British Journal of Economics, Management & Trade
15(1): 1-18, 2016, Article no.BJEMT.28689
ISSN: 2278-098X

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Institutional Reforms, FDI and Pollution Tax

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Authors' contributions

This work was carried out in collaboration between all authors. Author SSB handled the data and results presented in this paper. Authors LPZ and PCA made contributions in the methodology and prepared the final draft of the manuscript. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/BJEMT/2016/28689
Editor(s):
(1) Chen Zhan-Ming, School of Economics, Renmin University of China, Beijing, China.
Reviewers:
(1) António Bento Caleiro, University of Evora, Portugal.
(2) Burçak Polat, Nuh Naci Yazgan University, Turkey.
Complete Peer review History: http://www.sciencedomain.org/review-history/16096

Original Research Article

Received 30th July 2016
Accepted 2nd September 2016
Published 8th September 2016

ABSTRACT

This study develops a theoretical model of institutional economics and corruption in order to determine the optimum institutional level that would allow the government to achieve economic equilibrium in the country, under an oligopolistic scheme of Foreign Direct Investment (FDI). In parallel, this study calculates the optimum pollution tax, from the value of which is deduced a series of strategic environmental policies that aim to maximize welfare in the FDI host country, and to involve consumers, producers, and government, as well as dishonest public sector workers.

Keywords: Environmental policies; FDI; institutional level; pollution tax.

1. INTRODUCTION

An area of the utmost importance in economics is institutional economics, in that the establishment of viable and rational economic policy is fundamental for any social organization. Thus, the proposal of institutional economics is the study of the interactive norms and policies that govern relationships among economic agents. Said agreements and conventions are

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denominated by institutions, whose function it is to regulate and orient the behavior of those undertaking transactions in the market.[1]

In accordance with economic, social, political and cultural considerations, the literature on institutional economics can be grouped under two main headings. Firstly, there is that which refers to developed countries, on which there is an abundance of papers. These studies assume that the countries in question have solid institutions, further to a reliable legal framework and well established institutional policies that guarantee the efficient development of economic activities.[2]

On the other hand, there is a generalized perception that, in the case of developing countries, such as Mexico and other Latin American countries, their legal framework, institutions and property rights do not function in the most efficient manner, meaning that commercial interactions are seriously affected.[3] For example, corruption is widely generalized, with practices such as bribery frequently used to accelerate and simplify administrative, tax and commercial procedures.

In this sense, this study develops a model of institutional economics that considers the corruption found, in certain measure, in both commercial transactions and FDI, which is a permanent and substantial source of income for the economies of developing countries. Secondly, the model also considers the environmental factor, in that questions such as sustainability and the preservation of the natural environment through the control of pollution must be addressed in order for countries to grow.[4] The above factors must be studied on an integrated basis, in that, on the one hand, the entry into and permanence of foreign capital in developing countries must be encouraged in order to promote their economic development, while, on the other, the long-term preservation of a healthy environment and sustainable growth are also necessary.

In the literature, there are numerous studies on FDI [5], which demonstrate that it does not guarantee, *a priori*, development in developing countries. Furthermore, FDI must be complemented by policies that promote internal investment and support national industry in order to avoid an excessive and fragile dependency on foreign capital that does not necessarily translate into improved quality of life for the general population. For this reason, FDI must be implemented along with adequate institutional reforms that guarantee welfare in the FDI host country. In the last 20 years, the flow of FDI has become considerably accentuated owing to a marked and sustained tendency toward the global opening of markets, for which reason, governments have been applying different economic policies, from protectionist practices for industry and local markets to the total opening of markets to foreign capital.[6] Ideally FDI should be a complement to local investment, through integrated policies such as the introduction of new products, the opening of bilateral channels of commercialization with world markets, the innovation in and improvement of commercial techniques, and continuous human resources training, among others. On the other hand, it is an unquestionable fact that developing countries significantly contribute to the reception of FDI.[7]

In terms of the environmental factor, the majority of the extant literature focuses on the attractive pollution haven hypothesis, according to which

[1] A detailed review of the literature on institutional economics can be found in [1].

[2] For example, [2,3,4] could be cited.

[3] According to [5], Mexico is positioned above the average level of corruption found in other Latin American countries.

[4] In this way, according to [6], the ever more intensive use of natural resources in productive processes leads to greater levels of pollution (owing, principally, to the emission of large quantities of CO_2 into the atmosphere), whose effects are ever more devastating and costly. Thus, the adverse consequences are manifested, in terms of both human health, with the increased incidence of respiratory, intestinal and hearing conditions, and the environment, through the accelerated increase in global warming and the greenhouse effect. These environmental factors in turn increase the incidence and intensity of storms, hurricanes, tornados, droughts, frosts and fires, and lead, furthermore, to the alteration of certain ecosystems and the possible extinction of species. On the other hand, governments are cautious to apply extreme measures to reduce pollution, in that said policies can considerably increase industrial costs and considerably reduce companies' international competitiveness [7]. Thus, controlling pollution can become a commercial barrier and, as such, is subject to passionate debate in global free trade forums.

[5] For example, [8, 9] among others.

[6] Thus, for example, in 1995, the global flow of FDI was 341,137 million dollars, while, in 2005, this had increased to 927,402 million dollars, reaching a historic high of 1,871,702 million dollars in 2007, and then stabilizing in 2014 at 1,228,283 million dollars [10].

[7] Developing countries have progressed considerably in attracting and receiving FDI. In 1995, these countries received 117,767 million dollars, which represents 34% of global FDI wealth, while, in 2010, the same countries received 579,861 million dollars, which represents 44% of global FDI wealth. In 2014, these countries received 681,000 million dollars which represent 55% of global FDI flow [10].

multinational companies preferentially select, as the destination for their investment, countries with less strict environmental controls, which translates into the reduction of production costs [11]. Thus, countries with lax pollution controls will specialize in dirty technologies, while those with the strictest controls specialize in clean technologies, a situation which concurs with the theory of comparative advantage and Heckscher-Ohlin's theory on international trade, which considers the environment as a space in which pollution can be considered either an abundant or scarce good. The existence of pollution havens is very debatable with, on the one hand, no conclusive evidence existing that multinational companies prefer to invest and install themselves in countries which permit high levels of pollution. On the other hand, some studies suggest that multinational companies contribute to improving the environment in FDI receptor countries, in that the technology employed by these countries is, in general, superior to the often obsolete technology found in local countries. In any case, there is insufficient empirical evidence to either support or reject the pollution haven hypothesis. In any case, while the implementation of precise and strategic environmental policies that enable the entry of companies under an FDI scheme is recommendable, at the same time these must contribute to the conservation of the environment through the control and reduction of the pollution these companies emit.

The instrument for controlling polluting emissions that will be used in this study is pollution tax. The basic supposition of the pollution tax is "he who pollutes pays", in which case the government taxes companies for each unit of pollution emitted, a tax calculation based on an optimal level of pollution [12]. Thus, if emitting pollutants becomes expensive for the company, it will pollute less. The tax is the environmental policy that adjusts more to the principle of economic efficiency, in that it is taken from the principle that the polluter must pay for the damage caused, and indirectly attends to a related principle affirming that companies that pollute must assume the costs of reducing said pollution. Establishing an optimal tax for the emission of pollution supposes a detailed knowledge of the company's cost structure and of the potential damages to both the environment and the people. This means that both public and private information are involved, in that, on calculating, in theory, the optimum tax, there is an asymmetry of information between the polluter and the regulating authority, which is inconvenient from an economic perspective in terms of governmental intervention [13]. Even so, it is a tool that tends to be very efficient, in that it stimulates the reduction of pollution irrespective of the level emitted by the companies. Moreover, as a tax paid to the government, it is passed, ultimately, to public investment – at least in theory.

Thus, this study develops a partial equilibrium model for institutional and environmental economics, which determines the optimal institutional level that the government must implement, as well as the optimal pollution tax for companies entering the country via FDI, in order to maximize welfare in the FDI host country.[8] This model is applicable in developing countries, particularly in Mexico and some other Latin American countries, where the institutional level does not reach the levels of developed countries and where practices such as corruption and bribery are well established.[9]

The model proposed shows that, for FDI to maximize welfare in a host country, a series of punctual institutional and environmental policies must be implemented. Such policies will depend to a lesser or greater degree, on the level of governmental corruption, the pollution abatement cost, the social costs of pollution, as well as the size of the market for the good in question.

It can be concluded from the model that, if the illegal cost is lower than the legal cost, the typical case for a developing country with a high level of corruption would demand that the government impose a minimal institutional level, while for a low level of corruption, the government must impose a high institutional level. The model also proposes that, if the social costs of pollution are high, the government must establish strict controls for companies to reduce their emissions, which implies the imposition of high pollution taxes. However, when the social costs of pollution are not so high compared to the abatement cost, the government could permit certain pollution levels, or, in the absence of this, exempt companies from the applicable pollution tax.

The previous results emphasize the implementation of strategic institutional and environmental policies in countries with lax

[8] For more details on pollution tax, see [14].

[9] See [5], in which the level of corruption in the majority of Latin American countries is higher compared to developed countries.

institutional levels, such as developing countries which favor the entry of companies via FDI, and, at the same time, effectively control the emission of polluting particles for the preservation of the environment and, thus, achieve sustainable economic development.

The structure of the paper begins with the specification and delimitation of the model (Section 2). Secondly, the optimal institutional level and the optimal pollution tax are calculated, from which applicable institutional and environmental policies are deduced (Section 3). Lastly, the conclusions of this study are established in Section 4.

2. SPECIFICATION OF THE MODEL

There is a determined number of *n* foreign firms that are established in the host country.[10] These firms manufacture *X* amount of a certain good, which is consumed in totality by the FDI host country. It is assumed, furthermore, that while these companies do not have competition from local companies, they compete among themselves, under a Cournot oligopolistic scheme.[11] The marginal cost of production for each foreign business is C, which is constant and, therefore, equal to the average variable costs.[12] Furthermore, for simplicity, it can be assumed that the demand is linear, therefore,

$$p = a - bD = a - bnX \quad (1)$$

where *a* and *b* are positive constants, and the total demand is represented by *nX*.[13]

The utility for each of the *n* firms is given by,

$$\pi = (p - C)X \quad (2)$$

and, under the Cournot-Nash assumptions, the optimal quantity of a good manufactured by each FDI company is,[14]

$$X = \frac{a-C}{b(n+1)} \quad (3)$$

thus, the utility of each of the firms can be expressed as,[15]

$$\pi = bX^2 \quad (4)$$

The marginal cost per unit produced comprises three components,

$$C = c + v + \Delta \quad (5)$$

where *c* is the technological cost determined by market conditions, *v* is the cost of reducing the level of pollution per unit manufactured, and *Δ* is the unit tax cost that the company must cover for operational reasons, which depend on the institutional level of the host country.

Now,

$$v = \lambda(\theta - z) + tz \quad (6)$$

where λ is the marginal cost of abating one unit of pollution (abatement cost).[16] *θ* represents the amount of pollution emitted prior to implementing the environmental policy, with *z* being the amount of self-imposed pollution per unit produced, and *t* is the tax levied on the company per unit of pollution emitted, in such a way that,

$$z = \begin{cases} 0 & si \quad t \geq \lambda \\ \theta & si \quad t < \lambda \end{cases} \quad (7)$$

which is to say that, if the tax per unit of pollution emitted is greater than the abatement cost, the company prefers not to emit the unit of pollution. In the case of the opposite, the company will opt to emit the unit of pollution.

The model supposes that companies must pay a levy to the government, denoted by *Δ*; however, there are dishonest public servants disposed to receiving a bribe in return for eliminating or

[10] *The model proposed in this study is based on [15], which calculates the optimal institutional level with FDI, without including environmental variables. The model developed in this study is similar to [16], which uses pollution quotas instead of pollution taxes.*

[11] *That companies in the host country do not produce the good exemplifies, in good measure, the prevailing situation in many developing countries in terms of the production of some goods.*

[12] *The existence of a nummeraire good that is produced in perfect competition and for which there is only one factor of production whose price is determined by competitive market conditions can be considered as implicit.*

[13] *Consumer preferences in the FDI host country can be estimated through the function of utility,* $U = anX - \frac{bn^2X^2}{2} - \mu$, *in which X is the quantity of the good, and μ is the amount spent on the nummeraire good. Thus, maximizing U obtains a function of linear demand. At the same time, the use of such an estimate avoids some theoretical difficulties, such as the income effect.*

[14] *Please see appendix 1*

[15] *Please also see appendix 1*

[16] *The abatement cost depends on the technology available to the companies, with said cost including referents for measures for the continuous improvement of processes, recycling, the commercialization of waste, and the use of modern machinery, among others [14].*

reducing the tax expenditure for these firms. Thus, the total bribes must be added to the ordinary fiscal payments that companies must make to the government.

The model presupposes the existence of two types of people – the honest people who work in private firms and the dishonest people employed in the public sector. Such a hypothesis is intuitively founded on the strongly generalized opinion that people who work in the public sector are, to a greater or lesser degree, more dishonest than those working for private companies. However, it is undeniable that there are honest people working in the government. Similarly, it is often believed that the employees of private firms have higher levels of honesty than public sector workers, despite the fact that personal dishonesty also exists in private firms.[17] For reasons of the simplicity of the model, net dishonesty and honesty values for public and private employees, respectively, are considered.

However, employees at private firms receive a transfer given by the government, equal to the amount paid legally in tax by companies. The dishonest, for their part, receive an income through the bribes paid by private firms.[18] In this way, the government is able to regulate the quantities received, both from the legal and illegal structure, through the denominated institutional level, that involves, to a lesser or greater degree, the corruption of public service workers.

However, dishonest public servants can also lobby the government to achieve relaxed institutional policies, in order to obtain higher incomes through bribes from companies. Thus, this lobbying process will depend on the degree of governmental corruption, and will be determined by the disposition of the government to receive, in certain measure, the contributions of the dishonest. This lobbying occurs for obvious reasons in that it is, ultimately, the government that establishes the institutional level in the FDI host country. This study is based on the "political contributions" model.[19] Such a scheme assumes that those undertaking lobbying politically support the established party of government, and that said contributions are contingent on its political decisions.[20] The model developed here is based on the original work of [17] that, due to being a partial equilibrium model, assumes quasilinear preferences.

According to the above, it is possible to divide the tax cost into two components, the legal and the illegal. The first is paid by companies through the legal structure that depends on the government (the legal route), while the second is covered by an alternative structure (the illegal route). Both the legal cost paid to the government and the illegal cost paid to dishonest public sector workers depend on the institutional level (which includes the legal and institutional framework), which the government determines in order to regulate the economic transactions and political activities in the host country.

Consequently, given the high institutional level, the government is able to rigorously and efficiently control illegal practices. However, if the institutional level is weak, regulation is often lax and inefficient, which favors the proliferation of illegal activities. Thus, the government of the host country determines the institutional level through legal and institutional reforms with the objective of maximizing social welfare. Finally, given that these reforms are legal and institutional, both in their formulation and their implementation, they do not implicitly generate costs.

The government sets the institutional level, α, within the range of $0 \leq \alpha \leq 1$, with 0 corresponding to a null institutional or completely inefficient

[17] More information related to this matter can be found in [5].

[18] If the income of honest people can be assumed as a reward for working for private companies, it can be implicitly assumed that there is another good (which can be considered nummeraire) in a competitive market that is produced in a labor market under the assumption of perfect competition and constant returns. It is also considered that both goods have only one factor of production, work for example, that, for a perfect competitive market in which there is full employment, can be considered as a fixed good.

[19] The first to develop an integrated and consistent focus on political contributions were [17], based on the problem of common agency developed by [18]. Grossman and Helpman [17] used this focus to study the effect of economic policy on commercial transactions under conditions of quasilinear preferences. Years later, [19] generalized the idea of political contribution to general preferences, and, thus, examined the expected change in the function of the marginal utility of income.

[20] In questions of international economics, the analysis of the political process inherent in decision-making is of the utmost importance, especially when this refers to the pressure and influence exercised by interest groups [20]. Among the distinct schemes that have been proposed to analyze the political equilibrium, the following can be mentioned: the tariff formation approach [21]; the median voter approach [22]; the political support function approach [23]; the campaign contribution approach [24]; and, finally, the focus that will be used in this study, the political contribution approach [17].

level, and 1 to a maximum institutional or completely efficient level. Therefore, the tax unit cost, Δ, can be expressed as,

$$\Delta = \beta\alpha + \gamma(1 - \alpha) \tag{8}$$

where β is the unit cost of the legal structure and γ is the unit cost of the illegal structure, values which are weighted as α. In this way, $\beta\alpha$, the legal component of the tax cost increases when the institutional level is at 1, and falls when α nears 0. Similarly, $(1-\alpha)$, the illegal component of the tax cost increases when α nears 0, and reduces when α nears 1. Therefore, based on (5), (6), (7) and (8), the marginal cost of production for companies is,

$$C = \begin{cases} c + \lambda\theta + \beta\alpha + \gamma(1-\alpha) & si \quad t \geq \lambda \\ c + t\theta + \beta\alpha + \gamma(1-\alpha) & si \quad t < \lambda \end{cases} \tag{9}$$

designating the group of honest citizens with σ, and the group of dishonest citizens with ς. In this way, and supposing quasilinear preferences, the utility of honest people, is given by,

$$I^{\sigma} = \beta\alpha nX + C_s \tag{10}$$

where the first component, $\beta\alpha nX$, is the total payment made by companies. Such tax payments represent income from the group of honest citizens undertaken by means of a lump-sum scheme. C_s is, in turn, a consumer surplus.

On the other hand, the indirect utility of dishonest citizens is defined by,

$$I^{\varsigma} = \gamma(1 - \alpha)nX \tag{11}$$

In that the firms must consider dishonest public sector workers on calculating their tax costs (these individuals receive an income from bribes, through which they promote and preserve the illegal structure), it can also be assumed that the dishonest as a group do not consume the good produced.[21]

The institutional level is determined by the economic equilibrium and is nothing more than a political and economic tool implemented by the government. The calculation of said equilibrium was based on the model proposed by [19]. In this model, by making political contributions, dishonest people put pressure on the government in an attempt to influence its decisions, with said political contributions scheme giving $\Omega(\alpha, I^{\varsigma})$, which depends on the institutional level and indirect utility of dishonest people. Similarly, honest people exercise no type of pressure on the government in this scheme. For this reason, the function of welfare for the government, without yet considering the environmental question, is given by,[22]

$$\overline{G} = \rho\Omega + I^{\sigma} + I^{\varsigma} + n\pi \tag{12}$$

The level of corruption ρ is a constant parameter, $\rho \geq 1$, in that, if $\rho = 1$, contributions have no effect on political decisions. Equation (12) demonstrates that the government considers the welfare of the country as: sum of the contribution received, $\rho\Omega$; the utility of honest people, I^{σ}; the utility of dishonest people, I^{ς}; and, the benefit for the companies, $n\pi$.

According to [19], political equilibrium is achieved as a result of a game of two stages. In the first, dishonest people choose the form of their contribution. Subsequently, in the second stage, the government determines the institutional level. In this way, economic equilibrium is achieved, in the first instance, as a function of the political contribution, $\Omega^*(\alpha, I^{\varsigma})$, which maximizes benefit for the dishonest every time the government has also optimized its institutional level. Secondly, also contributing to economic equilibrium is the parameter of political type, α^*, which maximizes the function of government welfare (12), which considers the form of contribution as predetermined. The model proposed by [19] develops the concept of reliable equilibrium, calculating efficient solutions as described by Pareto. Analytically, if $(\Omega^0(\alpha^0, I^{\varsigma 0}), \alpha^0)$ is a reliable equilibrium in which $I^{\varsigma 0}$ is the utility of each dishonest individual, and, assuming quasilinear preferences $(\Omega^0(\alpha^0, I^{\varsigma 0}), \alpha^0, I^{\varsigma 0})$, can be specified by,

$$\Omega(\alpha, I^{\varsigma^0}) = max(0, \delta) \tag{13}$$

$$\alpha^0 = arg\, max_{\alpha}\{\rho\Omega(\alpha, I^{\varsigma^0}) + (I^{\sigma}(\alpha) + I^{\varsigma^0})\} \tag{14}$$

$$I^{\varsigma^0} = I^{\varsigma} - \delta \tag{15}$$

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[21] *It is supposed that dishonest people receive remuneration from the government. Furthermore, this salary is fixed, independent of the level of employee productivity, homogenous and relatively low (which is an incentive for the receipt of bribes) for all dishonest people. However, owing to the additional nature of the function of indirect utility of the income of the dishonest, it can be omitted due to the simplification of the model.*

[22] *See [15].*

The scheme of reliable contribution is determined by the value of the compensatory variations in the measure of equilibrium given the utility of dishonest citizens, which is shown in equations (13) and (15). The parameter, $\delta>0$, is the amount of the contribution and is the fundamental idea for compensatory variations. Thus, the amount of the contribution is equivalent to the increase in the utility of the dishonest citizen as a consequence of a specific political decision that augments their benefits. In this way, for a function of payment under reliable equilibrium conditions, any change in δ will provoke a change in the amount of the government contribution that will be the equivalent of the change in the utility of dishonest people, assuming that the payment made by both, both before and after the variation, is positive. Equation (14) expresses that the government takes the total utility of dishonest people as predetermined, and, thus, chooses the institutional level that maximizes the objective function (Equation 12).[23]

Grossman and Helpman [17] state that if there is a single pressure group that undertakes the political lobbying process, there are no conflicts of interest, and, in such a case, said group consigns the total surplus, given its political relationships with the government in question. Consequently, in the political equilibrium, the government obtains the same benefits that it would in the instance where it receives no contribution.

On the other hand, the total quantity of polluting emissions in the host country, *Z,* is equal to the total production of the good, *X*, which is given by the production of each company multiplied by the number of FDI companies participating in the market of the host country multiplied by the amount of pollution emitted per unit of product. Furthermore, Equation 7 implies that,

$$Z = \begin{cases} 0 & si \quad t \geq \lambda \\ n\theta X & si \quad t < \lambda \end{cases} \tag{16}$$

where ϕ is defined as the marginal disutility caused by pollution, which includes the environmental and social costs of pollution.[24] It is assumed to be a constant, as in the studies by [25] and [26].[25] Thus, ϕZ, expresses the total disutility of the pollution caused by the production of the good in question, and can be specified as,

$$\phi Z = \phi z n X \tag{17}$$

Finally, tZ represents the total pollution tax collected in the host country. Therefore, it is possible to generally construct the function of government utility, G, which, is described below,

$$G = \rho\Omega + I^{\sigma} + I^{\varsigma} + n\pi + tZ - \phi Z \tag{18}$$

Now, if, in (3), the marginal cost of production given in (9) is substituted, this gives,

$$X = \frac{a - c - t\theta - \beta\alpha - \gamma(1-\alpha)}{b(n+1)} \tag{19}$$

To sum up, if the number of companies is assumed to be endogenous, in that the government is able to influence the dynamic of the entry and exit of FDI firms through its decisions, which affect the instruments of economic policy. It is also possible to assume that the host country has a small presence in the FDI market, where the companies are able to enter and exit the host country if the FDI market conditions in the world market so merit.

In this way, the condition of FDI equilibrium is defined by,

$$\pi = \overline{\pi} \tag{20}$$

Then, from (19), (4), (9) and (20), the solution for *X* can be obtained,

$$X = \sqrt{\frac{\pi}{b}} = \sqrt{\frac{\overline{\pi}}{b}} \tag{21}$$

and, resolving *n* in (19), results in

$$n = \frac{a - c - t\theta - \beta\alpha - \gamma(1-\alpha)}{\sqrt{b\overline{\pi}}} - 1, \quad n \geq 1 \tag{22}$$

with which the specification of the model is concluded.

3. OPTIMAL INSTITUTIONAL LEVEL AND OPTIMAL TAXATION

The fundamental objective of this study is to determine the optimal institutional level and the optimal pollution tax, considering parameters

[23] *See [19] for a deeper analysis of the specification of (Ω^0 ($\alpha^0, I^{\varsigma 0}$), $\alpha^0, I^{\varsigma 0}$) for preferences distinct to the quasilinear.*

[24] *See [27,28] for more information about the social and environmental costs of pollution.*

[25] *Different authors, such as [29], assume that the marginal disutility of pollution is a growing function that depends on the last instance of the level of a firm's production.*

such as the level of governmental corruption and the social cost of pollution. Thus, the model includes variables of a social, technological, environmental and economic type in the determination of the equilibrium and the maximization of the welfare of the country. Two situations in which corruption exists are considered here. The first relates to the corruption of dishonest public sector workers, who influence, in one way or the other, the political decisions of the government. The second relates to the corruption that exists in the political environment of government, which can be considered as an exogenous variable. Both contexts described above can be presented simultaneously and are related. However, on establishing certain relationships between the two, results similar to the conclusions of this model were obtained, and thus, for reasons of simplicity, they were considered independently. The optimal institutional level will, therefore, be calculated first, and then the optimal pollution tax that permits the maximization of the function of government welfare. Similarly, the implications of said optimal values in the implementation of strategic institutional and environmental policies will be analyzed. Differentiating *n* with respect to *α* gives,

$$\frac{dn}{d\alpha} = \frac{\gamma-\beta}{\sqrt{b\bar{\bar{\pi}}}} = \frac{\gamma-\beta}{b\sqrt{\frac{\bar{\pi}}{b}}} \tag{23}$$

$$\frac{dn}{d\alpha} = \frac{\gamma-\beta}{bX} \tag{24}$$

which is,

$$\frac{dn}{d\alpha} > 0 \quad if \quad \gamma > \beta \quad and \tag{25}$$

$$\frac{dn}{d\alpha} < 0 \quad if \quad \gamma < \beta \tag{26}$$

Equation (25) indicates that if the legal option is less expensive than its illegal counterpart, then $\frac{dn}{d\alpha} > 0$, implying that the legal structure is more efficient. This signifies that firms prefer the cost of taxation from the legal structure, namely the cheaper and more favorable option, which, furthermore, brings with it the reduction of firms' marginal costs and the entry of more companies via FDI. On the other hand, Equation (26) implies that if the illegal option is less costly than its legal counterpart, firms opt for the illegal structure by means of bribes paid to dishonest public service workers, a strategy which brings with it a considerable increase in marginal costs and the lack of incentives for the entry of new FDI companies. Then, if $\gamma>\beta$, the number of FDI firms increases; however, if $\gamma<\beta$, the number of FDI firms decreases.

If, on the other hand, differentiating *n* with respect to *t* gives,

$$\frac{dn}{dt} = -\frac{\theta}{bX} \tag{27}$$

It can be noted that,

$$\frac{dn}{dt} < 0 \tag{28}$$

This implies that the entry of FDI companies will be seen to be more favored if taxation is reduced by the government. Equation (21) gives,

$$\frac{dX}{d\alpha} = 0 \tag{29}$$

$$\frac{dX}{dt} = 0 \tag{30}$$

The above results imply the neutral effect of an increase in the institutional level and optimal taxation on the level of companies' production, in that FDI automatically adjusts the modification in the product.

To obtain the optimal institutional level, the first order conditions are calculated,

$$\frac{dG}{d\alpha} = \frac{d(\rho\Omega + I^{\sigma} + I^{\varsigma} + n\pi + tZ - \phi Z)}{d\alpha} = 0 \tag{31}$$

differentiating, term for term, the above expression, obtaining,[26]

$$\alpha^* = \frac{-b\Big((\gamma-\beta)\big(b^{-1}(\theta\phi - t\theta - \gamma\rho) - X(n+1)\big) + Xn(\gamma\rho-\beta)\Big)}{(\gamma-\beta)(\gamma\rho-\beta)} \tag{32}$$

and, similarly, to determine optimal taxation, the first order conditions are obtained,

$$\frac{dG}{dt} = \frac{d(\rho\Omega + I^{\sigma} + I^{\varsigma} + n\pi + tZ - \phi Z)}{dt} = 0 \tag{33}$$

differentiating, again term for term, the above expression, thus obtaining,[27]

$$t^* = -\frac{b}{\theta}\left(X + b^{-1}\alpha\beta - b^{-1}\theta\phi + b^{-1}\gamma\rho(1-\alpha)\right) \tag{34}$$

The second order condition for *α* is given by,[28]

[26] *See appendix 2*
[27] *See appendix 3*
[28] *See appendix 4*

$$\frac{d^2G}{d\alpha^2} = \frac{(\beta+\gamma(1-2\rho))(\gamma-\beta)}{b} < 0$$

from which, the condition of concavity would be,

$$\beta > \gamma\rho \qquad (35)$$

The second order condition for *t* is given by,[29]

$$\frac{d^2G}{dt^2} = -\frac{\theta^2}{b} < 0 \qquad (36)$$

from which *G* is concave.

However, given that the condition of concavity is $\beta > \gamma\rho$, and remembering that,

$$\alpha^* = \frac{-b\Big((\gamma-\beta)\big(b^{-1}(\theta\phi-t\theta-\gamma\rho)-X(n+1)\big)+Xn(\gamma\rho-\beta)\Big)}{(\gamma-\beta)(\gamma\rho-\beta)}$$

it can be deduced that the sign α^* depends on $\theta\phi - t\theta - \gamma\rho$. In which case, the magnitude of the institutional level depends on the level of governmental corruption, the pollution tax, and the disutility of pollution. If the level of corruption is very high, or if the pollution tax is high, the government will impose a minimal institutional level, while, if disutility is high, the government will then implement a positive institutional level.

Formally, these can be expressed in the following two propositions.

Proposition 1. *If the cost per unit of product in the legal structure is greater than the illegal structure, then*

$$\alpha^* = 0 \quad if \quad \gamma\rho \gg \theta\phi$$
$$\alpha^* > 0 \quad if \quad \gamma\rho \ll \theta\phi$$

In the first case, $\gamma\rho$ is the measure, per unit produced, of the illegal cost reinforced by the level of corruption in the political system, and $\theta\phi$ is the measure, per unit produced, of the social cost of pollution. Thus, if the social cost of pollution is relatively low, this favors, given the inefficiency of the legal structure, the contribution of dishonest individuals to the function of the utility of government, starting with a relatively high level of corruption, in return for the social costs of pollution that this could imply. In order for this to occur, the level of corruption on the part of the government must be high, and, in this case, the government will favor those policies that maximize its income from the contributions of dishonest individuals. This, in turn, will increase government coffers, given that companies will prefer the illegal over the legal structure, and will elect to pay bribes. Obviously, the government will attempt to favor such a situation by being completely lax. Also, FDI and the consumer surplus will be seen to be indirectly benefitted by companies opting for the illegal routes, although it is certain that the transfers from the government to honest people decrease. In this situation, the social cost of pollution is relatively low. For this reason the government gets more income from the contributions of dishonest people, and, on the other hand, they also increase the benefits of FDI and consumer surplus. In other words, the institutional policy that maximizes general welfare is the establishment of a null institutional level.

In the event that $\theta\phi$ (the measure, per unit produced, of the social cost of pollution) is higher than $\gamma\rho$ (the measure, per unit produced, of the illegal cost reinforced by the level of corruption in the political system), the government will establish a positive institutional level. In this situation, if the social cost of pollution is relatively high, the contribution of the dishonest is considered on a much lower scale in terms of the function of government utility, starting with a relatively low level of corruption. Therefore, the government values more the introduction of a higher institutional level and the beneficial effect that this can bring in terms of FDI, the benefit for both producer and consumer, and even in the income of honest people, thus reducing the benefit that dishonest individuals receive through bribes.

Proposition 2. *If the cost per unit of product in the legal structure is higher than that in the illegal structure, then*

$$\alpha^* = 0 \quad si \quad t \gg \phi$$
$$\alpha^* > 0 \quad si \quad \phi \gg t$$

Intuitively, if $t \gg \phi$, namely if the pollution tax is very high in relation to the social cost of pollution, given that the legal structure is inefficient, this favors the contribution of the dishonest in the function of government utility, starting with a relatively high pollution tax, in return for the social costs of pollution that this could involve. Thus the government favors those policies that maximize its income through the contributions of dishonest people and the contributions from the companies through the illegal structure and the payment of bribes. Clearly, the government will attempt to favor such a situation by being completely obliging. FDI and the consumer

[29] *See appendix 4*

surplus will be indirectly benefitted when the companies choose the illegal mechanisms. Furthermore, the positive effect is prevalent in the function of welfare, on considering the pollution tax contribution against the social cost of pollution. In other words, the institutional policy that maximizes general welfare is that which establishes a null institutional level.

However, if $\phi \gg t$, namely if the social cost of pollution is very high in relation to pollution tax, the government will establish a positive level of institutionality. In this situation, if the social cost of pollution is very high, the contribution of the dishonest is considered to be in a much lower proportion in the function of government utility, starting with a relatively low pollution tax. Therefore, the government values more the introduction of a higher institutional level and the beneficial effect that this could bring in terms of FDI, the benefit for both producer and consumer, and, even, in terms of the income of honest people via transfers, thus reducing the benefit that dishonest people receive from bribes. There is, however, a combined negative effect between the pollution tax collected and the social cost of pollution in terms of the function of social welfare.

Considering the optimal tax pollution gives,

$$t^* = -\frac{b}{\theta}\left(X + b^{-1}\alpha\beta - b^{-1}\theta\phi + b^{-1}\gamma\rho(1-\alpha)\right)$$

Therefore, the sign t^* depends on the magnitude of $\theta\phi$, namely the disutility per unit of product compared to the other parameters. Basically, it can be affirmed that if $\theta\phi$ is very high, the government levies a pollution tax, through which the adverse effect of the social cost of pollution is prioritized over the other components of the function of social welfare. However, if $\theta\phi$ is not sufficiently high, governments opt not to levy tax, thus favoring, in this case, the positive effects for the benefit of the companies by reducing the marginal cost of production, and, consequently, for the benefit of consumers, when the foregoing is translated into lower prices. Further to the above, the companies' contributions to both the legal and illegal structure increase. It can be expressed in the following proposition.

Proposition 3. *In non-cooperative equilibrium, the optimal tax pollution is*

$$t^* > 0 \quad si \quad \phi \gg 0$$
$$t^* = 0 \quad si \quad \phi \to 0$$

Intuitively, if $\theta\phi \gg \alpha\beta$, when the social cost per unit of production is much higher than the legal tax contribution, an environmental component is imposed in the function of welfare onto the other terms of said function. Therefore, a positive pollution tax is established that inevitably increases the costs of production and the final price for the consumer, while, at the same time, it reduces the collection of both legal and illegal tax. Similarly, this occurs when $\theta\phi \gg \gamma\rho(1-\alpha)$, namely when the social cost per unit of product is sufficiently high compared to illegal tax collection.

It should be noted, moreover, that $\theta\phi \gg X$, which implies that, if the size of the market is not significantly large compared to $\theta\phi$, the government will also apply a pollution tax with the above described effects in terms of the function of welfare. However, if the market is larger than the social cost per unit of product, the optimal pollution tax is zero, thus favoring the productivity of companies on reducing the cost of production. The consumer surplus also increases when the price of the product is dropped, as does both the legal and illegal tax contribution.

On the other hand, the function W is not necessarily continuous with respect to t. Given the manner in which C is defined, the only point of discontinuity possible is $t=\lambda$. Analyzing the probable discontinuity of G, $t=\lambda$, by means of the calculation of unilateral limits and using (7), (9) and (16), gives,

$$lim_{t\to\lambda^+} G = \rho\Omega + I^\sigma + I^\varsigma + n\pi^* + tZ - \phi Z \qquad (37)$$

$$lim_{t\to\lambda^+} G = \rho\Omega + I^\sigma + I^\varsigma + n\pi^* \qquad (38)$$

$$lim_{t\to\lambda^-} G = \rho\Omega + I^\sigma + I^\varsigma + n\pi^* + tZ - \phi Z \qquad (39)$$

$$lim_{t\to\lambda^-} G = \rho\Omega + I^\sigma + I^\varsigma + n\pi^* + \lambda(n\theta X) - \phi(n\theta X) \qquad (40)$$

$$lim_{t\to\lambda^-} G = \rho\Omega + I^\sigma + I^\varsigma + n\pi^* + (\lambda - \phi)(n\theta X) \qquad (41)$$

thus (38) and (41) give

$$lim_{t\to\lambda^+} G - lim_{t\to\lambda^-} G = (\phi - \lambda)(n\theta X)$$

from which it can be concluded that

$$lim_{t\to\lambda^+} G - lim_{t\to\lambda^-} G > 0 \quad si \quad \phi > \lambda \qquad (42)$$

$$lim_{t\to\lambda^+} G - lim_{t\to\lambda^-} G = 0 \quad si \quad \phi = \lambda \qquad (43)$$

$$lim_{t\to\lambda^+} G - lim_{t\to\lambda^-} G < 0 \quad si \quad \phi < \lambda \qquad (44)$$

from which the following proposition can be deduced,

Proposition 4. *If $\phi \geq \lambda$, then the optimal pollution tax is $t^* \geq \lambda$, and, therefore, no pollution is emitted, while, if $\phi < \lambda$, then the optimal pollution tax is $t^* < \lambda$, and there is no reduction in pollution.*

Intuitively, if the disutility of pollution is very high, the benefit of reducing pollution is imposed on those other components of the function of welfare, causing the optimal pollution tax to be higher than the cost of abatement; therefore, companies prefer to not emit pollution at all. However, if marginal disutility is not significantly high, the optimal pollution tax is strictly lower than the abatement cost and, in this case, the companies opt against reducing the level of pollution they emit.

4. CONCLUSIONS

In terms of the optimal institutional level, if the level of corruption is high, the government imposes a null institutional level, and thus places more value on the political contribution from dishonest actors and the positive effects that this can bring in terms of the function of welfare. This can be seen in both the reduction of the marginal costs (in that the cost of the illegal structure becomes cheaper than the legal), and the increase in consumer surplus caused by the reduction in prices. However, there is a reduction in transfers. In addition, the increase in the social cost of pollution has adverse effects.

If, however, the disutility of pollution is sufficiently high, the positive effects produced by the political contribution from dishonest people pale in comparison with the negative repercussions seen in the social cost of pollution. Therefore, the government imposes a positive institutional level that, in some way, regulates the effect that both corruption and the illegal structure could have on the indiscriminate increase of contaminants in the environment.

At the same time, similar behavior is observed with the pollution tax. If the pollution tax is very high, the government establishes a minimal institutional level, causing its income to increase, both from the contributions of the dishonest (who benefit directly) and through the pollution tax contribution paid by FDI companies (in this case, the combined effect against the social cost of pollution is clearly favorable to the contribution received from pollution tax in the function of welfare). Even so, the effects on the marginal cost and the final prices of goods for the consumer is ambiguous, as, although the cost of the legal structure is lower, said cost also increases due to the pollution tax, which is very high. On the other hand, if the marginal disutility of pollution is significantly higher than the pollution tax, the government applies a positive institutional level, since the unfavorable consequences of pollution are imposed on the other components of the function of welfare, especially the contribution of the dishonest to government income.

In terms of the optimal pollution tax, this should be positive if marginal disutility is significantly high. Thus, if the social cost of pollution per unit of product is much higher than the marginal cost of the legal structure, said social cost of pollution dominates the other components of the function of welfare. The pollution tax is, therefore, levied, and, thus, necessarily increases the marginal costs of production and the final prices for the consumer, although tax collection – both legal and illegal – reduces in relative terms. In an analogue pattern, a positive tax is established when the social cost of pollution per unit of product is much higher than the marginal cost of the illegal structure. A positive pollution tax is also established when the size of the FDI market is not large enough, compared to the disutility of pollution per unit of product. However, if the size of the market is significantly large compared to the social cost per unit of product, the pollution tax set by the government is zero, which favors the competitiveness of the FDI companies, in that the costs of production and the prices for the consumer reduce, thus also increasing the tax contribution, both legal and illegal, although this means higher levels of pollution.

Finally, if the abatement cost is compared to the marginal disutility of pollution, it can be deduced that, if the latter is greater than the former, the optimal pollution tax must be higher than the abatement cost. For this reason, companies decide not to pollute at all, in that, evidently, it is cheaper to pay the cost of not polluting than to cover a high pollution tax. However, in the case of the contrary, if the marginal disutility of pollution is lower than the abatement cost, the optimal level of taxation should be lower than the abatement cost. Therefore, companies opt against an absolute reduction of pollution, in that the cost of abating pollution is obviously higher than the cost of paying the pollution tax.

In this way, the model proposed emphasizes the importance of the rational establishment of strategic environmental policies, which also take into account institutional variables, such as the institutional level and corruption, which act for the benefit of all economic agents involved in the FDI host country, such as the government, companies, consumers and public servants. Strategic environmental policies (harmoniously integrated elements that work in the function of welfare) which drive the sustainable development of the economy should be selected.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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MATHEMATICAL APPENDIX

1. Maximization of Production

According to the conditions of Cournot-Nash, *n* companies determine their production level considering the expected level of production from the remaining *n-1* companies. Therefore, the optimum level of any company is obtained as follows,

Substituting *p* (1), for *π* (2) gives:

$$\pi = (a - bnX - C)X \tag{45}$$
$$\pi = (a - bX - b(n-1)X - C)X = (a - bX - b(n-1)X_i - C)X$$
$$\pi = aX - bX^2 - b(n-1)XX_i - CX$$

Differentiating with respect to *X*,

$$\frac{d(aX - bX^2 - b(n-1)XX_i - CX)}{dX} = a - C - 2Xb + bX_i - nbX_i$$
$$= a - C - 2Xb + bX - nbX$$
$$= a - C - bX(n+1)$$

Then,

$$\frac{d\pi}{dX} = a - C - bX(n+1) = 0 \tag{46}$$

for which reason,

$$X = \frac{a - C}{b(n+1)}$$

but *p=a-bnX*, then

$$Xb = p - C \tag{47}$$

Substituting (47) in (2), gives:

$$\pi = bX^2 \tag{48}$$

2. Optimal Institutional Level

In order to find the optimal institutional level, the function G must be differentiated, differentiating each of its components in the following way,

$$\frac{dG}{d\alpha} = \frac{d(\rho\Omega + I^{\sigma} + I^{\varsigma} + n\pi + tZ - \phi Z)}{d\alpha}$$

$$\frac{dG}{d\alpha} = \frac{d(\rho\Omega)}{d\alpha} + \frac{d(I^{\sigma})}{d\alpha} + \frac{d(I^{\varsigma})}{d\alpha} + \frac{d(n\pi)}{d\alpha} + \frac{d(tZ)}{d\alpha} - \frac{d(\phi Z)}{d\alpha}$$

2.1 Derivative from political contributions

$$\frac{d(\rho\Omega)}{d\alpha} = \rho\left(\frac{dI^{\varsigma}}{d\alpha} + \frac{dI^{\varsigma 0}}{d\alpha}\right) = \rho\frac{dI^{\varsigma}}{d\alpha}$$

$$\frac{d(\rho\Omega)}{d\alpha} = \rho(b^{-1}\gamma(1-\alpha)(\gamma - \beta) - n\gamma X)$$

In that, $\frac{dI^{\varsigma 0}}{d\alpha} = 0$, and furthermore

$$\frac{d(I^{\varsigma})}{d\alpha} = \frac{d(\gamma(1-\alpha)nX)}{d\alpha} = \gamma X\frac{d((1-\alpha)n)}{d\alpha}$$

$$\frac{d(I^{\varsigma})}{d\alpha} = \gamma X\left((1-\alpha)\frac{\gamma-\beta}{bX} - n\right)$$

then,[30]

$$\frac{d(\rho\Omega)}{d\alpha} = \rho(b^{-1}\gamma(1-\alpha)(\gamma-\beta) - \gamma Xn) \tag{49}$$

2.2 Derivative from the indirect utility of the honest

$$\frac{d(I^{\sigma})}{d\alpha} = \frac{d(\beta\alpha nX + C_S)}{d\alpha} = \frac{d(\beta\alpha nX)}{d\alpha} + \frac{d(C_S)}{d\alpha}$$

differentiating term to term,

$$\frac{d(\beta\alpha nX)}{d\alpha} = \beta X\frac{d(n\alpha)}{d\alpha} = \beta X\left(a\frac{dn}{d\alpha} + n\right) = \beta X\left(a\frac{\gamma-\beta}{bX} + n\right)$$

$$\frac{d(\beta\alpha nX)}{d\alpha} = b^{-1}\alpha\beta(\gamma-\beta) + n\beta X$$

$$\frac{d(C_S)}{d\alpha} = \frac{d\left(b(nX)^2/2\right)}{d\alpha} = \frac{d\left(bn^2X^2/2\right)}{d\alpha} = (bX^2/2)\frac{dn^2}{d\alpha} = bX^2n\frac{dn}{d\alpha} = bX^2n\frac{\gamma-\beta}{bX}$$

$$\frac{d(C_S)}{d\alpha} = Xn(\gamma-\beta)$$

the previous equations give,

$$\frac{d(I^{\sigma})}{d\alpha} = b^{-1}\alpha\beta(\gamma-\beta) + n\beta X + Xn(\gamma-\beta) \tag{50}$$

2.3 Derivative from the benefits of FDI

$$\frac{d(n\pi)}{d\alpha} = \frac{d\left(nbX^2\right)}{d\alpha} = bX^2\frac{dn}{d\alpha} = bX^2\frac{\gamma-\beta}{bX}$$

for which reason,

$$\frac{d(n\pi)}{d\alpha} = X(\gamma-\beta) \tag{51}$$

2.4 Derivative from the tax collected on the emission of pollutants

$$\frac{d(tZ)}{d\alpha} = \frac{d(t\theta nX)}{d\alpha} = t\theta X\frac{dn}{d\alpha} = t\theta X\frac{\gamma-\beta}{bX}$$

then,

$$\frac{d(tZ)}{d\alpha} = b^{-1}t\theta(\gamma-\beta) \tag{52}$$

2.5 Derivative from the social cost of polluting

$$\frac{d(\phi Z)}{d\alpha} = \frac{d(\phi\theta nX)}{d\alpha} = \phi\theta X\frac{dn}{d\alpha} = \phi\theta X\frac{\gamma-\beta}{bX}$$

then,

$$\frac{d(\phi Z)}{d\alpha} = b^{-1}\phi\theta(\gamma-\beta) \tag{53}$$

[30] *Differentiating this component of the function of utility of government implicitly obtains the derivative from the indirect utility of the dishonest [19].*

2.6 Determination of *α**

Adding (49), (50), (51), (52), (53) and, simplifying, gives,

$$\frac{dG}{d\alpha} = nX(\beta - \gamma\rho) + b^{-1}(\gamma - \beta)\big(\gamma\rho + \alpha(\beta - \gamma\rho)\big) + X(n+1)(\gamma - \beta) + b^{-1}t\theta(\gamma - \beta) - b^{-1}\phi\theta(\gamma - \beta)$$

making $\frac{dG}{d\alpha} = 0$, and, solving *α*, gives the optimal institutional level,

$$\alpha^* = \frac{-b\Big((\gamma-\beta)\big(b^{-1}(\theta\phi - t\theta - \gamma\rho) - X(n+1)\big) + Xn(\gamma\rho - \beta)\Big)}{(\gamma-\beta)(\gamma\rho-\beta)}$$

3. Optimal Pollution Tax

In order to find the optimal pollution tax, the function *G* must be differentiated, differentiating each one of its components in the following manner,

$$\frac{dG}{dt} = \frac{d(\rho\Omega + I^{\sigma} + I^{\varsigma} + n\pi + tZ - \phi Z)}{dt}$$

$$\frac{dG}{dt} = \frac{d(\rho\Omega)}{dt} + \frac{d(I^{\sigma})}{dt} + \frac{d(I^{\varsigma})}{dt} + \frac{d(n\pi)}{dt} + \frac{d(tZ)}{dt} - \frac{d(\phi Z)}{dt}$$

3.1 Derivative from political contributions

$$\frac{d(\rho\Omega)}{dt} = \rho\left(\frac{dI^{\varsigma}}{dt} + \frac{dI^{\varsigma^0}}{dt}\right) = \rho\frac{dI^{\varsigma}}{dt} = b^{-1}\rho\gamma\theta(1-\alpha)$$

$$\frac{d(\rho\Omega)}{dt} = -b^{-1}\rho\gamma\theta(1-\alpha)$$

in that, $\frac{dI^{\varsigma 0}}{dt} = 0$ and, furthermore,

$$\frac{d(I^{\varsigma})}{dt} = \frac{d(\gamma(1-\alpha)nX)}{dt} = \gamma X(1-\alpha)\frac{dn}{dt} = \gamma X(1-\alpha)\left(-\frac{\theta}{bX}\right)$$

$$\frac{d(I^{\varsigma})}{dt} = -b^{-1}\gamma\theta(1-\alpha)$$

giving,

$$\frac{d(\rho\Omega)}{dt} = -b^{-1}\rho\gamma\theta(1-\alpha) \qquad (54)$$

3.2 Derivative from the indirect utility of the honest

$$\frac{d(I^{\sigma})}{dt} = \frac{d(\beta\alpha nX + C_S)}{dt} = \frac{d(\beta\alpha nX)}{dt} + \frac{d(C_S)}{dt}$$

differentiating term to term gives,

$$\frac{d(\beta\alpha nX)}{dt} = \alpha\beta X\frac{dn}{dt} = \alpha\beta X\left(-\frac{\theta}{bX}\right)$$

$$\frac{d(\beta\alpha nX)}{dt} = -b^{-1}\alpha\beta\theta$$

$$\frac{d(C_S)}{dt} = \frac{d\big(b(nX)^2/2\big)}{dt} = \frac{d\big(bn^2X^2/2\big)}{dt} = (bX^2/2)\frac{dn^2}{dt} = (bX^2/2)2n\frac{dn}{dt} = bX^2n\left(-\frac{\theta}{bX}\right)$$

$$\frac{d(C_S)}{dt} = -Xn\theta$$

then, the previous equations result in,

$$\frac{d(I^{\sigma})}{dt} = -b^{-1}\alpha\beta\theta - Xn\theta \tag{55}$$

3.3 Derivative from the benefits of FDI

$$\frac{d(n\pi)}{dt} = \frac{d(nbX^2)}{dt} = bX^2\frac{dn}{dt} = bX^2\left(-\frac{\theta}{bX}\right) = -X\theta$$

for which reason,

$$\frac{d(n\pi)}{dt} = -X\theta \tag{56}$$

3.4 Derivative from the tax collected on the emission of pollutants

$$\frac{d(tZ)}{dt} = \frac{d(t\theta nX)}{dt} = \theta X\frac{d(tn)}{dt} = \theta X\left(t\frac{dn}{dt} + n\right) = \theta X\left(t\left(-\frac{\theta}{bX}\right) + n\right) = Xn\theta - b^{-1}t\theta^2$$

then,

$$\frac{d(tZ)}{dt} = Xn\theta - b^{-1}t\theta^2 \tag{57}$$

3.5 Derivative from the social cost of polluting

$$\frac{d(\phi Z)}{dt} = \frac{d(\phi\theta nX)}{dt} = \phi\theta X\frac{dn}{dt} = \phi\theta X\left(-\frac{\theta}{bX}\right) = -b^{-1}\phi\theta^2$$

then,

$$\frac{d(\phi Z)}{dt} = -b^{-1}\phi\theta^2 \tag{58}$$

3.6 Determination of *t**

Adding (54), (55), (56), (57) and (58) gives,

$$\frac{dG}{dt} = -b^{-1}\rho\gamma\theta(1-\alpha) - b^{-1}\alpha\beta\theta - Xn\theta - X\theta + Xn\theta - b^{-1}t\theta^2 + b^{-1}\phi\theta^2$$

$$\frac{dG}{dt} = -b^{-1}\rho\gamma\theta(1-\alpha) - b^{-1}\alpha\beta\theta - X\theta - b^{-1}t\theta^2 + b^{-1}\phi\theta^2 \tag{59}$$

making $\frac{dG}{dt} = 0$, and solving *t* gives the optimal pollution tax,

$$t^* = -\frac{b}{\theta}\left(X + b^{-1}\alpha\beta - b^{-1}\theta\phi + b^{-1}\gamma\rho(1-\alpha)\right)$$

4. Conditions of Concavity

4.1 For the institutional level

$$\frac{d^2G}{d\alpha^2} = \frac{d\left(b^{-1}\rho\gamma(1-\alpha)(\gamma-\beta)\right)}{d\alpha} - \frac{d(\rho\gamma Xn)}{d\alpha} + \frac{d\left(b^{-1}\alpha\beta(\gamma-\beta)\right)}{d\alpha} + \frac{d(n\beta X)}{d\alpha} + \frac{d\left(Xn(\gamma-\beta)\right)}{d\alpha} + \frac{d\left(X(\gamma-\beta)\right)}{d\alpha} + \frac{d\left(b^{-1}t\theta(\gamma-\beta)\right)}{d\alpha} - \frac{d\left(b^{-1}\phi\theta(\gamma-\beta)\right)}{d\alpha}$$

differentiating term to term gives,

$$\frac{d\left(b^{-1}\rho\gamma(1-\alpha)(\gamma-\beta)\right)}{d\alpha} = b^{-1}\rho\gamma(\gamma-\beta)\frac{d(1-\alpha)}{dt} = -b^{-1}\rho\gamma(\gamma-\beta)$$

$$\frac{d(\rho\gamma Xn)}{d\alpha} = \rho\gamma X\frac{dn}{d\alpha} = \rho\gamma X\frac{\gamma-\beta}{bX} = b^{-1}\rho\gamma(\gamma-\beta)$$

$$\frac{d\left(b^{-1}\alpha\beta(\gamma-\beta)\right)}{d\alpha} = b^{-1}\beta(\gamma-\beta)$$

$$\frac{d(n\beta X)}{d\alpha} = \beta X\frac{dn}{d\alpha} = \beta X\frac{\gamma-\beta}{bX} = b^{-1}\beta(\gamma-\beta)$$

$$\frac{d\left(Xn(\gamma-\beta)\right)}{d\alpha} = X(\gamma-\beta)\frac{dn}{d\alpha} = X(\gamma-\beta)\frac{\gamma-\beta}{bX} = b^{-1}(\gamma-\beta)^2$$

$$\frac{d\left(X(\gamma-\beta)\right)}{d\alpha} = 0$$

$$\frac{d\left(b^{-1}t\theta(\gamma-\beta)\right)}{d\alpha} = 0$$

$$\frac{d\left(b^{-1}\phi\theta(\gamma-\beta)\right)}{d\alpha} = 0$$

adding the previous terms results in,

$$\frac{d^2G}{d\alpha^2} = -b^{-1}\rho\gamma(\gamma-\beta) - b^{-1}\rho\gamma(\gamma-\beta) + b^{-1}\beta(\gamma-\beta) + b^{-1}\beta(\gamma-\beta) + b^{-1}(\gamma-\beta)^2$$

$$\frac{d^2G}{d\alpha^2} = \frac{(\beta+\gamma-2\gamma\rho)(\gamma-\beta)}{b} = \frac{\left(\beta+\gamma(1-2\rho)\right)(\gamma-\beta)}{b}$$

for which reason,

$$\frac{d^2G}{d\alpha^2} = \frac{\left(\beta+\gamma(1-2\rho)\right)(\gamma-\beta)}{b}$$

thus the condition of concavity for *G* is $\beta-\gamma\rho>0$ or $\beta>\gamma\rho$

4.2 For the pollution tax

$$\frac{d^2G}{dt^2} = \frac{d\left(-b^{-1}\rho\gamma\theta(1-\alpha)-b^{-1}\alpha\beta\theta-Xn\theta-X\theta+Xn\theta-b^{-1}t\theta^2+b^{-1}\phi\theta^2\right)}{d\alpha}$$

$$\frac{d^2G}{dt^2} = \frac{d\left(-b^{-1}\rho\gamma\theta(1-\alpha)-b^{-1}\alpha\beta\theta-X\theta-b^{-1}t\theta^2+b^{-1}\phi\theta^2\right)}{dt}$$

The derivative of each of the terms with respect to *t* is zero except the term that includes *t*, therefore

$$\frac{d^2G}{dt^2} = -\frac{\theta}{b^2}$$

Thus *G* is concave.

Peer-review history:
The peer review history for this paper can be accessed here:
http://sciencedomain.org/review-history/16096