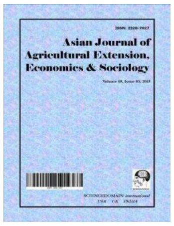

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Foreign Direct Investment, Institutional Level and Pollution Quota

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Authors' contributions

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

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ABSTRACT

This study develops a model of institutional economics that involves consumers, producers and government, as well as the dishonest agents that work in the public sector. This model is useful for determining the optimum institutional level that must be set by the government in order to attain economic and environmental balance in the country under an oligopolistic scheme of Foreign Direct Investment (FDI). Furthermore, the proposal enables the calculation of the optimal pollution quota.The results of the model can be used to deduce a series of recommendations for the area of environmental policy, which have the objective of maximizing welfare levels in the FDI host country.

Keywords: FDI; corruption; pollution quota; environmental policies.

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1. INTRODUCTION

Every day, institutional economics acquires greater importance in terms of the establishment of sound economic policies. In this way, to talk of institutional economics is to consider a group of norms and conventions that enable economic agents to relate to one another harmoniously. In this sense, societies comprise a collection of rules and agreements for action that govern the actors involved in economic affairs. Said norms and agreements are given the generic name of institutions and govern the conduct of economic entities undertaking transactions in the market. Said institutions also depend on issues that involve, to a greater or lesser extent, cultural aspects and the idiosyncrasies of each society. In this way, institutional economics is a recently developed multidisciplinary economic area of study whose perspectives take in such disparate subjects as sociology, political science, and organization theory, among others.[1]

From the political, cultural, social and economic differences, both well-known and general, the existing studies can be classified into two major categories. The literature focused on developed countries is of a wide and abundant nature. Generally, said publications begin with the supposition that said societies adhere strictly to the legal framework on which institutional policy is founded and whose day-to-day application in economic activity is very efficient.[2]

In the case of developing countries, such as in Latin America in general and Mexico in particular, the reforms applied in developed countries do not seem to function with the same efficacy, in that the institutions that regulate economic affairs, such as the legal framework and individual property rights are not well consolidated. It should be noted that bribery is a frequently used resource in such countries, functioning as a simplification system that avoids administrative procedures and costly taxation.[3]

Therefore, this study attempts to develop a theoretical model for institutional economics that identifies adequate institutional policy measures applicable to the environment of developing countries which involve other relevant economic issues such as FDI, which has become a pillar of nations' economic development. The study also seeks to identify the environmental issues that condition a country's economic growth to considerations of sustainability and the control of polluting emissions. [4] Such matters must be treated in an integrated manner in order to identify the institutional and environmental policies that, on the one hand, facilitate FDI in the interests of the economic welfare of developing countries, and, on the other, do not cause irrational damage to their environment. Numerous studies have been undertaken on FDI,[5] which recognize that FDI, while a factor in the economic development of nations, it is not a panacea. These studies also recognize that, unless it is complemented with governmental policies that promote internal investment and the development of the production base, FDI can be converted into an element of a country's economic dependency on foreign investment that does not, *a priori*, generate improved standards of living in the population. For this reason, the entry of FDI must adhere to the sound institutional reforms that guarantee the welfare of economic agents.

As the last twenty years has seen, owing to the growing global tendency toward the openness to trade, an ostensible growth in FDI, governments began to adopt certain measures in relation to FDI that evolved from protectionist measures in favor of local industry to policies designed to

[1] An exhaustive review of classical institutional economics can be found in [1].
[2] Among which studies the articles by [2,3,4] can be cited.
[3] According to [5], Mexico is found to be above the Latin American average for the majority of rubrics.

[4] In this sense, greenhouse effect, acid rain, additive and change in the temperature of the oceans are only a few adverse consequences derived from pollution. In this manner, pollution is blame for the increase in the social and economic costs caused by natural disasters like hurricans, twisters and floods. In accordance with [6], hurricanes, twisters and floods have cost to the USA government a yearly average of 16,972 million dollars in the 1955-2006 period at 1999 constant prices; even in some years the cost reached more than 100 billion dollars. Moreover, the effect of pollution on health of people (predominantly causing respiratory illness, intestinally illness and auditive illness) has reached alarming levels mainly in the big cities according to [7]. These devastating effects of pollution in the world call for a coordinated effort made by the governments all over the world. An example of this attempt was the unsuccessful Rio Conference in Brazil 1992 and the 2002 Johannesburg Summit. The intensive use of natural resources and intensity production process is blamed to be the main cause of pollution. However the governments are not willing to apply policies to reduce pollution because these policies may increase the industrial costs and undermine the international competitiveness of industries; so, pollution control is a barrier to trade and, nowadays, it is extensively discussed in the free trade agreements [8].
[5] For example, [9,10] to cite only a few.

facilitate the entry of foreign capital. [6] In this sense, FDI is currently seen as a complement to local investment, be this in terms of the opening of external channels for the commercialization of products from each country, the introduction of new products, technologies and administrative techniques, and the training of human resources, among others. Furthermore, it is an undeniable fact that developing countries are significant receivers of this type of investment.[7]

In parallel, in environmental terms, recent studies have focused on testing the hypothesis of the *pollution havens*, namely, contrasting the idea that multinationals emigrate to those countries where pollution controls are more lax and, therefore, where the compliance costs incurred are lower [12]. Thus, countries with strict controls specialize in clean technologies, while countries with weak controls specialize in dirty industries. This is a natural and intuitive consequence of the theory of comparative advantage and Heckscher-Ohlin's theory on international trade, in which the environment is considered a space where the factor of pollution can be considered either a very scarce or abundant good. The pollution haven hypothesis is the subject of great theoretical debate, with insufficient empirical evidence, at least meaningful evidence, showing that multinational companies emigrate to countries with high levels of pollution. As there is even, however, evidence that such companies use more efficient technology, substituting obsolete technologies from local industry for superior and cleaner technology from other countries, there are no conclusive results supporting either one or the other perspective. In any case, the establishment of environmental regulations is an indispensable part of a strategic environmental policy that fosters the entry of foreign capital via FDI, the preservation of the environment by reducing the emission of pollutants by companies.

On the other hand, the instrument for controlling polluting emissions that will be used in this study are pollution quotas, which are quantitative limits based on an emissions total, which entails a limit being placed on the quantity of contaminants emitted by companies. For example, industries emitting gases in a region, or discharging contaminated water into a certain river must not exceed the total stipulated by environmental policy. Said quota is determined based on technological considerations [13]. Generally, nations establish commissions of experts that study industrial activity in order to determine the maximum quantity of polluting emissions permitted per unit of production, based on analysis conducted using available technology, the associated costs (including the monetary cost), the average levels of pollution and consultation with direct and indirect interest groups. [8] In practice, this ensures that such quotas are economically viable for companies, namely, that the costs of achieving them are not too high and are technically possible. Moreover, exogenously fixed quotas based on the best technology available do not guarantee an ideal aggregate environmental quota, in that, generally, quotas per industry and unit of production are no guarantee that total emissions, taking into account the sum of economic activity, do not exceed an optimal global level.[9]

Finally, there are two principal concepts in terms of the costs of reducing pollution that will be used in this study – the cost of abatement and the social cost of pollution. Abatement costs are defined as the costs incurred in the reduction by one unit of pollution emitted by companies, a cost which depends on the technology available to the companies, which, generally, is possible to quantify precisely. Generally, said cost includes measures for the continuous improvement of processes, the recycling and commercialization of waste, and the use of modern machinery, among others [16]. The social cost of pollution is a much more complicated concept than that describing, in ideal terms, to the monetary value of offsetting the environmental damage caused by pollution, damage which can only be partially quantified. For example, while a company can calculate the costs of purifying the contaminated

[6] *Thus, for example, in 1990, the global flow of FDI was 204,896 millions of dollars, and, by 2000, the global flow of FDI was 1,363,215 millions of dollars. This reached a historic high of 1,871,702 in 2007, and then fell to 1,228,283 in 2014 [11].*

[7] *Developing countries progressed considerably in attracting and receiving FDI. In 1995, these countries received 34,608 million dollars, which represents 17% of global wealth. By 2000, they were receiving 232,216 million dollars, which represents 17% of the global FDI wealth, a figure which had risen to 579,861 million dollars by 2010, representing 44% of global wealth. By 2014, these countries received 681,000 million dollars, representing 55% of global wealth flow [11].*

[8] *Or per unit of prime material used, although the focus on units of production is that most commonly used by the Environmental Protection Agency (USA) and the European Environment Agency [14].*

[9] *Further to which, according to experts in green economy, said standard emissions quotas per sector depend on economic conditions, the location decisions made by companies, and the, occasionally, biased criteria of the commissions of experts [15].*

water discharged by another firm, there are other aspects that cannot be measured with all the precision required and, much less, be translated into monetary terms such as: The costs of the diseases caused by pollution; the effects of the emission of CFCs on the ozone layer; the consequences of the production of vast amounts of CO_2 on global warming and the greenhouse effect; the alteration of certain ecosystems; and, the possible extinction of species, among others [15]. In any case, measuring this cost is at least feasible in theory. The marginal social cost of pollution is known as marginal disutility.

Thus, this study intends to develop a theoretical partial equilibrium model that determines the optimal institutional level, the optimal level of permitted pollution, as well as the optimal quota per unit of pollution emitted, for those foreign companies that invest in the country through FDI. Such a model is applicable for developing economies, such as is the case for Mexico and other Latin American countries, which have lax institutional levels characterized by the presence of economic institutions such as corruption and bribery which are widely used in economic transactions.

The model developed in this study demonstrates that, in order for a country (that complies with the above mentioned conditions) to achieve the greatest level of welfare, it must institute detailed and precise environmental and institutional policies. The welfare function of a country will depend, on the one hand, on the degree of corruption present in the government and the size of the market, and, on the other hand, on the abatement costs per unit of pollution emitted, as well as the social cost of pollution.

The model proposes that, if the legal cost is greater than the illegal cost, that is, the typical situation in a developing country, then, given a high level of corruption, the government will impose the minimum acceptable institutional level. However, if the level of corruption is not high, then the government will implement a positive institutional level. On the other hand, if the social cost of pollution is high in relation to the abatement cost, then the government will establish strict controls, which implies a zero pollution quota. However, when the social cost of pollution is not so high compared to the abatement cost, the government will allow certain levels of contaminant emissions.

These results suggest more profound study of institutional and environmental policies applicable to markets that are not necessarily developed and have precarious institutional levels, such as is the case in Latin American countries and, particularly Mexico, which will facilitate the capture of foreign capital and, simultaneously, the preservation of the environment and its natural resources.

This study is structured in the following way. Beginning with the specification and delimitation of the model (Section 2). Secondly, the optimal institutional level and the optimal pollution quota are calculated, from which applicable institutional and environmental policies are deduced (Section 3). Finally, conclusions are established (Section 4).

2. SPECIFICATION OF THE MODEL

The model supposes the existence of *n* foreign companies that are established in the host country.[10]

These companies produce a certain quantity *X* of an good which is consumed in totality in the host country. The model assumes that there is no competition with local companies, due to the fact that these companies compete under a Cournot-type oligopolistic scheme, and, furthermore, that all production by the *n* companies is consumed by the host country. [11] The marginal cost for foreign companies is *C*, a cost which is constant, and, therefore, equivalent to the average variable costs. [12] For simplicity, the linear demand is considered in the form

$$p = a - bD = a - bnX \tag{1}$$

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

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[10] *This study closely follows the article by [17], which refers to the determination of the optimal institutional level for FDI, but which does not include variables of an environmental type.*

[11] *The fact that the article is uniquely based on FDI is a good characterization of the current situation in many under-developed countries in terms of the production of certain goods. Furthermore, it avoids the theoretical problem consisting in tracking the destination of companies from the receiving country on leaving the market for said good.*

[12] *Implicitly, there is a nummeraire good produced under conditions of perfect competition, and there is only one factor of production whose price is determined in a competitive market.*

[13] *The consumer preferences in the host country can be approximated by a function of direct utility* $(X, \mu) = u(X) + \mu$ *, in the quadratic form* $U = anX - \frac{bn^2X^2}{2} - \mu$*, where X is the good in question, and where μ is the expenditure earmarked for the nummeraire good. Thus, the linear demand emerges from the maximization of this utility function. The use of such approximation avoids many theoretical difficulties, such as the income effect.*

The benefit for each of the *n* companies is given by,

$$\pi = (p - C)X \tag{2}$$

Under the Cournot-Nash assumptions, the optimal quantity of a good produced by any FDI company is,[14]

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

Thus it is possible to express the benefits of the companies as,[15]

$$\pi = bX^2 \tag{4}$$

It is possible to break down the marginal cost into three components,

$$C = c + t + \Delta \tag{5}$$

where *c* is the component of technological cost that depends on the market conditions, t is the unit cost for the reduction of pollution imposed by environmental policy, and Δ is the cost of taxation in relation to the level of institutional efficiency that the company must pay for operational costs.

Now,

$$t = \lambda(\theta - z) \tag{6}$$

Where λ is the marginal cost of reducing one unit of pollution, θ represents the quantity of pollution emitted prior to implementing environmental policy, and z is the pollution quota per unit produced.

With regard to Δ, the model assumes that companies must pay a levy to the government. However, attempts to apply this have to be conducted through dishonest public servants who are susceptible to receiving bribes in return for the elimination or reduction of the companies' fiscal burden. In this way, bribery is considered a real practice that companies must take into account as part of their costs alongside the legal taxes levied by the government.

The model presumes that there are two types of people that live in a country – honest people who work for private companies and dishonest people who are found in the public sector. While this presumption in the model is very strong, it is intuitively based on the generalized understanding that people who work in public service are, to a lesser or greater extent, dishonest (independent of the fact that there could be honest workers in government). On the other hand, there is also the habitual perception that people who work in the private sector possess a higher degree of honesty compared with those working in the private sector.[16] In this way, for reasons of simplicity, net honesty and dishonesty rates in private and public sector workers, respectively, were considered.

However, honest private sector workers receive a transfer from the government, the equivalent to the amount of levies paid by the companies through the legal structure. In turn, dishonest workers earn income through the bribes paid to them by companies.[17] The government, then, can control these amounts distributed by companies through both the legal and illegal structure, thus establishing an institutional level that involves, to some degree, the corrupt practice of public sector workers.

However, dishonest people can lobby the government in order to obtain concessions in terms of the establishment of lax institutional policies which enable them to increase their income through bribes paid by companies. In this way, such lobbying will depend on the level of political corruption in government, namely its degree of susceptibility to receiving contributions from dishonest people.

This lobbying takes place, obviously in the FDI host country, in other words, in the country that will determine the institutional level. Lobbying is modeled following the approach of "political contributions".[18] This focus considers that those

[14] *See appendix 1.*
[15] *See appendix 1 also.*

[16] *For more detail, please see [5].*
[17] *The consideration of the income of honest workers as a remuneration for their work in companies must implicitly take into account the existence of a second good in a competitive market produced in a labor market in perfect competition under constant returns. Such a good is considered a nummeraire good. The two goods require a simple factor of production, which could be work, which is a fixed good under perfect competitive market and full employment. Furthermore, the income of the dishonest is considered as a fixed payment from the government, which, in the interests of the simplicity of the model can be ignored.*
[18] *Grossman and Helpman [18] were pioneers in the development of the focus on political contributions, (derived from the problem of common agency described by [19]). They who used it to analyze the effects of economic policy on the protection of trade with quasilinear preferences. Subsequently, [20] generalized the concept of contributions for general preferences, and were thus able to analyze variability in the marginal utility of income.*

undertaking lobbying make political contributions to the party in power, such contributions are contingent on the political decisions made by the government.[19] As it is a partial equilibrium model, the model proposed in this study will be based on the original focus of [18], which assumes quasilinear preferences.

In summary, the cost of taxation has two components, the legal and the illegal. The legal component is covered by companies through the legal structure enforced by the government (legal option), while the illegal component is covered through an alternative structure (illegal option). Both legal taxation paid to the government and that which is channeled to the dishonest through bribery depend on the efficiency of the institutional framework, which is understood as the legal and institutional environment which is established by the government to regulate economic and political activity in the country. In this way, if the institutions are efficient, a stricter and more effective control is exerted over illegal activities, while, if they are inefficient, a weak and lax control is exerted over such activities.[20] Considering the above, the model assumes that the government establishes the institutional level through reforms to the legal system, and that such reforms are the result of a process of maximization and political lobbying that invokes no cost to implement. As these reforms fall strictly within the legal sphere, both their drafting and modification do not invoke implicit costs.

Based on the foregoing, the government will define the institutional level by means of a parameter α($0\leq \alpha \leq 1$), known simply as the institutional level and, in this way, the cost of taxation Δ can be expressed by,[21]

$$\Delta = \beta\alpha + \gamma(1-\alpha) \quad (7)$$

where α is the level of institutional efficiency, β and γ are the unit cost of the legal and illegal structure respectively. It should be noted that, Δ depends on β, γ and α, observing also that, if α is close to zero, the institutional level is inefficient and, if α is close to 1, then the institutional framework is efficient, independently of the magnitudes of the parameters β and γ. Thus, these two components of the cost of taxation define the efficiency of two types of structure, the legal and illegal. Similarly $\beta\alpha$, the cost of the legal structure, is low when α, the institutional level, is close to zero, and high when α is close to 1. Therefore, based on (5), (6), and (7), the marginal cost of production for the companies is

$$C = c + \lambda(\theta - z) + \beta\alpha + \gamma(1-\alpha) \quad (8)$$

The group of honest people are represented as σ, while the dishonest people are represented as ς, with both types of people homogenous within their same type. It should be noted, then, that, on considering the tax cost, the companies encounter dishonest people, who favor and maintain the illegal structure which provides them with an income through bribes paid to them by companies seeking to cover their tax obligations. In contrast, the honest people work in the private sector, receiving an income through the legal taxation established for the producer. In this way, the indirect utility of the honest people, assuming quasilinear preferences, is defined by

$$I^{\sigma} = \beta\alpha nX + C_s \quad (9)$$

where $\beta\alpha nX$ is the legal payment of tax, the payment of tax obligations, representing income of the honest made in the form of a lump-sum transfer and C_S is the consumer surplus. The function of indirect utility of the dishonest is given by

$$I^{\varsigma} = \gamma(1-\alpha)nX \quad (10)$$

Obviously, the income of the dishonest constitutes the bribes that they receive from companies, supposing, furthermore, that such people do not consume the good.[22]

[19] In the taking of economic decisions in general, the political process is fundamental to that which relates to matters of international policy [21]. Particularly, the pressure and influence of interest groups has been widely studied in international economics. Thus, there are diverse approaches to modeling the political equilibrium, with for example: the tariff-formation function approach [22], the political support function approach [23], the median-voter approach [24], the campaign contribution perspective [25] and the political contributions approach [18].

[20] An institution is viewed as the rules of the game to which all the economic, social and political actors agree and accept to play.

[21] The range defined for α will enable this study to consider from an absolutely inefficient level (α=0) up to a level of maximum efficiency (α=1).

[22] Furthermore, it can be considered that dishonest people receive a fixed salary, w. Such as salary is independent of the level of production and is relatively low (for which reason it is an incentive to stop receiving bribes) and homogenous for all dishonest people. In this case, due to the additive nature of the indirect income of the dishonest, it does not affect the results for the model and, for reasons of simplification, it can be ignored.

The institutional level α is an instrument of government economic policy and is established by a political equilibrium. Such equilibrium is calculated based on [20]. In such a case, while honest people do not pressure the government, dishonest people do make political contributions in order to influence governmental decisions. This political contributions scheme is $\Omega(\alpha, I^{\varsigma})$ and, as can be seen, depends on the institutional parameter and the indirect utility of the dishonest. In this way, the function of the welfare function of government (without yet considering the adverse effect of pollution) is given by,[23]

$$\overline{G} = \rho\Omega + I^{\sigma} + I^{\varsigma} + n\pi \tag{11}$$

where ρ is the level of political corruption, ρ is a constant parameter greater than 1, then, if $\rho=1$, there is no effect of the contributions on political decisions. Equation (11) expresses the fact that the government considers the country's welfare as the sum of the total welfare of honest and dishonest citizens (I^{σ},I^{ς}), FDI ($n\pi$), and the total amount of contributions it receives ($\rho\Omega$). Based on [20], political equilibrium is the result of a two stage game. In the first stage, dishonest people choose their contributions scheme. Then, in the second stage of the game, the government sets its institutional policy. Thus, the political equilibrium is given, in the first place, by a function of political contributions, $\Omega^*(\alpha, I^{\varsigma})$, which maximizes the welfare of the dishonest when the government has previously optimized its institutional policy, and, in the second place, by a political variable, α^*, which maximizes the objective function of government given by (11), taking the contributions scheme as given.

Dixit et al. [20] develop a reliable concept of equilibrium that obtains efficient results, as described by Pareto. Formally, if $(\Omega^0(\alpha^0, I^{\varsigma^0}), \alpha^0)$ is a reliable equilibrium in which I^{ς^0} is the per-capita equilibrium level of utility for the dishonest, then, for quasilinear preferences $(\Omega^0(\alpha^0, I^{\varsigma^0}), \alpha^0, I^{\varsigma^0})$, it is defined by,

$$\Omega(\alpha, I^{\varsigma^0}) = max(0, \delta) \tag{12}$$

$$\alpha^0 = arg\,max_{\alpha}\{\rho\Omega(\alpha, I^{\varsigma^0}) + (I^{\sigma}(\alpha) + I^{\varsigma^0})\} \tag{13}$$

$$I^{\varsigma^0} = I^{\varsigma} - \delta \tag{14}$$

Equations (12) and (14) express that the reliable contributions scheme remains established at the level of the relative compensatory variations in the per-capita equilibrium level of utility for the dishonest. δ is the magnitude of the contributions, and $\delta>0$ is the basic concept of compensatory variations. These contributions are equal to the increase in the utility of the dishonest as a response to a political decision. Thus, supposing a function of payment of reliable equilibrium, any variation in the parameter δ will cause a variation in the contribution obtained by the government and will be the equivalent of the variation in the welfare of the dishonest, if the payment of both before and after the change is positive.

In Equation (13), the government takes the level of utility of the dishonest as given and, in this way, chooses the institutional level that optimizes its objective function (Equation 11).[24]

Grossman and Helpman [18] affirm that, in the event of there being only one pressure group undertaking lobbying with no opposition from competing interests, such a group would obtain the totality of the surplus through its political relationship with the government. Therefore, in this political equilibrium, the government obtains the same utility as that which would be obtained if no contribution had been received.

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. This is given by the production of each company multiplied by the number of FDI companies participating in the market of the host country and the pollution quota permitted per unit of product, which is,

$$Z = znX \tag{15}$$

If ϕ is taken as the marginal disutility caused by pollution, as in [26] and [27], it can be assumed that ϕ is constant.[25] Therefore, ϕZ represents the total disutility due to the emission of pollutants in the country, namely the social cost of pollution, and is defined by

$$\phi Z = \phi znX \tag{16}$$

[23] *See [17].*

[24] *See [20] for a more detailed explanation of the characterization of $\Omega((\alpha^0, I^{\varsigma^0}), \alpha^0, I^{\varsigma^0})$ which includes preferences different to the quasilinear.*

[25] *Other authors such as [28] consider that marginal disutility is a growing function that depends on the companies' levels of production.*

Therefore, the function of utility of the government G can be generally constructed as described below,

$$G = \rho\Omega + I^{\sigma} + I^{\varsigma} + n\pi - \phi Z \quad (17)$$

Now, it is possible to substitute in (3), the marginal cost of production given in (8), giving,

$$X = \frac{a-\left(c+\lambda(\theta-z)+\beta\alpha+\gamma(1-\alpha)\right)}{b(n+1)} \quad (18)$$

To finalize, the number of companies can be taken as endogenous, in that the government is able to influence the input and output dynamic for FDI companies through decisions which affect the instruments of economic policy. It can also be supposed that the host country is small in the FDI market, in that companies can enter and leave the host country should this by warranted by the global FDI market conditions. In this way, the condition of FDI equilibrium is defined by,

$$\pi = \overline{\pi} \quad (19)$$

Then, from (18), (4), (8) and (19), the particular solution for X can be obtained as follows

$$X = \sqrt{\frac{\pi}{b}} = \sqrt{\frac{\overline{\pi}}{b}} \quad (20)$$

and solving n in (18), results in

$$n = \frac{a-c-\lambda(\theta-z)-\beta\alpha-\gamma(1-\alpha)}{b\sqrt{\frac{\overline{\pi}}{b}}} - 1 \quad (21)$$

$$n = \frac{a-c-\lambda(\theta-z)-\beta\alpha-\gamma(1-\alpha)}{\sqrt{b\overline{\pi}}} - 1 \quad (22)$$

$$n \geq 1 \quad (23)$$

with which the specification of the model is concluded.

3. OPTIMAL INSTITUTIONAL LEVEL AND OPTIMAL POLLUTION QUOTA

The objective of the model previously established is to obtain the optimal institutional level from the parameters, such as the level of corruption and marginal disutility of polluting. In other words, the model will consider such aspects as the legal, technological, economic and environmental type in the determination of the internal political equilibrium. Beginning with two closely related scenarios of corruption, with, on the one hand, the corruption of dishonest people in public service, which can influence political decisions, and, on the other, the corruption of the political process in government, which can be considered exogenous. These two scenarios can coexist and are, very probably, closely related. However, on considering some type of relationship between the two, similar results were obtained with the results from this model. They were, thus, managed independently for the sake of simplicity. Therefore, only the optimal institutional level will be determined, as will, subsequently, the optimal pollution quota that enables the maximization of the function of utility of the government and the implications of such optimal levels of welfare.[26] Differentiating n with respect to α gives,

$$\frac{dn}{d\alpha} = \frac{\gamma-\beta}{\sqrt{b\overline{\pi}}} = \frac{\gamma-\beta}{b\sqrt{\frac{\overline{\pi}}{b}}} \quad (24)$$

$$\frac{dn}{d\alpha} = \frac{\gamma-\beta}{bX} \quad (25)$$

which is,

$$\frac{dn}{d\alpha} > 0 \quad if \quad \gamma > \beta \quad and \quad (26)$$

$$\frac{dn}{d\alpha} < 0 \quad if \quad \gamma < \beta \quad (27)$$

Formally, the last two equations can be expressed in the next proposition:

Proposition 1. *The number of companies entering in the host country depends on the parameters γ and β as follows:*

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

This implies that, if the illegal option is more costly than the legal option, then $\frac{dn}{d\alpha} > 0$, which means that the illegal structure is more inefficient, for which reason companies prefer the cost of taxation of the legal structure. In others words, the legal option is more convenient and cheaper, causing a decrease in the companies' marginal costs and the consequent entry of more companies through FDI. On the contrary, if the legal option is more expensive than the cost of the illegal structure, companies prefer this illegal route through bribes to dishonest public servants, which significantly increases the marginal costs and is a disincentive to the entry of more

[26] *See [17].*

companies through FDI. In other words, if $\gamma>\beta$ the number of foreign companies in the country increases, while, if $\gamma<\beta$ their number decreases.

If, on the other hand, differentiating *n* with respect to *z*, the following is obtained

$$\frac{dn}{dz} = \frac{\lambda}{bX} \tag{28}$$

It should be noted that

$$\frac{dn}{dz} > 0 \tag{29}$$

This implies that the entry of companies through FDI will be more likely with the widening of the pollution quota imposed by the government. From (20) the following is obtained,

$$\frac{dX}{d\alpha} = 0 \tag{30}$$

$$\frac{dX}{dz} = 0 \tag{31}$$

The results above imply that the effect of an increase in the institutional level and the optimal pollution quota for companies' level of production is neutral, in that FDI automatically adjusts the modification in the product. To determine the optimal institutional level, the first order conditions are obtained,

$$\frac{dG}{d\alpha} = \frac{d(\rho\Omega + I^{\sigma} + I^{\varsigma} + n\pi - \phi Z)}{d\alpha} = 0 \tag{32}$$

Thus for (9), (10), (16), (17), (25) and (30), the following is obtained (on differentiating each of the terms from the previous expression),[27]

$$\alpha^{*} = \frac{-b\Big((\gamma-\beta)\big(-X(n+1)+b^{-1}(z\phi-\gamma\rho)\big)+nX(\gamma\rho-\beta)\Big)}{(\gamma\rho-\beta)(\gamma-\beta)} \tag{33}$$

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

$$\frac{dG}{dz} = \frac{d(\rho\Omega + I^{\sigma} + I^{\varsigma} + n\pi - \phi Z)}{dz} = 0 \tag{34}$$

Thus from (9), (10), (16), (17), (28), and (31) the following is obtained (on differentiating each of the terms from the previous expression),[28]

$$z^{*} = \frac{b\big(X\lambda - nX(\phi-\lambda) + b^{-1}\alpha\beta\lambda + b^{-1}\lambda\gamma\rho(1-\alpha)\big)}{\lambda\phi} \tag{35}$$

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

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

From which, the condition of concavity would be,

$$\beta > \gamma\rho \tag{36}$$

In this case, the illegal structure is less costly than the legal structure, which is the situation most closely resembling those in certain developing countries. Thus, the existence and permanence of these illegal structures is explained, as these options are more efficient than the legal structures. In this way, FDI companies take advantage of bribery in response to the inefficiency of the formal administrative processes. Thus, following [1], the illegal structure is consolidated as an institution, with this institution having the objective of reducing or eliminating the uncertainty caused by an inefficient and uncertain administrative and legal system.

The second order condition for *z* is given by,[30]

$$\frac{d^2G}{dz^2} = -\frac{\lambda(2\phi-\lambda)}{b} < 0 \tag{37}$$

From which the condition of concavity would be,

$$2\phi > \lambda \tag{38}$$

Such a condition implies, in intuitive terms, that the abatement cost is not excessively high compared to the social cost of pollution, which ensures that production costs are not higher, and which, in turn, guarantees a certain level of competitiveness for those companies that do not have to load higher costs onto price levels to the detriment of the consumer.

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

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

It can observed that, the sign for α^* depends on $z\phi$-$\gamma\rho$. In this case, the magnitude of the institutional level depends on the level of corruption in government and the size of the market. If the level of corruption is very high, the government will impose a minimum institutional

[27] *See appendix 2.*
[28] *See appendix 3.*
[29] *See appendix 4.*
[30] *See appendix 4 also.*

level, while if the level of corruption is low, the government will impose a positive institutional level. Furthermore, in this case, the weight of the size of the market will make its presence felt. Formally, these can be expressed in the following way:

Proposition 2. *If the cost per unit of product from the legal structure is greater than the illegal structure, then*

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

For the first case, $\gamma\rho$ is the measure per unit produced from the illegal cost reinforced by the level of corruption in the political system and $z\phi$ is the measure per unit produced from the social cost of pollution. In this way, if the social cost of pollution is relatively low, is favored the contribution of dishonest in the utility function of the government, because the legal structure is inefficient and the level of corruption is high, in exchange for the social costs of pollution that this would imply.

In order for this to occur, the level of corruption in government must be high and, in this case, the government will favor those policies that maximize its income through the contributions of dishonest people that, in turn, will increase its coffers, given that the companies will prefer the illegal structure over the legal, paying bribes. Obviously, the government will attempt to facilitate the situation by being completely lax. The FDI will also be benefitted by opting for the illegal channels, due to them being the most efficient option. In terms of the income received by the honest, governmental transfers decrease, while consumer surplus increases. In this situation, the social cost of pollution is relatively low, for which reason, the government enjoys its largest income from the contributions of the dishonest, also increasing both the FDI producer's surplus and the income of honest people. In other words, the institutional policy that maximizes general welfare is that which establishes a zero institutional level policy.

In the event that $z\phi$, the measurement per unit produced for the social cost of pollution, is higher than $\gamma\rho$, which is the measurement per unit produced from the illegal cost as 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 the function of governmental utility, starting at a relatively low level of corruption. Therefore, the government places more value on the introduction of a greater institutional level and the beneficial effect FDI can bring, benefits for both the producer and consumer and even in the income of honest people, consequently reducing the benefit that dishonest individuals receive from bribery. In this case, the magnitude of the institutional level is facilitated by the size of the market, in that, when larger, the government stimulates a higher level of FDI entry, favoring the legal channels. This impacts directly on the benefits for the producer and consumers (who, furthermore, are the honest people who participate in the production of a good), although there is a decrease in terms of political contributions. When the market is small, so is the impact on the general function of welfare (or the function of governmental utility), in that the institutional level established by the government is positive. Therefore, if the level of corruption is low, the government establishes a positive institutional level, in that, although there is an obvious fall in the contribution from the dishonest, the government values more, to the extent that the market size is larger, the benefit obtained by honest people and FDI.

On the other hand, if we consider the optimal pollution quota, given that,

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

the sign for z depends on ϕ-λ. So, we can deduce the next proposition:

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

$$z^* = 0 \quad if \quad \phi \gg \lambda$$
$$z^* > 0 \quad if \quad \phi \ll \lambda$$

In this case, if the marginal disutility is much greater compared to the abatement cost, the best environmental policy is to completely prohibit the emission of pollutants. In this case, the social cost of pollution is very high due to the fact that the government attempts to impede the pollution produced by companies, although this elevates the costs of production and is directly prejudicial to profits from FDI, the income received by the honest and transfers from government. Furthermore, if ϕ is sufficiently high in relation to λ, the variables for corruption ρ, illegal cost γ, legal cost β and institutional level

α, only the magnitude of ϕ is adjusted to set the minimum level of pollution to be imposed by government.

When $\phi > \lambda$, but is not sufficiently high compared to λ, governments allow certain pollution quota for companies, which increases their competitiveness in terms of the reduction of production costs that this implies. Furthermore, consumer surplus is seen to be clearly favored by the impact that such reduction has on company costs, and, thus, the income received by the honest increases considerably. Under these circumstances, clearly the size of the market has a direct relationship with the magnitude of the pollution quota, which, when high, the size of both consumer and producer surpluses and transfers from government also increase. It is also notable that the variables for corruption and both illegal and legal cost have a direct effect on the magnitude of z, although it is weighted for the level of institutional development (note that α appears in the two remaining factors for z^* as α and $1-\alpha$ respectively) in order to set the emissions level imposed by the government.

4. CONCLUSIONS

In terms of what is referred to as the institutional level, a high level of corruption, given that the legal structure is inefficient, favors the contribution of the dishonest in the function of utility of the government, in exchange for the social costs of pollution that this can imply. The government would, then, favor policies that maximize its income through the contributions made by dishonest people that, in turn, increase their profits, given that companies prefer the illegal structure over the legal structure, namely the paying of bribes. Obviously, the government attempts to facilitate this situation with a minimal institutional level. In terms of the income received by the honest, on the one hand, consumer surplus increases, while, on the other, transfers from government decrease. It will be seen that FDI will benefit from the decision to choose the illegal option, in that it is rationally better compared to the legal option, which, in this sense, is considered costly. In this case, the social cost of pollution is relatively low, and, under these circumstances, the government establishes a policy of zero institutional level.

If the level of corruption is low and, given that the legal structure is inefficient, the contribution of the dishonest is valued on a much lower scale on the function of utility of the government. In this case, the government values more the introduction of a greater institutional level and the benefits this brings for FDI and the consumer, and even the income received by honest people through transfers, decreasing the benefits dishonest people receive from bribes. In this case the social cost of pollution is relatively high. In such a situation, the institutional level is seen to be favored by the size of the market, in that the larger the market, the higher the level of FDI entry will be induced by the government, thus facilitating the legal routes, which, in turn, brings benefits for both the producer and the consumer. However, there is a decrease in terms of political contributions.

Now, focusing on environmental policy, if marginal disutility is very high compared to the abatement costs, optimal environmental policy completely impedes the emission of pollutants. In such a situation, due to the social cost of high levels of pollution, the government prevents companies from polluting, even though production costs will be raised, which impacts negatively on FDI profits and the income received by honest people.

When the disutility of polluting is not sufficiently great compared to the abatement cost, the government authorizes a positive pollution quota for the companies, as this favors competiveness by reducing their costs, an effect from which consumers would also benefit. In such circumstances, the size of the market impacts on the magnitude of the pollution quota, which, if high, increases both producer and consumer surpluses, and the income received by the honest.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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MATHEMATICAL APPENDIX

1. Maximization of Production

In accordance with the Cournot-Nash conditions, *n* companies determine their level of production, taking into account the expected level of production from the remaining *n-1* companies. Therefore, the optimal level of any company is obtained in the following way, Substituting *p* (1), for *π* (2) gives:

$$\begin{aligned}
\pi &= (a - bnX - C)X \\
\pi &= (a - bX - b(n-1)X - C)X = (a - bX - b(n-1)X_i - C)X \\
\pi &= aX - bX^2 - b(n-1)XX_i - CX
\end{aligned} \tag{39}$$

Differentiating with respect to *X*,

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

then,

$$\frac{d\pi}{dX} = a - C - bX(n+1) = 0 \tag{40}$$

for which reason,

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

but *p*=*a*-*bnX*, then

$$Xb = p - C \tag{41}$$

Substituting (41) in (2), gives:

$$\pi = bX^2 \tag{42}$$

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,

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

2.1 Derivative from political contributions

$$\begin{aligned}
\frac{d(\rho\Omega)}{d\alpha} &= \rho\left(\frac{dI^{\varsigma}}{d\alpha} + \frac{dI^{\varsigma^0}}{d\alpha}\right) = \rho\frac{dI^{\varsigma}}{d\alpha} \\
\frac{d(\rho\Omega)}{d\alpha} &= \rho(b^{-1}\gamma(1-\alpha)(\gamma-\beta) - n\gamma X)
\end{aligned}$$

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

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

then,[31]

$$\frac{d(\rho\Omega)}{d\alpha} = \rho(b^{-1}\gamma(1-\alpha)(\gamma-\beta) - n\gamma X) \qquad (43)$$

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,

$$\frac{d(I^\sigma)}{d\alpha} = b^{-1}\alpha\beta(\gamma-\beta) + n\beta X + Xn(\gamma-\beta) \qquad (44)$$

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,

$$\frac{d(n\pi)}{d\alpha} = X(\gamma-\beta) \qquad (45)$$

2.4 Derivative from the social cost of polluting

$$\frac{d(\phi Z)}{d\alpha} = \frac{d(\phi znX)}{d\alpha} = \phi zX\frac{dn}{d\alpha} = \phi zX\frac{\gamma-\beta}{bX}$$

then,

$$\frac{d(\phi Z)}{d\alpha} = b^{-1}\phi z(\gamma-\beta) \qquad (46)$$

2.5 Determination of *α**

adding (43), (44), (45), (46) and, simplifying, gives,

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

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

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

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[31] *Differentiating this component of the function of utility of government implicitly obtains the derivative from the indirect utility of the dishonest [20].*

3. Optimal Pollution Quota

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

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

3.1 Derivative from the political contributions

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

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

$$\frac{d(I^{\varsigma})}{dz} = \frac{d(\gamma(1-\alpha)nX)}{dz} = \gamma X(1-\alpha)\frac{dn}{dz} = \gamma X(1-\alpha)\frac{\lambda}{bX}$$
$$\frac{d(I^{\varsigma})}{dz} = b^{-1}\gamma\lambda(1-\alpha)$$

giving,

$$\frac{d(\rho\Omega)}{dz} = b^{-1}\rho\gamma\lambda(1-\alpha) \quad (47)$$

3.2 Derivative from the indirect utility of the honest

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

differentiating term to term gives,

$$\frac{d(\beta\alpha nX)}{dz} = \alpha\beta X\frac{dn}{dz} = \alpha\beta X\frac{\lambda}{bX}$$
$$\frac{d(\beta\alpha nX)}{dz} = b^{-1}\alpha\beta\lambda$$
$$\frac{d(C_S)}{dz} = \frac{d\big(b(nX)^2/2\big)}{dz} = \frac{d\big(bn^2X^2/2\big)}{dz} = (bX^2/2)\frac{dn^2}{dz} = (bX^2/2)2n\frac{dn}{dz} = bX^2n\frac{\lambda}{bX}$$
$$\frac{d(C_S)}{dz} = Xn\lambda$$

then, the previous equations result in,

$$\frac{d(I^{\sigma})}{dz} = b^{-1}\alpha\beta\lambda + Xn\lambda \quad (48)$$

3.3 Derivative from the benefits of FDI

$$\frac{d(n\pi)}{dz} = \frac{d\big(nbX^2\big)}{dz} = bX^2\frac{dn}{dz} = bX^2\frac{\lambda}{bX} = X\lambda$$

for which reason,

$$\frac{d(n\pi)}{dz} = X\lambda \quad (49)$$

3.4 Derivative from the social cost of polluting

$$\frac{d(\phi Z)}{dz} = \frac{d(\phi znX)}{dz} = \phi X\frac{d(zn)}{dz} = \phi X\left(z\frac{dn}{dz} + n\frac{dz}{dz}\right) = \phi X\left(z\frac{\lambda}{bX} + n\right) = Xn\phi + b^{-1}z\lambda\phi$$

then,

$$\frac{d(\phi Z)}{dz} = Xn\phi + b^{-1}z\lambda\phi \quad (50)$$

3.5 Determination of *z**

Adding (47), (48), (49) and (50) gives,

$$\frac{dG}{dz} = b^{-1}\rho\gamma\lambda(1-\alpha) + b^{-1}\alpha\beta\lambda + Xn\lambda + X\lambda - Xn\phi - b^{-1}z\lambda\phi$$

making $\frac{dG}{dz} = 0$, and solving *z* gives the optimal pollution quota,

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

4. Conditions of Concavity

4.1 For the institutional level

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

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

differentiating term to term gives,

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

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

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

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

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

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

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

adding the previous terms results in,

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

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

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 quota

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

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

the first, second and fourth terms are equal to zero, developing the remainder gives:

$$\frac{d(Xn\lambda)}{dz} = X\lambda\frac{dn}{dz} = X\lambda\frac{\lambda}{bX} = b^{-1}\lambda^2$$
$$\frac{d(Xn\phi)}{dz} = X\phi\frac{dn}{dz} = X\phi\frac{\lambda}{bX} = b^{-1}\phi\lambda$$
$$\frac{d\left(b^{-1}z\lambda\phi\right)}{dz} = b^{-1}\lambda\phi\frac{dz}{dz} = b^{-1}\lambda\phi$$

adding the previous terms,

$$\frac{d^2G}{dz^2} = b^{-1}\lambda^2 - b^{-1}\phi\lambda - b^{-1}\phi\lambda = -b^{-1}\lambda(2\phi - \lambda)$$

for which reason,

$$\frac{d^2G}{dz^2} = -\frac{\lambda(2\phi-\lambda)}{b}$$

thus *G* is concave if and only if $2\phi-\lambda>0$, namely, $2\phi>\lambda$.

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