der Beek et al., 2016). However, there is a regional variation on the most consumed pharmaceuticals and PECriv, which implies that abatement benefits are inherent to each region.

In the next section, an impact assessment of pharmaceutical water pollution is presented.

Finally, the economic approach to evaluate the project is discussed.

4.1. Impact Assessment: Human Health and Environmental

Pharmaceutical consumption has a welfare-enhancing impact through its role in health improvement, but it also has an welfare-detracting impact because it pollutes the environment. In particular, pharmaceutical water pollution derived from nursing home effluents shows up in the environment and might affect ecosystems and human health. The majority of these impacts are in the long-run and are not known with certainty. The likely impacts on human health can result from different sources: (i) consumption of contaminated drinking water; (ii) consumption of contaminated food (such as fish and vegetables); and (iii) antibiotic resistance. As for the environment, a few studies concluded that pharmaceuticals can impact on the sustainability of specific organisms although further research is needed. It is also important to consider the socioeconomic uncertainties, such as those associated with the economic value of damages.

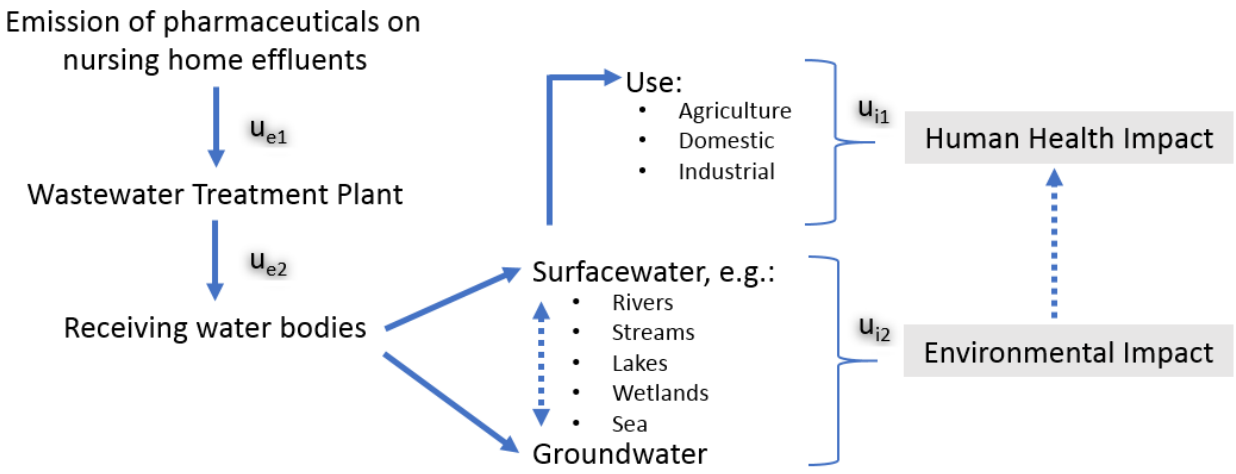

Figure 4.1. Impact assessment of pharmaceutical water pollution

The magnitude of the impact of pharmaceutical water pollution arising from nursing homes discharges depends mainly on two factors: patterns of pharmaceutical consumption and location of the nursing home. The pattern of consumption determines which pharmaceuticals will be released and in which concentrations. The location of the nursing homes will determine the destination of the effluent, i.e., the receiving water body, and the potential users of the treated water. WWTP effluents can be discharged directly into surface water, such as rivers, sea, wetlands, or it can be discharged indirectly into surface water via

groundwater or hyporheic water (Department of Environmental Quality, 2007). As noted by (Hernández-Sancho et al., 2010), the environmental benefit depends on the destination and the potential users of the treated water.

Uncertainty regarding human health and environmental impacts is denoted in Figure 4.1 by u_{i1} and u_{i2}, respectively. The level of uncertainty can be classified as recognized ignorance, i.e., "fundamental uncertainty about the mechanisms and functional relationships being studied" (Walker et al., 2003, p. 12). The uncertainty is reducible in the sense that can be resolved by conducting further research. The nature of this uncertainty is epistemic because it results from the imperfection of our knowledge.

In addition, there is uncertainty concerning pharmaceutical concentration in nursing homes and wastewater treatment plant (WWTP) effluents, denoted in Figure 4.1 by u_{e1} and u_{e2}, respectively. Taking as example the PEC estimation done by Lacorte et al. (2017), the former uncertainty is a consequence of the factors included in the calculation of predicted environmental concentration in effluents from senior residences (PECres) (drug consumption, excreted fraction of the unchanged drug, percentage of patients using incontinence pads and water consumed) and predicted environmental concentration in the sewage system (PECgrid) (PECres and expected dilution factor from senior residences to the general sewage grid). For example, pharmaceuticals can be excreted outside nursing homes which reduces the PECres. Also, the expected dilution factor from senior residences to the general sewage grid can vary substantially, e.g., due to discharges, rains (Lacorte et al., 2017), and the possibility of leakages in the grid. The latter uncertainty results from the factors included in the calculation of PECriv (removal fraction in WWTP and dilution factor from WWTP effluents to receiving water). The removal efficiency of pharmaceuticals depends on the configuration of the WWTP, which was not taken into account by Lacorte et al. (2017).

Also, the uncertainty regarding pharmaceutical concentration is statistical, more precisely, it is due to measurement inaccuracy, since the measurements might not represent the "true" value of pharmaceutical concentration (definition according to Walker et al. (2003)). This uncertainty can be reduced by measuring the concentration of pharmaceutical in effluents with improved analytical methods.

4.2. Environmental Cost-Benefit Analysis

Cost-benefit analysis (CBA) is an analytical technique that allows the incorporation of market failures in the evaluation of investment projects. In particular, environmental cost-benefit analysis (ECBA) includes the value of environmental improvement and/or of environmental deterioration related with the project, in addition to the "ordinary" benefits and costs (non-environmental) (Perman et al., 2003).

4.2.1. Estimating the Costs and Benefits of Abating Pollution

Regarding abatement costs, what matters are the net costs of emission reduction (total costs minus any positive side effects of the strategy) and not the total costs.

After the filter has been developed and tested, its deployment to a specific location will have capital and operational costs. The capital costs are the initial costs of the filter: expenses on the purchase of the equipment and costs involving the installation (construction labor, raw materials). The operational costs cover the repairs and maintenance (labor, raw materials, energy, disposal of by-products). Therefore, the costs can be written as C_t, where C_0 is the total initial investment cost and, for $t = 1, ..., T$, C_t is the operational cost at time t, with T the filter lifetime.

The benefits of abating pollution are related with the avoided damages due to the implementation of the filter. The benefits from applying a filter are more uncertain, given the lack of scientific knowledge about the impacts on environment and human health, which implies that they cannot be reliably quantified. In general, the benefits of removing pharmaceutical j at period t is a function of the avoided discharge of pharmaceuticals into the sewage systems, $\eta_j c_{jt}$, and their shadow prices, θ_j. The avoided discharge of pharmaceutical j at period t depends on the average pharmaceutical concentration measured in the raw influent, c_{jt}, and the percentage removal efficiency of the filter, η_j. Then, the benefits are given by:

$$b_{tj} = \eta_j c_{jt} \times \theta_j \tag{4.1}$$

Different assumptions on the socioeconomic development path imply different emission scenarios and, consequently, different estimates of benefits. Some possible factors that explains future concentration of pharmaceuticals in the environment are demographic and socio-economic factors, policies and available technologies.

Given the capacity of the filter to remove n pharmaceuticals, the total benefit function at time t is given by:

$$B_t = \sum_{j=1}^{n} b_{tj} \tag{4.2}$$

The policy objective is to maximize the net present value (NPV) function. Then, denoting the NPV function by W:

$$W = \sum_{t=0}^{T} \frac{B_t - C_t}{(1 + r(t))^t} = \sum_{t=0}^{T} \frac{\sum_{j=1}^{n} (\eta_j c_{jt} \times \theta_j) - C_t}{(1 + r(t))^t} \tag{4.3}$$

4.2.2. Discount Rate and Time horizon

The selection of the discount rate is essential to compare economic effects that occur at different points in time. The appropriate choice of the discount rate is hotly debated in economics, so a sensitivity analysis using various discount rates should be conducted. However, there is a universal agreement that "real" rates should be used instead of "nominal" rates. The social discount rate is the appropriate one for evaluating public projects. If there were no market failures, it would not be necessary to determine the discount rate because in this case the market rate of interest would be equal to the consumption discount rate and to the marginal rate of return on investment (Perman et al., 2003).

The discount rate is determined by time preferences of individuals and there are two approaches: (i) constant discount rate and (ii) variable discount rate (Pearce et al., 2006). A constant discount rate implies that a person's intertemporal preferences are time-consistent. However, several results suggest that people have hyperbolic discounting which means they exhibit a declining rate of time preference and therefore the discount rate should be declining along time (Frederick et al., 2002). There are different theoretical rationales for time-declining rates: one of them is the uncertainty about the state of the economy, as in Gollier (2002), and another one is the uncertainty about future interest rates, as in Weitzman (1998, 1999).

Weitzman (1998, 1999) calculates the certainty-equivalent discount rate, a declining discount rate, based on the probability-weighted average of the discount factors. The author suggests the following social discounting strategy: 3-4% for short run (until 25 years); around 2% for medium run (between 25 and 75 years); around 1% for long-run (between 75 and 300 years); and finally around 0% for the very long run (more than 300 years) (Weitzman, 1999).

Gollier (2002) recommends different discount rates according to time: risk free rate observable on financial markets for short time horizons; not larger than 5% for medium run (between 50 and 100 years); and 1.5% for very long run (more than 200 years).

The proper time horizon for the appraisal of a project is the one at which its impacts cease (Perman et al., 2003). In this case, we will consider it to be the operating period of the filter.

4.2.3. Uncertainty and Irreversibilities

This project appraisal is characterized by imperfect knowledge of the future which has implications on the decision-making process. The impacts of pharmaceutical water pollution involve uncertainty given that it is not possible to assign probabilities to all possible consequences and, even worse, it is not possible to enumerate all the possible consequences of a decision. Besides uncertainty, the project imposes sunk costs on society which is one kind of irreversibility.

According to Pindyck (2007), uncertainty over benefits and costs can affect policies in three ways: (i) optimal choice of policy instrument; (ii) optimal policy intensity; and (iii) optimal timing of policy implementation. When a project is characterized by uncertainty and irreversibility, it is important to consider issues of timing (Pearce et al., 2006; Pindyck, 2007). In addition, in situations facing long-term uncertainty where new scientific knowledge is expected, it is necessary to identify optimal short-term strategies that can be flexible to scientific development (Gollier and Treich, 2003). According to IPCC (1995), "the challenge is not to find the best policy today for the next 100 years, but to select a prudent strategy and to adjust it over time in the light of new information" (IPCC, 1995, p. 5).

Under conditions of imperfect scientific knowledge, it is important to consider a sequential approach which allows the optimization of actions by incorporating additional information over time (Gollier and Treich, 2003). The quasi-option value[1] is related with conditions of imperfect knowledge, although its calculation is redundant when using the sequential decision-making strategy (Freeman III et al., 2014).

It is important to describe the risk preferences of the decision makers and those they represent, because, in the case of extreme risk aversion, some extremely unlikely event may

[1] "Value of information gained by delaying a decision to commit to some irreversible action" (Pearce et al., 2006, p. 146).

be perceived as so undesirable that a "normal" decision rule is not appropriate. The presence of uncertainty implies that some policies may be acceptable, even with negative NPV, if they reduce uncertainty (IPCC, 1995; Pearce et al., 2006). The magnitude of acceptable negative NPV depends on society's degree of risk aversion and the magnitude of the risk (IPCC, 1995).

Uncertainty in the damage function and risk aversion justify the use of the precautionary approach (IPCC, 1995). As proclaimed in the principle 15 of the Rio Declaration of Environment and Development, the precautionary approach shall be applied "where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation" (UNCDE, 1992, p. 3). The measures based on the precautionary principle should be revaluated and adjusted in accordance with the development of scientific knowledge (CEC, 2000). In our project, the investment in the filter is a precautionary investment, i.e., a risk-reducing expenditure.

Gollier and Treich (2003) discuss, within an expected utility/Bayesian framework, the conditions under which the prospect of obtaining better scientific information in the future may lead to a more precautionary policy today. The authors point out two effects: the "irreversibility effect" and the "precautionary effect". The latter effect justifies a precautionary policy because it changes the risk borne in the future even without any sort of irreversibility (Gollier et al., 2000).

The impacts of pharmaceutical water pollution are also characterized by ambiguity, since it is a situation where it is not possible to assign probabilities to all uncertain variables. Although, this possibility is not cover here, see more in Etner et al. (2012) which reviews the decision theory under ambiguity, such as Choquet expected utility, Arrow and Hurwicz α maxmin, multiple priors and so forth.

In environmental policies there are two kinds of irreversibilities that are relevant: (i) environmental damage; (ii) and sunk costs on society. On the one hand, irreversible environmental damage can lead to a more "conservationist" policy than the optimal one. The option value, which is the maximum WTP for something in a risky situation in which the outcomes are uncertain (Pearce et al., 2006), explains this bias toward protection. On the other hand, sunk costs leads to policies that are less "conservationist" than the optimal one (Pindyck, 2002, 2007).

According to Pindyck (2007), "the greater the current uncertainties, and the greater the

rate at which they will be resolved, the greater will be the opportunity costs and benefits associated with policy adoption" (Pindyck, 2007, p. 48).

4.2.4. Sensitivity Analysis

Within a CBA performing a sensitivity analysis allows an assessment of the robustness of results. The sensitivity analysis aims to assess how the outputs of the project react to changes in the parameters about which there is uncertainty. These changes require assumptions about optimistic and pessimist scenarios without assessing the distribution of values between these limits (Pearce et al., 2006). The sensitivity analysis helps to select the action that meets the goals of the project across a variety of plausible futures. A robust decision-making process is iterative and adaptive by nature which implies learn, act and revise (Hallegatte et al., 2012).

Regarding this project, it is important to assess the following variables and parameters given the inherent uncertainty:

- Benefits of abating pollution
- Discount rate
- Key cost components
- Estimated time of knowledge development
- Alternative options such as development of social responsability

4.2.5. Scale of the Project

Given the uncertainty and irreversibilities of the project, it is important to determine the optimal scale of the project. According to Pearce et al. (2006), the optimal scale is where the marginal social benefits are equal to the marginal costs. In this case, the scale varies according to the number of nursing homes that should implement the filter.

The selection of nursing homes could be based on the number of residents, quantity of consumed pharmaceuticals and/or pharmaceutical risk assessment. Also, it is important to consider the destination of nursing home effluents and to prioritize effluents with impacts on sensitive areas, i.e., wetlands and rivers, especially from highly urbanized areas.

5. Model Simulation

The model simulation is applied to two different pilots: (i) combined MBR with photo-oxidation process and (ii) solar process. The treatment capacity for the combined MBR with photo-oxidation pilot is estimated at 20 L/day while for the solar pilot it is 10 L/day. The considered time horizon is 20 years, which is the expected filter lifetime.

The target pharmaceuticals are carbamazepine (anti-epileptic), ibuprofen (anti-inflammatory), diclofenac and paracetamol (analgesics). According to the PBT profiler[1], all the target pharmaceuticals are considered toxic (see Table 5.1). Analyzing EC50[2] values, carbamazepine can pose a high risk at low concentrations which is of concern taking into account detected concentration in each nursing home, in particular at S1. Besides, ibuprofen and paracetamol could pose risks at high concentrations in water, which direct our attention for the high concentrations of paracetamol, in particular in F2, S1 and S2. Finally, although diclofenac is considered toxic under the PBT profiler, according with the EC50 values, it is the least worrying pharmaceutical compared to the other target pharmaceuticals.

Pharmaceutical	PBT profiler			Detected concentration (µg/L)[3]						EC50 (mg/L)[4]
	P[5]	B[6]	T[7]	F1	F2	P1	P2	S1	S2	
Carbamazepine	38	19	0.9	1.488	0.023	0.035	0.249	9.236	0.061	< 10
Diclofenac	38	3.2	4.6	0.037	1.238	0.066	0.558	2.808	0.498	> 1000
Ibuprofen	15	3.2	4.9	0.087	7.92	0.443	1.255	28.966	17.575	< 100
Paracetamol	15	3.2	0.48	9.422	168.049	26.169	26.986	229.159	230.128	< 100

Table 5.1. Main characteristics of the target pharmaceuticals (Innovec'EAU, 2018)

The information was obtained from different sources, as detailed below. Part of the data were collected in February 2019 during a visit to institute PROMES (Procédés, Matériaux

[1]PBT profiler predicts a chemical's potential to persist (P) in the environment, bio-concentrate (B) in food chains, and be toxic (T).

[2]EC50 is "the molar concentration of an agonist that produces 50% of the maximal possible effect of that agonist" (Neubig et al., 2003, p. 600).

[3]Substances detected in a concentration >1 µg/L are highlighted yellow.

[4]EC50 highlighted green would not pose a toxicity in water (side), highlighted blue could induce an effect when found at high concentrations in waters, and highlighted red at low concentration can place a high risk on the environment.

[5]P highlighted green is not persistent.

[6]B highlighted green is not bioaccumulative.

[7]T highlighted red is toxic.

et Énergie Solaire), in Perpignan (France), where both pilots were installed. The members of the Innovec'EAU team working in PROMES provided valuable information[8]. In some cases, that information came from external sources (such as the quotes provided by the firms that installed the pilots). In other cases, in the absence of formal data, the members of the team provided estimations based on their experience (in those cases, the source is identified as "engineer estimate").

The prices used for the estimation of operational costs are specified in Table 5.2. The energy cost is based on the average electricity prices in 2014 excluding taxes and levies for medium-size consumers (annual consumption in the range of 500 MWh and 2,000 MWh). The labor cost is estimated based on the mean earnings of plant and machine operators and assemblers (ISCO08)[9] in each country (retrieved from European Union Structure of Earnings Survey of 2014). The price of chemical inputs for each pilot was provided by engineers working in the filters' development.

Parameter	Unit	Country	Value	Reference
Electricity	€/kWh	France Spain Portugal	0.0765 0.1185 0.1029	Eurostat
Labour	€/h	France Spain Portugal	13.89 10.69 4.82	Eurostat
MBR+Photo Oxidation pilot's chemical input	€/kg	All countries	3	Engineer estimate
Solar pilot's chemical input	€/kg	All countries	40	Engineer estimate

Table 5.2. Baseline unit costs

5.1. Cost Estimate of the Combined Membrane Bioreactor with Photo-Oxidation Pilot

The combined MBR with photo-oxidation pilot has a treatment capacity of 20 L/day and an expected lifetime of 20 years. The investment cost covers the necessary equipment for both MBR and photo-oxidation as well as the assembly. Both technologies include a

[8]We are particularly grateful to Gael Plantard.

[9]NACE_R2: Industry, construction and services (except public administration, defense, compulsory social security).

control/command. The operational costs are determined by electrical energy cost, chemical consumption, equipment maintenance and replacement. The main characteristics are described in Table 5.3. Regarding energy consumption, the combined MBR with photo-oxidation pilot operates 24 hours/day, excluding a compressor that operates 4h/day. The pilot's maintenance is expected to be 15 hours/month which includes the control of leaks, changing of damaged tubes, among other interventions. Additionally, an annual risk budget is included, to cover the possibility of equipment replacement, and every two years there is a budget for membrane replacement.

Parameter	Unit	Value	Reference
Investment cost (tax included 20%)	€	53,664.00	Supplier quote and Engineer estimate
Energy consumption	kWh/month	1,081.12	Supplier quote and Engineer estimate
Chemical consumption	kg/month	0.0304	Engineer estimate
Equipment maintenance	hours/month	15	Engineer estimate
Equipment replacement	€/year[10]	200	Engineer estimate
	€/every two years[11]	200	Engineer estimate

Table 5.3. Main characteristics of the combined MBR with photo-oxidation pilot

The cost estimation for each country is described in Table 5.4, differentiating investment costs and operational costs. The (discounted) aggregation of both kinds of costs is displayed in the last column, which reveals that the 20-year present-value total cost is very similar for France and Spain and noticeably lower for Portugal due to operational cost. From the data displayed in Table 5.2, we know that this difference is due, basically, to lower labor costs. Figure 5.1 shows the weight of each cost component for all three countries. Investment and electricity cost have a relatively larger weight on Portugal than in the other countries, while it is the other way around for labor. Chemical costs, in turn, are basically insignificant compared with other costs for all countries.

[10]Risk budget covering the eventual possibility to buy any component to replace.
[11]Membranes replacement.

Nursing Home	Investment Cost (€)	Operational Cost (€/year)	Operational Cost (€/every two years)	Total Cost (present value, T=20)
France	53,664.00	3,693.76	3,893.76	112,786.32
Spain	53,664.00	3,662.65	3,862.65	112,301.24
Portugal	53,664.00	2,403.66	2,603.66	92,674.72

Table 5.4. Cost estimation of the combined MBR and photo-oxidation pilot (present value with a discount rate of 2.5%)

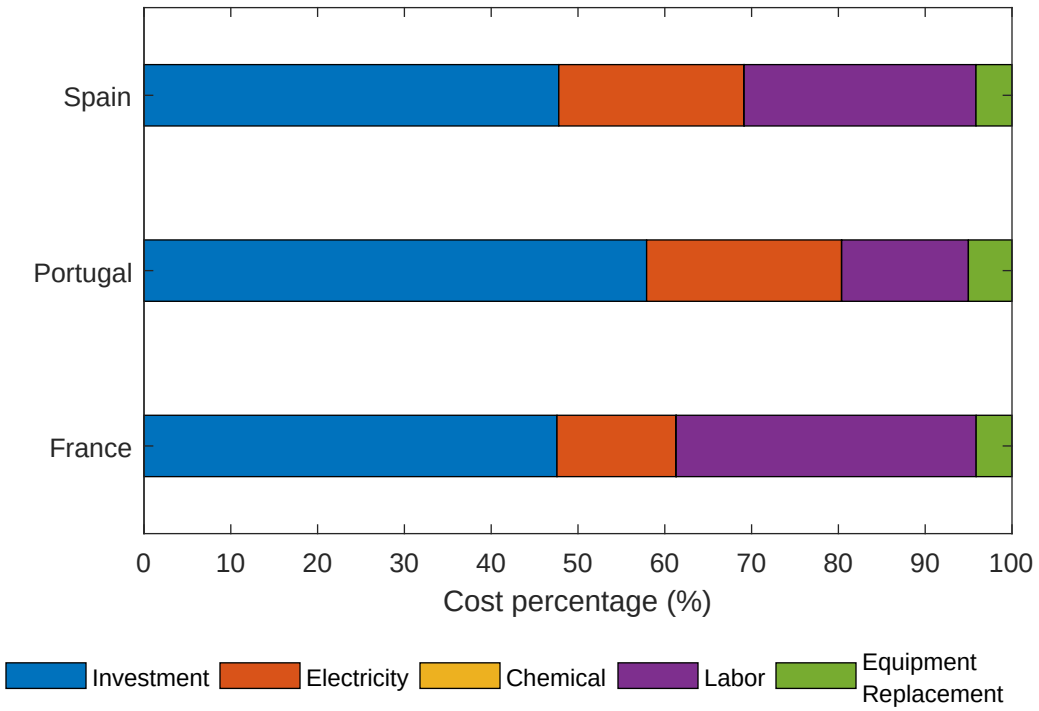

Figure 5.1. Cost percentage of the total present value cost (discount rate of 2.5% and combined MBR with photo-oxidation pilot lifetime of 20 years)

To have a relative measure of costs, the discounted average total cost in terms of treated water is displayed in Table 5.5, taking into account total treated water during the expected pilot lifetime (T=20). Regardless the differences in operational cost across countries, the average total cost is lower in Portugal, being very similar between France and Spain.

Nursing Home	Average Total Cost (€/L)
France	0.772
Spain	0.769
Portugal	0.634

Table 5.5. Discounted average total cost of the combined MBR and photo-oxidation pilot (T=20, discount rate of 2.5%)

5.2. Cost Estimate of the Solar Pilot

The solar pilot has a treatment capacity of 10 L/day and an expected lifetime of 20 years. The investment cost covers all the necessary equipment and also the assembly of it. Similar to the combined MBR with photo-oxidation pilot, the operational costs are determined by electrical energy cost, chemical consumption, equipment maintenance and replacement. Its main characteristics are described in Table 5.6. Regarding energy consumption, it is assumed that the solar pilot operates on average 13 hours/day per year. The solar pilot's maintenance is expected to be 8 hours/month which includes the control of leaks, changing of damaged tubes, among other interventions. Additionally, an annual risk budget is included to cover the possibility of equipment replacement.

The cost estimation for each country is described in Table 5.7. As compared to the combined pilot, investment costs are lower but operational costs are higher. Across countries, similar to the combined pilot, Portugal has the lower present-value total cost, mainly as a result of low labor costs. Also, as can be seen in Figure 5.2, the cost component that most contribute to the difference between Portugal and the other two countries is the filter maintenance. Electricity costs have a higher relative impact in total costs for Portugal compared to Spain and especially to France. Different from the combined pilot, chemical costs are an important cost component that counts for more than 50% of operational costs.

Parameter	Unit	Value	Reference
Investment cost (tax included 20%)	€	25,960.8	Supplier quote
Energy consumption (operating 13 hours/day)	kWh/month	676.61	Supplier quote
Chemical consumption	kg/month	10	Engineer estimate
Equipment maintenance	hours/month	8	Engineer estimate
Equipment replacement	€/year	500	Engineer estimate

Table 5.6. Main characteristics of the solar pilot

Nursing Home	Investment Cost (€)	Operational Cost (€/year)	Total Cost (present value, T=20)
France	$25,960.80$	$7,254.57$	$139,053.46$
Spain	$25,960.80$	$7,288.38$	$139,580.57$
Portugal	$25,960.80$	$6,598.20$	$128,821.21$

Table 5.7. Cost estimation of the solar pilot (present value with a discount rate of 2.5%)

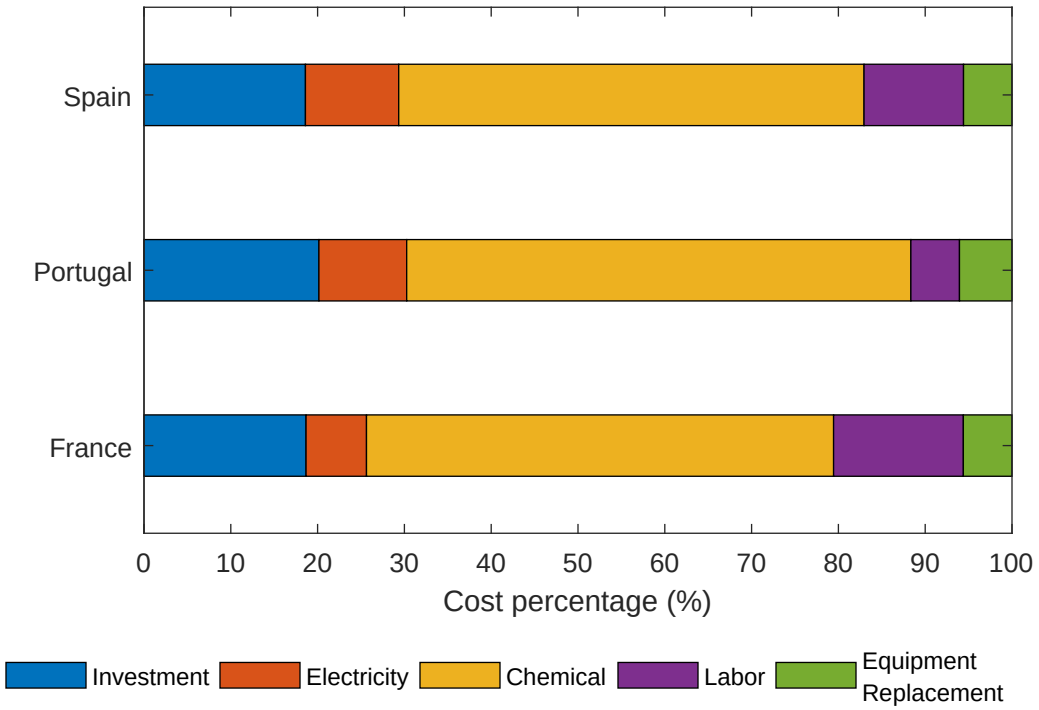

Figure 5.2. Cost percentage of the total present value cost (discount rate of 2.5% and solar pilot lifetime of 20 years)

Similar to the combined pilot, the discounted average total cost per liter of treated water is presented (see Table 5.8). As in the first case, the average cost is very similar between France and Spain, and relatively lower in Portugal. Comparing with the combined MBR with photo-oxidation pilot, the solar pilot has a higher average total cost, although its treatment capacity is smaller.

Nursing Home	Average Total Cost (€/L)
France	1.904
Spain	1.911
Portugal	1.764

Table 5.8. Discounted average total cost of the solar pilot (T=20, discount rate of 2.5%)

5.3. Benefit Estimate

The benefits of abating pharmaceutical pollution are associated to the positive effect of having cleaner water. Unfortunately, there is not a market price for this effect and, thus, we have to rely on shadow prices that we take from the literature (see Table 5.9). Such prices crucially depend on the destination of the treated water: sensitive or non-sensitive[12].

To perform an accurate assessment of the benefits of pharmaceuticals removal at the nursing homes selected in our study, we would need precise date about the degree of sensitivity of the destination of discharged water in each of them. Since we don't have that information, our approach is to offer the estimates both for sensitive and non-sensitive destinations. These estimates play the role of an upper bound and a lower bound respectively for the expected benefits. Also, we do not have data about pharmaceuticals' removal rate of the pilots, therefore it was assumed that the overall removal rate for both pilots is 80%, as it is an acceptable rate and it is generally the minimum rate in the literature.

Pharmaceutical	CAS	Shadow Price (€/mg)		Reference
		Sensitive	Non-sensitive	
Carbamazepine	298-46-4	0.55	0.1	Bellver-Domingo et al. (2017)
Diclofenac	15307-86-5	0.00005347	0.0000422	Molinos-Senante et al. (2013)
Ibuprofen	15687-27-1	9.75	1.2	Bellver-Domingo et al. (2017)
Paracetamol	103-90-2	113.95	14.2	Bellver-Domingo et al. (2017)

Table 5.9. Shadow price of target pharmaceuticals for sensitive and non-sensitive destinations

It can be seen from Table 5.10 that the benefits of treating nursing home effluents are significantly higher in sensitive destinations compared to non-sensitive (around 8 times higher). The highest benefit of treating wastewater is at S1 ad S2 which have the highest detect concentration of the target pharmaceuticals. Also, the benefit is higher at F2. From the target pharmaceuticals, paracetamol and ibuprofen are the top contributors to the benefits of implementing a filter, while diclofenac has the lowest contribution.

[12]Bellver-Domingo et al. (2017) calculated the shadow prices of carbamazepine, ibuprofen and paracetamol for three destinations: wetland, river and sea. For the purposes of this work, these destinations were classified into sensitive and non-sensitive according with the following assumptions: (i) wetland and river were assumed to be sensitive destinations, therefore the shadow price in Table 5.9 is an average of these two values; (ii) sea was assumed to be a non-sensitive destination.

Nursing Home	Benefits (€/L)	
	Sensitive	Non-sensitive
F1	0.8602	0.1072
F2	15.3811	1.9166
S1	21.1201	2.6318
S2	21.1156	2.6311
P1	2.3890	0.2977
P2	2.4699	0.3078

Table 5.10. Benefits per liter of treating nursing home effluents (removal rate of 80%)

Nursing Home	Solar Pilot Benefits (€/year)		MBR with Photo-Oxidation Pilot Benefits (€/year)	
	Sensitive	Non-sensitive	Sensitive	Non-sensitive
F1	3,141.97	391.67	6,283.94	783.35
F2	56,178.43	7,000.39	112,356.87	14,000.78
S1	77,139.70	9,612.42	154,279.41	19,224.85
S2	77,123.07	9,610.01	154,246.15	19,220.02
P1	8,725.78	1,087.36	17,451.56	2,174.71
P2	9,021.28	1,124.16	18,042.56	2,248.33

Table 5.11. Benefit of treating nursing home effluents (removal rate of 80%; solar pilot treatment capacity of 10 L/day; combined MBR with photo-oxidation pilot treatment capacity of 20 L/day)

As a result of the benefits per liter of treating nursing home effluents, the benefits per year and the present value of benefits are higher for S1, S2 and F2; and smaller for F1. Also, the benefits of the combined pilot are higher than the benefits of the solar pilot due to its higher treatment capacity (see Table 5.11 and Table 5.12).

Nursing Home	Solar Pilot Benefits Present Value (€)		MBR with Photo-Oxidation Pilot Benefits Present Value (€)	
	Sensitive	Non-sensitive	Sensitive	Non-sensitive
F1	48,980.72	6,105.86	97,961.44	12,211.71
F2	875,774.74	109,130.22	1,751,549.47	218,260.44
S1	1,202,543.34	149,849.65	2,405,086.68	299,699.31
S2	1,202,284.11	149,811.98	2,404,568.22	299,623.97
P1	136,027.57	16,950.97	272,055.14	33,901.93
P2	140,634.18	17,524.78	281,268.37	35,049.56

Table 5.12. Present value of the benefits of treating nursing home effluents (removal rate of 80%; pilot lifetime of 20 years; discount rate of 2.5%; solar pilot treatment capacity of 10 L/day; oxidation pilot treatment capacity of 20 L/day)

5.4. Net Present Value

Combining the results about benefits and costs, it is computed the NPV for both pilots. As can be seen in Table 5.13, the NPV differs across countries and also depends on the type of destiny of wastewater: whether it is sensitive or non-sensitive. The most favorable cases are the Spanish ones, S1 and S2, in which the NPV of both pilots is always positive, even for non-sensitive destinations and, of course, even more for sensitive destinations. In the Portuguese nursing homes, both pilots display a positive NPV only for sensitive destinations but not for non-sensitive ones. Finally, the result is mixed in France. The less favorable case is home F1, in which the NPV of both pilots is negative even for sensitive destinations and, of course, even more negative for non-sensitive ones. Finally, in F1 both pilots have a positive NPV for sensitive destinations but, for non-sensitive destinations, only the mixed pilot, not the solar one, display a positive NPV.

Nursing Home	Solar Pilot Net Present Value (€)		MBR with Photo-Oxidation Pilot Net Present Value (€)	
	Sensitive	Non-sensitive	Sensitive	Non-sensitive
F1	−90,072.74	−132,947.61	−14,824.89	−100,574.61
F2	736,721.27	−29,923.24	1,638,763.15	105,474.11
S1	1,062,962.77	10,269.09	2,292,785.44	187,398.07
S2	1,062,703.54	10,231.42	2,292,266.98	187,322.72
P1	7,206.35	−111,870.25	179,380.42	−58,772.78
P2	11,812.97	−111,296.44	188,593.65	−57,625.16

Table 5.13. Net Present Value (pilot lifetime of 20 years and discount rate of 2.5%)

As a relative measure, the benefit-cost ratio is computed for all nursing homes (see Table 5.14). Regardless of the nursing home and the destination of wastewater, the benefit-cost ratio is significantly higher in the combined pilot when compared with the solar pilot, reflecting the higher treatment capacity of the combined pilot.

Nursing Home	Solar Pilot Benefit-Cost Ratio		MBR with Photo-Oxidation Pilot Benefit-Cost Ratio	
	Sensitive	Non-sensitive	Sensitive	Non-sensitive
F1	0.35	0.04	0.87	0.11
F2	6.30	0.78	15.53	1.94
S1	8.62	1.07	21.42	2.67
S2	8.61	1.07	21.41	2.67
P1	1.06	0.13	2.94	0.37
P2	1.09	0.14	3.04	0.38

Table 5.14. Benefit-Cost Ratio (pilot lifetime of 20 years and discount rate of 2.5%)

5.5. Sensitivity Analysis

To conclude our study, we perform some sensitivity analysis. For the solar pilot the analysis includes the discount rate and the chemical price, an important cost component for this pilot. For each analysed variable is presented the benefit-cost ratio (see Figure 5.3 and Figure 5.5) as the NPV (see Figure 5.4 and Figure 5.6). Comparing the two variables being analyzed, the impact of the chemical price is more significant than the impact of the discount rate. The discount rate has a positive impact in the NPV in one of the French nursing home, F1, for both wastewater destinations. This is the result of the smaller impact of costs due to a higher discount rate. The same happens in F2, P1 and P2, all for non-sensitive destinations, although at a smaller scale. The chemical price has an important impact given that countries where the NPV is positive turns to be negative at higher chemical prices which is the case of Portugal (P1 and P2) for sensitive destinations and Spain (S1 and S2) for non-sensitive destinations.

For the combined pilot is presented a sensitive analysis regarding the discount rate (see Figure 5.7 and Figure 5.8), given that chemical costs are insignificant in this case. Similar to the solar pilot, in one of French nursing homes for non-sensitive destinations, F1, a higher discount rate has a positive impact in the NPV as costs turns to have a smaller impact. The same occurs in the Portuguese nursing homes for non-sensitive destinations, although the effect is very small.

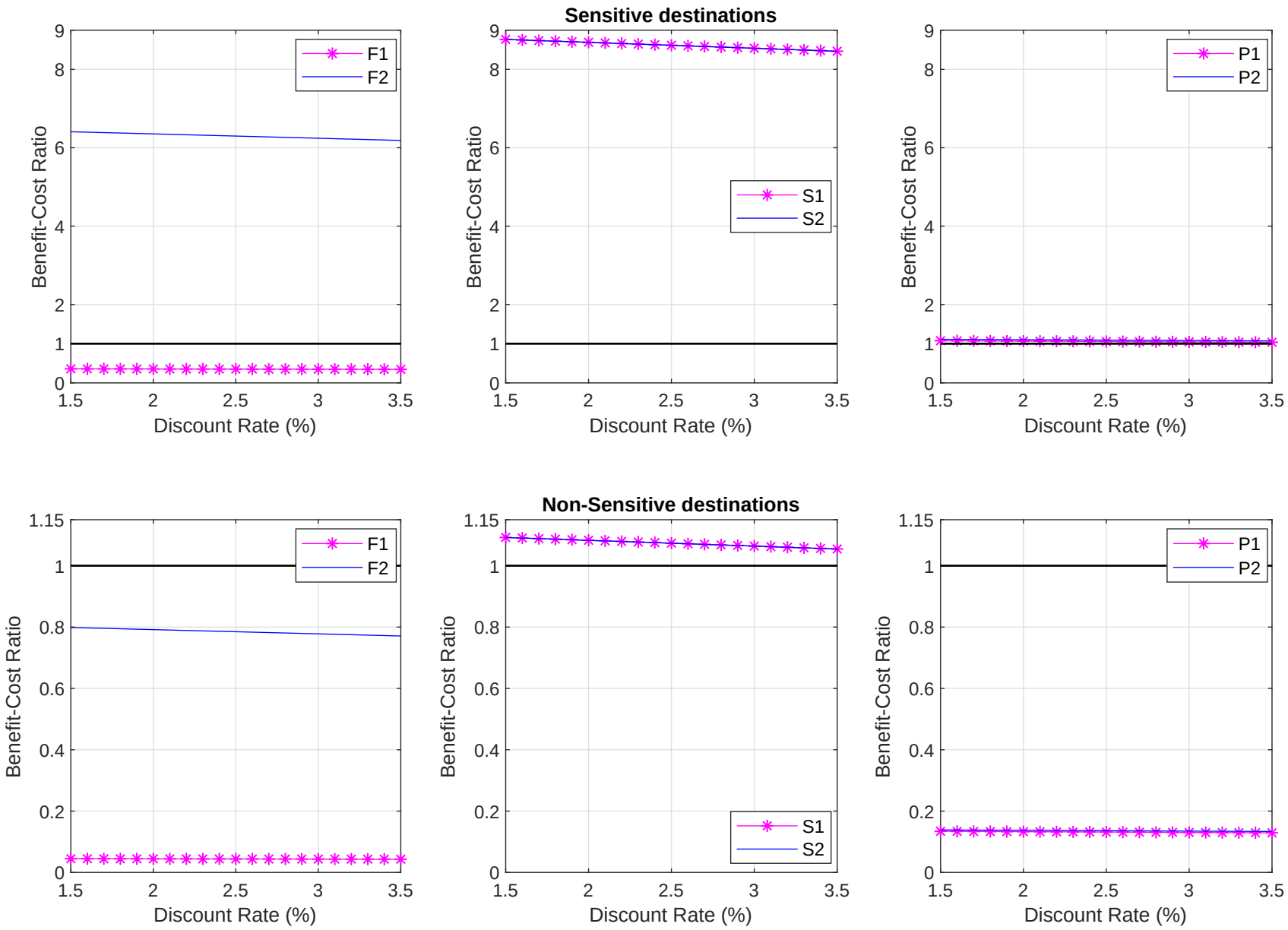

Figure 5.3. Sensitivity analysis (benefit-cost ratio) regarding the discount rate of the solar pilot (discount rate variation between 1.5% and 3.5%)

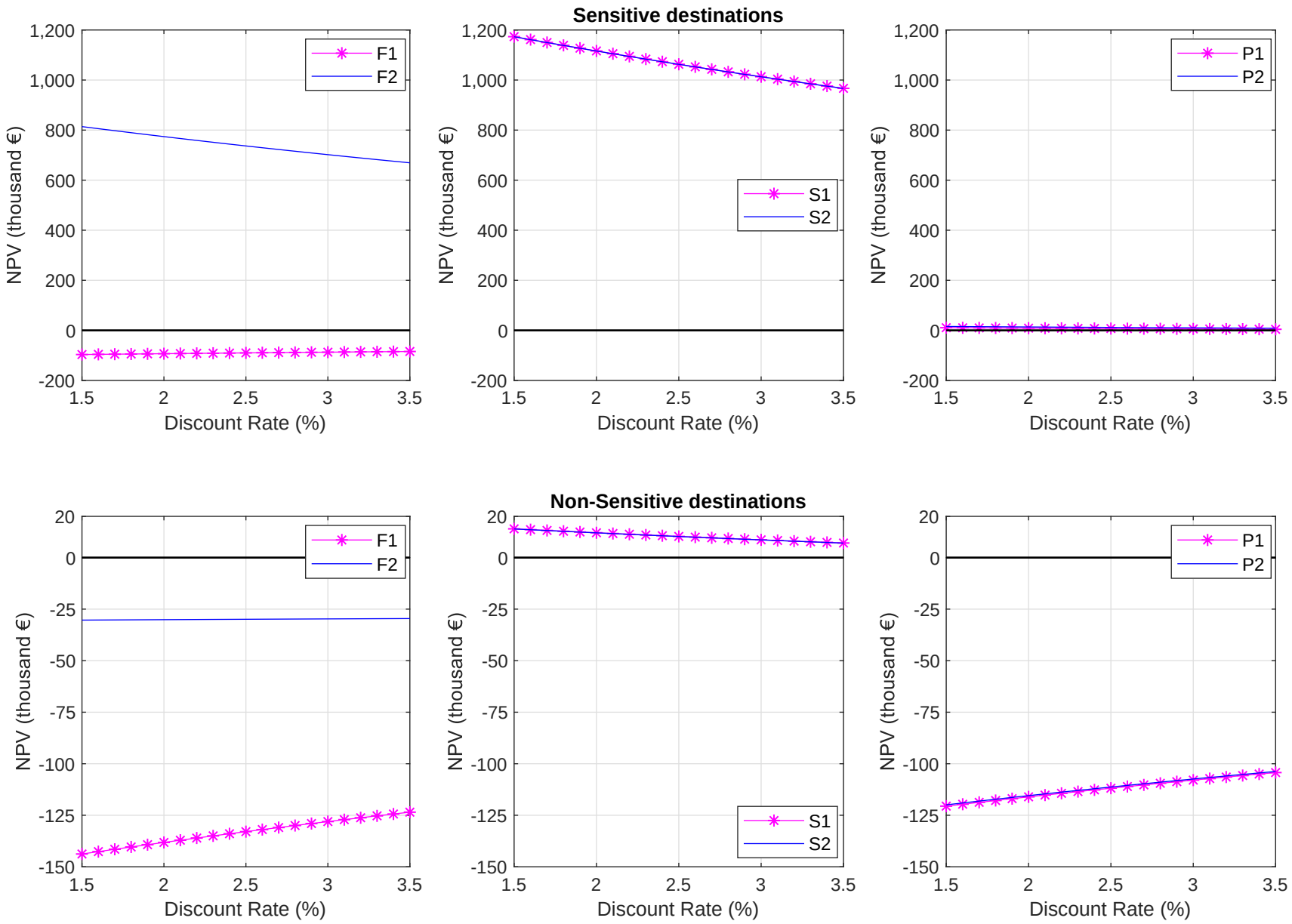

Figure 5.4. Sensitivity analysis (net present value) regarding the discount rate of the solar pilot (discount rate variation between 1.5% and 3.5%)

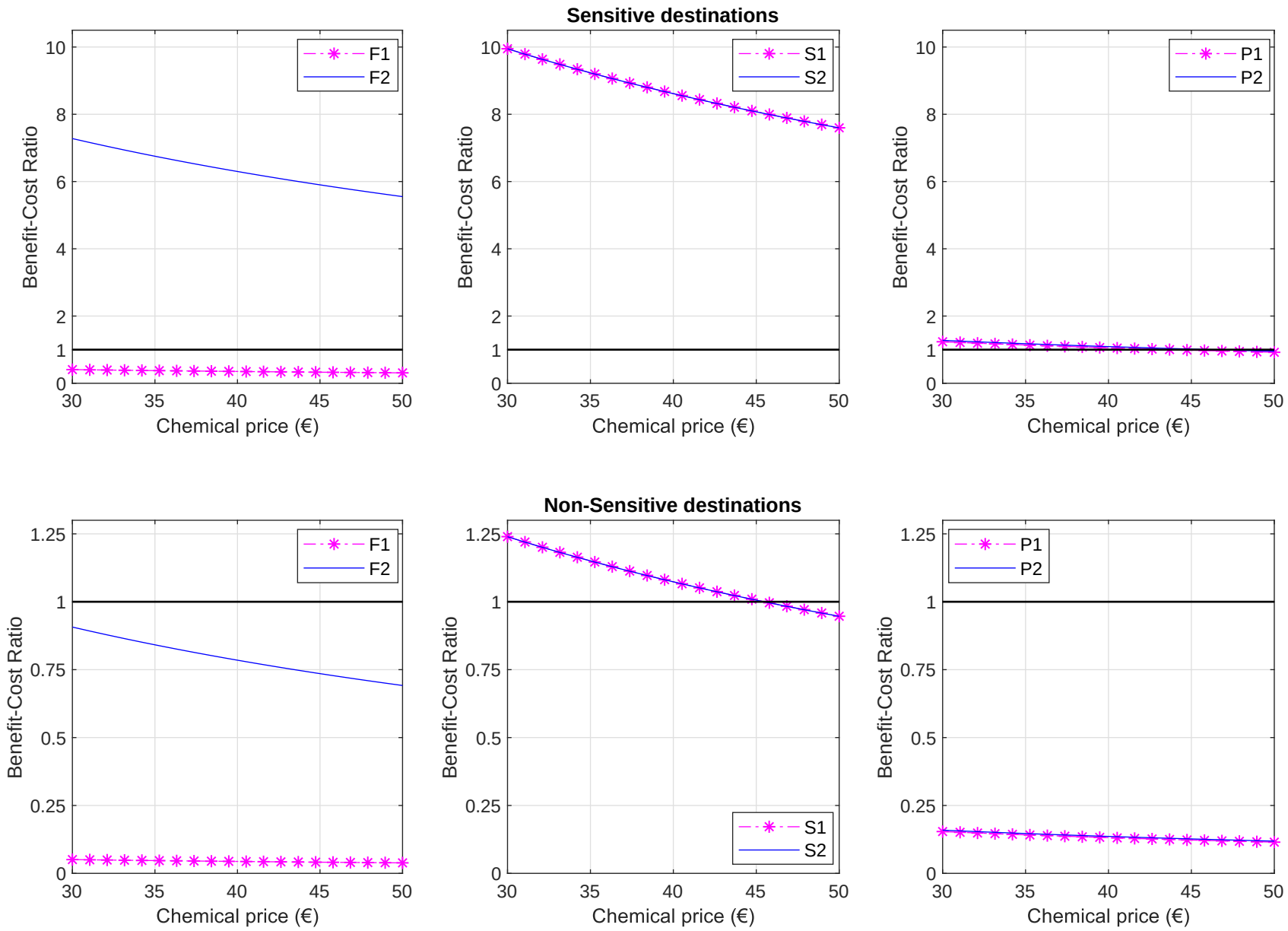

Figure 5.5. Sensitivity analysis (benefit-cost ratio) regarding the chemical price of the solar pilot (chemical price variation between 30€ and 50€)

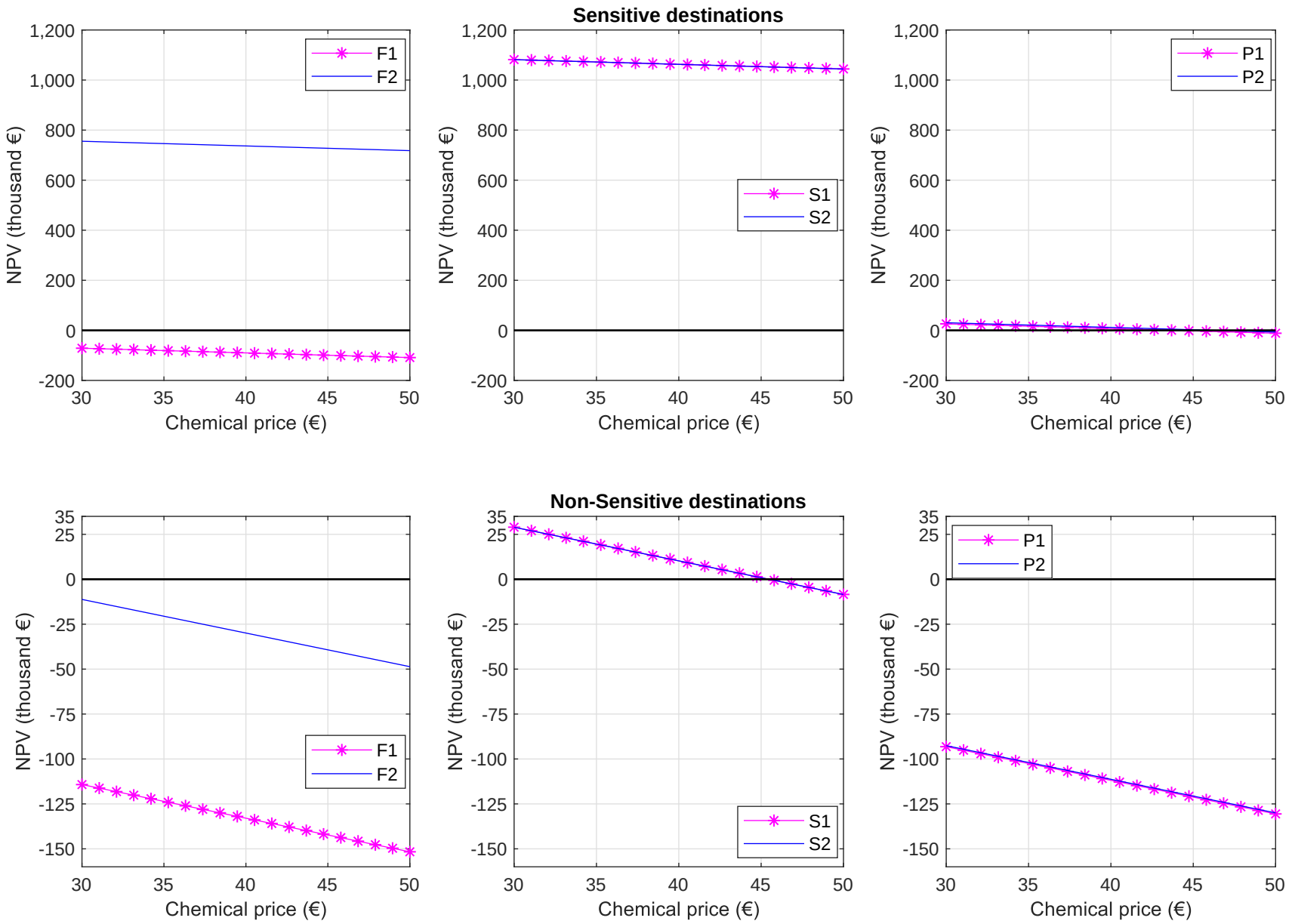

Figure 5.6. Sensitivity analysis (net present value) regarding the chemical price of the solar pilot (chemical price variation between 30€ and 50€)

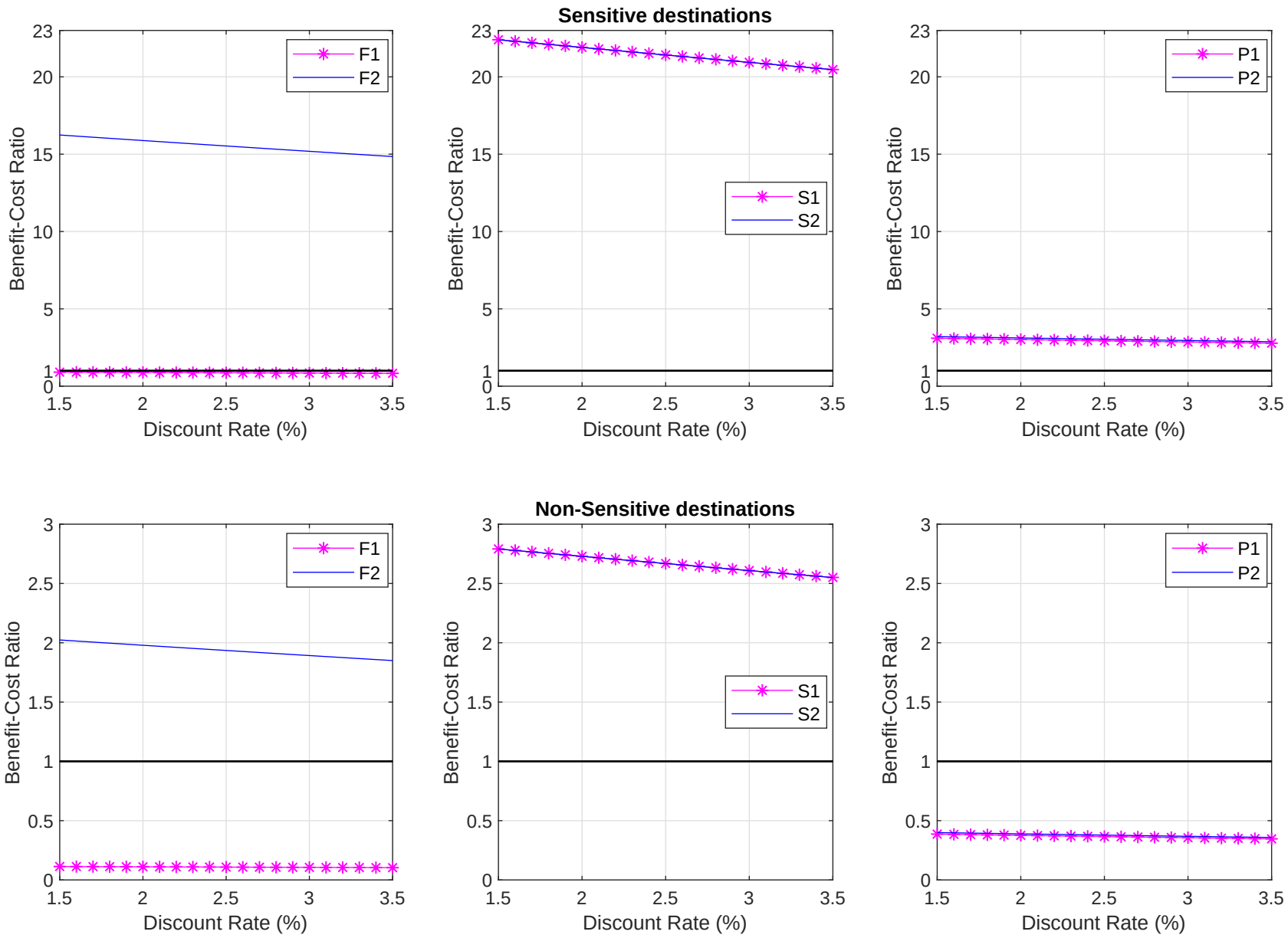

Figure 5.7. Sensitivity analysis (benefit-cost ratio) regarding the discount rate for the combined MBR with photo-oxidation pilot (discount rate variation between 1.5% and 3.5%)

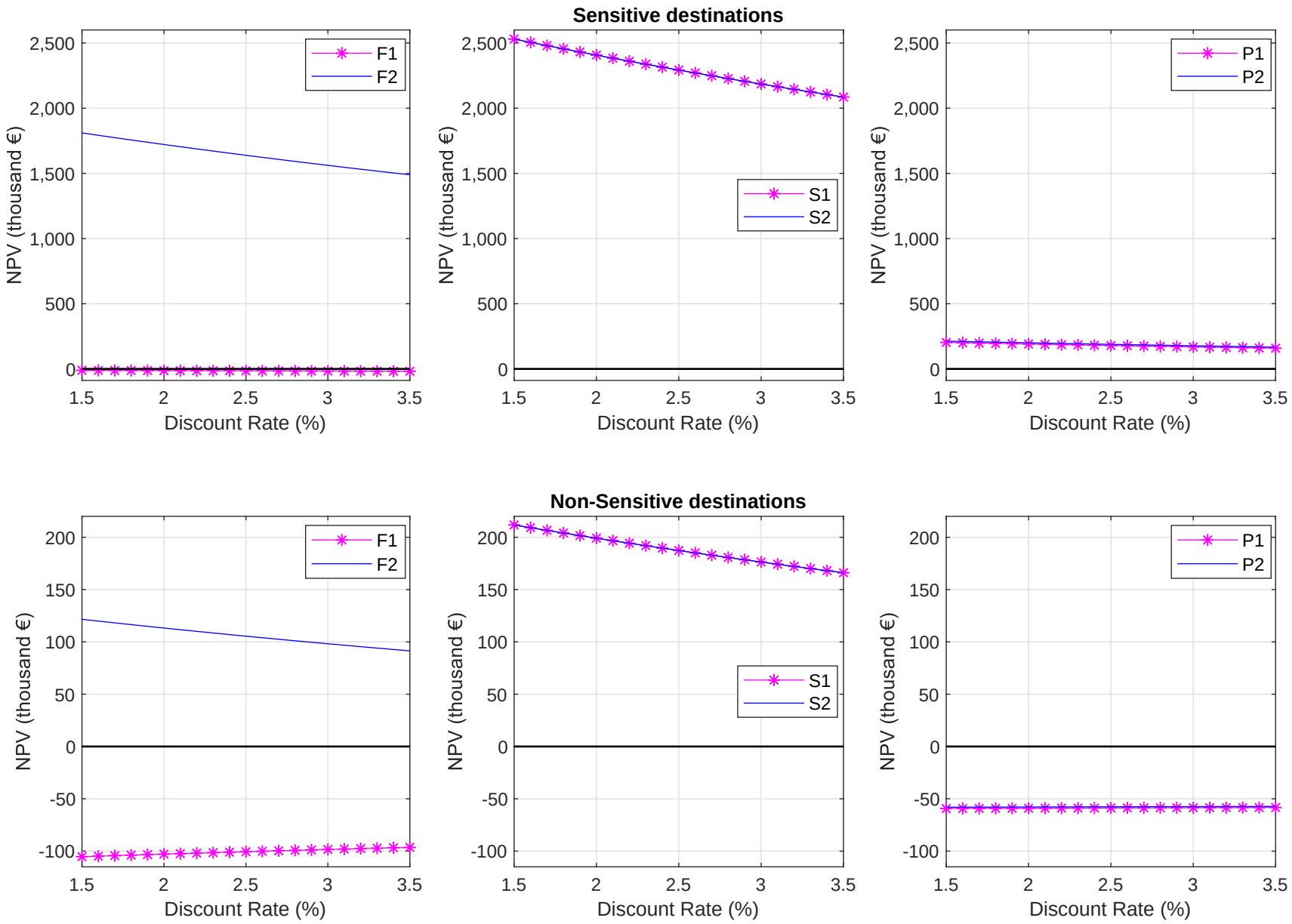

Figure 5.8. Sensitivity analysis (net present value) regarding the discount rate for the combined MBR with photo-oxidation pilot (discount rate variation between 1.5% and 3.5%)

6. Conclusion and Discussion

Our literature search shows that very little work has been done in economics to study the costs and benefits of treating pharmaceutical polluted water even though it might be a relevant approach. Therefore, it seems relevant to increase the efforts in this line.

For both pilots, we observe that, due to lower labor costs, the discounted operational cost, and thus total discounted cost is lower in Portugal than in France and Spain. Investment and electricity costs have a relatively larger weight in Portugal than in the other countries, while it is the other way around for labor. The main difference between the pilots is the contribution of chemical costs which are basically insignificant in the combined pilot while in the solar pilot are an important cost component that counts for more than 50% of operational costs.

Average total costs (discounted value in terms of € per treated liter of water) are similar between France and Spain, being lower in Portugal compared with the other two countries. The average total cost of the combined pilot varies between 0.634 €/L and 0.772 €/L and that of the solar pilot varies between 1.764 and 1.911 €/L.

The benefits of abating pharmaceutical pollution are estimated based on shadow prices taken from the literature, which are very different from sensitive to non-sensitive destinations. The highest benefit of treating wastewater at nursing homes takes place in the Spanish nursing homes (S1 and S2) and also in one of the French homes (F2), as they have the highest detected concentration. From the target pharmaceuticals, paracetamol and ibuprofen are the top contributors to the benefits of implementing a filter, while diclofenac has the lowest contribution. The benefits of the combined pilot are higher than the benefits of the solar pilot due to its higher treatment capacity.

Considering costs and benefits together, the combined pilot displays a higher NPV than the solar pilot and, obviously, the value is higher in sensitive than non-sensitive destinations. Under the assumption of sensitive destination, the NPV is positive for both pilots in all nursing homes, except one of the French ones (F1). Assuming non-sensitive destinations, the NPV is negative for both filters in the Portuguese nursing homes and positive for the Spanish ones. In one of the French homes (F1) the NPV of both filters is negative. Finally, in the other French home (F2), the NPV is positive for the combined pilot but negative for

the solar-alone pilot.

A few words regarding the limitations of these results are in order. The estimations are strongly determined by the specific characteristics of our case studies (nursing homes and, more importantly, pilots). One might wonder to what extent these procedures could be applied in real life and how profitable they would be. Although our results provide a first approximation, a big deal of additional work should be done to have a reliable answer to these questions. The scale of the project is prone to affect drastically the costs and the benefits. Give the small scale of the pilots, the investment costs represent a very large proportion of total cost. This weight would be considerably alleviated at a larger scale. The installation of these filtering facilities would also be affected by the specific regulation in each country.

Other limitations of our study refer to the scarcity of data and also to the simplifying assumptions that had to include in order to make the problem tractable. One of this simplification has to do with the timing of the decision. In the presence of uncertainty, the (expected) arrival of new information can be an essential input for the decision-making process. In this respect, decision-makers could decide to wait for further data before deciding on the installation of a new filter. This dimension has not been addressed in this study and could be in the future. A sketch of such an approach is included in appendix A.

Finally, an alternative option, which can be used in combination with the filter, is the development of social responsibility. Although pharmaceuticals are essential to the effectiveness of medical treatment, unnecessary emissions can result from the inappropriate and excessive consumption (aus der Beek et al., 2016). This could be the case of Spain where the average consumption of pharmaceuticals in the sample facilities is very high. Moreover, some pharmaceuticals could be replaced by more environmentally friendly substances.

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Appendices

A. Sequential Approach: Two-Period Model

The decision-making of this project will be based on the two-period model of Pindyck (2002). This is an optimal timing problem of a discrete action and not a "continuous control" problem in which some objective function is maximized though the continuous adjustment over time of one or more control variables (Pindyck, 2002).

Consider a problem of sequential rationality with two periods: the first period is characterized by lack of scientific knowledge about the impacts of pharmaceutical water pollution; and in the second period there is a development of scientific knowledge. The life time of the filter is greater than the period of time for knowledge development.

There are two possible strategies: implementation of the filter and do-nothing. Therefore, three scenarios are possible (see Figure A.1):

- Implementation of the project in the first period, means that it will remain in the second period
- Implementation only in the second period
- No implementation of the project

Defining some variables:

- B^1 - present value of the benefits from the filter in the first period
- B^2 - present value of the benefits from the filter in the second period
- C^1 - costs in the first period
- C^2 - costs in the second period

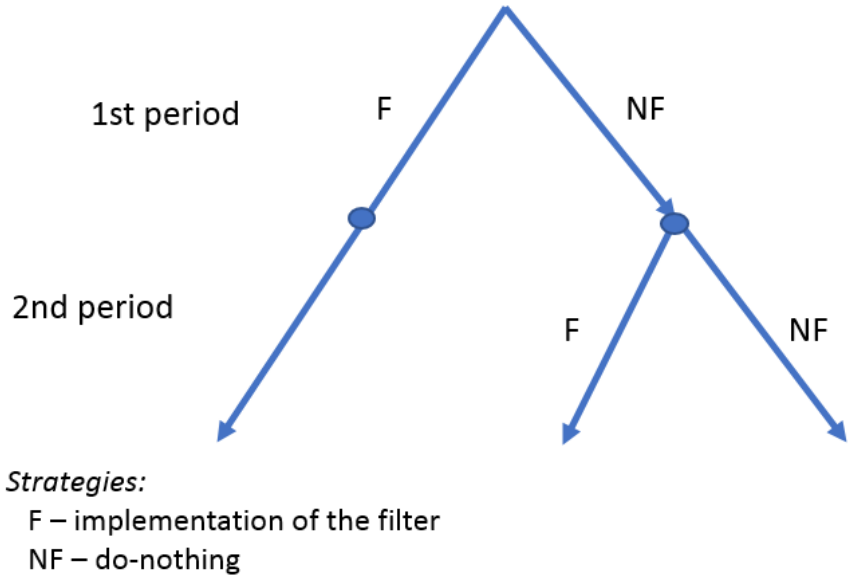

Figure A.1. Sequential approach: two-period model