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AN ANALYSIS ON THE NETWORK ACCESS PRICING RULES

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RÉSUMÉ

C'est une tendance mondiale qui introduit de la compétition aux industries de réseau auparavant monopolistes. Afin d'augmenter le bien-être, les régulateurs de différents juridictions dépensent beaucoup d'effort pour restructurer les industries de manière efficace via la sélection adéquate, le design et l'implémentation de régimes d'un prix d'accès.

Dans ce mémoire, on analyse quelques principes généraux, des faits fondamentaux et des points critiques sur le développement de réseaux et l'accès à ces derniers. Ensuite on continue avec une discussion sur les théories classiques de prix d'accès : la règle efficiente d'attribution de prix (ECPR, Efficient Component Pricing Rule), la règle d'attribution de prix de Ramsey, la limite globale de prix, et la politique d'attribution de prix selon les coûts. Après on applique les options réelles et on calcule les moments optimaux d'investissement pour deux cas: avec ou sans la menace d'une compagnie entrante. Finalement, on conclut ce mémoire en interprétant les résultats de l'analyse et en fournissant quelques conséquences des politiques choisies.

Traditionnellement, l'attribution de prix prend en considération l'utilisation efficiente du réseau; ce mémoire décrit l'impact du prix d'accès sur l'incitation pour investir au réseau.

On n'emploie que la recherche secondaire, y compris des périodiques, des monographies et sources de l'internet. L'une des limitations majeures de ce mémoire est qu'on n'emploie pas des données réelles des problèmes pratiques parce qu'il s'agit d'une analyse générale.

Mots-clés: options réelles, développement de réseaux, accès aux réseaux, politique d'attribution de prix d'accès, réglementation

ABSTRACT

There is a worldwide trend to bring competition into the formerly monopolistic network industries. To increase total welfare, regulators across different jurisdictions spend significant amount of resources aiming to effectively and efficiently restructure the industries via proper selection, design, and implementation of access pricing regimes.

In this mémoire, I first review some general principles, fundamental facts, and critical issues regarding network development and network access. Secondly, I proceed with a discussion on the "classical" access pricing theories including Efficient Component Pricing Rule (ECPR), Ramsey Pricing Rule, Global Price Cap, and Cost-based Pricing Rule. Thirdly, I present the real option approach of calculating the incumbent's thresholds of investment under two different assumptions: with and without the threat of entry. Finally, I conclude the paper by interpreting the results of the analyses and providing some policy implications.

Traditionally, access pricing deals with the efficient use of existing network; my contribution with this mémoire is to characterise the impact of access price on the incentives to invest in network development.

Only secondary research method is employed, including journals, books, and internet resources. One of the main limitations of this mémoire is the fact that real-life data on practical problems encountered are not employed due to the nature of this generalized analysis.

Keywords: real options, network developments, network access, access pricing rules, regulations

LISTE D'ABRÉVIATIONS

CRTC: Canadian Radio-television and Telecommunications Commission, 50

ECPR: Efficient Component Pricing Rule, 13

FCC: Federal Communications Commission, 34

FDC: Fully Distributed Cost, 31

GAAP: Generally Accepted Accounting Principles, 32

GBM: Geometric Brownian Motion, 43

GPC: Global Price Cap, 27

LRAIC: Long Run Average Incremental Cost, 31

LRIC: Long Run Incremental Cost, 52

M-ECPR: Market Determined Efficient Component Pricing Rule, 20

TELRIC: Total Element Long Run Incremental Cost, 34

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[1] CIRANO: Centre interuniversitaire de recherche en analyse des organisations / Center for Interuniversity Research and Analysis on Organizations, Montréal

1 INTRODUCTION

In industries such as electricity transmission, natural gas transportation, railway tracks, and local telecommunication services, final product supply typically requires access to essential[2] facilities, in particular, the networks. There is typically a dominant firm that possesses and controls the supply of one or more inputs that are vital for its competitors. There is a worldwide trend to bring competition into the formerly monopolistic network industries. To increase total welfare, regulators across different jurisdictions spend significant amount of resources aiming to effectively and efficiently restructure the industries via proper selection, design, and implementation of access pricing regimes.

The access prices are the prices charged by the dominant firm for connection to its network, so that the competitors could be able to provide service to their end users. If the network owner charging for interconnection is also a supplier of the final product that travels through the network, it has an obvious incentive to overcharge the competing companies; not only to enhance revenue, but also to increase the competing company's cost and thus to effectively block entry. Therefore, a fair access pricing rule is useful for easing hostile competition and improving efficiency. Extra care must be taken in forming the regulation, as a failure to select the appropriate pricing rule might result in the potential gains from restructuring network utilities not being maximized and/or shared fairly between the users and the owners of the essential facilities (Valletti & Estache, 1998).

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[2] In terms of essentialness, for example, under Canadian legislation, the network is typically required as an critical input by competitors to provide services in a relevant downstream market; it is usually controlled by a firm that possesses upstream market power such that withdrawing mandated access to the facility would likely result in a substantial lessening or prevention of competition in the relevant downstream market; and last but not least, it is not practical or feasible for competitors to duplicate the functionality of the facility (CRTC, 2008).

2 ACCESS PRICING: FUNDAMENTAL FACTS & ISSUES

With the traditionally vertically integrated and heavily regulated network industries undertaking transition toward a more competitive environment and structure, there is a global movement toward deregulation, restructuring and privatization. Although monopolistic or oligopolistic markets are known for achieving high level of coordination and in turn benefiting the society with their economies of scale, it is believed that the competitive market structure is the most efficient way to credibly incite firms to provide efforts in minimizing costs and to offer their different classes of clients and customers the best quality products optimally matched to their specific needs (Boyer & Robert, 1998).

However, it may not be desirable to introduce competition in all segments of the network industry because some of them are subject to economies of scale and the services of essential facilities is sometimes too costly or inefficient to duplicate. The stages of production that are necessary inputs to the potentially competitive segments should remain monopolies. Thus, one of the main policy focuses of promoting effective competition should be a regulated environment guaranteeing that competitors have sufficient access to the networks.

2.1 Background Information

Duplication of the networks is generally considered economically unprofitable, socially undesirable or simply infeasible. For instance, it would make little sense to build and maintain two parallel electricity transmission networks in the same geographical area. However some activities which use the network as an input, or, in other words, a mean to transfer the goods and services, are in fact potentially competitive. The benefits of economies of scale are less important over certain links where the "*invisible hand*" could bring about efficient level of suppliers and hence competitions. For example, the generation of electricity, the exploration and production of natural gas, the supply of long distance telecommunication services, and the supply of passenger and freight services.

It is therefore important to first separate the network itself from the goods and services traveling through it then identify the bottleneck and the potentially competitive segments of the network.

2.2 The Role of the Regulatory Commission

Taking into account the critical role of the essential facilities as a compulsory input, also the considerable initial capital layout associated with the investment, the owners of the networks are regarded as having certain amount of monopolistic powers. How to promote efficiency and to determine the level of goods and services provided that is both economically and socially optimal are thus the central policy issues to be considered.

The regulatory commissions are responsible for setting the rules to prevent the incumbent from exercising market power and predatory self-dealings, to make certain that the proper goods and services are produced, and to ensure that the firms with access to essential facilities are the most efficient in using it. For the potential competitive segments, by carefully selecting access pricing scheme to allow the entrants to use the network facilities and to compete with the natural monopolies, the regulatory commissions could rely on the market forces to lead to an efficient number of parallel suppliers ensuring an adequate level of competition to emerge (Boyer & Robert, 1998).

2.3 The Importance of the Appropriate Access Pricing

Increasing competition and the associated demand for access to the network raise the important question: what is the reasonable access price to be charged?

When the price is too low, the incumbent has no incentive for investment and innovation. It is equivalent to providing a subsidy to the entrant and encouraging inefficient entry. In other words, if the income from granting the access is not sufficient to cover sunk costs, the network provider is simply not compensated enough to take on the project or maintain the network; thereby social welfare is reduced due to future insufficient supply of final goods and services.

When the price is too high, the efficient entrants are discouraged from entering, which in turn causes competition not to prevail. Also, the competitors may begin to have incentive to inefficiently bypass the incumbent's facilities. In this case, the current social welfare will be reduced because of the reduction in competition.

In addition, in terms of appropriate access pricing there are two policy implication of particular importance: first, the long-term impact on infrastructure construction as well as the associated productive efficiency (the cheapest cost for a given output mix) and allocative efficiency (the best product mix for society for a given level of scarcity of recourses); and second, the profits enjoyed by entrant and incumbent.

In the following, several access pricing rules will be introduced. It is important to determine the proper regulation for attaining an efficient allocation of resources via setting efficient access charges. Hypothetically, under the optimal pricing scheme, it will be the incumbent's best interest to grant the most efficient firms with access to the bottleneck segments, even if this means bringing in competition into the previously monopolistic or oligopolistic environment.

3 ACCESS PRICING RULES

The classical methods introduced below are static; therefore, they assume prospective events with certainty and do not account for stochastic changes in cash flows. Also they generally disregard the significance of sunk costs and the irreversibility of the investments.

All the following access pricing methods have their advantages and disadvantages. The quality of the pricing rules should be judged on their effectiveness of encouraging competitions, avoiding inefficient bypasses, as well as creating incentives for both timely and efficient investment, maintenance, and utilization of network infrastructures.

3.1 The Efficient Component Pricing Rule: (ECPR)

3.1.1 General Information

As discussed in Baumol & Sidak (1994), Laffont & Tirole (1994) and Armstrong et al. (1996) the "Baumol-Willig Efficient Component Pricing Rule" (ECPR) basically states that the appropriate access price charged by the incumbent to the providers of a complementary component or service, which the incumbent also produces, is a fee equal to the sum of the average incremental costs of the access and the incumbent's opportunity costs of providing the access, including any forgone revenues from a associated reduction in the incumbent's sales of the complementary component. Hence, it is often expected the access price to exceed the direct incremental costs of access.

Access price = Direct incremental costs of access + Incumbent's opportunity costs of providing access (lost revenue)

ECPR ensures that competitors of the complementary component would decide to enter the market only if they are at least as efficient as the incumbent in the production of the complementary component; i.e. the ECPR ensures that the production will not be diverted to an inefficient producer since only firms who are more efficient than the incumbent will find it profitable to enter the market and access the network.

3.1.2 The Assumptions of the ECPR

The ECPR holds only under some very restricted assumptions. For example, it is assumed that the incumbent's price for the complementary service has been based on a marginal-cost pricing rule; the incumbent's and the competitors' components are perfect substitutes; the production technology of the component experiences constant return to scale; the competitors have no market power; and the incumbent's marginal cost of production of the component can be accurately observed. The application of ECPR rule is thus considered relatively complicated due to the complexity of the assumptions (Armstrong, Doyle, & Vickers, 1996).

3.1.3 The Logic of the ECPR

Suppose that there are two firms in a network industry: namely, an incumbent and an entrant, both of which produce a homogeneous product using the same network as an input. The price of the incumbent's final product is fixed by regulation[3] and hence the total quantity demanded is fixed as well. The entrant is a "price taker" and assumed to take the incumbent's price of the final product as given.

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[3] The assumption, that the final prices being optimally set by the regulator to eliminate monopoly rent, is observed often in real practice.

Based on the ECPR, the access price should be set as the following: $a = c_i + (p - c_m)$

a	$\equiv$	Price of a unit of access
c_i	$\equiv$	Incumbent's incremental (direct marginal) costs incurred from giving the access to an entrant
p	$\equiv$	Given price of the final product
c_m	$\equiv$	Incumbent's marginal cost of production (including both the cost of upstream essential facility and the downstream products)
$p - c_m$	$\equiv$	Incumbent's marginal profit from supplying final product itself; the marginal opportunity cost incurred by the incumbent in providing a unit of access to the entrant

When $p = c_m$, the access price is priced to be equal to the incumbent's incremental costs incurred from giving access to the entrant, thus $a = c_i$.

The logic of the ECPR will be readily demonstrated by a numerical example in terms of natural gas transmission services (the other industries mentioned above could be easily applied).

The incumbent owns the network of pipelines P, processes natural gas at site S, and then transfers it to residential and commercial customers, denoted C_r and C_c respectively, via P. All of the customers must receive the product through the incumbent's network. There is at least one other potential or actual natural gas producer/processor that could supply its product to the customers. However, we assume that the competitor only owns the production facilities at site $S*$; while the incumbent owns both the production facilities at site S and the network P. Therefore, P is the bottleneck, and S is the complementary component that is potentially under competition.

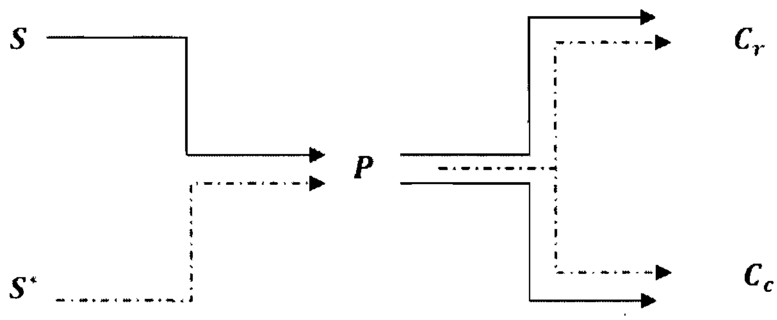

Figure 1. Illustration of a network system with the incumbent and the entrant.

Suppose that the incumbent charges a price of $10/MMBTU for transferring a unit of natural gas to C_r or C_c from S via P. Suppose further that the incumbent's marginal cost of providing this service is $2 for segment SP and $5 for segment PC_r or PC_c (including the relevant marginal costs of network P). The EPCR simply states that the appropriate price or fee for the incumbent to charge to the competitor for having access to network P and for providing the product to C_r or C_c via the network P is $8: the $5 of marginal cost relevant to segment PC_r or PC_c plus the forgone net revenue of $3 that the monopolist loses when the rival for transferring natural gas to C_r or C_c from S* via P in lieu of the incumbent.

If the rival is being charged a fee of $8 for access, and the incumbent is charging $10 as its price for SPC_r or SPC_c, then the rival will be able to offer its product without incurring losses only if its marginal costs for segment $S*P$ are at or below $2: i.e. at or below the marginal costs over SP of the incumbent.

Thus by construction, the ECPR ensures the competitor entering and producing in the market only if its costs are not greater than those of the incumbent. It guarantees the inefficient diversion of production away from the incumbent not to occur.

Under the previous assumption, i.e. identical technology, cost structure, and products, with the presence of access charges, firms would still compete and undercut each other till no extra profits left in the final market. Thus the price to the final users should be set to equal the marginal cost of production. In other words, if setting the prices equal to marginal costs does not result in a loss to any players of the market; both productive and allocative efficiencies are achieved at the same time. The optimal situation for society as a whole is achieved since the marginal benefit to the society (price that consumer is willing to pay) of one more unit of production is exactly identical to the marginal cost to the society (the production cost of the firm). Thus the resulting allocation from ECPR is said to provide global efficiency and therefore is the "first best access pricing policy" (Armstrong, Doyle, & Vickers, 1996).

The incumbent's opportunity cost $P\text{-}C_m$ is basically the displacement of the incumbent's market due to granting access to the entrant. This displacement then results in a loss of variable profits for the incumbent. This reduction will in turn cause the incumbent not able to cover its fixed costs. Hence, to achieve optimal efficiency, the entrant is obligated to cover this loss by compensating the incumbent's opportunity cost of providing access.

The ECPR therefore has two important properties. First, it sends the right social signal to potential entrants since only the more efficient entrants will find it profitable to enter. Second, being fully covered under ECPR, it is indifferent for the incumbent to grant the access or not; the profit for the incumbent should be the same with or without access.

3.1.4 Relaxing Some of the Assumptions

The market displacement for the incumbent can be evaluated in different contexts. In order to build a more comprehensive model to tackle some complex and realistic cases, the assumptions of no bypass and homogeneous products of the previous model are relaxed. In reality, product differentiation (heterogeneous products), bypass (competitor building another network facilities), uncertainty in demand, input substitution, multiproduct firms and multi-access (entry in the network at different points or nodes) all have different impact on incumbent's opportunity cost of giving the access.

Let us now place our attention on product differentiation in the environment of possible bypassing. If the entrant, while still requiring the network as a critical input, offers a new final product different from the final product offered by the incumbent; it is then not necessary for the entrant to be fully responsible for the displacement of the incumbent's market. The loss of incumbent should no longer be fully compensated by the entrant, since the reduction in sales may result from the diversity in products. Hence an entrant with a differentiated product may still increase the social welfare even if it means that the incumbent is not fully covered. In the extreme case of independent products, the entrant has no impact on the incumbent's market; therefore, the ECPR would fix the access price at the direct cost of access only.

To represent the above-mentioned effects, the second term on the right hand side of the ECPR equation is modified into $\sigma(p - c_m)$ with $\sigma = \frac{\hat{X}_a}{-\hat{Z}_a}$.

$\hat{X}(P, a)$	$\equiv$	Incumbent's equilibrium production of the final products
$\hat{Z}(P, a)$	$\equiv$	Equilibrium demand for access by the entrant
σ	$\equiv$	Displacement ratio, represents the reduction in demand for the incumbent's products caused by providing the competition with the marginal unit of access

The expression $\sigma(p - c_m)$ is the opportunity cost to the incumbent in providing the marginal unit of access to the entrant. In particular, it strictly measures the part of the loss in incumbent's profit that is due to providing the access.

Hence, under more complex environment without homogeneous goods and with bypass possibilities, the equilibrium access price will be based on opportunity cost that is the product of the incumbent's marginal profit per unit sold and the ratio of the marginal impact of an increase in access charge on the incumbent's output and the marginal impact of this increase on the demand for access by the entrants.

Consequently, the equation for access price is now revised into:

$$a = c_i + \sigma(p - c_m); \; \sigma = \frac{\hat{X}_a}{-\hat{Z}_a}.$$

3.1.5 The Limitation of the ECPR

The main controversy regarding the ECPR is its dependency on the incumbent's retail prices. As the ECPR takes price of the final good as given, if the incumbent were not to price efficiently in the first place, it is possible that the monopoly rents is embedded in the final price. Thus, the loss of revenue to the incumbent due to the entry should not be completely borne by the entrant.

Also, the proper method of accounting for the lost market share is also a concern. How to distinguish the demand that is taken away by the entrant from the incumbent and the new demand created by the entrant itself is a critical issue in determined the opportunity cost of the incumbent.

In general, it is extremely difficult to achieve the theoretical "first best" allocation with pricing based on marginal costs. When the market is not contestable[4], by simply setting the access price equal to the sum of incumbent's incremental cost incurred from giving access to the entrant and its corresponding opportunity cost, only the lost variable costs are recovered. One should not forget that the bottleneck owner also incurs a fixed cost F which represents the initial investment for setting up the network or some other costs deriving from social obligations that cause losses to the bottle neck provider (Valletti & Estache, 1998). Following the ECPR, the incumbent could only recover the variable costs and would suffer a loss equal to the fixed cost, if it were not compensated by a third party such as the regulatory commission. Consequently, instead of the "first best", regulators often try to come up with an access pricing rule attempting to achieve the "second best[5]".

3.1.6 The M-ECPR

According to Sidak and Spulber (1997), a Market Determined Efficient Component Pricing Rule, M-ECPR, could be applied when the entrant supplies the final good at the price lower than the incumbent's. The main difference between the M-ECPR and ECPR is that the entrant's final price is employed instead of the incumbent's; that is:

$$a = c_i + (p_{Entrant} - c_m)$$

$p_{Entrant}$ = Entrant's price of the final product

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[4] The real world effect of uncertainty and irreversibility is assumed away under the contestability arguments.

[5] If one optimality condition in an economic model is not satisfied, it is possible that the next-best solution involves changing other variables away from the ones that are usually assumed to be optimal. In other words, second best is considered when the true optimum (the first best) is unavailable due to constraints on policy choice. For more information please refer to "The General Theory of Second Best" (Lipsey & Lancaster, 1956).

More specifically, the M-ECPR "corrects" the ECPR. In essence, by linking the access charge together with the entrant's price of final goods, it is expected that the M-ECPR, while keeping the benefits of ECPR (only allowing efficient competitors to entry) will eliminate the possible monopoly rent due to ECPR's dependency on the pricing of the incumbent.

However, the validity of the M-ECPR is sometimes criticized. For example, due to the fact that the network industry is typically not a competitive market, the "market determined" price does not actually exist. Furthermore, argued by Economides (1997), the pricing rules, such as the ECPR and the M-ECPR, based on private opportunity costs, would result in pricing inefficiency and lower social surplus than the pricing based on social opportunity costs. Here the private opportunity costs refer to the benefit or cost to a private party of a certain activity; and in general does not reflect the cost of resources to society.

3.2 The Ramsey Pricing Rule

3.2.1 General Information

Given the cost structure of most regulated sectors, the ECPR is deficient for full recovery of fixed costs. Suppose that the monopolist is unable to earn sufficient revenue in the bottleneck market to cover its total costs; many of the economic studies intend to solve this problem by introducing variations to the marginal cost pricing. In the absence of any other source of funds, aiming to eliminate the incumbent's loss of fixed cost, the regulator could set the efficient access price subject to a budget constraint face by the firm. In other words, it attempts to minimize the distortions of the marginal cost pricing and to allow the incumbent to break even.

Before proceeding further, it is necessary to point out the premise of the following analyses. In practice, the final products supplied are generally not homogeneous. For the instance of a natural gas company, it often offers different products to meet the different needs of its residential, commercial, or industrial customers. Even if the physical attributes of the final products were similar, they might still carry different value to different downstream users. It is thus expected that each group of consumers has different price elasticity of demand.

In order to recover the fixed cost, the firm could choose the strategy of charging each group of customers with different prices for the same products or services, and be benefit from receiving the maximum prices that each group is willing to pay. The customized mark-ups[6] on top of the marginal costs should be inversely related to the elasticities of demand. Comparing to the "first best" situation under the ECPR, only the "second best" is feasible under this methodology. In literatures, it is mostly referred to as the Ramsey or sometimes the Boiteux-Ramsey Pricing Rule suggested by F. P. Ramsey (1927) or M. Boiteux (1956). To achieve global efficiency, the Ramsey Pricing Rule chooses the incumbent's retail prices and access charges simultaneously to maximize welfare (Laffont & Tirole, 1994). In other words, the regulator selects the set of prices for final products that maximizes the consumer's surplus while manages covering both the variable and fixed costs.

Theoretically, contributions from the customers are extracted from the prices they pay for the final products. The resulting Ramsey price would involve, in essence, a tax that is imposed on the final products. If the rival is the low cost producer, the rival pays the tax to the monopolist as a part of the access charge. To ensure the optimality, the regulator would need to standardize directly the tax and the resulting price of the final products.

[6] Here the "Mark-up" is defined as the difference between the price and the marginal cost and has the same unit as price. The word "mark-up" is expected to be interchangeable with word "tax" in the following paragraph.

3.2.2 The Logic of the Ramsey Pricing Rule

Assume there are two related segments of one industry, one upstream, the network (bottleneck), and one downstream, the potentially competitive sector segment. The bottleneck is fully controlled by an incumbent firm denoted by I. In the downstream market, the incumbent faces competition from an entrant denoted by E who needs access to the bottleneck as a critical input in order to produce the final goods.

Instead of a homogeneous product, consider the pricing problem of the incumbent supplying n different products. Following the analysis of Vickers (1997), the price and marginal cost of product i are denoted by p_i and c_i respectively. The demands of products $q_1(p_1), q_2(p_2), q_3(p_3), \ldots, q_n(p_n)$ are independent; and the inverse demand function is $p_n(q)$. The total cost of producing all the products is $c(q_1, q_2, q_3, \ldots, q_n)$. All activities exhibit constant returns to scale, except for a fixed cost F incurred in constructing the bottleneck. Assume one unit of the bottleneck is needed to produce one unit of a final product. Finally, denoted by a, the access charge is paid by the entrant for the access to the network.

The optimal access charge a is derived together with the prices of the final goods. By construction, every customer is required to contribute to the recovery of the fixed costs. In order to reduce distortions, customers less price-sensitive are expected to contribute more; i.e. the more elastic the demand for the final product is, the smaller the mark-up will be. As a result, the mark-ups over marginal costs are higher in "inelastic" groups.

Under the Ramsey Pricing Rule, the goal is to maximize the sum of consumer welfare and total industry profits, subject to a break-even constraint for the incumbent.

Total revenue is:

$$R(p,q) = \sum_{i=1}^{n} p_n q_n(p_n) \tag{3.1}$$

The total surplus is:

$$TS(p,q) = \sum_{i=1}^{n} \left(\int_0^{q_i(p_i)} p_i(q) dq \right) - C(q_1, q_2, q_3 \dots q_n) \tag{3.2}$$

The regulator is facing the problem of maximizing *TS(p,q)* subject to the constraint that the profit equals to the fixed cost F:

$$R(p,q) - C(q_1, q_2, q_3 \dots q_n) = F \tag{3.3}$$

The first-order conditions are (there are *n* first-order conditions):

$$p_i - C_i = \lambda(R_i - C_i) \tag{3.4}$$

R_i : the partial derivative of total revenue with respect to q_i

C_i : the partial derivative of total cost with respect to q_i

λ : the Lagrange multiplier

According to Valletti & Estache (1998), the conditions could be rewritten as:

$$\frac{p_i - C_i}{p_i} = -\frac{\lambda}{1+\lambda} \frac{1}{\widehat{\eta_i}} \tag{3.5}$$

η_i : the elasticity of demand for service i

Equation (3.5) indicates that the mark-ups over the marginal costs are inversely proportional to the elasticity of the demand for goods. As discuss before, because of the fixed costs, “first best” could not be achieved; instead, distortions such as the mark-ups were introduced. The distortion is least damaging when mark-ups are set to be high in the markets with customers who are less price sensitive; as it would allow cost recovering of the incumbent without affecting the consumer behavior too much.

In particular, the recovery of fixed costs could be viewed as coming from three sources. Two sources are accrued directly to the incumbent through his customers: one from the bottleneck segment denoted by b and the other from the competitive segment denoted by c. The third source comes from the entrant denoted by e; and it is passed along to the incumbent via the access charge. Thus:

From the incumbent:

$$\frac{p_b - c_b}{p_b} = \frac{\lambda}{1+\lambda}\frac{1}{\eta_b} \tag{3.6}$$

$$\frac{p_c - c_b - c_c}{p_c} = \frac{\lambda}{1+\lambda}\frac{1}{\eta_c} \tag{3.7}$$

From the entrant:

$$\frac{p_e - c_b - c_e}{p_e} = \frac{\lambda}{1+\lambda}\frac{1}{\eta_e} \tag{3.8}$$

Since the entrant is a price-taker, its price p_e received from the additional unit produced has to be equal to the cost of the additional unit ($a + c_e$). From equation (3.8) we derive the optimal access price:

$$a = p_e - c_e = c_b + \frac{\lambda}{1+\lambda}\frac{p_e}{\eta_e} \tag{3.9}$$

Access price = Direct cost of access + Modified Ramsey term

From equation (3.9), to calculate the access price, the regulatory commissions would require information on the marginal cost of the bottleneck segment (c_b), the price of the services of the entrant (p_e), the elasticity of demand for services from the entrant (η_e), and the value of the Lagrange multiplier (λ).

If the coefficient $\frac{\lambda}{1+\lambda}$ equals to 0, this condition represent the situation under competition. This indicates that the access is priced equal to the incumbent's incremental costs incurred from giving access to the entrant. There is no monopoly rent embedded in the price of the final good. As the coefficient approaches 1, the price gets higher than the price of a competitive market thus less quantity would be sold. If the coefficient $\frac{\lambda}{1+\lambda}$ equals to 1, it represents the situation of monopolistic price discrimination.

3.2.3 The "Second Best" Allocation

One might wonder why the Ramsey Pricing Rule sometimes produces outcomes similar as if the incumbent exerts the monopoly power. First of all, to set the record straight, no party under Ramsey Pricing Rule possesses monopoly power. The higher than marginal cost access price is strictly result from the regulator maximizing the total profits and social welfare subject to the constraint of making the incumbent breaking even. The main purpose of employing Ramsey pricing is to promote as well as to protect the incumbent for making an investment that creates economies of scale.

The Ramsey Pricing Rule aims at making sure that the proper goods and services are provided, and creates as small distortions as possible from the "first best" allocations. Imagine that the customers of the entrant are not particularly price responsive. It is thus possible to charge them a relatively high price. Part of such high price is passed on to the incumbent via a high access charge. This is in the interest of the society as a whole because it allows other prices to be reduced without violating the incumbent's budget constraint. For example, if consumers of the incumbent are price sensitive, they would be charged a low final price; so that their consumption is not significantly distorted. Hence as the "second best", the equilibrium under Ramsey Pricing Rule is in between the ordinary monopoly and perfect competition.

3.2.4 Possible Implementation Difficulties

The main problem encountered in the implementation of the Ramsey Pricing Rule is that it suffers from very demanding information gathering: the incumbent's cost and production function as well as the different elasticties of demand of the consumers are required to be known. Even if all the variables were measureable, the regulators may still be constrained by asymmetric information as the firms are more informed on the characteristics of the cost and demand conditions than the regulators.

Furthermore, the mark-ups could potentially drive the customers with inelastic demand substituting away from the existing products and seeking for alternatives. In this case, it is a "lose-lose situation" for both of the incumbent and the entrants as their market shrinks, which in turn implies lower demand and revenue.

Moreover, while attaining a desirable level of efficiency, the Ramsey Pricing Rule typically overlooks equity considerations. After all, individuals with relatively inelastic demand are people who find the product most essential. As a result, this income distribution problem often causes the regulators political and legal difficulties in putting the Ramsey access charge into practice.

Finally, price discrimination is typically viewed as a byproduct of Ramsey

Pricing Rule and is sometimes accused as an illegal or socially undesirable exploitation of monopoly power, which may in turn cause anti-trust offence under certain circumstances.

3.3 The Global Price Cap: (GPC)

3.3.1 General Information

Suppose that the Ramsey Pricing Rule were chosen despite of all the complexities; it is expected that the regulations would be followed closely by the firms regardless of the ever changing industry conditions. To avoid sticky prices and the associated destruction on business viability, as well as to exploit the decentralized and firm-specific information, a pricing discretion could be given to the firm. However, it is critical for the regulators to effectively manage the firms' freedom over their prices.

A Global Price Cap on the firm's product range is proposed by J.J. Laffont and J. Tirole (1996) to effectively influence and constrain the exercise of pricing discretion of the firms. The Global Price Cap is designed to attain the "second best" efficiency by a decentralized implementation of the Ramsey Pricing Rule.

In general, the price cap imposed on the incumbent is determined in reference to a weighted average of the prices for a "basket" of products and services (from the incumbent's point of view, the network is one of its services/products that could be sold to potential entrants thus would be included in the computation of the cap). For example, in the telecommunication industry, a "basket" could be composed of telephony, fax, internet, voice mail services as well as the local network and exchange. Under this regime, if the weights were proportional to the forecasted quantities sold and if the incumbent had knowledge of his cost function, the Ramsey structure would be the incumbent's profit maximizing vector of prices.

3.3.2 The Logic of the Global Price Cap

To be "Global", the price cap is applied to just one "basket" assembling all the products and services required to be controlled. In the following analysis, i is used to indicate the specific product or service in reference to a weighted average of the prices included in the "basket". The associated weighted price value $w_i p_i$ of product i is just the cross-product between the weight w_i and the price p_i

Suppose that there are n products and services in one "basket", rather than fixing the prices explicitly, a cap $\overline{p}$ is defined by the regulator. Consequently, the prices could be freely chosen by the owner of the basket as long as the constraint $w_1 p_1 + w_2 p_2 + \cdots + w_a p_a + \cdots + w_n p_n \leq \overline{p}$ is respected, in particular, the term $w_a p_a$ denotes the weighted price value of the network.

This pricing scheme encourages the incumbent to maximize its profits by properly designing the price structures and adapting effective cost-reduction strategies. Accordingly, firms would emphasize more on optimal effort, operational efficiency, and technological advancement.

In order to understand exactly how the Ramsey prices could be induced via imposing a Global Price Cap, let us consider a simple problem of a non-regulated incumbent with the threat of entry(s). By setting a price cap $\overline{p}$, the regulators aim to maximize the sum of consumer surplus and total industry profits.

The firm hence faces the following problem:

Max:

$$\pi(p_1, p_2, \ldots, p_a, \ldots, p_n)$$

Subject to:

$$\sum_{i=1}^{n} w_i p_i \leq \bar{p} \qquad (w_1 p_1 + w_2 p_2 + \cdots + w_a p_a + \cdots + w_n p_n \leq \bar{p})$$

Suppose that the prices of other services are not affected by changes in the prices of one given service ($\frac{\partial p_x}{\partial p_y} = 0$). Using the Lagrange method, the first order conditions are:

$$\frac{\partial \pi}{\partial p_i} = \gamma w_i$$

π ≡ profit of the incumbent

γ ≡ Lagrange multiplier

When p_i is increased by a unit, w_i units of consumer surplus would be lost (here w_i is interpreted as representing the predicted demand of good i). From this analysis we could see that under the Glòbal Price Cap, firm not only achieves pricing flexibility but also internalizes the consumer surplus in proportion to the weights set in the cap. In other words, since the incumbent receives a portion of the benefit w_i, while pricing the different products and services, it creates minimum distortion to the total social welfare.

3.3.3 The Advantages of the Global Price Cap

Not necessarily knowing the firm-specific information requested under the Ramsey Pricing Rule, the regulator could induce the firm to achieve the "second best" allocation by imposing a Global Price Cap. In order to respect the cap, the firm will set the prices of the basket based on its private information such as the demand and cost structures as well as the consumer preferences.

Generally, there is no need for the regulators to measure the demand elasticities of different groups of customers. The weights are set by the regulators, and are exogenous and proportional to the predicted quantity sold of products and services (including the network access). To keep the price cap updated, the regulators may constantly monitor and verify the inflation rate benchmarks such as the Consumer Prices Index (CPI).

The important task left for the incumbent is to carefully design its prices to maximize the profit while respecting the Global Price Cap: it will set the prices of the basket based on its private information such as the demand and cost structures as well as the consumer preferences.

3.4 The Cost-Based Pricing: Backward-Looking and Forward-Looking

3.4.1 General Information

To start with, the sophisticated "first best" ECPR is not very much feasible. Furthermore it is impossible for the regulators to capture all the competitive and demand related information for applying Ramsey Pricing Rule. Moreover, to correctly predict the output level for setting the optimal weights for the price cap index is also a difficult and costly process. Consequently, the Cost-based Pricing Rule is often suggested and implemented in literatures and real practice. Taking the importance of both productive and allocative efficiency into consideration, instead of marginal costs, regulators typically set access prices at average total costs or the long-term incremental costs of the service provided, as these cost measures allow for reasonable return on initial investments. For example, the Fully Distributed Cost (FDC) and Long Run

Average Incremental Cost (LRAIC) are widely used around the world.

One generalized formula for access charge based on average pricing is:

$$a_{ap} = c_{dm} + \frac{F}{Q}$$

a_{ap}	≡	Access charge based on average pricing
c_{dm}	≡	Incumbent's direct marginal cost from giving access to the entrant(s)
F	=	Incumbent's fixed cost which could be interpreted as the set up cost of the network or some other costs deriving from social obligations
Q	=	Total quantity of the final good

According to Armstrong (2002), one of the main benefits of employing Cost-based Pricing is its relatively simple implementation as only the cost of the network is needed to be estimated. There is no further information required on the characteristics of demand or the potential entrants. Also, when disregarding the efficiency concerns, this is the only policy gives the entrants a clear signal on whether to lease or duplicate the network when bypass is possible. Moreover, the Cost-based Pricing Rule is fair and non-discriminatory and does not depend on the rivals' usage of the network; thus the entrants will not be offered with different terms. In addition, the Cost-based Pricing Rule compensates the incumbent for undertaking the project early. If the incumbent were to wait for the initial outlay to fall, it may not enjoy as high profit as before. In other words, higher investment cost means higher access charge; thus higher cash inflow after the network has been built.

This brings about a critical issue: how to measure the costs? What kind of valuation and depreciation method is appropriate? Should the regulator use historical costs in accordance with most of the accounting policies[7]; or should it choose the less reliable but more relevant market value reflecting the current replacement costs? In other words, should the regulator adopt the "backward-looking cost rules" and value the network at the initial investment cost; or should it adopt the "forward-looking cost rules" and value the network at present value to reflect its current market price?

A number of regulatory commissions mandate historical costs as the basis for cost accounting because historical values are more reliable; as they are readily available and could be easily verified. Furthermore, according to the analysis conducted by Guthrie et al. (2006), the incumbent bearing the irreversibility nature of its investment, in a world of uncertainties, would invest earlier under a backward than forward-looking cost rule and will lead to a higher total welfare.

Nevertheless, historical costs bear some obvious disadvantages. For example, they may distort decisions when technology is evolving rapidly. Also incumbents with high historical costs will be able to charge higher prices no matter whether they are efficient or not. However, when determining optimal access prices, the potential entrant should not be responsible for the high costs of the incumbent just because the incumbent invested at the time when costs were high.

In terms of the forward-looking cost-based rule, it is based on the estimated current costs of re-constructing the network. In particular, this pricing scheme well rewards efficient incumbents' sound investment choices. In addition, since forward-looking rule evaluates the replacement cost by incorporating the latest technology available, it reflects the most current market conditions and

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[7] Both the U.S. and Canadian Generally Accepted Accounting Principles (GAAP) regulate most of the fixed assets to be valued at their historical costs; only certain assets such as marketable securities could be valued under current prices.

thus is helpful for both the incumbent and the entrant to make sound investment and production decision.

However, as the market price fluctuates, the access price under the forward-looking cost-based rule diverges from its initial value which in turn creates additional uncertainties and risks to the incumbent.

Overall, regardless of the accounting methods, there are still some general criticisms on the cost-based access pricing rule. For example, since the cost-based pricing rule does not employ marginal cost to set the access price, it is often criticized on the lacking of economic efficiency. Additionally, there is not yet a generally acceptable allocation methodology that could be implemented to optimally divide the fixed cost into units.

3.4.2 The US Experience: the Telecommunication Industry

With the passing of the Telecommunication Act of 1996, authorizing the competitors to lease a part of incumbent's network, the US Federal Communications Commission (FCC) mandated the TELRIC[8][9] method to give the potential entrants ready and economical access. In essence, it is a forward-looking cost-based method for determining the fees at which the entrants need to pay for using the network. According to the TELRIC, the price is determined based on the costs of building an efficient network using the best available technology rather than the actual cost of the incumbent's network. It is understood that the value of the capital investment falls as the time passes since it requires more maintenance and repair. It is also expected to eventually become obsolete as newer and better technologies are introduced and adopted. Therefore, the TELRIC method used to determine the capital costs takes the

[8] TELRIC: Total Element Long Run Incremental Cost

[9] Sometimes it is referred as the TSLRIC: Total Service Long Run Incremental Cost. The incremental costs equal marginal costs for small output changes but may differ substantially if it involves large output changes up to the entire services.

effects of depreciation and obsolescence into account.

Although the FCC policy allows for the recovery of the cost of investment as well as variable costs of providing the services over the economic lifetime of the investment; as discussed in Hausman (1999), it fails to take notice of the irreversibility and the according risks of the initial capital outlay. As a result, it causes underestimation of the network investments which in turn could lead to less innovation and untimely investment.

3.4.3 The Pricing Tools

As mentioned in section 3.3, constraints are helpful for retaining some regulatory control in case the incumbent is given too much freedom to set the access prices. For example, a ceiling could be implemented to prevent the incumbent from exploiting its market power by requesting excessively high access prices. According to Vogelsang (2003), the average stand-alone costs of a (hypothetical) whole-sale operator could be an appropriate upper limit for access prices charged by an intergraded incumbent under the Cost-based Pricing Rule. This holds because pricing above stand-alone costs would be unsustainable under (hypothetical) competitive conditions. Conversely, a floor is often used to prevent aggressive pricing with a predatory intention. Vogelsang (2003) proposed the lower limit to be average incremental costs or short run marginal costs. If the access price set under the Cost-based Pricing Rule is lower than it, the access service would be cross subsidized.

3.5 A Comparison of the Rules

The objective of the ECPR is to allow efficient entry under the assumption of no monopoly rents embedded in the price of the final products. In contrast, the Ramsey Pricing Rule aims for global efficiency while attaining the economies of scale. To avoid the obvious difficulties of information gathering associated with the above-mentioned two rules, the Global Price Cap is employed as an alternative path of achieving the "second best" efficiency. However, the economies of scale often imply that marginal cost pricing, absent subsidy, will not allow the incumbent to break even. Instead, for the ease of implementation, the Cost-based Access Pricing rule is typically mandated by the regulators around the world.

One of the main criticisms of the ECPR is that, under this pricing scheme, if the incumbent was earning inappropriately high profits in the first place, the monopoly rent will be continually earned even with the presence of the entrant. Furthermore, since the problem of asymmetric information between the firm and the regulatory commission has not been solved, as both the ECPR and the Ramsey pricing rule require detailed information on the demand and competition interactions, they are still theoretical and far from actual implementation. Moreover, although the implementation of a Global Price Cap could greatly eliminate the asymmetric information problems, it will only manage to approximate the desirable results. Last but not least, the access prices determined under the Cost-based Pricing Rule might give investors not sufficient incentive, as it removes the incumbent's advantages of being the first mover in the market, while leaves it with uncovered downward risks (as the incumbent still needs to support the network even if the market condition is undesirable).

4 THE REAL OPTION APPROACH

4.1 Overview

The issue of asymmetric risk sharing between the incumbent and the entrants has surfaced in the literature concerning the linkage between the current access pricing policies, the uncertainty, the irreversibility, and the incentives for investments. It arises from the possibility that the entrant has the option of accessing the incumbent's facilities on a short-term basis. Consequently, if market conditions for the final goods deteriorate, the entrant can exit the market but the incumbent still has to support the investment. In this case, a free "exit option[10]", is given to the entrant. Also, if a contract were to be signed for granting the network access, the contract covering shorter period of time would have higher prices because comparing to a long-term contract, a short-term one involves less uncertainty.

In general, the access price set under the previously discussed "classical" access pricing rules could not adequately compensate the incumbent for the risk taken by investing irreversibly in an uncertain market. Economic analysis of irreversible investment under uncertainty implies that due to the sunk cost, for a project to be undertaken, it typically is expected to offer returns well above the "breakeven". Therefore, if the "classical" access pricing rules were to be used, the entrants would be subsidized.

4.2 Some Critical Concepts

4.2.1 General Information

The following analysis considers a single firm that has an initial monopoly

[10] Since the option can be exercised at any time before the "expiration" date, it is equivalent to an American put option

over a network construction opportunity. By committing to take on the investment, the firm constructs a network. The access to the network could be granted to its competitors. Each competitor then has the choice of developing its own network (bypassing) or renting the existing facilities.

The main focus is not only to incorporate the role of investment, and maintain the supply of final goods and services but also to consider the irreversible nature of the investment and the effects of the uncertainty and flexibility on the investment decision. There are costs and benefits associated with building a network, since it requires significant upfront capital outlay but the benefits carry tremendous uncertainty. This sometimes creates an incentive to defer the commitment of the irreversible investments. On the other hand, the construction of a network could possibly make the firm a natural monopoly of the industry.

When firms face a choice of whether to take on the investment, it is considered as holding a real option. Specifically, it is an "option to grow", which involves investing in an initial market, product line or technology to develop a platform for future growth opportunities. This is common in the infrastructure projects, which demand high initial capital outlays with no immediate returns. For example, the natural gas transmission companies often spend considerable resources to develop networks of pipelines without receiving positive cash flows during the initial construction period, and only to target possible future opportunities of delivering natural gas when the network is built.

This "option to grow" is in fact a compound option; that is, option(s) on option(s). Each phase of the project is modeled by one or more financial options. The value of an earlier option is affected by the value of the options later in the investment sequence. They interact with each other, so their combined value may differ from the sum of their separate value.

The value of a network depends on how it is operated and licensed and most importantly on the ever changing market condition. Therefore, the rules governing the investment decisions in network development must be conditioned on the irreversibility of the investment, the uncertainties of the project and the according management flexibilities.

4.2.2 The Sources of Uncertainty

In a dynamic world, market condition, technology innovation, factor prices and many other parameters of interest to a company are subject to uncertainty. Among the above mentioned factors, the main source of uncertainty is the market demand for final goods and services, which in turn could bring about significant impact on the cash flow, project evaluation, and profitability of the enterprise.

Uncertainty can make a substantial difference in determining the access prices. The value of the network construction project evolves according to the random processes of several critical variables; hence the sources of uncertainty could be multiple. Variables such as the quantity and price of the goods and services to be delivered, the input prices, the possible technological innovations, the legal and environmental aspects of the project, and the regulation governing the production activities could all play a role in influencing the value of the investment.

4.2.3 The Points of Flexibility

When holding a real option of building a network facility, depending on the investment and market conditions, the incumbent has the flexibilities to delay the investment, to pause the project of several phases, to increase or contract the goods and services provided temporarily by controlling both its own and the leasee's usage of the network, to postpone the decision of future growth to the next period if possible or simply abandon the project, and so on.

On the other hand, the entrant has the flexibility to choose when (the timing of entry) and how (leasing the facilities or bypassing) to obtain the access of the network for transferring its goods and services as well as when to stop having the access following the ever changing market conditions.

4.2.4 The Significance of Irreversibility

If the decision is reversible, one can always recover the input of funds and there is no or minimal cost to modify or even annul the investment when circumstances change. In reality, however, perfect reversibility does not exist; therefore it is considered as a sunk cost. This irreversible cost is a significant portion of the total cost of many public utilities projects and plays a critical role in influencing the market structures, the timely investments, as well as the effective and efficient resource allocations.

Once the investment is made, the firm looses the opportunity to delay the project further in waiting for better market conditions. However this opportunity cost has yet been commonly acknowledged by the public in making the pricing decisions. Comparing to the entrants leasing the facilities to deliver their goods and services, the incumbent does not have the convenience to withdraw from using the network when it is not profitable. While the incumbent assumes the full ownership and receives benefit from it, it is also responsible for the possible burden of the network. Thus the incumbent should be compensated for undertaking an irreversible investment.

4.2.5 The Optimal Access Price

Under uncertainty and irreversibility, it is difficult to maintain incentives for the investors by relying on some of the above-mentioned "classical" access pricing schemes because it could possibly lead to under-investment or undesirable delay of investment. For example, if the access price is too low thus makes it impossible to cover the irreversible sunk costs, the network provider will not have the incentive to invest in new or maintain the existing network. Therefore, it decreases future social welfare by creating unnecessary delays in the introduction of socially desirable goods and/or by reducing the supply of future final goods and services. When designing the proper access pricing policy, the regulator should take all of these aspects into account.

Ideally, an optimal access price should be able to reward the network provider for undertaking the uncertain and irreversible investment.

4.2.6 The Evaluation of Real Options

4.2.6.1 Options of Incumbent

Firms of certain industries such as telecommunication companies, railway operators, electric power generation and transmission companies, as well as the natural gas production and transmission companies could expand their operation via building a new network to deliver their products and services. Before taking on the project, managers normally will make some thorough analyses to evaluate the viability of the project by determining the market condition, the infrastructural and financial requirements, as well as any potential legal and environmental constraints.

The value of the decision to expand its operation now or defer the network construction to a future date is equivalent to an American call option with an exercise price equal to the required investment. The manager will compare the present value S_t of the expanded project with the investment cost K and he will decide to invest if $S_t \geq K$. If not, the manager has the option to defer an investment up to a date T in the future. In any moment from now until that date T, he will decide whether or not to invest, contingent on the changing market conditions. For a date $t \in [0,T]$, he will compare the cost of investment with the present value of the project. The payoff will be $\max(S_t - K, 0)$ should the manager choose to invest at t.

If market conditions become worse than initially expected, managers can decide to contract by operating below capacity and temporarily suspending the further development of project to save the investment outlays. If the manager had planned to spend K dollars in investments at any time $t \in [0,T]$, the option to contract will save the company K[illegible] . If S_t represents the value of the project lost with contraction, the payoff will then be $\max(K - S_t, 0)$. Generally, the option to contract is analogous to an American put option.

4.2.6.2 Options of Entrant

If the market declines severely, the entrant might decide to stop leasing the network. For example, if a product is replaced because of a technological innovation, its demand will sharply drop. Suppose that discontinuing its access of the network will cost the entrant K. If S_t represents the value of the project at time t, abandoning it will cost S_t. The payoff is then $\max(K - S_t, 0)$. Therefore, abandoning a project could be evaluated as equivalent to an American put option.

Suppose that a natural gas substitute is subsequently discovered with less production and transportation costs, as a result, the demand and price for natural gas will drop significantly. In this case, the manager might choose to permanently abandon the project in exchange for a salvage value of K.

4.3 The Framework: With and Without the Threat of Entry

Operating the network and only utilizing it for the sole purpose of producing its own goods and services is materially different from bearing the possibility of granting its competitors with access to a part of the network. In the latter case, the incumbent is expected to suffer financially due to the entry of the rival because of a reduced market share. Since the firm's investment decision is largely influenced by the threat of entry, it is then assumed that the value of the network project with the possibilities of entry is different from the one without.

By undertaking the project, the incumbent forgoes the value of the "option of waiting to invest", therefore when estimating the access prices, the incumbent is expected to be compensated for not only a part of the initial investment of building the physical network but also the lost value of the "option of waiting to invest." The focus should be to set the access price considering the risk taken and the according value forgone by the incumbent so the network will be built in timely fashion and the access will be granted following the demand of the entrant.

4.3.1 General Information

The following analyses of firm's investment decision are under two possible scenarios: 1) there is no threat of entry: the incumbent is the sole user of the network; and 2) the incumbent must readily grant access to the entrant on demand: there are possibly two users of the network. Furthermore, it is assumed that the incumbent has an obligation to serve the final good's market.

X	$\equiv$	Cost of building the network unit (infinite life with no depreciation)
p	$\equiv$	Price of the final good (suppose that only one homogeneous good is produced): it evolves stochastically through time. Since prices of the final goods are assumed to be positive, we let p follow a process of Geometric Brownian Motion (GBM) with drift to reflect the stochastic innovations as well as any long-term trend in price evolution: $dp_t = \mu p_t dt + \sigma p_t dz_t$ The parameter μ is the drift, the expected rate of price growth; σ is the diffusion, the standard deviation of $\frac{dp_t}{p_t}$; it represents the short-term variability of the price. The term dz_t is the increment of a Weiner process, which may be interpreted as the difference of $z_{t+h} - z_t$ for some small positive h.
c_I	$\equiv$	The incumbent's cost of producing the final good
c_E	$\equiv$	The entrant's cost of producing the final good
c_N	$\equiv$	The incremental cost of providing the access
a	$\equiv$	The access price; one unit of access is required as an input to supply one unit of the final good.
q_E	$\equiv$	The entrant's share of the network.
r	$\equiv$	Risk less interest rate

4.3.1.1 The Computational Methodologies

There are in general four basic computational methodologies for assessing real option values: closed-form analytic solutions, lattice or tree models, simulation models, and numerical solutions to partial differential equations.

Closed-form analytic solutions are the best approach to use when the variables are measureable and obtainable. However, often there are several critical variables in a formula, and most of the times it is too complicated a task to properly identify and collect all variables to work out the real option value.

Also, it would be a problem for simulation models. Closed-form is the best approach when the solutions for the differential equations are known.

For example, there are five drivers in the Black-Scholes formulas for European put and call options: present value of a project's operating assets to be acquired which is analogous to the "stock price" of the Black-Scholes financial option model; the expenditure required to acquire the project assets to the "exercise price"; the length of time the decision may be deferred to the "time to expiration"; the time value of money to the "risk-free rate of return"; and the riskiness of the project assets to the "variance of returns on stock" (Luehrman, 1998). In the case of network access valuation, because of the often unstable technological, economical, and political environment as well as the unpredictable nature of the local regulations governing the network industry; accurately collecting five drivers at once is a challenging task.

Lattice or tree models are useful because they are easy to understand and work well for both American and European options. In the case of only one risk driver, this technique can be easily applied on a spreadsheet, where one axis is time and the other is the price level or value of the underlying risk driver. Their complication arises when multiple risk drivers are at presence. Instead of a generic spreadsheet, a programming language such as Matlab is required. Considering the complexity of the access pricing problem and the associated multiple risk drivers, it is advised to adopt a programming language to compute the optimal trigger strategy and option value by using the backward recursion, which is also known as dynamic programming.

Simulation models implement a forward approach, with the underlying asset starting at a fixed price and undergoing random increments. It can be efficiently used to estimate the conditional expected payoffs and continuation values. Moreover, simulation can easily handle multiple risk drivers and complex processes, which is a distinct advantage over the lattice approach. To apply the real option valuation technique to evaluate the optimal access price, "Monte Carlo" approach is often used. It simulates many sample paths and finds the solution for each replication. The Monte Carlo simulation makes a draw from the underlying stochastic distribution to determine the economic outcome. This procedure is repeated many times. The random distribution of the outcome is given from the significant number of times that the model is run, each time with a different random set of inputs that are drawn randomly from the same underlying distribution.

Numerical solutions to differential equations are generally useful in academic real option settings. Since the focus of this study is to determine the proper timing of building the network under different circumstances; that is to characterise the impact of access price on the incentives to invest in network development, the numerical solutions to differential equations will be employed in the following analyses.

Nevertheless, since it is not cost effective to build a custom partial differential equation for every network access pricing problem; the lattice models and simulation models are often implemented in real practice.

4.3.2 The Value of the Network: Without the Threat of Entry

Let us first examine the investment opportunity of creating a network without the threat of entry. In other words, the owner of the network is not under the regulatory pressure to grant access to any of the competitors.

The firm could make a capital outlay of X to construct a network which is expected to generate cash flows in the future continuously. Thus undertaking the project has an expected present value of $V^{no\ access}$, which depends on the price of the final good that varies stochastically following a GBM.

$$dp_t = \mu p_t dt + \sigma p_t dz_t \tag{4.1}$$

When the incumbent is the sole supplier of the final goods and services, it faces no risk of having to give access. The profit of the incumbent at time t is:

$$\pi_I - p_t - c_I - c_N \tag{4.2}$$

When the current price is equal to P_0, the value of the (existing) network to the incumbent without access is equal to:

$$V^I(no\ access)(P_0) = E\{\int_0^{\infty} [(p_t - c_I - c_N)]e^{(-rt)}\, dt \mid p_0 = P_0\} \tag{4.3}$$

Before making the investment, it is as if the firm is holding an "option to invest". The value of this option is the difference between the expected present value of the investment and the actual investment outlay. There is a critical value P_T. At time t, the company will invest if $P_t \geq P_T$ and will delay the investment if $P_t < P_T$. The objective of the incumbent is to choose the optimal investment date (τ) in order to maximize the expected present value of the investment.

The value of the "option to invest" is equal to:

$$F(P_0) = \max_{\tau \in [0, \infty)} E[(V^I(no\ access)(p_t) - X)e^{(-r\tau)} \mid p_0 = P_0] \tag{4.4}$$

$F(P_0)$ ≡ The value of the "option to invest" at time 0

τ ≡ The time the investment will be made

Assume that during the "waiting period", as *F(p)* yields no cash flow, the only return is from the capital appreciation at the risk-free discount rate:

$$rFdt = E(dF) \tag{4.5}$$

By Ito's Lemma:

$$dF = \frac{dF}{dp}dp + \frac{1}{2}\frac{d^2F}{dp^2}(dp)^2 \tag{4.6}$$

From equation (4.3):

$$\begin{aligned}(dp)^2 &= (\mu pdt + \sigma pdB_t)^2 \\ &= \mu^2 p^2 (dt)^2 + 2\mu\sigma p^2 dtdB_t + \sigma^2 p^2 dB_t^{\,2} \\ &= \sigma^2 p^2 dt\end{aligned} \tag{4.7}$$

From equation (4.8):

$$dF = \frac{dF}{dp}(\mu pdt + \sigma pdB_t) + \frac{1}{2}\frac{d^2F}{dp^2}\sigma^2 p^2 dt \tag{4.9}$$

Take expectations, also since $E[dB_t] = 0$:

$$E[dF] = \mu p \frac{dF}{dp} dt + \frac{1}{2}\sigma^2 p^2 \frac{d^2F}{dp^2} dt \tag{4.10}$$

Substitute equation (4.5) into (4.10) then divide the result by d_t to find the differential equation, (also referred to as the Bellman's equation):

$$\frac{1}{2}\sigma^2 p^2 \frac{d^2F}{dp^2} + \mu p \frac{dF}{dp} - rF = 0 \tag{4.11}$$

Substitute $\mu = r - \delta$, where δ is considered as a dividend yield or an opportunity cost; equation (4.11) could be written as:

$$\frac{1}{2}\sigma^2 p^2 \frac{d^2F}{dp^2} + (r - \delta)p \frac{dF}{dp} - rF = 0 \tag{4.12}$$

The value of the "option to invest" *F(p)* must satisfy the following boundary conditions:

$$\lim_{p \to 0} F(p) = 0 \tag{4.13}$$

$$F(p^*) = p^* - X \tag{4.14}$$

$$F'(p^*) = 1 \tag{4.15}$$

Condition (4.13) implies that when price is zero, the project investment has no value. Condition (4.14) indicates that at the time the investment is made, the payoff of the project is $p^* - X$. Condition (4.15) ensures smoothness and continuity of the solution.

The solution to the differential equation is (for detailed explanation please refer to Appendix A):

$$F(p) = c_1 p^{\beta_1} \tag{4.16}$$

The parameter c_1 is a constant to be determined; and β_1 is a known constant that depends on the coefficients of the differential equation.

$$c_1 p^{*\beta_1} = \frac{1}{r}(p^* - c_I - c_N)X \tag{4.17}$$

$$\beta_1 c_1 p^{*\beta_1 - 1} = \frac{1}{r} \tag{4.18}$$

From the above-mentioned boundary condition, the price level at which is optimal for the incumbent to invest is:

$$p^* = \frac{\beta_1}{(\beta_1 - 1)(c_I + c_N + rX)} \tag{4.19}$$

With:

$$c_1 = \frac{p^* - 1}{(p^*)^{\beta_1}} = \frac{(\beta_1 - 1)^{\beta_1 - 1}}{\beta_1{}^{\beta_1} X^{\beta_1 - 1}} \tag{4.20}$$

$$\beta_1 = \frac{1}{2} - \frac{(r-\delta)}{\sigma^2} + \sqrt{\left[\frac{(r-\delta)}{\sigma^2} - \frac{1}{2}\right]^2 + \frac{2r}{\sigma^2}} > 0 \tag{4.21}$$

4.3.3 The Value of the Network: With the Threat of Entry

Assume that before making an investment to build a network, the incumbent *I* is regulated to give access to the entrant *E* at the access price *a*.

4.3.3.1 A Case Study: the Telecommunication Industry of Canada

In real practice, a great portion of access pricing rules mandated by the regulatory commissions are based on incremental costs incorporating a mark-up that makes allowance for the other costs of the access provider. The mark-up may be calibrated by the regulators tailored to individual cases, or it could be left to the discretion of an incumbent but with certain restrictions such as a price cap for eliminating predatory or excessive pricing.

Canadian Radio-television and Telecommunications Commission (CRTC) recently[11] ruled out the possibility of adopting a market-based approach of pricing essential services, instead, the cost-based approach based on the associated prospective incremental costs (phase II cost[12]) plus a mark-up is mandated for the Canadian telecommunication industry. A mark-up of 15%[13] is generally agreed upon by the associated parties. Let us now examine the Canadian telecommunication industry and its according access pricing policies.

In the following paragraphs, the access pricing under Canadian legislation will be compared to the access price under the ECPR, the pricing rule that produces the "first best" allocation.

With the 15% mark-up the access price mandated by the CRTC is:

$$a_{Canadian} = c_N(1+\omega),\ \omega = 0.15 \tag{4.22}$$

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[11] Please refer to Telecom Decision CRTC 2008-17 (Revised regulatory framework for wholesale services and definition of essential service) issued on 3 March 2008

[12] In Telecom Decision 79-16, the Commission defined the resources associated with the provision of a new product/service under four categories. (1) The direct resources are the major additional resource quantities to provide a service over the study period. They consist of those units of management, labour, plant, equipment, material, and supplies which can be readily identified and quantified. (2) The indirect resources are generally minor in nature and are those resources that can be readily identified in support of the direct resources. (3) The variable common (VC) resources are those remaining resources where the quantities of or payments for the resources are variable with the scale of operations of which the service represents a portion. The costs associated with these resources include proportions of the variable costs of all operations involved in providing a service which are not identified and estimated as direct or indirect costs. (4)The fixed common (FC) resources primarily consist of plant and equipment which are employed to provide the service but the cost of which will not vary over the life of the service.

The costs of the resources used for a new product/service within the first three categories are to be attributed to the new product/service and are referred to in this Decision as causal costs or Phase II costs and, if expenses, as causal expenses or Phase II expenses.

[13] Instead of 15%, the mark-up for Télébec and TCC in its operating territory of Quebec is 25%.

Denote the access price under the ECPR as a_{ECPR}. By definition, the access price a_{ECPR} leaves the incumbent indifferent between giving access or not. Consequently, if the regulator were to choose to implement the ECPR, it should have:

$$a_{ECPR} = c_N + (p_t - c_N - c_I) = p_t - c_I \tag{4.23}$$

The access price mandated by the CRTC will achieve the "first best" allocation, if and only if $a_{Canadian} = a_{ECPR}$; that is $1.15c_N = p_t - c_I$. However, since it is assumed that p_t undergoes a GBM, the price of the final goods is time-independent and will vary stochastically. Thus, under the CRTC regulation, with this cost-based fixed access scheme, a clear call to entry or exit will be automatically signaled to the entrant. Since the entrant has the option to interrupt the incumbent's production when profitable and withdraw its presence when the net revenue is negative; the value of entrant accessing the network is always positive. If the mark-ups are insufficient, the incumbent might choose to deteriorate access quality or exclude rivals. In conclusion, under the CRTC regulation, there are insufficient incentives provided for optimal investment, innovation and competition.

4.3.3.2 A General Expression

Practically, instead of gathering information on marginal costs and demand, the cost-based access charges with a possible mark-up have come to prevail worldwide. The regulatory commissions often arbitrarily decide what portion of the incumbent's total costs of the network could be covered. Under most of the regulations, the access price typically depends on forward looking incremental costs. Also, the fixed charge is commonly incorporated into the determination. For example, in the telecommunication industry, the "Long Run Incremental Cost (LRIC)" and the "Total Element Long Run Incremental Cost (TELRIC)" are adopted by Australia and the United States respectively.

Furthermore, in the United Kingdom, the access price is regulated to be proportional to the fixed cost.

In the following analysis, the access price is set to be in proportion to the incumbent's total costs (including both incremental costs and the fixed costs) associated with the network:

$a = m(c_N + rX)$

m : A parameter arbitrarily chosen by the regulator to arrive at an appropriate access price; $m > 0$

To begin, suppose that the entrant can freely enter and exit the market at no cost. The incumbent must grant access to the entrant at a price of a . The entrant is able to lease an exogenously determined proportion $q_E \in [0,1]$ of the network.

Following the analysis of Boyer, Gravel, & Lasserre (2008), the profit function of the incumbent is:

$$\pi_I = \begin{cases} p_t - c_I - c_N & if\ p_t < c_E + a \\ q_E(a - c_N) + (1 - q_E)(p_t - c_I - c_N) & if\ p_t > c_E + a \end{cases} \tag{4.22}$$

Under the cost-based access pricing rule, when the current price is equal to P_0, the value of the network to the incumbent is:

$$V^{access}(P_0) = E\{\int_0^\infty \pi_I(t) e^{(-rt)} dt | p_0 = P_0\} \tag{4.23}$$

Equation (4.23) needs to satisfy the Bellman equation. The differential equation for the value of the project is:

$$1/2\, \sigma^2 p^2 \left[V^{access}(p,t)\right]'' + \mu \left[V^{access}(p,t)\right]' - rV^{access}(p,t) + \pi_I(p) = 0$$

(4.24)

The term $\pi_I(p)$ is defined differently when $p < c_E + a$ and when $p > c_E + a$. Therefore we solve the equation separately for the two regions and examine the solutions at the point where $p = c_E + a$.

In this case, the value of the network could be expressed as:

$$V^{access}(p) = \begin{cases} k_1 p^{\varphi_1} + \dfrac{p - c_I - c_N}{r} & if\ p < c_E + a \\ k_2 p^{\varphi_2} + \dfrac{q_E(a - c_N) + (1 - q_E)(p - c_I - c_N)}{r} & if\ p > c_E + a \end{cases}$$

(4.25)

The potential investor of a network maximizes the expected present value of the investment by choosing the optimal investment time τ . Since the price fluctuates stochastically and the value of the network to the incumbent is characterized by different equations when $p \neq c_E + a$. We now define the region where $p > c_E + a$ as U , and the region where $p < c_E + a$ as L .

The "option of waiting to invest" has a value of:

$$F_U(p) = \max_{\tau \in [0,\infty)} E\left[\left(V^{access}(p) - X\right) e^{-r\tau}\right]$$

(4.26)

It also must satisfy the Bellman equation:

$$1/2\, \sigma^2 p^2 \left[F_U(p)\right]'' + \mu \left[F_U(p)\right]' - rF_U(p) = 0$$

(4.27)

$$\frac{1}{2}\sigma^2 p^2 \frac{d^2F}{dp^2} + \mu p \frac{dF}{dp} - rF = 0 \tag{4.28}$$

The solution is (for more information, please refer to Appendix B):

$$F_U(p) = n_1 p^{\varphi_1} \tag{4.29}$$

To find the price level p_U^* at which it is optimal for the incumbent to invest, solve the system:

$$n_1 p_U^{*\,\varphi_1} = k_2 (p_U^*)^{\varphi_2} + \frac{q_E(a - c_N) + (1 - q_E)(p_U^* - c_I - c_N)}{r} - X \tag{4.30}$$

$$\varphi_1 n_1 p_U^{*\,\varphi_1 - 1} = \varphi_2 k_2 p_U^{*\,\varphi_2 - 1} + \frac{(1 - q_E)}{r} \tag{4.31}$$

This gives equation of p_U^*:

$$(\varphi_1 - \varphi_2)(p_U^*)^{\varphi_2} + (\varphi_1 - 1)\frac{p_U^*(1 - q_E)}{r} - \varphi_1\left[\frac{(1 - q_E)(c_I + c_N) - q_E(a - c_N)}{r} + X\right] = 0 \tag{4.32}$$

Now suppose that the incumbent invests in the region L where $p < c_E + a$. By solving the system:

$$n_1 p_L^{*\,\varphi_1} = k_1 p_L^{*\,\varphi_1} + \frac{p_L^* - c_I - c_N}{r} - X \tag{4.33}$$

$$\varphi_1 n_1 p_L^{*\,\varphi_1 - 1} = \varphi_1 k_1 p_L^{*\,\varphi_1 - 1} + \frac{1}{r} \tag{4.34}$$

The optimal p_L^* is:

$$p_L^* = \frac{\varphi_1}{\varphi_1 - 1}[c_N + c_I + rX] \tag{4.35}$$

When the price of the final products is smaller than the sum of the entrant's cost of production and the access price ($p < c_E + a$), the optimal investment thresholds with and without the threat of entry are identical ($p_L^* = p^*$). This observation makes economic sense because when $p < c_E + a$, the entrant's revenue is simply not enough to cover its costs. Although under regulation, the incumbent has to grant access on demand; its competitors will not enter the market till the price reaches that level that could cover all its costs.

4.2.3.3 The Possible Investment Decisions

Denote the price at time t as p_t, and the price at which the entrant finds it profitable to take the access of the network as $\bar{p}$, where $\bar{p} = c_E + a$. In summary, at t, the price could fall within four possible regions relevant to the incumbent in making an investment decision.

In the first region, $\bar{p} > p_t > p_L^*$, the competitors will not demand for access since the prospective revenue simply could not cover both its production and access costs. On the other hand, the incumbent may find it profitable to develop the network without sharing with its rivals. Hence, an investment will be made in building the network.

In the second region, $\bar{p} > p_L^* > p_t$, not only the potential entrant will not be interested, the incumbent will also hesitate to invest due to a lack of sufficient incentive. As a result, no network will be built. For the time being, both parties wait for the market condition to improve.

In the third region, $p_U^* > p_t > \bar{p}$, even though it is attractive for the entrant to request for access, it will not be cost-effective for the incumbent to invest. Accordingly, no network will be built for the moment.

In the fourth region, $p_t > p_U^* > \bar{p}$, the incumbent and the entrant will both benefit from investing and taking on the access respectively. Consequently, the investment will be made.

5 SIMULATION

5.1 The Impact of Access Price on the Incentives to Invest

In the following analysis, p_U^* and p_L^* obtained from the previous section and the generalized access price formula $a = m(c_N + rX)$ will be used in conjunction with different values of m to investigate the impact of access price on the incentives to invest in network development.

To simplify the analysis, it is assumed that the drift is equal to zero $(\mu = r - \delta = 0)$. Thus:

$$dp_t = \sigma p_t dz_t$$

The values of the parameters are:

r	=	10%
σ	=	0.1
c_N	=	0.5
c_I	=	1.5
c_E	=	1
q_E	=	0.3
X	=	5

There are three possible scenarios:

- $p_U^* > \bar{p}$ and $p_L^* > \bar{p}$
- $p_L^* < \bar{p}$ and $p_U^* < \bar{p}$
- $p_L^* > \bar{p}$ and $p_U^* < \bar{p}$

Table 1: $0.1 \le m \le 2.9$

m	p_U^*	p_L^*	$\bar{p}$
0.1	3.6052		1.1000
0.3	3.4979		1.3000
0.5	3.3904		1.5000
0.7	3.2829		1.7000
0.9	3.1754		1.9000
1.1	3.0678		2.1000
1.3	2.9601		2.3000
1.5	2.8523		2.5000
1.7	2.7443		2.7000
1.9	2.6362 (Take the value of $\bar{p}$)		2.9000
2.1	2.5278 (Take the value of $\bar{p}$)		3.1000
2.3		3.1250	3.3000
2.5		3.1250	3.5000
2.7		3.1250	3.7000
2.9		3.1250	3.9000

1. $p_U^* > \bar{p}$ **and** $p_L^* > \bar{p}$

By construction, if $p_L^* \ge c_E + a$ the solution $p_L^* = \frac{\varphi_1}{\varphi_1 - 1}[c_I + rX]$ is irrelevant. The incumbent's investment threshold obtained according to the cost-based access pricing should be equal to p_U^*. If the network has been built, the entrant's threshold to enter the market is $\bar{p}$. From the table, it is observed that as the compensation increases, the trigger price decreases for the incumbent and increases for the entrant.

In this case, the access price is set too low, thus the incumbent is undercompensated. On the other hand, the entrant will always find it beneficial to demand for access as soon as the network is built. Consequently, inefficient entry might be encouraged; also investment might be untimely delayed.

2. $p_L^* < \bar{p}$ and $p_U^* < \bar{p}$

Under this scenario, p_U^* becomes irrelevant, the incumbent's investment threshold is equal to p_L^*. It is observed that as the compensation increases, the trigger price for the incumbent (p_L^*) remains unchanged, and the trigger price for the entrant ($\bar{p}$) increases.

This is because the access price is set too high; the incumbent is overcompensated. However, the competitors will not be able to profit from entering,the market by leasing the existing network from the incumbent when the price is in the region where $p_L^* < p_t < \bar{p}$. Consequently, the network will be built and the incumbent will be alone in the market for a while. In the distant future, the price may reach $\bar{p}$. At that time the entrant will find it beneficial to demand for access. Therefore, no entry will be demanded for the moment; competitors might choose to bypass by duplicating the network.

3. $p_L^* > \bar{p}$ and $p_U^* < \bar{p}$

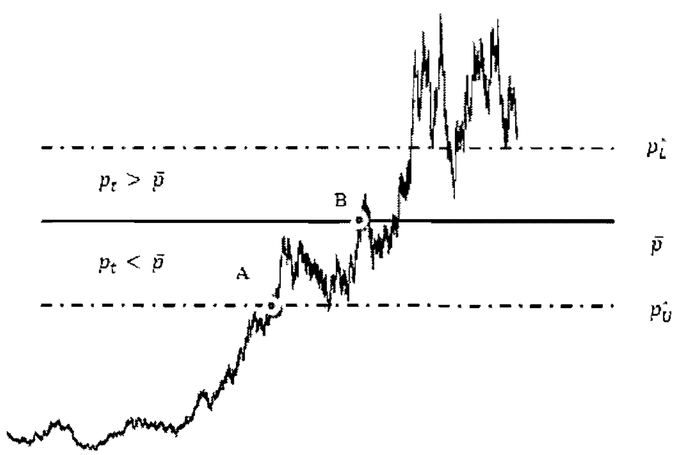

Figure 2. Price of the final good undergoing the GBM.

When m is equal to 1.9 and 2.1, p_L^* is irrelevant since it falls into the region where $p_t > c_E + a$. However, the validity of the values of p_U^* requires further discussion. From Table 3, it is observed that the values of p_U^* are all in the region where $p_t < \bar{p}$. As indicated in Figure 2, the price reaches p_U^* at point A. For the region $p_t < \bar{p}$, the solution of p_U^* is considered irrelevant. However, the price is expected to reach $\bar{p}$ at some point later in time because of the nature of the GBM. As soon as the price hits point BB where $p_t = \bar{p}$, it becomes beneficial for the incumbent to make an investment. Thus, instead of taking the values of p_U^* as the optimal threshold to invest, the incumbent will start to build the network whenever the price reaches $\bar{p}$ at which the competitor also finds it profitable to entry.

6 CONCLUSION: THE POLICY SUGGESTIONS

When the access price is not optimally determined, cēterīs paribus, the incumbent will invest later than it should as the upward potential for the incumbent is undesirably mitigated by the fixed access cost scheme while being trapped with the unbounded downward risks.

Typically, the firm will delay investment until the present value of the investment covers the costs including the value of the "option to wait" that would be forgone once the investment is made. To ensure the timely development of the network, on top of the fixed access price, the entrant should make a lump sum payment to the incumbent to compensate its irreversible cost of launching the network. Thus, the incumbent will not be discouraged or delay in making the necessary but uncertain and irreversible investment.

In essence, it is a "sharing" of investment costs between the incumbent and the entrant. If the entrant were to request for access to the upstream essential facility, it is obligated to bear a part of the investment costs, which are determined by the time of entry and the portion of the network it leases.

Ideally the lump sum charge should be the value of the real option that the entrant obtained when its access were granted: it thus has the freedom of enter and stay in the market when $p > c_E + a$ and leave the market when $p < c_E + a$. It is as if the entrant has purchased an option that allows him to keep on buying q_E as long as the price of the final goods and services is over the "strike price"[14].

[14] The strike price is equal to the sum of production cost of the entrant and access price; that is $p^{strike} = c_E + a$.

ANNEXE A

This appendix shows how to solve the following equation:

$$\frac{1}{2}\sigma^2 p^2 \frac{d^2 F}{dP^2} + (r-\delta) p \frac{dF}{dP} - rF = 0 \qquad \text{(A.1)}$$

Assuming $\sigma \neq 0$, divide equation (A.1) by $\frac{1}{2}\sigma^2$:

$$p^2 \frac{d^2 F}{dp^2} + \frac{2(r-\delta)}{\sigma^2} p \frac{dF}{dp} - \frac{2r}{\sigma^2} F = 0 \qquad \text{(A.2)}$$

Equation (A.2) is the Euler's equation and of the form

$$x^2 y'' + \rho x y' + \theta y = 0 \qquad \text{(A.3)}$$

The general solution of (A.3) in any interval not containing the origin is determined by the roots β_1 and β_2 of the equation:

$$f(\beta) = \beta(\beta-1) + \rho\beta + \beta = 0 \qquad \text{(A.4)}$$

If there are two different real roots:

$$y = c_1 |x|^{\beta_1} + c_2 |x|^{\beta_2} \qquad \text{(A.5)}$$

We now guess that the solution to equation (A.3) has the form

$$y = x^\beta \qquad \text{(A.6)}$$

Substituting (A.6) into the (A.3) yields:

$$x^2 \left[(x^\beta)\right]'' + \rho x \left[(x^\beta)\right]' + \theta (x^\beta) = x^\beta \left[\beta(\beta-1) + \rho\beta + \beta\right] \qquad \text{(A.7)}$$

Thus, if β is a root of the quadratic equation (A.4), then the Euler equation evaluates to zero and $y = x^{\beta}$ will be a solution. The roots of the (A.4) are:

$$\beta_{1,2} = \frac{-(\rho - 1) \pm \sqrt{(\rho - 1)^2 - 4\theta}}{2} \tag{A.8}$$

If the roots are real and not equal, there are two independent solutions for (A.3): $y_1(x) = x^{\beta_1}$ and $y_2(x) = x^{\beta_2}$.Therefore if c_1 and c_2 are two arbitrary constants.

The general solution is:

$$y = c_1 x^{\beta_1} + c_2 x^{\beta_2} \ (x > 0) \tag{A.9}$$

It can be shown that this solution is unique.

If apply the theorem to (A.2), the Euler equation, then, by inspection:

$$\rho = \frac{2(r - \delta)}{\sigma^2} \tag{A.10}$$

$$\theta = -\frac{2r}{\sigma^2} \tag{A.11}$$

The roots are therefore:

$$\beta_1 = \frac{1}{2} - \frac{(r - \delta)}{\sigma^2} + \sqrt{\left(\frac{(r - \delta)}{\sigma^2} - \frac{1}{2}\right)^2 + \frac{2r}{\sigma^2}} \tag{A.12}$$

$$\beta_2 = \frac{1}{2} - \frac{(r - \delta)}{\sigma^2} - \sqrt{\left(\frac{(r - \delta)}{\sigma^2} - \frac{1}{2}\right)^2 + \frac{2r}{\sigma^2}} \tag{A.13}$$

Since $\beta > 0$, the expression under the radical sign is strictly positive, which means the roots are real and different. Thus, we must have the general solution:

$$F(p) = c_1 p^{\beta_1} + c_2 p^{\beta_2} \ (p > 0) \tag{A.14}$$

Check that β_2 is always negative (because $\beta > 0$). Condition $\lim_{P\to 0} F(p) = 0$ implies that $c_2 = 0$. Hence, the solution to the differential equation $\frac{1}{2}\sigma^2 p^2 \frac{d^2F}{dp^2} + (r - \delta)p\frac{dF}{dP} - rF = 0$ must be:

$$F(p) = c_1 p^{\beta_1} \tag{A.15}$$

ANNEXE B

This appendix shows how to solve the following equation when $p < c_E + a$ and when $p > c_E + a$.

$$\frac{1}{2}\sigma^2 p^2 \frac{d^2F}{dp^2} + (r-\delta)p\frac{dF}{dp} - rF = 0 \qquad \text{(B.1)}$$

Assuming $\sigma \neq 0$, divide equation (B.2) by $\frac{1}{2}\sigma^2$:

$$p^2\frac{d^2F}{dp^2} + \frac{2(r-\delta)}{\sigma^2}p\frac{dF}{dp} - \frac{2r}{\sigma^2}F = 0 \qquad \text{(B.2)}$$

Equation (B.2) is the Euler's equation and of the form

$$x^{\prime}2\ y^{\prime\prime} + \rho x y^{\prime} + \theta y = 0 \qquad \text{(B.3)}$$

The general solution of (B.3) in any interval not containing the origin is determined by the roots φ_1 and φ_2 of the equation:

$$f(\varphi) = \varphi(\varphi-1) + \rho\varphi + \varphi = 0 \qquad \text{(B.4)}$$

If there are two different real roots:

$$yy = k_1|x|^{\varphi_1} + k_2|x|^{\varphi_2} \qquad \text{(B.5)}$$

We now guess that the solution to equation (B.3) has the form

$$yy = x^{\varphi} \qquad \text{(B.6)}$$

Substituting (B.6) into the (B.3) yields:

$$x^{\prime}2\ [[(x]^{\prime}\varphi)]^{\prime\prime} + \rho x\, [[(x]^{\prime}\varphi)\ [(x]^{\prime}\varphi)]^{\prime} + \theta(x^{\prime}\varphi) = x^{\prime}\varphi\,[\varphi(\varphi-1) + \rho\varphi + \varphi]$$

(B.7)

Thus, if φ is a root of the quadratic equation (B.4), then the Euler equation evaluates to zero and $yy = x^{\varphi}x^{\varphi}$ will be a solution. The roots of the (B.4) are:

$$\varphi_{1,2} = \frac{-(\rho - 1) \pm \sqrt{(\rho - 1)^2 - 4\theta}}{2} \tag{B.8}$$

If the roots are real and not equal, there are two independent solutions for (B.3): $y_1(x) = x^{\varphi_1}$ and $y_2(x) = x^{\varphi_2}$. Therefore if k_1 and k_2 are two arbitrary constants, we must have the general solution:

$$yy = n_1 x^{\varphi_1} + n_2 x^{\varphi_2} \; (x > 0) \tag{B.9}$$

It can be shown that this solution is unique.

If we apply the theorem to (B.2) the Euler equation, then, by inspection, we find that:

$$\rho = \frac{2(r - \delta)}{\sigma^2} \tag{B.10}$$

$$\theta\theta = -\frac{2r}{\sigma^2} \tag{B.11}$$

The roots are therefore:

$$\varphi_1 = \frac{1}{2} - \frac{(r - \delta)}{\sigma^2} + \sqrt{\left(\frac{(r - \delta)}{\sigma^1} - \frac{1}{2}\right)^2 + \frac{2r}{\sigma^2}} \tag{B.12}$$

$$\varphi_2 - \frac{1}{2} - \frac{(r - \delta)}{\sigma^2} - \sqrt{\left(\frac{(r - \delta)}{\sigma^1} - \frac{1}{2}\right)^2 + \frac{2r}{\sigma^2}} \tag{B.13}$$

Since $\varphi > 0$, the expression under the radical sign is strictly positive, which means the roots are real and different. Thus, we must have the general solution:

$$FF(p) = n_1 p^{\varphi_1} + n_2 p^{\varphi_2} \; (p > 0) \tag{B.14}$$

Check that φ_2 is always negative (because $\varphi > 0$) . Condition $\lim_{P \to 0} F(p) = 0$ implies that $k_2 = 0$. Hence, the solution to the differential equation $\frac{1}{2}\sigma^2 p^2 \frac{d^2F}{dp^2} + (r - \delta)P\frac{dF}{dp} - rF = 0$ must be:

$$F(p) = n_1 p^{\varphi_1} \tag{B.15}$$

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