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The Value of Flexibility to Switch between Water Supply Sources

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Abstract

Technological innovations lead to the construction of water utilities characterized by a high operational flexibility and high irreversible sunk costs. It is quite common today to design integrated aqueduct systems (namely vertical integrated systems with several interconnections between the network infrastructures). The interconnection and integration between supply sources, in fact, enables the system to handle crisis in the provision of the service caused, for example, by pollution emergencies or peaks in day demand curves. We argue that this operational and technical flexibility has an economic value which might turn out to be economically relevant in terms of the provider's profits if optimally exercised. The interconnection of water abstraction plants, in fact, gives, de facto, the provider the option to strategically decide the optimal switching rule between two different water sources in order to maximise its profits. According to the real option theory, we develop an investment decision model under uncertainty which takes into account the value of the flexibility to switch and we show that interconnection between water sources, though it costly and involves high irreversible sunk costs, may be more profitable than investing in a single-source water abstract plant.

Mathematics Subject Classification: 60G50, 90B50, 90B90

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1 Introduction

The supply of drinking water is a key issue all over the globe. Growing competition for the use of fresh water and degraded sources – sometimes by pollutants or climate change unpredictable effects – worsen the consequences of this problem. Water is a merit good and a scarce resource. Water scarcity is perceived nowadays both in countries where its availability is poor because of natural and geophysical conditions, and in highly industrialized countries where the demand for water quality and competitive uses of the resource are constantly and substantially increasing. In particular, changes in urban populations with regards to water resources must be seen in the context of the level of urbanization, the rate of urban growth, and changes in lifestyles that demand more consumption of water and higher degrees of water quality. Moreover, the explosive growth of urbanization, particularly in emerging and developing countries with the emergence of megacities, exacerbates the situation in these locations[1].

The provision of drinking water on the one hand and its conservation on the other hand are, therefore, key issues worldwide. Where supplies are plentiful or water is cheap, or waste prevention measures are slack, consumer waste is high. Since drinking water is a primary good, every government has to exercise some control over public water supply because piped water together with waterborne sewerage are two essential requirements for urbanized life[2].

In order to avoid insufficient volumes of water supply and to favour the socio-economic development of a given territory, there must be sufficient quantities of water and a set of infrastructures that can guarantee continuity in the provision of the service to final users. This issue is particularly crucial in Italy where the situation has deteriorated in recent years because of the lack of investments in infrastructures and water facilities. In 2002, the Report of the Italian Agency for Water Services ([5]) highlighted the urgent need for investments (about 15,8 euro per capita) in infrastructures and in particular in aqueduct systems in order to increase the efficiency of existing water utilities, build new infrastructures and find new supply sources ([5]). At a national level, there is overall agreement that investments must be made in aqueduct systems and, at the same time, resources must be managed and planned more effectively in order to take advantage of economies of scope and reduce wastage

[1]As a total the urban population in less developed countries is expected to nearly double in size between 2000 and 2025, from less than 2 billion to more than 3.5 billion especially in very large cities ([23]).

[2]For example, governments must guarantee that water supplies are free of contaminants that are harmful to citizens, that the tap water can be used as drinking water, and that all citizens have access to safe water ([44]). Water provision is nearly always controlled by a monopoly and the development of public water supplies entails the use of large amounts of capital.

through technical and managerial innovations in the industrial organization of the water service sector. In recent years the lack of efficient infrastructures and long periods of draught have led to an increase in the frequency of emergencies and crises: the two water demand crises that occurred in Italy in 2002 and 2003 are emblematic in this respect.

In this context the issue of the reliability of aqueduct systems is crucial mainly for the need for constant improvement of both the service levels[34] (i.e. the standards of supply) and the performance of aqueduct systems as set by the Italian Legislation and EU Directives[5].

The ability of the system to supply consumers' requirements under different operating conditions has become widely investigated in the literature by engineers and mathematicians[6]. However, given that drinking water is a primary good and that service provision is mandatory, the system risk of failure is a fundamental decision variable not only from the technical point of view but primarily from an economic perspective according to which an integrated technical and financial risk management model should be implemented in order to allocate assets and financial resources efficiently.

The intuition in the present paper is that the reliability of the supply system is to some extent analogous to the specific risk that the service provider can hedge by diversifying investments. Main challenges for the water service provider are in fact to provide high quality water in sufficient quantity at affordable costs whilst maintaining the various ecosystems and better match water demand with the resource availability. For these reasons, and namely to hedge risk, the provider might be willing to invest in flexible projects and reduce specific risk by exercising operating options embedded in the projects themselves[7].

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[3]The three principal level of service which relate to the performance of aqueduct systems are: a) hydraulic performance which refers to the minimum pressure and flow domestic users should experience; b) continuity of supply, which is measured by the number, duration and circumstances relating interruptions of deficiencies of supply; c) water quality standards set by national legislation for the quality of water supplied together with sampling and reporting ([44]).

[4]The quality of water required for supplying mankind, industry, agriculture or even fish farming and swimming are not the same. The most demanding requirements relate to drinking water and certain industrial uses such as those in the food industry.

[5]See in particular EU Directive n. 2000/60/CE and at national level Law n. 36/1994 and Government Decree n. 152/2006.

[6]Starting from the seminal works of [30], [14], [17], [15], a variety of reliability algorithms for water distribution networks have been developed over recent years to take into account reliability aspects arising from the mechanical failure of the system components and nodal demand variation.

[7]Alternatively, the provider might decide to buy an insurance policy for partially hedging specific risk and subscribe an insurance contract to cover risks related to interruptions in service provision. The value of the contract can be analogous to default options sold by creditors to the firm's shareholders. Risk managers can evaluate dynamically the trade-

Interconnected water supply systems (i.e. aqueduct systems where multiple water sources are interconnected one another) are, in fact, a typical example of flexible investments and can be viewed as a portfolio of options to switch between different operating modes. These systems have a higher probability to supply water demand than single source ones, are characterized by a high operational flexibility and can easily adapt to changes in the state variables (e.g. average day demand, input prices, temporary shortfall of water sources, etc.).

It is indeed very difficult to guarantee the reliability of aqueduct systems and continuity in the provision of drinking water by using a single source. Nevertheless, quite surprisingly, drinking water management is typically modelled, particularly in Italy, as a single source serving a group of consumers. Interconnection is commonly said by practitioners and designers to be extremely costly. If on the one hand the interconnection of multiple sources involves high irreversible sunk costs, on the other hand it protects users against uncertainties in service provision by generating operational flexibility. This flexibility gives the provider the option to strategically decide the optimal conjunctive use of multiple supply sources and can significantly contribute to profit maximization and hedging of risk. In other words, if optimally exercised, operational flexibility can be economically relevant and its value is strongly related to the provider's ability to decide its investment strategy and planned course of action in the future, given then-available information.

In the water service sector capital budgeting and investment decisions are made accordingly to the Net Present Value (NPV) rule. It is widely recognized that the NPV rule and traditional Discounted Cash Flow (DCF) analysis fail because they can not properly capture managerial flexibility to adapt and revise later decisions in response to unexpected market developments. DCF approaches presume management's passive commitment to a "certain static operating strategy" ([39]). As new information arrives and uncertainty about future cash flows is gradually resolved, management may have valuable flexibility to alter its initial operating strategy in order to capitalize on favourable future opportunities. In particular traditional capital budgeting techniques fail to capture the value of flexibility that characterizes water supply systems switching from one source to another when exogenous market conditions change or water shortage occurs. Indeed, the importance of such operating options becomes critical when, as in the water service sector case, the environment is volatile and the technology is flexible, thus permitting managerial intervention at limited cost. The possibility to switch into an alternative "mode of operation" less affected by adverse economic realizations reduces investments

off between costs and expected benefits generated by insurance ([27]; [35]). It is however extremely costly and quite difficult to buy insurances to hedge risks in the water service sector, particularly in Italy.

irreversibility and mitigate losses ([20]; [1]).

The real option approach, by endogenizing the optimal operating rules and explicitly capturing the value of flexibility, provides for a consistent treatment of risk.

In the last decades, following early papers by [2], [25], [26], [22] and [28][8], there has been an increasing literature concerning applications of the real option approach to investment decisions in different industrial sectors[9].To our knowledge, though, there are few contributions referring to investments decisions in the water service sector and in particular in drinking water supply systems[10].

This paper applies real option results to capital budgeting in the interconnection of water supply sources. We propose a temporal model under uncertainty to evaluate the operational flexibility that arises when water supply sources are interconnected. Our aim is to identify the trade-off between the reliability of aqueduct systems and providers' profit maximization. We investigate the value of flexibility not captured by traditional DCF techniques and the strategic dimension of investments in interconnection of supply sources. We focus on drinking water supply arguing that operating flexibility to switch might turn out to be economically relevant if optimally exercised.

The rest of the paper is organized as follows. Section 2 illustrates the key issues on the interconnection of supply sources and the reliability of aqueduct systems. In section 3 we introduce a dynamic programming procedure to evaluate the flexibility to switch and in section 4 we present an application of the model to the water service sector. Finally, section 5 illustrates the concluding remarks.

2 The reliability of aqueduct systems and the interconnection of supply sources

Although usually drinking water supply management is typically modelled as a single source serving a group of consumers, resource managers must often decide to manage multiple sources simultaneously.

It might be very difficult and costly to guarantee reliability of the supply system and continuity in the service provision by using a single source. Consequently the problem might be better set as one of a single demand supplied by multiple sources. There is, indeed, a constant need for developing new water projects and transfer schemes in order to keep ahead of the ever-increasing requirements due to the growing population and improved living standards,

[8]See also [12] and [39] for a systematic treatment of the real option approach.
[9]See [37], [38], [39], [4] and [34].
[10]See [9] and [10].

on the one hand, and to climate change on the other. Therefore, when more than one resource is available, optimal management involves conjunctive use of different water sources. Economic models of conjunctive use consider at least two sources one of which is flow and the other is stock[11]. *De facto*, conjunctive use of multiple sources protects users against uncertainty in provision[12] and makes it possible to ensure the reliability of the supply system since we admit the possibility that water scarcity may become greater in one resource than the other[13] as well as extraction from one source may become more costly than the other. The joint use of two or more sources can therefore lead to a cheaper supply than that gained by their independent use ([45]) and, to some extent, interconnected aqueduct systems add improved urban water supply management efforts.

Thanks to technological innovations, nowadays it is possible to construct complex integrated aqueduct systems (i.e. namely vertical integrated systems with several interconnections between the network infrastructures) where multiple water sources are interconnected one another in order to combine different availabilities and quality levels. A typical aqueduct system will therefore combine whatever surface water supplies are available (e.g. stream/river flows, lakes, reservoirs, etc.) with groundwater resources to improve the reliability of the supply system.

While easier to obtain, surface flows are often stochastic and surface water sources derived from snowmelt and rainfall typically fluctuate randomly from year to year and within a year. Moreover, in addition to water quantity considerations, providing sufficient downstream compensation flows has to be taken in consideration jointly with the long-term effects of disinfection by-products. Groundwater stocks, on the other hand, are relatively stable because the slow subsurface flows tend to smooth out inter and intratemporal fluctuations and, in general, groundwater is more favourable to direct abstraction and less costly treatment than surface water. Given that groundwater is the more widely used source of water, the crucial issue surrounding groundwater as a water source is the alarming fact that major groundwater aquifers are not being sustained, though it is clearly contingent on the balance between abstraction and recharge. Therefore, even when it is well managed, groundwater remains a fragile resource vulnerable to adverse interactions with human activities and pollution.

In the light of the above considerations, interconnection is an imperative

[11] The task of how to use groundwater in conjunction with surface water has been widely investigate in agricultural economics. Starting from [3], there are several papers on this issue. See for example [40], [18], [29], [43], [33], [13], [11].

[12] This issue has been widely investigated in the economic literature with respect to both agricultural and domestic use. See among others as an example [43], [46], [41],[42], [36], [11].

[13] The importance of managing groundwater and surface water sources conjunctively increases with both water scarcity and inter and intratemporal flucttutations in precipitations.

that must be addressed to enable systems to withstand crisis situations (e.g. occasional pollution, flooding, exceptional drought conditions, electrical power failures) given that continuity of service is a major public health issue when it comes to drinking water and it is also important to the local economy. In developed countries, where quantity demand is stable, a high percentage of investments are now being directed towards the creation of interconnections all of which contribute to limiting the risk of service interruptions. Thanks to the interconnection and the integration of water supplies, interconnected aqueduct systems are characterized by high operational flexibility. This flexibility has an economic value which is strongly related to the provider's ability to decide whether and when it is optimal to switch between different water supply sources. In fact, when more than one resource is available, optimal management involves not only how much to extract but how much to extract from each source: the final goal for the provider of a water utility is always to guarantee adequate service to user who should pay for this service to the best of his/her abilities. Therefore, the interconnection of water sources might become a recognized method for providing an overall operational safety of a drinking water system and making optimal investment decisions.

3 The model

Investments in the water service sector and in particular investments in water supply systems are capital intensive, have usually a very long technical life involve high irreversible sunk costs, but are characterized by high operational flexibility. The importance of such operating options becomes crucial when the environment is highly volatile and the technology is flexible, thus permitting managerial intervention at little cost. This is the case of interconnected aqueduct systems, where different operating options are embedded. For example, when facing exogenous stochastic prices a project with operating options can protect itself against some of the adverse price movements by switching into an alternative mode of operation (i.e. an alternative water supply source) that is less affected by the adverse price realizations. The volatility of prices becomes in fact an important determinant of investment, both in terms of the type of the investment (i.e. rigid versus flexible technologies) and in terms of the quantity of investment (i.e. the value of Tobin's q of flexible investments increases as volatility increases).

We extend the models by [8] and by [21] in order to estimate the value of the option to switch between two different operating modes in the case of interconnected water supply sources. We revisit and generalize the option to switch basic model, allowing for managerial decisions to switch, at specified switching costs, among alternative "mode" of operation at multiple decision points.

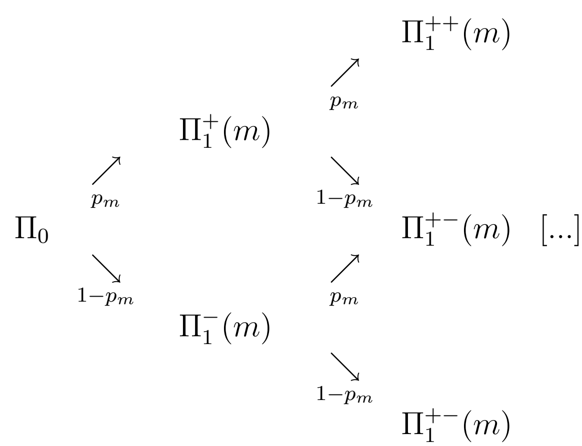
We consider two different projects A and B whose operation is rigid. The cash flows of both projects A and B follow a stationary multiplicative binomial process over successive periods.

We assume that there are n decision points ($t = 0, 1, 2, \dots$) and that the useful life of the two projects is equal to $T = n$ years.

For simplicity, we introduce the following hypotheses:

- the market is frictionless;
- the cash flow generated by each single project m, say $\pi(m)$, is a stationary moltiplicative binomial process, where the cash flow at the beginning of a given period may increase by a multiplicative factor u with probability p or decrease by a multiplicative factor d ($d < 1$) with complementary probability $(1 - p)$ at the end of the period;
- the risk free rate of return, say r, is constant over time;
- there is a single source of uncertainty[14];
- the switching is costless.

Given that the options to switch are path dependent, the net cash flow generated in year t, π_t, depends on the evolution of the state variable and the operating mode m:



where:

[14]Generalized models (see [24]) take into consideration two sources of uncertainty. We implicitly assume here that the two uncertainties are perfectly correlated so that to introduce a single source of uncertainty for the underlying asset (e.g. the price of energy).

$\pi_t^s(m)$ = net cash flow generated in year t if found in state s (where $s = +$ or $-$ in year 1, $++, +-, -$ in year 2, etc.) when using technology m;

$t = 0, 1, 2, \ldots n$;

$s = +, -, ++, +-, -, [\ldots]$;

p = probability that the net cash flow generated by project m increases by a moltiplicative factor u;

$1-p$ = probability that the net cash flow generated by project m decreases by a moltiplicative factor d, where $d = 1/u$.

The model allows to evaluate the value of the flexible project F that can switch between alternative technologies A and B at any given time t.

In the case with no switching costs, the value of the flexibility to switch is the sum of n European options to switch from A to B.

The right with no obligation to switch between the two technologies, say $F(A \longrightarrow B)$, makes the equity value of the flexible system greater than the value of either the rigid technologies A and B.

The present value of cash flows from each project m can be equivalently obtained by discounting expected cash flows using the actual probability p at the expected rate of return or by discounting risk-neutral expected values using the risk-neutral probabilities at the risk-free rate ([7]; [16]). The risk-neutral probability can be obtained as follows:

$$q = \frac{(1+r) - d}{u - d} \tag{1}$$

As anticipated above, in the case of zero switching costs, it can be demonstrated that the value of flexibility is the sum of n European options, say S_t, exercised respectively at time $t = 0, 1, 2, \ldots n$:

$$F(A \longrightarrow B) = S_0(A \longrightarrow B) + S_1(A \longrightarrow B) + ... + S_n(A \longrightarrow B) \tag{2}$$

And therefore the present value of project F is:

$$PV(F) = PV(A) + F(A \longrightarrow B) \tag{3}$$

where $PV(A)$ is the present value of project A and $F(A \longrightarrow B)$ is the value of flexibility.

Let $c_t^s(A \longrightarrow B)$ be the additional cash pay-off from switching from technology A to B in year t and state s if convenient to do so.

That is:

$$c_t^s(A \longrightarrow B) \equiv \max\left[\pi_t^s(B) - \pi_t^s(A), 0\right] \tag{4}$$

Therefore, if the adoption of technology B is profitable, we get:

$$S_0(A \longrightarrow B) = \max\left[\pi_0(B) - \pi_0(A), 0\right] \tag{5}$$

$$\begin{array}{lll} & & e_1^+(A \longrightarrow B) = \max\left[\Pi_1^+(B) - \Pi_1^+(A), 0\right] \\ & \nearrow & \\ S_1(A \longrightarrow B) & & \\ & \searrow & \\ & & e_1^-(A \longrightarrow B) = \max\left[\Pi_1^-(B) - \Pi_1^-(A), 0\right] \end{array}$$

$$\begin{array}{lllll} & & & & e_2^{++}(A \longrightarrow B) = \max\left[\Pi_2^{++}(B) - \Pi_1^{+}(A), 0\right] \\ & & & \nearrow & \\ & & [...] & & \\ & \nearrow & & \searrow & \\ S_2(A \longrightarrow B) & & & & e_2^{+-}(A \longrightarrow B) = \max\left[\Pi_2^{+-}(B) - \Pi_2^{+-}(A), 0\right] \\ & \searrow & & \nearrow & \\ & & [...] & & \\ & & & \searrow & \\ & & & & e_2^{--}(A \longrightarrow B) = \max\left[\Pi_2^{--}(B) - \Pi_2^{--}(A), 0\right] \end{array}$$

and analogously for any time period t.

In particular at node (t, j) where $t = 0, 1, \ldots n-1$, $j = 0, 1, \ldots, t$ the value of the underlying asset is:

$$\pi_{tj} = \pi_0(m) u_m^j d_m^{t-j} \tag{6}$$

Consequently according to assumption of risk neutrality and to the risk-neutral probability q, the value of the option can be obtained working back recursively as follows:

$$S_{tj}(A \longrightarrow B) = \frac{q S_{t+1,j+1}(A \longrightarrow B) + (1-q) S_{t+1,j}(A \longrightarrow B)}{(1+r)} \tag{7}$$

Since at the expiration date n:

$$S_{nj}(A \longrightarrow B) = \max\left[\pi_0(A)u_A^j d_A^{n-j} - \pi_0(B)u_B^j d_B^{n-j}, 0\right] \tag{8}$$

where u_A and d_A are the multiplicative factors relative to mode A and u_B and d_B are the multiplicative factors relative to mode B, we can start at the expiration date and apply equation 8 working back recursively. Therefore we obtain at time $t = 0$:

$$S_0 = \frac{\sum_{t=0}^{n} \begin{pmatrix} n \\ q \end{pmatrix} q^t (1-q)^{n-t} \max\left[\pi_0(A)u_A^j d_A^{n-j} - \pi_0(B)u_B^j d_B^{n-j}, 0\right]}{(1+r)^n} \tag{9}$$

In equation 9, the first part $[n!/t!(n-t)!]q^t(1-q)^{n-t}$ is the binomial distribution formula giving the probability that the cash flow will take t upward jumps in n steps, each with risk neutral probability q. The last part, $max\left[\pi_0(A)u_A^j d_A^{n-j} - \pi_0(B)u_B^j d_B^{n-j}, 0\right]$, gives the value of the option conditional on the cash flow following t ups each by $u\%$, and $n-t$ downs each by $d\%$ within n periods[15].

The flexible project F should be preferred over the project A as long as the incremental cost of acquiring F over A, say $I(F)$, is less than the value of flexibility, i.e:

$$I(F) - I(A) < F(A \longrightarrow B) \tag{10}$$

where $I(A)$ is the cost of acquiring project A, i.e. is the investment cost of project A.

It can be demonstrated that, in the case of no switching costs, the present value of the flexible system can be thought of as equivalent to operating project B with the flexibility to switch from technology B to A when profitable, i.e.:

$$PV(F) = PV(B) + F(B \longrightarrow A) \tag{11}$$

It is important to note that without switching costs the general dynamic problem is equivalent to a series of simplex myopic problems, with the combined package value being equal to the sum of the separate component values.

[15] The summation of all the possible option values at expiration, multiplied by the probability that each will occur, gives the expected terminal option value, which is then discounted at the risk-less rate of return over the n periods.

The above approach can be generalized for multiple periods to cover any number of states ($s = 0, 1, 2, .., n$) and for multiple operating modes ($i = 0, 1, 2, \dots, M$) within a backward iterative process, seen as a discrete economically adjusted version of the Bellman equation of dynamic programming [39][16].

The process can be applied iteratively moving back until the beginning ($t = 0$) project's value is obtained, along with the optimal operating schedule[17].

4 The value of interconnecting water sources

The following section aims to exemplify that, under certain circumstances, the value of flexibility is greater than the additional costs paid to acquire a flexible technology with respect to a rigid technology.

We refer to the Italian context and we assume that the provider of a water service has to supply drinking water (i.e. X cubic meters) to new users and has the possibility to use two different water sources. Consequently the provider has the option to decide between two different alternatives: a) construct a new groundwater abstraction plant (made of a well field[18]) henceforth alternative A, designed on the basis of volume X; b) construct a river abstraction plant, henceforth alternative B, designed on the basis of volume X; c) construct a flexible system obtained by interconnecting the two water supply sources above described, henceforth alternative F. We also assume that the net cash flows generated by the two alternative A and B depends on a single exogenous stochastic state variable and the useful life of both of the alternatives is $T = 30$ years.

Alternative A consists of: a) well field (3 wells); b) pumping station; c) treatment plant; d) storage system (capacity equal to 10,000 m^3); e) treatment plant; f) electrical system for the equipment installed. The treatment plant includes a filtration process on Granular Activated Carbon (GAC) and the storage system includes disinfection and chlorination procedures[19].In fact groundwater extraction guarantees the provision of good quality water, which does not need highly specific treatment to meet the regulations for drinking water standards.

[16] Starting from the end and moving backward, the value of a flexible project in state s at any time, $t-1$, should be obtained from the expected future values in the up $(s+1)$ or down $(s-1)$ states calculated one step earlier.

[17] See [20].

[18] A well field is the sinking of several moderately sized boreholes, spaced apart in some pattern, their yields being collected together. This system is used in order to develop a good yield from an area where a single well could not be expected to guarantee a large enough yield.

[19] For a more detailed overview of technical solutions, technologies and design criteria see [44].

The project's useful life T is equal to 30 years and the system guarantees a water provision X of about $300l/s$ (equivalent to $9,460,800$ m^3/year) but it is subject to water losses in the network, say i, ranging from 20 to 30%. We assume that the plant's construction and instalment costs I_A are not time-dependent and amount to about $3,125,000$ *Euros*.

Alternative B consists of: a) intake; b) coagulation-flocculation-sedimentation process; c) sand filtration system; d) activated carbon adsorption; e) storage system (capacity equal to 10,000 m^3); e) clarification and disinfection procedure[20].

Analogously to alternative A, the project's useful life T is equal to 30 years[21] and the system guarantees a water provision X of about $300l/s$ (equivalent to $9,460,800$ m^3/year), subject to water losses in the network i, ranging from 20 to 30%. We assume that the plant's construction and instalment costs I_B are not time-dependent and amount to about $3,250,000$ Euros.

Alternative F is a flexible system obtained by interconnecting the two water supply sources above described. We assume that project F can switch between alternative A and alternative B at zero costs and we assume a total switch between A and B. The project's construction and instalment costs I_F are not time-dependent and amount to about $5,275,000$ Euros.

We finally introduce the following simplifying hypothesis for both of the two projects A and B:

1. the discounted value of the project's future cash flows is a good approximation of the present value of the asset and is linear in X:

$$\Pi_t(m) = \pi_t^m V_E = R_t^m(1-i)V_E - c_t^m V_E \tag{12}$$

where

$m = A, B$;

$\Pi_t(m)$ = net cash flow at time t of project m;

π_t^m = net cash cash flow per cubic meter at time t relative to project m;

R_t^m = revenues per cubic meter at time relative to project m;

i = water losses in the network[22];

c_t^m = operating cost per cubic meter at time t relative to project m

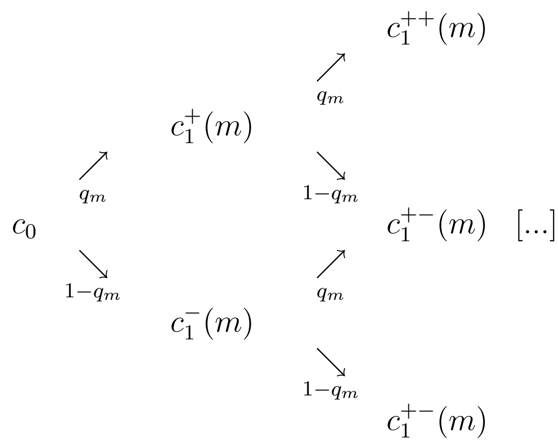
[20] For a more detailed overview of technical solutions, technologies and design criteria see [44].

[21] 30 years is the usual concession length in Italy for the provision of water services.

[22] Water losses are assumed to be constant. A loss of 20% of the network's volume is considered as a benchmark case.

2. revenues derives from tariffs charged to users and are deterministic[23];

3. operating costs[24] (sum of production, maintenance and running costs) follow a random walk process[25]



where
$c_t^s(m)$ = operating cost per cubic meter generated in year t if found in state s when using technology m;
$s = +, -, ++, +-, -+, -, \ldots$.

4 the risk free interest rate of return, say r, is deterministic and constant over time;

[23]Tariffs are calculated according to the Italian regulation and in particular according to the Government Decree 1.08.1996, known as "Metodo Tariffario Normalizzato". The provider is subject to a price cap regulation but it is also guaranteed at time t to recover from the costs of service paid at time t-1. Moreover, as far as the domestic water use, it is likely that demand is rigid in the short term. We draw their value using projections of water price and demand estimated by the local regulators (ATO) on the basis of the "Metodo Tariffario Normalizzato" over the entire concession period. When the service can apply a water price that is above the financial equilibrium price, this constitutes an endowment that is intended for self-financing purposes given the stringent budget constraints that the Government was facing when the reform of the water service sector in Italy was introduced in 1994 (see National Law n. 36/1994).

[24]The operating costs include labour, management and maintenance costs, supply costs (electricity, treatment chemicals), direct maintenance costs (replacement parts), general costs (premises, management, veichles). Variable costs, in particular the expenditure for chemicals used in water treatment (chlorination) and energy (pumping station), are the most relevant ones as regards an abstraction plant consisting of wells. In this case the expenditure for chemicals is non-significant when compared with energy costs and can therefore be ignored. The price of energy is likely to follow an exogenous random walk stochastic process.

[25]Fixed operating costs can be estimated as a percentage of total operating costs and range between 20% and 30%. These costs may vary significantly depending on the management and the organization of the specific firm providing the service.

5 the project's salvage value at the end of its lifetime is zero;

6 switching costs I_s are null.

Technical and economic data relative to alternative A and B are listed below:

- the water volume supplied is $V_E = 9,460,800$ m^3/year;
- the projects' useful life is $T = 30$ years;
- average revenues per cubic meter are $R_A = R_B = R = 0,5$ Euro/m^3[26];
- volume losses i amount to 20%;
- operating costs per cubic meter at time $t = 0$ are $c_0^A = 0,15$ Euro/m^3[27] and $c_0^B = 0,17$ Euro/m^3[28];
- the risk free discount rate is $r = 5\%$[29].

Under these assumptions, the right with no obligation to switch between the two technologies makes the equity value of the flexible system greater than the value of either the rigid projects. That is:

$$PV(F) \geq \max\left[PV(A), PV(B)\right]$$

or in other words:

$$PV(F) = PV(A) + F(A \longrightarrow B)$$

[26] Average revenues per cubic meter have been determined by a statistical analysis performed over a distribution whose parameters have been estimated on the basis of the average tariff paid by users for the provision of drinking water. The data refer to ATO Bacchiglione in the Veneto Region. This result is consistent with the average revenues estimated for the provision of drinking water in Italy by CONVIRI ([6]), i.e. the national Authority in charge of controlling and supervising local regulators. Moreover, average revenues per cubic meter are coincident with the tariff piad per cubic meter, therefore project A's average revenues per cubic meter are equal to project B's average revenues cubic meter: $R_A = R_B = R$.

[27] Designers and industry experts interviewed agree on estimating the average operational costs of this type of plant at around 0.15 Euro/m^3. The average has been calculated over a distribution. Variance has been estimated considering analogous investment projects realized in the past, whose operating costs were known throughout the project life. A scenario analysis was conducted to prove the consistency of these estimates which can be considered representative for this type of plant.

[28] Designers and industry experts interviewed agree on estimating the average operational costs of this type of plant at around 0.17 Euro/m^3. Analogously to the case of alternative A, the average has been calculated over a distribution. Variance has been estimated considering analogous investment projects realized in the past, whose operating costs were known throughout the project life. A scenario analysis was conducted to prove the consistency of these estimates which can be considered representative for this type of plant.

[29] The risk-free rate is assumed to be equal to the rate of return of stated-owned bonds.

where:
$PV(F)$ = present value of project F;
$PV(A)$ = present value of project A;
$F(A \longrightarrow B)$ = value of flexibility to switch from A to B.

The value of flexibility is the sum of n European options to switch S_t $(t = 0, 1, 2, \ldots, n)$ that can be exercised at any time t:

$$F(A \longrightarrow B) = S_0(A \longrightarrow B) + S_1(A \longrightarrow B) + ... + S_n(A \longrightarrow B)$$

In order to illustrate the properties of the option model, we provide some numerical solutions and discuss the applications of 10. We performed comparative statics to study the effect of changes in u_A and u_B.Table 1 displays the results of the simulations performed assuming different values for u_A and u_B respectively.

When $u_A = u_B = 1.1$ the value of flexibility is high and it is convenient to build an interconnected aqueduct system. As expected, the option value to switch increases with increasing volatility. In particular, as long as the volatility on asset A increases and the multiplicative factor u_B is respectively equal to 1.1 and 1.2 it is not convenient to invest in the flexible project, since the extra costs that the provider has to bear in order to acquire flexibility with respect to the "rigid" technology is offset by the value of flexibility itself. Therefore, under these assumptions, the rigid technology dominates the flexible project. It is worth noting that the option to switch is more valuable around the point at which the two operating costs are indifferent: this because the probability of a switch is higher at this indifference point, making flexibility more valuable. In other words, when the flexible project is operating in the A mode, the project contains a call option that can be exercised to switch to B. On the other hand, when it is operating using B, the flexible project contains a put option that can be exercised to switch to A.

The value of flexibility increases when the time horizon increases: i.e. for increasing t the option's payoff increases.

The equivalence according to which in the absence of switching costs $NPV(A) + F(A \rightarrow B) = NPV(B) + F(B \longrightarrow A)$ does not hold when the switching is costly. When there are costs associated with switching from one operating mode (i.e. water supply source) to another, the separate switching options are no longer independent and the option-value additivity breaks down ([39]). If the switching is costless the potential exercise of an earlier switching option affects the current payoff but has no effect on a subsequent option. On the contrary, when switching costs are not null, the switching affects the current decision and cash payoff but also alters the exercise costs and switching options in future periods. In other words, the exercise of a prior option creates a series of nested new options to switch in the future analogous to a compound option, invalidating option-value additivity.

5 Concluding Remarks

We have presented a simple model of flexibility that can be used to obtain the option value to switch between different modes of operations by means of interconnecting water supply sources.

Investing in a flexible project, that is the result of the interconnection of groundwater and surface water, allows the provider of the water service to hedge specific risk, analogously to an investor who diversifies his/her portfolio. The provider might be therefore incentivated to invest in a flexible technology in order to hedge uncertainties related to both the fluctuations of water availability and the volatility of variable operating costs.

The interconnection of water supply sources allows the firm to reduce specific risk by exercising operating options embedded in the flexible project and increase the reliability of aqueduct systems ensuring continuity in the provision of drinking water. Indeed, if on the one hand the interconnection of multiple sources involves high irreversible sunk costs, on the other hand it protects users against uncertainties in service provision by generating operational flexibility. This flexibility gives the provider the option to strategically decide the optimal conjunctive use of multiple supply sources and can significantly contribute to profit maximization and hedging of risk.

There is a trade-off between the implementation of a costly but flexible system (involving the interconnection of water supply sources) and a rigid project of greater size (involving just one supply source). In addition, analogously to the "Just in Time" inventory strategy, the possibility to switch from one water supply source to another allows the provider to implement a more rational resources use. Moreover, the possibility to interconnect water sources might reduce the need for reservoirs and the related investment costs. When the number of interconnections increases, the value of flexibility increases which in turn increases as the time horizon increases. This flexibility might have a relevant economic value if the operating options embedded in the flexible project are optimally exercised. In particular, when facing exogenous stochastic prices of inputs a project with operating options can protect itself against some of the adverse price movements by switching into an alternative mode of operation that is less affected by the adverse price realization. Real option techniques by explicitly capturing the flexibility and its effects on uncertainty, provide for a consistent treatment of risk in the valuation of interconnected aqueduct systems.

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