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Design choices and environmental policies*

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Résumé/abstract

This paper studies the impact of environmental policies when firms can adjust product design as they see fit. In particular, it considers cross relationships between product design dimensions. For example, when products are designed to be more durable, this may add production steps and increase pollutant emissions during production. More generally, changes applied to one dimension can affect the cost or environmental performance of other dimensions. In this theoretical model, a firm interacts with consumers and a regulator. Before the production stage, the firm must choose the levels of three design dimensions: 1) energy performance during production, 2) energy performance during use, and 3) durability. Depending on the assumptions, the dimensions are said to be complementary, neutral, or competitive. The regulator can promote greener designs by applying targeted environmental taxes on emissions during production or consumption. The main results shed light on the consequences of modifying public policies. When some design dimensions are competitive, a targeted emission tax can result in environmental burden shifting, with an overall increase in pollution. This paper also explores the social optimum and the development of second-best policies when some policy instruments are imperfect. Under given conditions, a government would want to regulate and constraint the level of durability.

Mots clés/keywords : green design, environmental policies, durability

Codes JEL/JEL Codes : L10, O13, Q53, Q55, Q58

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1 Introduction

Product environmental quality and green design have been largely explored in the literature.[1] The novelty of this paper is that it formally considers the multidimensionality of product design as well as the potential for complementarity or competition in the selection of product attributes.

During a product life cycle, pollution is generated at all stages: during material extraction, production, consumption, and end-of-life treatment and disposal. However, many of these environmental impacts actually result from decisions taken during the product development stage. Design choices influence material choices, production technologies, energy performance during use, recyclability, durability, and so on. These are referred to as design dimensions.

This paper focuses on the types of cross relationships between design dimensions. For example, new composite materials in aircraft design reduce aircraft weight and gas consumption. However, these materials are almost completely nonrecyclable. The result is an environmental trade-off between energy consumption during use and end-of-life treatment, which makes for a competitive scenario. Conversely, if a given technology simultaneously improves product durability and recyclability, these dimensions would be considered complementary.

There is a large variety of impact categories (*e.g.*, global warming, water pollution, resource depletion), yet policies generally target specific pollutants, specific sectors or specific life cycle stages in isolation.[2] Consequently, pollution externalities may be subject to different tax rates, either because the nature of pollutants emitted during production and consumption differs (*e.g.*, CO2 emissions, toxic waste), or because a single pollutant is taxed

[1] See, for instance, Fullerton and Wu 1998; Eichner and Runkel 2005.

[2] For example, the Clean Air Act (1970) deals with air pollutants, the Montreal Protocol (1989) with substances that deplete the ozone layer, and the Kyoto Protocol (2005) with greenhouse gas emissions. On the other hand, the End of Life Vehicles (2000) and the Waste of electrical and electronic equipment (2003) directives both target end-of-life management.

differently in different sectors or life cycle stages. Firms may therefore select design attributes that come with uneven political incentives for reducing their environmental impacts.

In this theoretical model, a firm interacts with consumers and a regulator. Before the production stage, the firm must choose the levels of three design dimensions: 1) energy performance during production, 2) energy performance during use, and 3) durability. Depending on the assumptions, the dimensions are said to be complementary, neutral, or competitive. The regulator can apply targeted environmental taxes on emissions during production or consumption.

Several studies have investigated green design as a single dimension, such as durability, recyclability, or remanufacturability.[3] For example, Bernard (2015) shows that, when granted flexibility, firms may respond to environmental policies by adapting product designs in ways that compromise the original policy objectives. When several public policies are in force, the total effect on green design may be ambiguous or counterintuitive.

Similarly, Gandenberger et al. (2014) show how policy interactions discourage the recycling of plastic packaging waste in Germany. Once recycling quotas have been reached, thermal recovery and incineration become more advantageous options. This is because, apart from targeted recycling policies, other waste management and climate policies indirectly affect plastic recycling. By extension, we may surmise that such policy interactions may also reduce incentives for design toward recyclability.

Some authors have investigated product design using two dimensions. In Fullerton and Wu's (1998) model, in which firms decide on product recyclability and the amount of packaging, various market failures that lead to inefficient waste production or insufficient incentives for green design are examined. The results show how different combinations of policy instruments can lead to the optimal outcome. For example, they consider a case where the government avoids imposing a collection tax that people would try to circumvent with il-

[3] See, for example, Runkel (2003); Eichner and Pethig (2001 and 2003); Debo et al. (2005); and Bernard (2011 and 2015).

legal dumping. Applying a mixed policy that combines a packaging tax with recyclability subsidies can also lead to the optimal social outcome. Although a pioneer in the field, their study only considers two dimensions that show a neutral relationship.

Although Chen (2001), Eichner and Runkel (2003) and Subramanian et al. (2009) do not formally define cross relationships between dimensions, their implicit assumptions provide interesting insights. Chen (2001) extends the multidimensionality of design attributes to nonenvironmental dimensions. He proposes a scenario in which a firm chooses the environmental performance and a traditional attribute such as vehicle safety. His results indicate that in order to prevent green customers from switching to a traditional product, the environmental quality of the traditional product is decreased.

Eichner and Runkel (2003) argue that the use of thicker materials in product design would not only improve durability, it would also facilitate product recuperation. In their model, product weight correlates positively with both durability and recyclability. According to our definitions, these dimensions would be considered complementary. This argument has significant implications for public policy making. For example, in a scenario where durability is fully integrated in the market, market mechanisms will drive firms to internalize consumer preferences and choose optimal durability for their products. However, in the absence of a market for recyclability, firms will not choose optimal product recyclability. Consequently, due to the complementarity between the two dimensions, the choice of durability would also be inappropriate. Therefore, a public policy that encourages recycling could also restore product durability to the optimal level.

Subramanian et al. (2009) examine design choices that affect product environmental performance during product use and product remanufacturability. Due to consumer heterogeneity, a trade-off is made between the two dimensions, which therefore become competitive. The "efficient" consumer type is offered a product with higher performance, which lowers the usage cost such that the product is replaced less often. This results in lower disposal costs, which in turn lowers the incentive for remanufacturability.

The above examples illustrate the importance of the cross relationships between design dimensions. However, the nature of these relationships and their impact on various outcomes remain unclear.

The main results of the present study shed light on the consequences of modifying public policies. In particular, when some design dimensions are competitive, a targeted emission tax can result in environmental burden shifting, with an overall increase in pollution. Another result shows how a tax on emission during production can precisely discourage investment in environmental quality during production. This study also explores the social optimum, and second-best policies. As long as pollution externalities are internalized, the government can ignore the possibility for firms to adjust the level of durability. However, when some policy instruments are inappropriate, the choice of durability matters. Under given circumstances, the government will want to regulate and constraint durability.

2 The Model

2.1 Production, emission and taxes

In this economy, a single durable good is produced by a monopolist. The product design includes three dimensions: *i)* the environmental quality during production, q_1;[4] *ii)* the environmental quality during consumption, q_2; and *iii)* durability, δ. The environmental qualities q_1 and q_2 are linearly related to the level of pollution emissions during production and during one consumption period, respectively. The parameter δ is the share of new products that remain in good condition after one consumption period, and can be used for a second period. Durability δ does not generate externalities, but determines the frequency of emissions during production.

[4] In particular, quality q_1 can be interpreted as (the combination of) any dimension for which the environmental impact occurs only once during the product lifetime, e.g., raw material extraction or waste and end-of-life treatment.

Emissions $e_i(q_i)$, for $i = 1, 2$, are such that $e_i'(q_i) = -1$. It is assumed that there is no depreciation in the good's quality when it lasts for two periods. Emission levels depend strictly on the good's qualities as selected at the production stage. The pollution generated by one product over its lifetime is $D = e_1(q_1) + (1 + \beta\delta)e_2(q_2)$, where β is a discount factor. Because the product is useful for more than one period, it is said to provide $1 + \beta\delta$ (discounted) functional units. Pollutant emissions can be expressed per functional unit as follows:

$$D_f = \frac{e_1(q_1)}{(1 + \beta\delta)} + e_2(q_2).$$

The firm's unit production cost is $c(q_{1,t}, q_{2,t}, \delta_t)$ where $c'(\bullet) > 0$, $c''(\bullet) > 0$, and all the cross derivatives follow the assumption made for the cost cross relationships between the three dimensions. A positive (negative) cross derivative indicates a competitive (complementary) relationship. For example, $c_{q_1\delta} > 0$ means that improving product durability raises the cost of meeting a low-emission standard during production.

The social planner establishes a political platform where τ_1 and τ_2 are targeted environmental taxes on emissions during production and during one consumption period, respectively.

2.2 The demand and supply

An infinitely lived representative household needs a given functionality or service supplied by the produced good. For instance, the household needs one washing machine, one toaster, or one vacuum cleaner. In this scenario, the parameter α represents the willingness to pay for one consumption period, which is the corresponding welfare. At no time will the household possess more than one of these goods.[5] For instance, toasters sold at lower prices do not

[5] These assumptions allow us to focus the analysis on design choices and the corresponding pollutant emissions per unit of good. This avoids the time inconsistency problem, where firms, in subsequent periods,

induce households to consume more of that functionality. For simplicity, we assume that the household keeps the product until the end of its useful life.

The environmental quality during consumption is directly related to energy consumption, and it reduces the cost of using the product. For constant emission production per unit of energy consumption, the price of energy p_e is expressed in terms of the emissions. As a result, the household's net willingness to pay for a new good is affected by the good's life duration δ and the environmental quality during consumption q_2. The household's willingness to pay for a new good is then $WTP_t = (1 + \beta\delta_t)(\alpha - p_e e(q_{2,t}))$, where β is a discount factor.

If a tax on emission during consumption τ_2 is applied, willingness to pay for new products becomes:[6]

$$WTP_t = (1 + \beta\delta_t)(\alpha - (p_e + \tau_2)e_2(q_{2,t})).$$

Given the price of new products p_t, purchase occurs only if $WTP_t \geq p_t$. For each period, the market size depends on products durability. In particular, the demand at time t, x_t^d, respects the following rule:

$$x_t^d = \begin{cases} 1 - \delta_{t-1}x_{t-1} & \text{if } WTP_t \geq p_t \\ 0 & \text{otherwise.} \end{cases}$$

where x_{t-1} is the market size in equilibrium in period $t-1$.

Because the producer is a monopolist, the price schedule, which is the rental value for

overproduce while ignoring the rental value of previously sold goods (see, e.g., Coase 1972 or Bulow 1986). In an argument *à la* Bagnoli et al. (1989), our representative household is, in fact, a finite market size and time inconsistency does not hold.

[6] τ_2 can be considered as a tax on gas or energy. Alternatively, τ_2 could be charged to the producer as a tax on expected emissions during consumption. For the monopoly scenario, the results remain the same.

the lifetime of each product, fully internalizes the consumer surplus:[7]

$$p_t(q_{2,t}, \delta_t; \tau_2) = (1 + \beta\delta_t)(\alpha - (p_e + \tau_2)e_2(q_{2,t})).$$

With π being the producer's profit, the supply function is such that:

$$x_t^s = \begin{cases} 1 - \delta_{t-1}x_{t-1} & \text{if } \pi(1 - \delta_{t-1}x_{t-1}) \geq 0 \\ 0 & \text{otherwise.} \end{cases}$$

In equilibrium, $x_t^d = x_t^s = x_t$, and it is assumed that $\pi(1 - \delta_{t-1}x_{t-1}) \geq 0$ at all time so that the market exists, i.e., $x_t = 1 - \delta_{t-1}x_{t-1}$ and $p_t(q_{2,t}, \delta_t; \tau_2) = (1 + \beta\delta_t)(\alpha - (p_e + \tau_2)e_2(q_{2,t}))$.

3 The equilibrium

The firm's intertemporal maximization problem is therefore:

$$\begin{aligned} \max_{\{q_{1,t}, q_{2,t}, \delta_t, x_t\}} V_0 = \sum_{t=0}^{T} \beta^t x_t \left[p(q_{2,t}, \delta_t; \tau_2) - c(q_{1,t}, q_{2,t}, \delta_t) - \tau_1 e_1(q_{1,t})\right] \\ \text{s.t. } x_{t+1} = 1 - \delta_t x_t \qquad (1) \\ x_0 = \overline{x}_0 \text{ given} \\ \text{and where } p(q_{2,t}, \delta_t; \tau_2) = (1 + \beta\delta_t)(\alpha - (p_e + \tau_2)e_2(q_{2,t})), \end{aligned}$$

where the state equation (1) can be written as $x_{t+1} - x_t = 1 - \delta_t x_t - x_t$. To solve for the dynamic problem, we use the Hamiltonian:

$$H_t = \beta^t x_t \left[p(q_{2,t}, \delta_t; \tau_2) - c(q_{1,t}, q_{2,t}, \delta_t) - \tau_1 e_1(q_{1,t})\right] + \lambda_t(1 - \delta_t x_t - x_t) \qquad (t = 0, 1, ..., T)$$

[7] Bulow (1986) suggested that the monopolist could overcome the time inconsistency problem and increase profits by renting the good instead of selling it. By assumption, we have that the monopolist will indifferently sell or rent the good.

and the first order conditions are (for $t = 0, 1, ..., T$):

$$\begin{aligned}
\frac{\partial H_t}{\partial q_{1,t}} &= 0 \Leftrightarrow -\frac{\partial c(q_{1,t}, q_{2,t}, \delta_t)}{\partial q_{1,t}} + \tau_1 = 0 \\
\frac{\partial H_t}{\partial q_{2,t}} &= 0 \Leftrightarrow (1 + \beta\delta_t)(p_e + \tau_2) - \frac{\partial c(q_{1,t}, q_{2,t}, \delta_t)}{\partial q_{2,t}} = 0 \\
\frac{\partial H_t}{\partial \delta_t} &= 0 \Leftrightarrow \beta^t x_t \left(\beta(\alpha - (p_e + \tau_2) e_2(q_{2,t})) - \frac{\partial c(q_{1,t}, q_{2,t}, \delta_t)}{\partial \delta_t} \right) - \lambda_t x_t = 0 \\
\frac{\partial H_t}{\partial x_t} &= \lambda_{t-1} - \lambda_t \Leftrightarrow \beta^t \left[p(q_{2,t}, \delta_t; \tau_2) - c(q_{1,t}, q_{2,t}, \delta_t) - \tau_1 e_1(q_{1,t}) \right] - \lambda_t \delta_t - \lambda_{t-1} = 0 \\
\frac{\partial H_t}{\partial \lambda_t} &= x_{t+1} - x_t \quad (t = 0, 1, ..., T - 1)\,.
\end{aligned}$$

In steady state, $q_{1,t} = q_{1,t+1} = q_1$; $q_{2,t} = q_{2,t+1} = q_2$; and $\delta_t = \delta_{t+1} = \delta \ \forall t$, and these equilibrium conditions can be reduced to:

$$\widehat{q}_1(q_1, q_2, \delta; \tau_1) :\Rightarrow f_1(q_1, q_2, \delta; \tau_1) = -\frac{\partial c(q_1, q_2, \delta)}{\partial q_1} + \tau_1 = 0 \tag{2}$$

$$\widehat{q}_2(q_1, q_2, \delta; \tau_2) :\Rightarrow f_2(q_1, q_2, \delta; \tau_2) = (1 + \beta\delta)(p_e + \tau_2) - \frac{\partial c(q_1, q_2, \delta)}{\partial q_2} = 0 \tag{3}$$

$$\widehat{\delta}(q_1, q_2, \delta; \tau_1) :\Rightarrow$$

$$f_\delta(q_1, q_2, \delta; \tau_1) = -\frac{\partial c(q_1, q_2, \delta)}{\partial \delta} + \left(\frac{\beta}{1 + \beta\delta} \right) [c(q_1, q_2, \delta) + \tau_1 e_1(q_1)] = 0 \tag{4}$$

$$\text{and } \widehat{x} = \frac{1}{1 + \widehat{\delta}}. \tag{5}$$

Equation (2) states that for each production period, the marginal cost of q_1 is equal to the marginal benefit of saving the pollution tax τ_1 by reducing emission $e_1(q_1)$. Equation (3) means that q_2 is chosen so that its marginal impact on the selling price, which is weighted by the discount factor β and durability δ, equals its marginal cost. Finally, equation (4) states that the marginal cost of durability δ must be equal to its discounted long-term impact, which includes the fact that production costs $c(q_1, q_2, \delta)$ and the tax on emission during production $\tau_1 e_1(q_1)$ are paid less often. This result recalls Swan (1970) where, for given q_1

and q_2, the choice of durability minimizes the cost of supplying a given functionality from a stock of durable goods.

4 The impact of taxes

This section examines the impact of a change in a series of parameters on the design choices (q_1, q_2, δ). In particular, we study the parameters $\phi = \tau_1, \tau_2$ and τ, where τ represents a uniform tax: $\tau_1 = \tau_2 = \tau$. The Hessian matrix is:

$$\boldsymbol{\mathcal{H}} = \begin{bmatrix} -c_{q_1q_1} & -c_{q_1q_2} & -c_{q_1\delta} \\ -c_{q_1q_2} & -c_{q_2q_2} & \beta\left(p_e+\tau_2\right)-c_{q_2\delta} \\ -c_{q_1\delta} & \beta\left(p_e+\tau_2\right)-c_{q_2\delta} & -c_{\delta\delta} \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} & h_{13} \\ h_{12} & h_{22} & h_{23} \\ h_{13} & h_{23} & h_{33} \end{bmatrix} \tag{6}$$

All the elements on the diagonal are negative, $\beta\left(p_e+\tau_2\right)$ is positive and the sign of the other elements depends on the assumption made about the cost cross relationships. Note that when all the design dimensions are cost neutral, *i.e.*, all the cost cross derivatives are zero, environmental quality during consumption q_2 and durability δ remain complementary with $h_{23} = \beta\left(p_e+\tau_2\right) > 0$. When goods are more durable, consumers give more weight to energy consumption in the future.

We assume that the solution for the optimization problem is a general maximum, which implies that the Hessian matrix is negative definite. We also assume that $\boldsymbol{\mathcal{H}}$ is invertible, and $\det \boldsymbol{\mathcal{H}} < 0$. For a change in a given tax ϕ, we have the following relationships:[8]

$$\begin{bmatrix} d\widehat{q_1}/d\phi \\ d\widehat{q_2}/d\phi \\ d\widehat{\delta}/d\phi \end{bmatrix} = -\boldsymbol{\mathcal{H}}^{-1} \begin{bmatrix} \partial f_1/\partial\phi \\ \partial f_2/\partial\phi \\ \partial f_\delta/\partial\phi \end{bmatrix} = \frac{-1}{\det \boldsymbol{\mathcal{H}}} \begin{bmatrix} H_{11} & H_{12} & H_{13} \\ H_{12} & H_{22} & H_{23} \\ H_{13} & H_{23} & H_{33} \end{bmatrix} \begin{bmatrix} \partial f_1/\partial\phi \\ \partial f_2/\partial\phi \\ \partial f_\delta/\partial\phi \end{bmatrix} \tag{7}$$

and $\det \boldsymbol{\mathcal{H}} = H_{11}h_{11} + H_{12}h_{12} + H_{13}h_{13} < 0$.

From equations (2) to (4), partial derivatives $\partial f_1/\partial\phi$, $\partial f_2/\partial\phi$, $\partial f_\delta/\partial\phi$ give the direct impact of a change in the parameters on the choice of design dimensions. They are:

$$\begin{array}{ll} \frac{\partial f_1}{\partial \tau_1} = \frac{\partial f_1}{\partial \tau} = 1 \geq 0 & \frac{\partial f_1}{\partial \tau_2} = 0 \\ \frac{\partial f_2}{\partial \tau_1} = 0 & \frac{\partial f_2}{\partial \tau_2} = \frac{\partial f_2}{\partial \tau} = (1+\beta\delta) \geq 0 \\ \frac{\partial f_\delta}{\partial \tau_1} = \frac{\partial f_\delta}{\partial \tau} = \left(\frac{\beta}{1+\beta\delta}\right) e_1(q_1) \geq 0 & \frac{\partial f_\delta}{\partial \tau_2} = 0 \end{array} \tag{8}$$

The total effect of a change in the parameters on the tree dimensions is given by the equations in (7). Because each element H_{ij} (for $i, j = 1, 2, 3$, $i \neq j$) depends on the interaction between all the cross relationships, they will be referred to as the *relative* relationships between dimensions. For example, a direct change in q_2 resulting from a variation in a parameter, $\partial f_2/\partial\phi$, will have an impact weighted by H_{12} on q_1. Note also that all the elements on the diagonal H_{ii} (for $i = 1, 2, 3$) are positive under the dominant diagonal condition.[9]

[8] We use $\begin{bmatrix} H_{11} & H_{12} & H_{13} \\ H_{12} & H_{22} & H_{23} \\ H_{13} & H_{23} & H_{33} \end{bmatrix} = \begin{bmatrix} h_{22}h_{33} - h_{23}^2 & h_{13}h_{23} - h_{12}h_{33} & h_{12}h_{23} - h_{13}h_{22} \\ h_{13}h_{23} - h_{12}h_{33} & h_{11}h_{33} - h_{13}^2 & h_{13}h_{12} - h_{11}h_{23} \\ h_{12}h_{23} - h_{13}h_{22} & h_{13}h_{12} - h_{11}h_{23} & h_{11}h_{22} - h_{12}^2 \end{bmatrix}$

[9] The *dominant-diagonal condition* states that the direct effects on one dimension are larger than all the indirect effects. The diagonal (h_{11}, h_{22}, h_{33}) has the largest elements.

4.1 When relationships between design dimensions are neutral, cost neutral or complementary

When all relationships are neutral and cost neutral, $\boldsymbol{\mathcal{H}}$ takes the following forms, respectively:

$$\boldsymbol{\mathcal{H}} = \begin{bmatrix} -c_{q_1 q_1} & 0 & 0 \\ 0 & -c_{q_2 q_2} & 0 \\ 0 & 0 & -c_{\delta\delta} \end{bmatrix} \text{ and } \boldsymbol{\mathcal{H}} = \begin{bmatrix} -c_{q_1 q_1} & 0 & 0 \\ 0 & -c_{q_2 q_2} & \beta\left(p_e + \tau_2\right) \\ 0 & \beta\left(p_e + \tau_2\right) & -c_{\delta\delta} \end{bmatrix}$$

whereas if all the relationships are complementary, $\boldsymbol{\mathcal{H}}$ takes the form of matrix (6), where all the elements not on the diagonal are positive. When all relationships are neutral, the total impact of a change in the parameters depends strictly on their direct impact, as given by the equations in (8). For the cost neutral and the complementary cases, the impact depends on the complementarity between dimensions. This is summarized in the following tables:

Neutral

	$\boldsymbol{\tau}_1$	$\boldsymbol{\tau}_2$	$\boldsymbol{\tau}$
$\mathbf{q}_1$	≥ 0	$= 0$	≥ 0
$\mathbf{q}_2$	$= 0$	≥ 0	≥ 0
$\boldsymbol{\delta}$	≥ 0	$= 0$	≥ 0

Cost neutral

	$\boldsymbol{\tau}_1$	$\boldsymbol{\tau}_2$	$\boldsymbol{\tau}$
$\mathbf{q}_1$	≥ 0	$= 0$	≥ 0
$\mathbf{q}_2$	≥ 0	≥ 0	≥ 0
$\boldsymbol{\delta}$	≥ 0	≥ 0	≥ 0

Complementary

	$\boldsymbol{\tau}_1$	$\boldsymbol{\tau}_2$	$\boldsymbol{\tau}$
$\mathbf{q}_1$	≥ 0	≥ 0	≥ 0
$\mathbf{q}_2$	≥ 0	≥ 0	≥ 0
$\boldsymbol{\delta}$	≥ 0	≥ 0	≥ 0

For the cost neutral case, the environmental quality during production q_1 is unaffected by a change in the tax on emissions during consumption τ_2, *i.e.*, $d\widehat{q_1}/d\tau_2 = 0$. This is because the choice of q_1 does not directly depend on this parameter, and the cross relationships with the two other dimensions are neutral. For the environmental quality during consumption q_2, however, the direct impact of an increase in the tax on emissions during production τ_1 is nil (see equations in 8), but the positive variation in durability δ improves q_2, and the total impact of τ_1 on q_2 is therefore positive, i.e., $d\widehat{q_2}/d\tau_1 \geq 0$. This is the result of the complementarity between the environmental quality during consumption q_2 and durability δ, which also induces the positive effect of a tax on emissions during consumption τ_2 on durability δ, or $d\widehat{\delta}/d\tau_2 > 0$.

Proposition 1 *When the relationships between design dimensions q_1, q_2 and δ are all neutral or complementary,*

- *an increase in the tax on emissions during production τ_1 or during consumption τ_2, or an increase in a uniform tax τ always improve green design and reduces pollution emissions per functional unit D_f.*

4.2 When some relationships between design dimensions are competitive

The impact of a change in the tax on emission during production and consumption, τ_1 and τ_2, are respectively:

$$\begin{aligned}
\frac{d\widehat{q}_1}{d\tau_1} &= \frac{-1}{\det \boldsymbol{\mathcal{H}}}\left(H_{11} + H_{13}\left(\frac{\beta}{1+\beta\delta}\right)e_1(q_1)\right) \lesseqgtr 0; \quad & \frac{d\widehat{q}_1}{d\tau_2} &= \frac{-1}{\det \boldsymbol{\mathcal{H}}} H_{12}(1+\beta\delta) \lesseqgtr 0 \\
\frac{d\widehat{q}_2}{d\tau_1} &= \frac{-1}{\det \boldsymbol{\mathcal{H}}}\left(H_{12} + H_{23}\left(\frac{\beta}{1+\beta\delta}\right)e_1(q_1)\right) \lesseqgtr 0; \quad & \frac{d\widehat{q}_2}{d\tau_2} &= \frac{-1}{\det \boldsymbol{\mathcal{H}}} H_{22}(1+\beta\delta) > 0 \\
\frac{d\widehat{\delta}}{d\tau_1} &= \frac{-1}{\det \boldsymbol{\mathcal{H}}}\left(H_{13} + H_{33}\left(\frac{\beta}{1+\beta\delta}\right)e_1(q_1)\right) \lesseqgtr 0; \quad & \frac{d\widehat{\delta}}{d\tau_2} &= \frac{-1}{\det \boldsymbol{\mathcal{H}}} H_{23}(1+\beta\delta) \lesseqgtr 0
\end{aligned}$$

Which gives us the following proposition.

Proposition 2 *When some of the relationships between design dimensions q_1, q_2 and δ are competitive, the full impact of a change depend on the relative relationships between dimensions.*

- *A change in the tax on emission during production τ_1 has ambiguous effects on the three dimensions.*

- *A change in the tax on emission during consumption* τ_2 *has ambiguous effects on the quality during production* q_1 *and durability* δ*, and positively affects quality during consumption* q_2*.*

The following example illustrates how relative relationships become important. If we assume that q_1 and q_2 are neutral; q_1 and δ competitive; and q_2 and δ complementary ($h_{12} = 0$, $h_{13} < 0$ and $h_{23} > 0$), this results in the following impacts:

$$\frac{d\widehat{q}_1}{d\tau_2} < 0; \; \frac{d\widehat{q}_2}{d\tau_2} > 0; \text{ and } \frac{d\widehat{\delta}}{d\tau_2} > 0$$

Even if q_1 and q_2 are neutral, higher quality during consumption q_2 boosts the durability choice δ, which in turn has a negative impact on q_1. Dimensions q_1 and q_2 become relatively competitive (*i.e.*, $H_{12} < 0$).

Various scenarios have been explored in a simulated economy in Appendix A. In a first scenario, environmental quality during consumption q_2 is complementary with both quality during production q_1 and durability δ, while quality during production q_1 and durability δ are competitive. The second scenario proposes a technology in which environmental quality during consumption q_2 is complementary with quality during production q_1, while the two other cross relationships are competitive. Results give the following proposition:

Proposition 3 *Under given conditions, competitive relationships between some design dimensions* q_1*,* q_2 *and* δ *lead to the following results:*

- *an increase in* τ_1 *can have adverse effects in terms of emissions per functional unit* D_f*, that is:*

$$\frac{dD_f}{d\tau_1} > 0.$$

- *an increase in the tax on emissions during production τ_1 can reduce the environmental quality of the good during production q_1, causing therefore an increase in emissions during production e_1, that is:*

$$\frac{d\widehat{q}_1}{d\tau_1} < 0 \text{ and } \frac{de_1(q_1)}{d\tau_1} > 0.$$

Proposition 3 says that a targeted tax on emissions during production possibly leads to an increase in the overall emissions, or an increase in the targeted pollutant per unit of good. While aiming for lower emissions of a specific pollutant, an environmental policy may have adverse effects.

5 Optimal policies

5.1 Social optimum

The pollution generated by one product over its lifetime is $D_t = e_1(q_{1,t}) + (1 + \beta\delta_t)e_2(q_{2,t})$.

The social planner maximizes the current value of profits and consumer surplus, while taking into account the environmental damage. Note that in the current scenario, the monopolist receives the benefit of the consumer's full willingness to pay, and the consumer's surplus is null at all times:

$$\max_{\{q_{1,t},q_{2,t},\delta_t,x_t\}} W_0 = \sum_{t=0}^{T} \beta^t (V_t - D_t) \tag{9}$$

$$\text{s.t. } x_{t+1} = 1 - \delta_t x_t$$

$$x_0 = \overline{x}_0 \text{ given}$$

and where $p(q_{2,t}, \delta_t) = (1 + \beta\delta_t)(\alpha - p_e e_2(q_{2,t}))$.

Using the Hamiltonian, we find the following steady-state conditions for the social optimum:

$$q_1^*(q_1, q_2, \delta) :\Rightarrow -\frac{\partial c(q_1, q_2, \delta)}{\partial q_1} + 1 = 0 \tag{10}$$

$$q_2^*(q_1, q_2, \delta) :\Rightarrow (1 + \beta\delta)(p_e + 1) - \frac{\partial c(q_1, q_2, \delta)}{\partial q_2} = 0 \tag{11}$$

$$\delta^*(q_1, q_2, \delta) :\Rightarrow -\frac{\partial c(q_1, q_2, \delta)}{\partial \delta} + \left(\frac{\beta}{1 + \beta\delta}\right)[c(q_1, q_2, \delta) + e_1(q_1)] = 0 \tag{12}$$

$$\text{and } x^* = \frac{1}{1 + \delta^*}. \tag{13}$$

Comparing equations (2)-(5) to (10)-(13), we see that the social optimum is reached when all pollution externalities are fully internalized. This is stated in the following proposition:

Proposition 4 *The socially optimal levels of design are reached when* $\tau_1^{FB} = \tau_2^{FB} = 1$.

5.2 Second-best policies

5.2.1 When one of the policy instruments is inappropriate

In some contexts, the social planner may be unable to correctly enforce one of the policy instruments. Adjusting the other emission tax $\psi = \tau_1, \tau_2$ is essential to reach a second-best outcome. The social planner will then chose ψ and the state variable x_t by maximizing the objective function (9) while taking the constrained tax level and the firm's reaction functions, equations (2)-(4), as givens. We use the following Hamiltonian:

$$\begin{aligned} H_t = \beta^t x_t \quad & \left[p(\widehat{q}_{2,t}, \widehat{\delta}_t) - c(\widehat{q}_{1,t}, \widehat{q}_{2,t}, \widehat{\delta}_t) - e_1(\widehat{q}_{1,t}) - (1 + \beta\widehat{\delta}_t)e_2(\widehat{q}_{2,t})\right] \\ & +\lambda_t(1 - \widehat{\delta}_t x_t - x_t) \qquad (t = 0, 1, ..., T)\,. \end{aligned}$$

In steady state, we have (see Appendix B.1 for details):

$$\left(-\frac{\partial c(q_1,q_2,\delta)}{\partial q_1}+1\right)\frac{d\widehat{q}_1}{d\psi}+\left((1+\beta\delta)p_e-\frac{\partial c(q_1,q_2,\delta)}{\partial q_2}+(1+\beta\delta)\right)\frac{d\widehat{q}_2}{d\psi}-$$
$$\left(\frac{\beta}{1+\beta\delta}\left(-c(q_1,q_2,\delta)-e_1(q_1)\right)+\frac{\partial c(q_1,q_2,\delta)}{\partial\delta}\right)\frac{d\widehat{\delta}}{d\psi}=0 \qquad (14)$$

<u>**Scenario** $\tau_1=\overline{\tau}_1$</u>: the government faces a political constraint on the tax on emissions during production $\tau_1=\overline{\tau}_1$ and chooses $\psi=\tau_2$. Using (14) and the firm's reaction functions (2)-(4), the optimal tax on emissions during consumption τ_2^{SB} for any given $\overline{\tau}_1$ is such that:

$$\tau_2^{SB}:\Rightarrow(1-\overline{\tau}_1)\frac{d\widehat{q}_1}{d\tau_2}+(1-\tau_2^{SB})(1+\beta\delta)\frac{d\widehat{q}_2}{d\tau_2}+(1-\overline{\tau}_1)\frac{\beta}{1+\beta\delta}\left(e_1(q_1)\right)\frac{d\widehat{\delta}}{d\tau_2}=0$$

which can be rewritten as

$$\tau_2^{SB}:\Rightarrow(1+\beta\delta)\left(1-\tau_2^{SB}\right)+(1-\overline{\tau}_1)\left(\frac{H_{12}}{H_{22}}+\frac{\beta}{1+\beta\delta}e_1(q_1)\frac{H_{23}}{H_{22}}\right)=0 \qquad (15)$$

where the relative relationships H_{12} and H_{23} also depend on the selected tax on emission during consumption τ_2^{SB}. Using equation (15)'s first derivative, comparative static tells us that

$$\begin{aligned}\operatorname{sign}\frac{d\tau_2^{SB}}{d\overline{\tau}_1} &= \operatorname{sign}\left(\beta(1-\tau_2^{SB})\frac{d\widehat{\delta}}{d\overline{\tau}_1}-\left(\frac{H_{12}}{H_{22}}+\frac{\beta}{1+\beta\delta}e_1(q_1)\frac{H_{23}}{H_{22}}\right)\right.\\ &\left.-(1-\overline{\tau}_1)\left(\left(\left(\frac{\beta}{1+\beta\delta}\right)^2e_1(q_1)\frac{d\widehat{\delta}}{d\overline{\tau}_1}+\frac{\beta}{1+\beta\delta}\frac{d\widehat{q}_1}{d\overline{\tau}_1}\right)\frac{H_{23}}{H_{22}}\right)\right)\end{aligned}$$

When evaluated at $\overline{\tau}_1=\tau_1^{FB}=1$, and knowing that $\tau_2^{SB}(\overline{\tau}_1=\tau_1^{FB})=1$, we have that

$$\operatorname{sign}\left.\frac{d\tau_2^{SB}}{d\overline{\tau}_1}\right|_{\overline{\tau}_1=1}=-\operatorname{sign}\left(H_{12}+\frac{\beta}{1+\beta\delta}e_1(q_1)H_{23}\right).$$

<u>**Scenario** $\tau_2=\overline{\tau}_2$</u>: the government faces a political constraint on the tax on emissions

during consumption $\tau_2 = \overline{\tau}_2$, and chooses $\psi = \tau_1$. Using (14) we obtain:

$$\tau_1^{SB} :\Rightarrow \left(1 - \tau_1^{SB}\right) \left(\frac{d\widehat{q}_1}{d\tau_1} + \frac{\beta}{1+\beta\delta} \left(e_1(q_1)\right) \frac{d\widehat{\delta}}{d\tau_1} \right) + \left(1 - \overline{\tau}_2\right) \left(1 + \beta\delta\right) \frac{d\widehat{q}_2}{d\tau_1} = 0 \qquad (16)$$

and we have that

$$\operatorname{sign} \left. \frac{d\tau_1^{SB}}{d\overline{\tau}_2} \right|_{\overline{\tau}_2 = 1} = -\operatorname{sign} \left(H_{12} + \frac{\beta}{1+\beta\delta} e_1(q_1) H_{23} \right).$$

Proposition 5 *When the tax on emissions during production (consumption) is fixed, $\tau_1 = \overline{\tau}_1$ ($\tau_2 = \overline{\tau}_2$), the policy maker can reach a second-best outcome with $\tau_2 = \tau_2^{SB}$ ($\tau_1 = \tau_1^{SB}$). When $\overline{\tau}_1$ ($\overline{\tau}_2$) deviates from the first best policy, we have that*

$$\begin{aligned} \mathit{sign}\ (\tau_2^{SB} - \tau_2^{FB}) &= \mathit{sign}\ (1 - \overline{\tau}_1) \left(H_{12} + \frac{\beta}{1+\beta\delta} e_1(q_1) H_{23} \right) \\ & \quad \mathit{and} \\ \mathit{sign}\ (\tau_1^{SB} - \tau_1^{FB}) &= \mathit{sign}\ (1 - \overline{\tau}_2) \left(H_{12} + \frac{\beta}{1+\beta\delta} e_1(q_1) H_{23} \right), \\ & \quad \mathit{respectively.} \end{aligned}$$

Proposition 5 can be interpreted in the following way. The second-best tax on emissions during consumption τ_2^{SB} will depend on the ratio of relative relationships weighted by the marginal environmental impacts. It also depends on how is the constrained tax level $\overline{\tau}_1$ compare to the first-best level $\tau_1^{FB} = 1$. If $\overline{\tau}_1$ is too low (*i.e.*, $\overline{\tau}_1 < 1$), and if dimensions are relatively complementary ($H_{12} > 0$ and $H_{23} > 0$), then the policy maker will choose $\tau_2^{SB} > \tau_2^{FB}$ as an increase in quality during consumption q_2 will stimulate better quality during production q_1 and longer durability δ. Conversely for competitive relationships, the first-best level of tax on emissions during consumption τ_2^{FB} would be too large both because it would discourage investment in the other design dimensions, and because a lower q_1 already stimulates q_2. If $\overline{\tau}_1$ is too large (*i.e.*, $\overline{\tau}_1 > 1$), we observe the opposite effects.

5.2.2 When the government also regulates the level of durability

Using $\frac{\partial f_2}{\partial q_2}\frac{d\widehat{q}_2}{d\tau_1} = -\frac{\partial f_2}{\partial q_1}\frac{d\widehat{q}_1}{d\tau_1} - \frac{\partial f_2}{\partial \delta}\frac{df_\delta}{d\tau_1}$, we can reorganize equation (14):

$$\underbrace{\left((1-\tau_1) - (1-\overline{\tau}_2)\,(1+\beta\delta)\,\frac{\partial f_2/\partial q_1}{\partial f_2/\partial q_2}\right)}_{A} + \tag{17}$$

$$\underbrace{\left((1-\tau_1)\frac{\beta}{1+\beta\delta}\,(e_1(q_1)) - (1-\overline{\tau}_2)\,(1+\beta\delta)\,\frac{\partial f_2/\partial \delta}{\partial f_2/\partial q_2}\right)}_{B}\underbrace{\frac{d\widehat{\delta}/d\tau_1}{d\widehat{q}_1/d\tau_1}}_{C} = 0$$

When externalities are fully internalized ($\tau_1 = \tau_2 = 1$), the instrument τ_1 brings the appropriate incentive for both quality during production q_1 and durability δ. When τ_2 is inappropriate, however, τ_1 becomes insufficient to account for all indirect impacts. Equation (17) shows how the use of a second policy instrument would allow to aim for variations in q_1 and δ more precisely (terms A and B, respectively). When available, the government could reach a second-best outcome by choosing τ_1 as a targeted tax for q_1 and by regulating durability δ.[10] In that case, the Hamiltonian is:

$$\begin{aligned} H_t = \beta^t x_t \quad & [p(\widehat{q}_{2,t}, \delta_t) - c(\widehat{q}_{1,t}, \widehat{q}_{2,t}, \delta_t) - e_1(\widehat{q}_{1,t}) - (1+\beta\delta_t)e_2(\widehat{q}_{2,t})] \\ & + \lambda_t(1-\delta_t x_t - x_t) \qquad (t = 0, 1, ..., T)\,. \end{aligned}$$

and the social planner chooses τ_1, δ_t and the state variable x_t (see Appendix B.2 for details).

[10] The law on planned obsolescence (France, 2015) is a recent example of a regulation for δ.

In steady state, we obtain:

$$\tau_1^{SB2} = 1 - (1 - \overline{\tau}_2)\left(1 + \beta\delta^{SB2}\right)\frac{\partial f_2/\partial q_1}{\partial f_2/\partial q_2} = 1 - (1 - \overline{\tau}_2)\left(1 + \beta\delta^{SB2}\right)\frac{h_{12}}{h_{22}} \tag{18}$$

$$\begin{aligned}\delta^{SB2} :\Rightarrow\ & \frac{\beta}{1+\beta\delta}\left(c(q_1, q_2, \delta^{SB2}) + e_1(q_1)\right) - \frac{\partial c(q_1, q_2, \delta^{SB2})}{\partial \delta} + \\ & (1 - \tau_1^{SB2})\frac{d\widehat{q}_1}{d\delta} + (1 + \beta\delta^{SB2})(1 - \overline{\tau}_2)\frac{d\widehat{q}_2}{d\delta} = 0 \qquad (19)\\ = & \frac{\beta}{1+\beta\delta}\left(c(q_1, q_2, \delta^{SB2}) + e_1(q_1)\right) - \frac{\partial c(q_1, q_2, \delta^{SB2})}{\partial \delta} + \\ & (1 - \tau_1^{SB2})\frac{H_{13}}{H_{33}} + (1 + \beta\delta^{SB2})(1 - \overline{\tau}_2)\frac{H_{23}}{H_{33}} = 0\end{aligned}$$

And we have that

$$\begin{aligned}\left.\frac{d\tau_1^{SB2}}{d\overline{\tau}_2}\right|_{\overline{\tau}_2=1} &= \left(1 + \beta\delta^{SB2}\right)\frac{h_{12}}{h_{22}} \\ \text{sign}\left.\frac{d\delta^{SB2}}{d\overline{\tau}_2}\right|_{\overline{\tau}_2=1} &= \text{sign}\left(\left(1 + \beta\delta^{SB2}\right)H_{23} - \beta h_{11}\frac{\partial c(q_1, q_2, \delta^{SB2})}{\partial q_2}\right)\end{aligned} \tag{20}$$

Proposition 6 *When the tax on emissions during consumption is fixed, $\tau_2 = \overline{\tau}_2$, the policy maker can reach a second-best outcome with the policy mix $(\tau_1^{SB2}, \delta^{SB2})$. When $\overline{\tau}_2$ deviates from the first best policy, we have that*

$$\begin{aligned}sign\ (\tau_1^{SB2} - \tau_1^{FB}) &= sign\ (1 - \overline{\tau}_2)h_{12} \quad \text{and} \\ sign\ (\delta^{SB2} - \delta^{FB}) &= -sign\ (1 - \overline{\tau}_2)\left(\left(1 + \beta\delta^{SB2}\right)H_{23} - \beta h_{11}\frac{\partial c(q_1, q_2, \delta^{SB2})}{\partial q_2}\right).\end{aligned}$$

5.2.3 When durability δ is ignored

Suppose that the policy maker has only partial information on product design and ignores the possibility, for the firm, to adjust some of the design dimensions. To illustrate this, assume that the government sets its policies while taking durability δ as fixed.

First-best scenario: both tax instruments are available. The policy maker uses the optimality conditions for q_1 and q_2 (10) and (11), takes into account the firm's responses (2) and (3), but ignores the choice of durability (4). The government sets $\tau_1 = \tau_2 = \tau_1^{FB} = \tau_2^{FB}$, and obtains the first-best outcome. When all externalities are internalized, incentives are in place for the optimal choice of durability as well.

Scenario $\tau_2 = \overline{\tau}_2$: the social planner uses the second-best strategy described by equation (18) and sets $\widetilde{\tau}_1^{SB}$. Then the firm chooses the level of durability $\widetilde{\delta}^{SB}$ according to equation (4): $\widetilde{\delta}^{SB} = \widehat{\delta}(\widetilde{\tau}_1^{SB})$.

We have that

$$\widetilde{\tau}_1^{SB} = 1 - (1 - \overline{\tau}_2)\left(1 + \beta\widetilde{\delta}^{SB}\right)\frac{\partial f_2/\partial q_1}{\partial f_2/\partial q_2} = 1 - (1 - \overline{\tau}_2)\left(1 + \beta\widetilde{\delta}^{SB}\right)\frac{h_{12}}{h_{22}} \tag{21}$$

$$\widetilde{\delta}^{SB} :\Rightarrow \left(\frac{\beta}{1 + \beta\widetilde{\delta}^{SB}}\right)\left[c(q_1, q_2, \widetilde{\delta}^{SB}) + \widetilde{\tau}_1^{SB} e_1(q_1)\right] - \frac{\partial c(q_1, q_2, \widetilde{\delta}^{SB})}{\partial \delta} = 0 \tag{22}$$

and, using $H_{22} = h_{11}h_{33} - h_{13}^2$,

$$\begin{aligned}
\left.\frac{d\widetilde{\tau}_1^{SB}}{d\overline{\tau}_2}\right|_{\overline{\tau}_2=1} &= \left(1 + \beta\widetilde{\delta}^{SB}\right)\frac{h_{12}}{h_{22}} \\
\operatorname{sign}\left.\frac{d\widetilde{\delta}^{SB}}{d\overline{\tau}_2}\right|_{\overline{\tau}_2=1} &= \operatorname{sign}\left(-h_{33}\left(1 + \beta\widetilde{\delta}^{SB}\right)H_{23} + \beta H_{22}\frac{\partial c(q_1, q_2, \widetilde{\delta}^{SB})}{\partial q_2}\right) \\
&= \operatorname{sign}\left(\left(1 + \beta\widetilde{\delta}^{SB}\right)H_{23} - \beta h_{11}\frac{\partial c(q_1, q_2, \widetilde{\delta}^{SB})}{\partial q_2} + \beta\frac{h_{13}^2}{h_{33}}\frac{\partial c(q_1, q_2, \widetilde{\delta}^{SB})}{\partial q_2}\right).
\end{aligned} \tag{23}$$

When comparing the equilibrium conditions (18), (19), and (21), (22), we see that if the tax on emissions during consumption is constrained to the first best value $\overline{\tau}_2 = \tau_2^{FB} = 1$, the selected tax on emission during production will also be optimal whether or not the government regulates the level of durability $\tau_1^{SB2} = \widetilde{\tau}_1^{SB} = \tau_1^{FB} = 1$. This results in the first best level of durability $\delta^{SB2} = \widetilde{\delta}^{SB} = \delta^*$. Equations (20) and (23) describes what occurs when the tax on emissions during consumption deviates from the first best value. This leads to the following result:

Proposition 7 *When evaluated at the first best values, if* $\left(\frac{\beta}{1+\beta\delta}\right)\frac{\partial c(q_1,q_2,\delta)}{\partial q_2}\left(\frac{h_{13}^2}{h_{33}}-h_{11}\right) \leq -H_{23} \leq \left(\frac{\beta}{1+\beta\delta}\right)\frac{\partial c(q_1,q_2,\delta)}{\partial q_2}(-h_{11})$*, we have*

$$sign\left.\frac{d\widetilde{\delta}^{SB}}{d\overline{\tau}_2}\right|_{\overline{\tau}_2=1} < 0 \text{ and } sign\left.\frac{d\delta^{SB2}}{d\overline{\tau}_2}\right|_{\overline{\tau}_2=1} > 0$$

in which case, if the tax on emissions during consumption becomes inappropriately low, $\overline{\tau}_2 < 1$*, the social planner would want to regulate and constraint durability:* $\delta^{SB2} < \widetilde{\delta}^{SB}$*.*

Proposition 7 describes the importance of taking into account all design dimensions as soon as one of the pollution externalities is not internalized appropriately. Because of the relative competitiveness between q_2 and δ ($H_{23} < 0$), too little tax on emissions during consumption makes δ more attractive. When the government selects the level of durability, the firm takes durability as given when choosing the other dimensions. When the firm is free to choose the level of durability, it considers all the indirect impacts. Under given circumstances, the firm would choose a level of durability too high compare to the second-best optimum.

6 Conclusion

This paper explores the interplay between a set of product design attributes and environmental policies.

In the model, a monopolist chooses the levels of three design dimensions (environmental quality during production, environmental quality during consumption, and durability) while taking the taxes on emissions during production and during consumption as givens. Also, incentives for green design emerge from the market because consumers are willing to pay more for goods that are more durable and more economical in terms of energy consumption. The main assumption is that the cross relationships between design dimensions are complementary, neutral, or competitive.

The impact of changes in tax policies was examined. When all design dimensions are complementary or neutral, tax increases always spur greener design and reduce emissions. However, when some design dimensions are competitive, the adverse effects may occur when a more stringent environmental tax induces the production of more polluting goods.

The social optimal taxation level implies a uniform tax on emissions during both production and consumption. Any deviation from the optimal tax levels can impact all three dimensions, with adverse environmental consequences. Second-best policies must take into account crossed effects.

To conclude, targeted environmental policies should take into account firms' responses in terms of product design, especially when design dimensions show competitive cross relationships.

A Simulations

We build an economy where we define the following functional forms for the unit production cost and pollution emissions:

$$\begin{aligned} c(q_1, q_2, \delta; \tau_1, \tau_2) &= \frac{aq_1^2}{2} + \frac{dq_2^2}{2} + \frac{i\delta^2}{2} + bq_1q_2 + cq_1\delta + fq_2\delta \\ e_i(q_i) &= z_i - q_i \text{ for } i = 1, 2 \end{aligned}$$

where the signs of b, c and f denote the cost cross relationship between the dimensions. The Hessian matrix becomes:

$$\boldsymbol{\mathcal{H}} = \begin{bmatrix} -c_{q_1q_1} & -c_{q_1q_2} & -c_{q_1\delta} \\ -c_{q_1q_2} & -c_{q_2q_2} & \beta\left(p_e+\tau_2\right) - c_{q_2\delta} \\ -c_{q_1\delta} & \beta\left(p_e+\tau_2\right) - c_{q_2\delta} & -c_{\delta\delta} \end{bmatrix} =$$

$$\begin{bmatrix} h_{11}<0 & h_{12} & h_{13} \\ h_{12} & h_{22}<0 & h_{23} \\ h_{13} & h_{23} & h_{33}<0 \end{bmatrix} = \begin{bmatrix} -a & -b & -c \\ -b & -d & \beta\left(p_e+\tau_2\right) - f \\ -c & \beta\left(p_e+\tau_2\right) - f & -i \end{bmatrix}$$

Note that optimality conditions for the choice of design, equations (2) to (4) can be rewritten as:

$$\begin{aligned} \widehat{q}_1(\delta;\tau_1,\tau_2) &= \frac{1}{H_{33}}\left[d\tau_1 - b(p_e+\tau_2) + H_{13}\delta\right] \\ \widehat{q}_2(\delta;\tau_1,\tau_2) &= \frac{1}{H_{33}}\left[a(p_e+\tau_2) - b\tau_1 + H_{23}\delta\right] \\ \widehat{\delta}(q_1,q_2,\delta;\tau_1,\tau_2) &\Rightarrow \beta\left(\frac{aq_1^2}{2}+\frac{dq_2^2}{2}-\frac{i\delta^2}{2}+bq_1q_2+\tau_1(z_1-q_1)\right) - (i\delta + cq_1 + fq_2) = 0 \end{aligned}$$

which highlight the role of H_{13} and H_{23} in influencing the impact of δ on q_1 and q_2, respectively.

We assign the parameters the following values:

$$a = 5; d = i = 6;\ b = -1; f = -.5;\ \text{and } c = 4.5$$

which means that environmental quality during consumption q_2 is complementary with both quality during production q_1 and durability δ, whereas quality during production q_1 and durability δ are competitive. Other parameters take the values:

$$\beta = .97;\ p_e = 2.4; z_1 = 1.8; z_2 = 2.5 \text{ and } \tau_2 = 1.$$

We obtain interior solutions for $\tau_1 \in [8.3, 9]$. The Hessian matrix is negative definite. In the range of interior solutions, an increase in the targeted tax τ_1 favors q_1 and brings a simultaneous reduction in q_2 and δ. The overall result is that for lower values of τ_1, i.e., for $\tau_1 \in [8.3, 8.7]$, a tax increase increases the level of emission per functional unit D_f. This is illustrated in Figure 1.

Figure 2 shows the results using the following set of parameters:

$$\begin{aligned} a &= 1,730; d = 6.69; i = .10;\ b = -8; f = 3.30;\ \text{and } c = 9.49 \\ \beta &= .97;\ p_e = 2.4; z_1 = 1.8; z_2 = 2.5 \text{ and } \tau_2 = 1, \end{aligned}$$

which assume that environmental quality during consumption q_2 is complementary with quality during production q_1, and that the other cross relationships are competitive. We see that an increase in the targeted tax on pollution during production τ_1 makes products design more polluting during the production stage, *i.e.*, q_1 decreases.

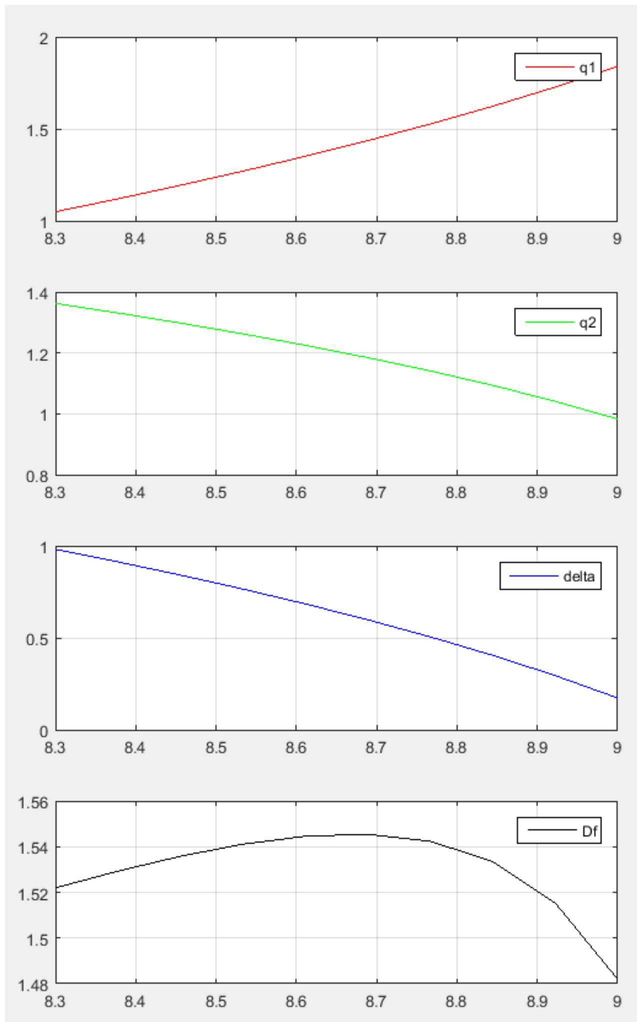

Figure 1: Variation in the three design dimensions q_1, q_2 and δ; and the emissions per unit of functionality D_f with respect to τ_1.

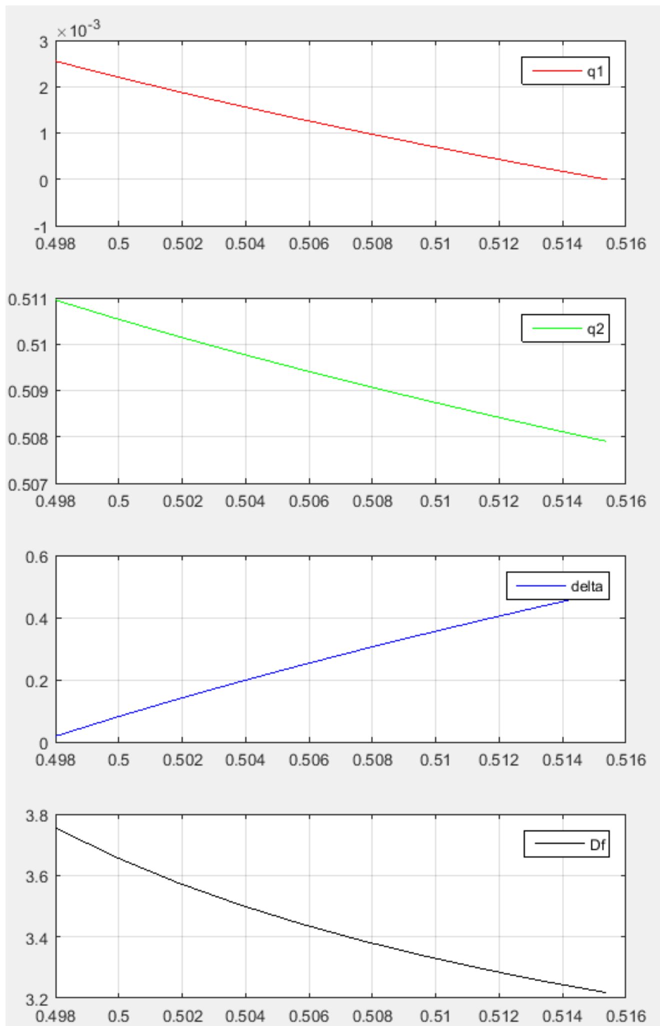

Figure 2: Variation in the three design dimensions q_1, q_2 and δ; and the emission per unit of functionality D_f with respect to τ_1.

B Second-best policies

B.1 When one of the policy instruments is inappropriate

The optimality conditions are (for $t = 1, ..., T$):

$$\frac{\partial H_t}{\partial \psi_t} = 0 \Leftrightarrow \beta^t x_t \left[\left(-\frac{\partial c(q_{1,t}, q_{2,t}, \delta_t)}{\partial q_{1,t}} + 1 \right) \frac{d\widehat{q}_{1,t}}{d\psi_t} + \right.$$
$$\left((1+\beta\delta_t)p_e - \frac{\partial c(q_{1,t}, q_{2,t}, \delta_t)}{\partial q_{2,t}} + (1+\beta\delta_t) \right) \frac{d\widehat{q}_{2,t}}{d\psi_t} +$$
$$\left. \left(\beta(\alpha - p_e e_2(q_{2,t})) - \frac{\partial c(q_{1,t}, q_{2,t}, \delta_t)}{\partial \delta_t} - \beta e_2(q_{2,t}) \right) \frac{d\widehat{\delta}_t}{d\psi_t} \right] - \lambda_t x_t \frac{d\widehat{\delta}_t}{d\psi_t} = 0$$

$$\frac{\partial H_t}{\partial x_t} = \lambda_{t-1} - \lambda_t \Leftrightarrow \beta^t \left[p(q_{2,t}, \delta_t) - c(q_{1,t}, q_{2,t}, \delta_t) - e_1(q_{1,t}) - (1+\beta\delta_t)e_2(q_{2,t}) \right]$$
$$- \lambda_t \delta_t - \lambda_{t-1} = 0$$

$$\frac{\partial H_t}{\partial \lambda_t} = x_{t+1} - x_t \quad t = 0, 1, ..., T-1.$$

B.2 Scenario $\tau_2 = \overline{\tau}_2$

When $\tau_2 = \overline{\tau}_2$ and the government chooses τ_1, δ_t, the firm must take durability as given and equation (4) is no longer applicable. The Hessian matrix (6) becomes $\boldsymbol{\mathcal{H}} = \begin{bmatrix} -c_{q_1 q_1} & -c_{q_1 q_2} \\ -c_{q_1 q_2} & -c_{q_2 q_2} \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{12} & h_{22} \end{bmatrix}$ and the full impact of a change in a parameter (7) is

$$\begin{bmatrix} d\widehat{q}_1/d\phi \\ d\widehat{q}_2/d\phi \end{bmatrix} = -\boldsymbol{\mathcal{H}}^{-1} \begin{bmatrix} \partial f_1/\partial\phi \\ \partial f_2/\partial\phi \end{bmatrix} = \frac{-1}{\det \boldsymbol{\mathcal{H}}} \begin{bmatrix} h_{22} & -h_{12} \\ -h_{12} & h_{11} \end{bmatrix} \begin{bmatrix} \partial f_1/\partial\phi \\ \partial f_2/\partial\phi \end{bmatrix}$$

and $\det \boldsymbol{\mathcal{H}} = h_{11}h_{22} - h_{12}^2 = H_{33} > 0$.

The optimality conditions are (for $t = 1, ..., T$):

$$\frac{\partial H_t}{\partial \tau_1} = 0 \Leftrightarrow \left(-\frac{\partial c(q_{1,t}, q_{2,t}, \delta_t)}{\partial q_{1,t}} + 1\right) \frac{d\widehat{q}_{1,t}}{d\tau_1} + \left((1+\beta\delta)p_e - \frac{\partial c(q_{1,t}, q_{2,t}, \delta_t)}{\partial q_{2,t}} + (1+\beta\delta_t)\right) \frac{d\widehat{q}_{2,t}}{d\tau_1} = 0$$

$$\frac{\partial H_t}{\partial \delta_t} = \beta^t x_t \left[\left(\beta(\alpha - p_e e_2(q_{2,t})) - \frac{\partial c(q_{1,t}, q_{2,t}, \delta_t)}{\partial \delta_t} - \beta e_2(q_{2,t})\right)\right] - \lambda_t x_t + \frac{\partial H_t}{\partial q_{1,t}} \frac{d\widehat{q}_{1,t}}{d\delta_t} + \frac{\partial H_t}{\partial q_{2,t}} \frac{d\widehat{q}_{2,t}}{d\delta_t} = 0$$

$$\frac{\partial H_t}{\partial x_t} = \lambda_{t-1} - \lambda_t \Leftrightarrow \beta^t \left[p(q_{2,t}, \delta_t) - c(q_{1,t}, q_{2,t}, \delta_t) - e_1(q_{1,t}) - (1+\beta\delta_t)e_2(q_{2,t})\right] - \lambda_t \delta - \lambda_{t-1} = 0$$

$$\frac{\partial H_t}{\partial \lambda_t} = x_{t+1} - x_t \quad t = 0, 1, ..., T-1.$$

and we use the following properties:

$$\begin{aligned}
\frac{\partial f_1}{\partial \delta} &= -c_{q_1\delta} = h_{13} \\
\frac{\partial f_2}{\partial \delta} &= \beta(p_e + \tau_2) - c_{q_2\delta} = h_{23} \\
\frac{d\widehat{q}_1}{d\delta} &= \frac{-1}{\det \boldsymbol{\mathcal{H}}}(h_{22}h_{13} - h_{12}h_{23}) = \frac{H_{13}}{H_{33}} \\
\frac{d\widehat{q}_2}{d\delta} &= \frac{-1}{\det \boldsymbol{\mathcal{H}}}(-h_{12}h_{13} + h_{11}h_{23}) = \frac{H_{23}}{H_{33}}
\end{aligned}$$

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