New Technology Adoption Games: An Application to the Textile Industry

Alcino F. Azevedo[1,2]* and Dean A. Paxson*

Manchester Business School,

Booth Street West

Manchester M15 6PB, UK

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[1] Corresponding author: Alcino.azevedo@gmail.com; +44(0)1612756510.
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Abstract

In this paper we use three real option models to determine the optimal adoption time of a new technology in two Portuguese textile companies, Lameirinho and Coelima. In the derivations of the models we take into account both uncertainty and competition. In the first model, we decompose the uncertainty into two types: market and technical uncertainty; in the second model, we subdivide the uncertainty into three types: market, technical and technological; and in the third model, we consider only market uncertainty, but in a context where there are two technologies available whose functions are complementary. In all models we assume that there is a first-mover advantage and derive analytical expressions for the leader and the follower value functions, and their respective investment trigger values, in a game-choice setting considering the pre-emption effect.

Our results show the importance of considering technical uncertainty when adopting a new technology whose reliability cannot be fully tested in a laboratory before adoption, illustrate the influence of the technological progress on new technology adoption time, and emphasize the effect on optimal time of adoption of complementary aspects of two technologies on their.

Keywords: Multi-Factor Model, Duopoly Investment Game, Pre-emption Games, Real Options Empirical Application.

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1. Introduction

The investment problem that is underlying this paper can be described as follows: there are two firms operating in a duopoly market which have the opportunity to launch a new textile product in the US, for which they need to replace 130 weaving machines currently in place in their plants for 72 new and more sophisticated ones. We use three real options models, derived in Appendices A, B and C, to determine the optimal time to adopt these new weaving machines. In the first model, we decompose the uncertainty into two types: market and technical uncertainty; in the second model, we subdivide the uncertainty into three types: market, technical and technological uncertainty; and in the third model, we treat the uncertainty as a unique variable, but in a context where there are two complementary technologies available.
We derive, for each of the models above, analytical expressions for the leader and the follower value functions, and their respective investment trigger values, in a game-choice setting where it is assumed that there is a first-mover advantage. In this paper we test these models using consistent parameters. Some of the parameters used in our calculations are assumed; others estimated from empirical data.

Our choice to apply the three real option models derived by Azevedo and Paxson (2006, 2007, 2008), and summarized in Appendix A, to the textile industry is related to the use of the variable "the efficiency of a new technology after adoption" and technological complementarity. The use of the variable "efficiency of a new technology after adoption" is appropriate for cases where the reliability of the new technology cannot be fully tested before adoption, either because the real conditions in which the new technology will operate after adoption cannot be replicated in a laboratory, or because it is simply physically impossible or too expensive to perform such analysis. The consideration of the concept of "technological complementarity" is applicable to cases where the new technology is a complement of a technology that is either already in operation or available for adoption.

Due to its idiosyncrasies, the textile industry is one of the industries that fit both of the requirements above. All the real option models used in this paper were derived for duopoly markets, so we chose two dominant Portuguese firms, Lameirinho and Colima, for the empirical application.

The rest of the paper is organized as follows. In Section 2, we briefly describe the two firms, Lameirinho and Coelima. In Section 3, we describe some basic technical aspects about the management of weaving technologies, show the economic impact on the value of the adoption of a new technology of a misjudgment about its "efficiency after adoption", and describe the intuition underlying the application of three real option models to the evaluation of investment decisions on new textile technologies. In Section 4, we present the models parameters and compute and comment on our results. In Section 5 we conclude.

2. The Two Firms: a brief Description

Lameirinho and Coelima are two of the most important Portuguese textile companies, with more than forty years of experience in manufacturing textiles. These firms do not have their own distribution chain, their products are sold in big supply chains, such as Wal-Mart, LLBean, Sears, Next, Debenhams, Littlewood and Mark & Spencer, all over the world, but with especial emphasis on the US and the European markets. They produce about the same mix of products and have about the same production capacity. In Figure 1 we present some general information about each of these firms.

Information about the two Firms	Lameirinho	Coelima
Founded	1947	1922
Type of Management	Family type	Family type
Annual Turner Over (2006)	75 Million Euros	62 Million Euros
Nº Employees	1,100	980
Type of Organization	**Vertical organization*:** Spinning, Weaving, Printing, Painting, Finish Treatments, and Make-up	**Vertical organization*:** Spinning, Weaving, Printing, Painting, Finish Treatments, and Make-up
Portfolio of Products	Bed sheets, pillow cases, duvets, fitted sheets, quilts, curtains and table cloths.	Bed sheets, pillow cases, duvets, fitted sheets, quilts, curtains and table cloths.
Main Materials Used	Cotton, Synthetic fibers, Mixtures with Linen**.	Cotton, Synthetic fibers, Mixtures with Linen**.
Main Production Techniques used	Percale, Satin, Dobby, Jacquard, Flannel, Embroidery, Print, Dyed yarns.	Percale, Satin, Dobby, Jacquard, Flannel, Embroidery, Print, Dyed yarns.
Main Markets	**USA (55%)** Europe (30%) Portugal (10%) Others (5%)	**USA (35%)** Europe (45%) Asia (5%) Others (5%)

* Although some of these activities are partially outsourced.
** In Lameirinho this product is less than 1% of sales while contributes to 6% of the sales in Coelima.

Table 1 – General Information about Lameirinho and Coelima.

Although Lameirinho and Coelima outsource some of their non-strategic production processes, most of the components used in their products are made in their plants using their own production techniques. An illustration of the organization of the production systems of these firms is in Figure 1.

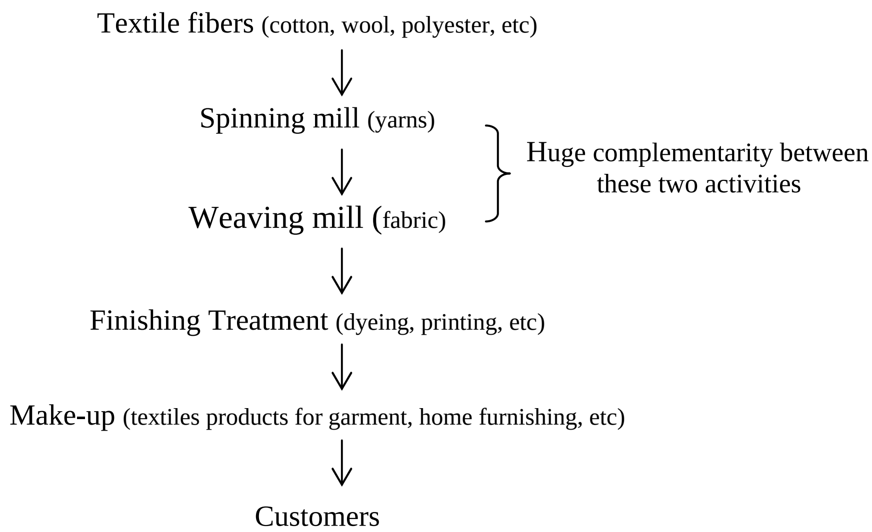

Figure 1 – Organization of the Production System at Lameirinho and Coelima.

The textile industry begins with the fiber production of cotton, flax, and other fibrous plants; in husbandry of sheep, silkworms and other animals; in mining of metals and minerals; in forestry for wood and in chemical research and production of synthetic fibers. All these fibers are then processed into yarns and the yarns are transformed into fabrics which, after being appropriately finished, can be sold for industrial and consumer uses.

The organization of a production system as illustrated in Figure 1 creates a phenomenon we call "technological complementarity". This means that the performance of the spinning mill depends on the quality of the fibers and the performance of the weaving mill depends on the quality of the yarns, and so forth. Each activity affects the performance of the activity that follows and is affected by the activity that precedes it. The third real option model assesses the value of the adoption of a new technology considering the effect of the complementarity between two technologies (or production activities)[3].

[3] Note that in this type of production system, it might not be wise to adopt very sophisticated weaving machines, without first studying whether the spinning machines currently in place

3. The Adoption of New Weaving Machines

Weaving machines produce textile fabrics. The efficiency (performance) of a weaving mill depends on the characteristics of the fabric that is being produced, the quality of the yarns used, the weavers' skills, the quality of the planning and organization of the production activities and the sophistication and reliability of the weaving machines and auxiliary equipment[4].

3.1 Basic Aspects on Weaving

The weaving is one method of producing textile fabrics. A weaving machine (also called loom) transforms yarns into fabrics. In order to do so it works simultaneously with thousands of yarns, depending on the width and compactness of the fabric[5]. During the weaving operation there are several events that can reduce the pace of the production (some of them, to some extend, unavoidable), such as yarn ruptures, technical problems in the weaving machines and auxiliary equipment, inadequate planning and organization of the production activities, etc.

During the weaving operation as soon as one of the thousands of the yarns used in the construction of the fabric breaks, an electronic system detects the problem and immediately stops the weaving machine, in order to solve the problem. As the number of yarns used in a fabric is very high, so yarn ruptures are quite frequent, even when yarns of good quality are used. On the other hand, in a weaving mill, the number of weaving machines per weaver varies between 10 and 20, depending on the type of fabric that is being produced, the type of weaving machine used and the

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are capable of producing yarns with the quality standards that are required by the new weaving machines.

[4] Auxiliary equipment in a weaving mill facilitate the replacement of the warp beams and the fabric rolls and the air conditioning system, which keeps the purity, temperature and the "relative humidity" of the air inside the plant at the appropriate levels, essential for a good weaving.

[5] A fabric of 3 meters width can have, depending on its compactness, between 10,000 and 120,000 yarns.

weaver's experience. Consequently, in a work day, the time during which weaving machines are inactive can be very high[6].

In Table 2 is a summary of the most important causes of the inefficiencies (stops) of a weaving machine:

Main Causes of the Inefficiencies in a Weaving Machine	
Cause	**Description**
1	Yarn ruptures
2	Replacement of warp beams
3	Reliability of the weaving machine (electric, electronic and mechanical problems)
4	Predictive maintenance
5	Inadequate planning and organization of the production activities

Table 2 - Causes of the Inefficiencies in a Weaving Machine.

3.1.1 The Relationship between Efficiency and Output Production

Figure 2 shows the relationship between the "efficiency" and the "production" of the 130 weaving machines at one of Lameirinho's weaving mills.

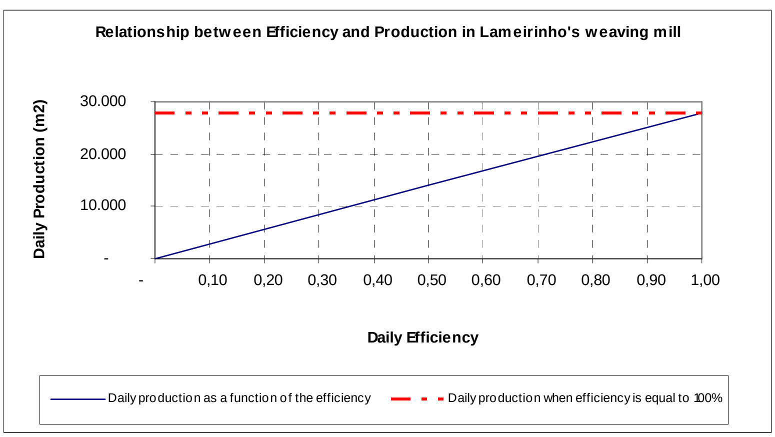

Figure 2 – The Relationship between "Daily Efficiency" and "Daily Production" at one of Lameirinho's Weaving Mills.

[6] These facts justify our assumptions regarding the use of the variable "efficiency of the new technology after adoption" and the assumption that this variable follows a geometric Brownian motion process.

The straight line above represents, for a specific fabric, the relationship between the "daily efficiency" (%) and "daily production" (square meters of fabric) in a weaving mill. In this case, it shows that that there is a linear relationship between these two variables. The higher the efficiency of the weaving mill, the higher its production per unit of time. Looking at the two extremes of the efficiency variable, we can see that, in this weaving mill, when the "daily efficiency" is 100 percent (the highest level possible), it produces 28,000 m^2 of fabric per day ($Q_{E=1.00} = 28,000 \text{ m}^2$) and when "daily efficiency" is zero (the lowest level possible) it produces zero square meters of fabric per day ($Q_{E=0.00} = 0.00 \text{ m}^2$). The slope of the straight line depends on the specificities of the fabric that is being produced. The higher the complexity of the fabric, the lower the slope of the straight line[7].

In a weaving mill, once this linear relationship between the variables "efficiency" and "production" is quantified, it is possible to compute the production rate from a given efficiency, and vice versa.

3.2 A New Investment Behavior

Lameirinho and Coelima adopted the, now, 130 old weaving machines in 1997. As we mentioned earlier, at the moment, these two firms are considering the possibility of lunching a new textile product in the US, for which they will have to replace the 130 weaving machines currently in place in their plants by 72 new and more sophisticated ones. Below we described briefly the story behind the adoption of the 130 weaving machines that are now in place in both firms.

The supplier chosen was Sulzer-ruti, a Swedish company and, currently, the world leader in the development of this type of technology. Over the forty years of experience in fabric manufacturing, Lameirinho and Coelima have adopted, with great success, several versions of weaving machines developed by this supplier. Therefore, in 1997, the trust of Lameirinho and Coelima on the reliability of the

[7] The intuition is that for a given efficiency level, the more complex the production of a fabric (compactness), the lower the weaving machine's production per unit of time.

Sulzer-ruti's weaving machines was so high that they adopted them without questioning whether the technical performance that was advertised by the supplier could be reached.

Since during the previous forty years there was no any serious technical problem with the Sulzer-ruti's weaving machines, Lameirinho and Coelima assumed that technical uncertainty could be neglected. According to the technical information given by Sulzer-ruti at the time, the new weaving machines, after adoption, would operate with an average efficiency of 96 percent. Both firms adopted them based on that expectation, but, for the first time in more than thirty years of a commercial relationship between these firms and the supplier of weaving machines Sulzer-ruti, things went terribly wrong. Below is a detailed description of the results of the investment. In Figure 3, we show records of the efficiency of the 130 those machines during the first 15 months of activity at one of Lameirinho's weaving mills. In Coelima the results were similar.

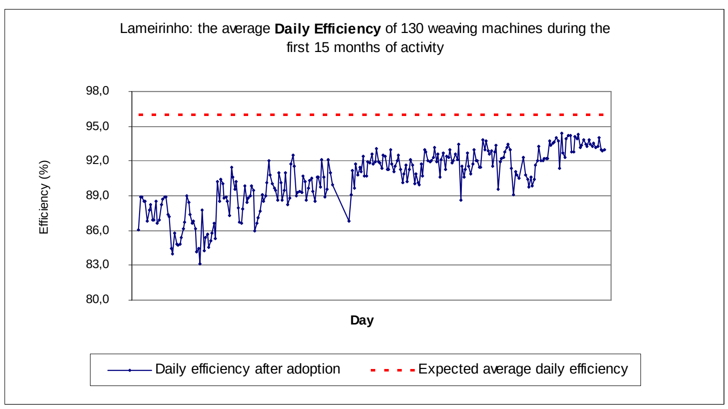

Figure 3 – The Efficiency of the Previous Version of the Newest Sulzer-ruti's Weaving Machines during their First 15 Months of Activity.

In Figure 3, the dashed line represents the level of efficiency promised by Sulzer-ruti at the time of the adoption. The uninterrupted line represents the level of efficiency that was effectively achieved after adoption, during the first 15 months of operations. Comparing both lines in Figure 3, the conclusion is obvious: the weaving machines are not capable of operating with the average 96 percent efficiency that was promised by Sulzer-ruit. Sulzer-ruti's predictions and the expectations of Lameirinho and

Coelima regarding the efficiency of the new weaving machines after adoption were wrong.

Looking more carefully at Figure 3 we can see that the average efficiency of the weaving mill (the 130 weaving machines) during the first 15 months of activity was 93 percent, and that although its efficiency has improved over time, it never reached the 96 percent that was expected. This information altogether with the fact that during the last three months of activity shown in Figure 3 the variations in the volatility of the efficiency diminished considerably, may indicate that the weaving machines efficiency may stabilize at a maximum efficiency level of 93 percent. Considering this information, in Table 3 we summarize the Lameirinho's efficiency/production problem caused by the "unexpected" bad technical performance of the weaving machines.

Performance	**Value**
Efficiency promised by Sulzer-ruti at the Time of Adoption	96.00%
Efficiency achieved 15 Months After the Adoption	93.00%
"Unexpected" Efficiency lost per day	3.00%
"Unexpected" lost in Production Capacity per day	3.00%

Table 3 - Summary of the Efficiency/Production Problem.

Using the straight line of Figure 2, we determine the impact of the 3 percent "unexpected" lost in daily efficiency (96.0% - 93.0% = 3.0%) on the daily weaving mill production (square meters of fabric produced per day). In Figure 6.2 we show that the relationship between daily efficiency and daily production is linear and that when the efficiency of the weaving mill is equal to 100 percent, it produces 28,000 m^2 of fabric per day. Consequently, by simple calculations we determine that a daily lost of 3 percent in efficiency represents a daily lost in production of 840.00 m^2 of fabric. In Figure 4 we represent this result graphically.

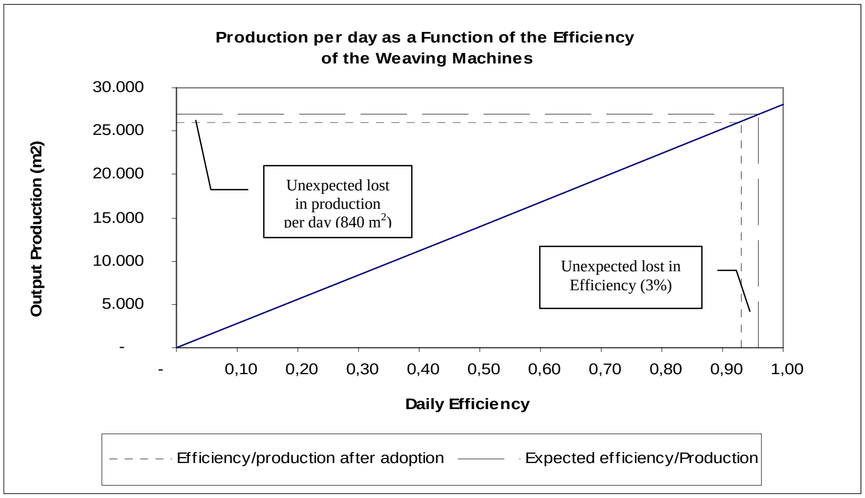

Figure 4 – The Impact of an "Unexpected" Loss in the Efficiency of the New Weaving Machines on the Daily Production of the Weaving Mill.

Multiplying 840.00 m^2 by 30 days, we obtain the lost of production per month; multiplying it by 343, we get the loss production per year. Doing these calculations we determine that the "unexpected" technical problems with the 130 weaving machines led to a lost production of 25,200.00 m^2 of fabric per month and 643,600.00 m^2 of fabric per year.

The experience above changed the behavior of Lameirinho and Coelima regarding the analysis of investment on new weaving technologies. They are now dealing again with the adoption of new weaving machines, nine years after the events described above. But their previous (terrible) experience has lead them to demand for a more sophisticated investment model.

Their intuition is that in an investment like this, technical uncertainty must be taken into account, regardless of the level of guarantees given by the supplier. Competition should be considered, because they are operating in a duopoly market and the opponent is looking at the same investment opportunity. Technological uncertainty should be included in the investment analysis because there are other suppliers of weaving machines in the market, which can launch, at a yet unknown date, new and more efficient machines, and make their previous investment suboptimal. The phenomenon of complementarity between the spinning technology they have currently in their spinning mills and the new weaving machines that are about to be adopted should be studied, given that they have doubts about whether the spinning machines they have currently in place will be capable of producing yarns with the quality level demanded by the new weaving machines. Finally, a first-mover advantage should be taken into account, because they were advised by Sulzer-ruti that, due to restrictions in its production capacity, it could not deliver 72 new weaving machines to both firms at the same time, meaning that the first to set the order will be the first to get the new machines.

The three real option models derived in Appendix A, altogether, allow us to study each of these uncertainties in a slightly more restricted context, but in any case give us to have an idea about the influence of each of the aspects that are the main concerns of Lameirinho and Coelima regarding their investment decision.

In the next section we present our real option model parameters and compute and comment our results.

	Real Option Models					
Uncertainty Factors	**Model I (Appendix A1)**		**Model II (Appendix A2)**		**Model III (Appendix A3)**	
Competition	- Duopoly Market		- Duopoly Market		- Duopoly Market	
Type of Uncertainty	- Market - Technical		- Market - Technical - Technological		- Market - Technological Complementary	
Underlying Variables	- Net Revenues, $X(t)$ - Efficiency, $E(t)$		- Net Revenues, $X(t)$ - Efficiency, $E(t)$ - Technological Uncertainty, λ		- Saving Costs, $S(t)$ - Investment Cost, $I_1(t)$, $I_2(t)$ - Degree of Technological Complementary, γ	
Model Parameters	**Input**	**Nature**	**Input**	**Nature**	**Input**	**Nature**
	σ_X	Assumed	σ_X	Assumed	σ_C	Assumed
	σ_E	Estimated	σ_E	Estimated	σ_{I_1}	Assumed
	μ_X	Assumed	μ_X	Assumed	σ_{I_2}	Assumed
	μ_E	Estimated	μ_E	Estimated	μ_C	Assumed
	$\rho_{X,E}$	Assumed	λ	Estimated	μ_{I_1}	Assumed
	r	Assumed	$\rho_{X,E}$	Assumed	μ_{I_2}	Assumed
	$de_{1_L 0_F}$	Assumed	r	Assumed	γ_1	Estimated
	$de_{1_L 1_F}$	Assumed	$de_{2_L 0_F}$	Assumed	γ_2	Estimated
			$de_{1_L 0_F}$	Assumed	γ	Estimated
			$de_{2_L 2_F}$	Assumed	ρ_{C,I_1}	Assumed
			$de_{1_L 1_F}$	Assumed	ρ_{C,I_2}	Assumed
			$de_{1_L 2_F}$	Assumed	r	Assumed
					$ds_{1_L 0_F}$	Assumed
					$ds_{1_L 1_F}$	Assumed
					$ds_{2_L 2_F}$	Assumed
					$ds_{12_L 12_F}$	Assumed
					$ds_{12_L 1_F}$	Assumed
					$ds_{0_L 0_F}$	Assumed

Table 3 - Models Parameters.

4. Model Results

4.1 Model I

In this section we apply the real option model derived in Appendix A1 to determine the optimal time to adopt the new weaving machines for both the leader and the follower. We deterministically assigned that in case of adoption Lameirinho will be the first (the leader) and Coelima the second (the follower) to adopt. In this model we consider uncertainty and competition and the uncertainty is decomposed into two types, market and technical uncertainty. We assume that there is a first mover advantage. In the next section we present the model inputs and compute and comment our results.

4.1.1 Information Available

The information currently available to both firms is in Table 4:

Model I (Inputs)	**Value**
Expected Net Present Value (NPV)	-1.96 Million Euros
Expected NPV Revenues, $X(t)$	11.50 Million Euros
Expected Efficiency after Adoption, $E(t)$	0.96
Expected NPV of Revenues weighted with the Efficiency, $\varphi(t)$	11.04 Million Euros
Investment cost, I	13.00 Million Euros
Revenues Volatility, σ_X	0.30
Efficiency Volatility, σ_E	0.07
Revenues drift, μ_X	0.04
Efficiency drift, μ_E	0.02
Riskless rate, *r*	0.09
Correlation Coefficient between Revenues/Efficiency, $\rho_{X,E}$	0.50
Competition Factors:	
Leader's Advantage when alone in the Market, $de_{1_L 0_F}$	0.10 Million Euros
Leader's Advantage after the Follower entry, $de_{1_L 1_F}$	0.30 Million Euros

Table 4 - Model Inputs.

4.1.2 Results

Trigger Values	Value
Leader's Investment Trigger Value, φ_L^*	2.13 Million Euros
Follower's Investment Trigger Value, φ_F^*	12.06 Million Euros

Table 5 – Firms' Investment Trigger Values.

4.1.3 Conclusions

According to our results, the leader (Lameirinho) should adopt now, since $\varphi(t) > \varphi_L^*$. The follower (Coelima) should wait until the "expected revenues weighted with the efficiency" reaches 12.06 Million Euros, i.e., $\varphi(t) > \varphi_F^*$.

Note that in the present conditions (at time *t*), the NPV of the investment is negative (-1.96 Million Euros). According to the NPV methodology, none of the firms should invest until the NPV of the investment is positive. Our real options model, however, evaluates this business opportunity in a very different way. We consider the effect of competition, assuming that firms have fear of pre-emption and that there is a first-mover market and efficiency advantage and these assumptions justify the investment at a time where the NPV is negative. Note that this is only an apparent irrational behavior, because although investing at time where the NPV is negative, Lameirinho is conscious of the fact that as soon as it invests it will benefit from monopolistic revenues from that point until the follower investment. Using our results as example, we can see that, the leader should invest right now, since $\varphi(t) = 11.04$ Million Euros and $\varphi_L^* = 2.13$ Million Euros; the follower should wait until $\varphi(t)$ reaches 12.06 Million Euros. In between the leader investment time, *t*, and the follower investment time, the former benefits from monopolistic revenues.

4.2 Model II

In this section we apply the real options model derived in Appendix A2 to determine the optimal time to adopt the new weaving machines for both the leader and the follower. Again, we deterministically assigned that in case of adoption Lameirinho will be the first (the leader) and Coelima the second (the follower) to adopt. In this model we consider both uncertainty and competition. In this model both uncertainty and competition are taken into account. The uncertainty is decomposed into three types: market, technical and technological uncertainties, and it is assumed that there is a first mover advantage. In the next sections we present the model inputs and compute and comment on our results.

4.2.1 Information Available

Model II (Inputs)	**Value**
Expected Net Present Value (NPV)	-1.96 Million Euros
Expected NPV of Revenues, $X(t)$	11.50 Million Euros
Expected Efficiency after Adoption, $E(t)$	0.96
Expected NPV of Revenues weighted with the Efficiency, $\varphi(t)$	11.04 Million Euros
Technological Uncertainty, λ	0.20
Investment cost, I	6.00 Million Euros
Revenues Volatility, σ_X	0.30
Efficiency Volatility, σ_E	0,07
Revenues drift, μ_X	0.04
Efficiency drift, μ_E	0.02
Riskless rate, *r*	0.09
Correlation Coefficient between Revenues/Efficiency, $\rho_{X,E}$	0.50
Competition Factors:	
Leader's Advantage when alone in the Market with Tech 2, $de_{2_L 0_F}$	0.10 Million Euros
Leader's Advantage when alone in the Market with Tech 1, $de_{1_L 0_F}$	**0.10 Million Euros**
Leader's Advantage when both Firms are in the Market Operating with *tech 2*, $de_{2_L 2_F}$	0.05 Million Euros
Leader's Advantage when both Firms are in the Market Operating with *tech 1*, $de_{1_L 1_F}$	0.03 Million Euros
Leader's Advantage when both Firms are in the Market, the Leader operating with *tech 1* and the Follower operating with *tech 1*, $de_{1_L 2_F}$	**0.01 Million Euros**

Table 6 - Model Inputs.

4.2.2 Results

Trigger Values	Value
Leader's Investment Trigger Value, $\varphi^*_{L_{12}}$	6.50 Million Euros
Follower's Investment Trigger Value, $\varphi^*_{F_{21}}$	30.16 Million Euros

Table 7 - Firms' Investment Trigger Values.

4.2.3 Conclusions

According to our results, the leader (Lameirinho) should be in the market operating with the new weaving machines, since $\varphi(t) > \varphi^*_{L_{12}}$. The Follower (Coelima) should wait until the "expected revenues weighted with the efficiency", $\varphi(t)$, reaches 30.16 Million Euros, i.e., $\varphi(t) > \varphi^*_{F_{21}}$.

$\varphi^*_{L_{12}}$ is the optimal time for the leader to adopt the weaving machines currently available in the market, on the assumption that the follower will wait for the new weaving machines release, whose likelihood of being released and become a success we assume to be 20 percent ($\lambda = 0.20$). $\varphi^*_{F_{21}}$ is the optimal time for the follower to adopt the new weaving machines that may be released in the future with a 20 percent chance ($\lambda = 0.20$), given that the leader has adopted the new weaving machines that are currently available. We denote the new weaving machines that are currently available by *tech 1* and the new weaving machines that may be released in the future by *tech 2*, hence the notation used.

The results above, when compared with the results of the previous real option model allow us to see the influence of the technological progress (technological uncertainty) on Lameirinho and Coelima investment behavior. In Table 8 we compare the results of both models.

Real Option Model	Trigger Values	Value
Expected Net Revenues weighted with the Efficiency, $\varphi(t)$		11.04 Million Euros
Model I (Appendix A1) **(Azevedo and Paxson, 2006)** (No technological uncertainty)	Leader's Investment Trigger Value, φ_L^* Follower's Investment Trigger Value, φ_F^*	2.13 Millions Euros 12.06 Millions Euros
Model II (Appendix A2) **(Azevedo and Paxson, 2007)** (Technological uncertainty is considered, $\lambda = 0.20$)	Leader's Investment Trigger Value, $\varphi_{L_{12}}^*$ Follower's Investment Trigger Value, $\varphi_{F_{21}}^*$	6.50 Millions Euros 30.16 Millions Euros

Table 7 - Firms' Investment Trigger Values.

Note in this paper Model II (Appendix A2) is an extension of Model I (Appendix A1). They were derived under exactly the same assumptions except that in the former we assume that there technological progress and therefore a new and more efficient weaving machine can arrive in the market at a given chance and, in the latter, technological uncertainty (progress) is neglected. Consequently, the differences between the results of Model I and II are due to the introduction in the latter of the technological uncertainty, using the parameter $\lambda = 0.20$.

Looking more carefully at the results of both models we can conclude that a 20 percent chance of a second new and more efficient weaving machine in the market leads both firms to delay their investment. This effect is more serious for the follower (Coelima) than for the leader (Lameirinho), since with the introduction of the technological uncertainty in the investment problem, the former increases from an investment threshold of 12.06 to 30.16 Million Euros, and the latter increases from an investment threshold of 2.13 to 12.06 Million Euros. Since $\varphi(t) = 11.04$ Million Euros and is greater than φ_L^* and $\varphi_{L_{12}}^*$, Lameirinho (the leader) adopts the weaving technology currently available for both scenarios, although its investment trigger is higher in the former case. The follower (Coelima) delays the investment in both the case where technological uncertainty is considered and the case where it is neglected.

In the case where technological uncertainty is not considered, Colima's investment trigger value is close to the current "expected net revenues weighted with the efficiency" ($\varphi(t) = 11.04$ and $\varphi_F^* = 12.06$). When technological uncertainty is considered the difference between Coelima's investment trigger value and the current "expected net revenues weighted increases significantly ($\varphi(t) = 11.04$ and $\varphi_{F_{21}}^* = 30.16$), making its investment much less likely to occur in the near future. Therefore, the conclusion is that for the inputs used, Coelima is affected by the existence of technological uncertainty more than Lameirinho.

The result above was expected, since the leader is the first to adopt and as soon as it adopts, in a context of technological progress, it makes sense for the follower to delay the investment in the weaving technology that is available when there is a chance that a better and more efficient weaving machine will arrive in the near future. Regarding the leader's investment threshold, our initial intuition was that it should be affected by the technological uncertainty but not as much as for the follower. Our results confirm that intuition.

4.3 Model III

In this section we apply the real options model derived in Appendix A3 to determine the optimal time to adopt the new weaving machines for both the leader and the follower. Again, we deterministically assigned that in case of adoption Lameirinho will be the first (the leader) and Coelima the second (the follower) to adopt. In this model we consider both uncertainty and competition. We assume that the cost savings that can be made through the adoption of the new weaving machines are a proportion of the firm's operating costs, which are uncertain. In addition we consider that there is a complementarity between the adoption of the new weaving machines and the spinning machines currently in place in both firms.

4.3.1 Information Available

Model III (Inputs)	Value
Expected Operating Costs Net Present Value, $C(t)$	17.00 Million Euros
Expected Investment Cost: Weaving Machines, $I_1(t)$	13.00 Million Euros
Expected Investment Cost: Spinning Machines, $I_2(t)$	22.00 Million Euros
Operating Costs Volatility, σ_C	0.20
Investment Cost Volatility: Weaving Machines, σ_{I_1}	0.10
Investment Cost Volatility: Spinning Machines, σ_{I_2}	0.10
Drift of the operating costs, μ_C	0.05
Drift of the Investment Cost: Weaving Machines, μ_{I_1}	-0.05
Drift of the Investment Cost: Spinning Machines, μ_{I_2}	-0.10
Correlation Coefficient between the Variables $C(t)$ and $I_1(t)$, ρ_{C,I_1}	0.40
Correlation Coefficient between the Variables $C(t)$ and $I_2(t)$, ρ_{C,I_2}	0.40
Riskless rate, *r*	0.09
Technological Complementarity Factors:	
Proportion of the Firms' Operating Cost Saved through the Adoption of *Tech 1*, γ_1	0.15
Proportion of the Firms' Operating Cost Saved through the Adoption of *Tech 1*, γ_2	0.15
Proportion of the Firms' Operating Cost Saved through the Adoption of *Tech 1*, γ	0.40
Competition Factors:	
Leader's Advantage when alone in the Market with *Tech 1*, $ds_{1_L 0_F}$	0.30 Million Euros
Leader's Advantage when both firms are in the Market Operating with *tech 1*, $ds_{1_L 1_F}$	0.10 Million Euros
Leader's Advantage when both firms are in the Market Operating with *tech 2*, $ds_{2_L 2_F}$	0.08 Million Euros
Leader's Advantage when both firms are in the Market Operating with *Tech 1* and *Tech 2*, $ds_{12_L 12_F}$	0.08 Million Euros
Leader's Advantage when both Firms are in the Market, the Leader Operating with *Tech 1* and *Tech 2* and the Follower Operating with *Tech 1*, $ds_{12_L 1_F}$	0.05 Million Euros
Leader's Advantage when both firms are inactive, $ds_{0_L 0_F}$	0.00 Million Euros

Table 8 - Model Inputs.

4.3.2 Results

Trigger Values	**Value**
Leader's Investment Trigger Value, $\varphi^*_{1_L}$	0.91
Leader's Investment Trigger Value, $\varphi^*_{2_L}$	1.05
Leader's Investment Trigger Value, $\varphi^*_{1+2_L}$	0.57
Follower's Investment Trigger Value, $\varphi^*_{1_F}$	1.35
Follower's Investment Trigger Value, $\varphi^*_{2_F}$	1.67
Follower's Investment Trigger Value, $\varphi^*_{1+2_F}$	1.00

Table 9 - Firms' Investment Trigger Values.

4.3.3 Conclusions

For the inputs used, and according to the results above, the sequence of the investment is as follows: Lameirinho (the leader) adopts first both the weaving and the spinning machines (*tech 1* and *tech 2*), when the ratio "operating cost over the investment costs" (i.e., cost of *tech 1* and *tech 2*) reaches 0.57. The follower adopts second, also both technologies, when the ratio "operating cost over the investment costs" reaches 1.00. In case for some technical reason the adoption of the weaving and the spinning technologies could not be done at the same time, Lameirinho should adopt first the weaving machines (*tech 1*), when the ratio "operating cost over the investment costs" reaches 0.91. The same criterion should be followed by Coelima, but this firm should adopt the weaving machines a little later, when the ratio "operating cost over the investment costs" reaches 1.35.

5. Conclusions

Our results are in general intuitive. They show that technological uncertainty delays the adoption of the technology currently available for both firms but the follower is more affected. The effect of complementarity between two technologies leads firms to adopt both technologies at the same time, instead of adopting them sequentially.
For the inputs used in Model III, the leader should adopt immediately both the new weaving machines and the new spinning machines. The follower should wait until its investment trigger value is reached. It is not yet clear for the follower whether it will

adopt the weaving machines alone or both the weaving machines and the spinning machines altogether. That depends on the future evolution of its operating costs and the cost of both technologies, which are uncertain.

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Appendix A

1. Derivation of Model I

1.1 The Follower

1.1.1 Value Function

$$F_F(\varphi) = \begin{cases} A\varphi^{\beta_1} + \dfrac{\varphi de_{01}}{r - \mu_X - \mu_E} & \varphi < \varphi_F \\ \dfrac{\varphi de_{11}}{r - \mu_X - \mu_E} - I & \varphi \geq \varphi_F \end{cases} \tag{A1.1}$$

$$A = \frac{\varphi_F^{\ (1-\beta_1)}}{\beta_1} \frac{de_{11} - de_{01}}{r - \mu_X - \mu_E} \tag{A1.2}$$

$$\beta_{1(2)} = \frac{1}{2} - \frac{(\delta_E - \delta_X)}{\sigma_m^{\ 2}} + (-)\sqrt{\frac{2\delta_E}{\sigma_m^{\ 2}} + \left[\frac{(\delta_E - \delta_X)}{\sigma_m^{\ 2}} - \frac{1}{2}\right]^2} \tag{A1.3}$$

$\sigma_m = \sqrt{\sigma_X^{\ 2} + \sigma_E^{\ 2} + 2\rho\sigma_X\sigma_E}$, $\delta_X = r - \mu_X$ and $\delta_E = r - \mu_E$.

1.1.2 Investment Trigger Value

$$\varphi_F = \frac{\beta_1}{\beta_1 - 1} \frac{(r - \mu_X - \mu_E)}{de_{11} - de_{01}} I \tag{A1.4}$$

1.2 The Leader

1.2.1 Value Function

$$F_L(\varphi) = \begin{cases} \left(\dfrac{\varphi}{\varphi_F}\right)^{\beta_1} \dfrac{de_{1_L1_F} - de_{1_L0_F}}{r - \mu_X - \mu_E}\varphi_F + \dfrac{\varphi de_{1_L0_F}}{r - \mu_X - \mu_E} - I & \varphi < \varphi_F \\ \dfrac{\varphi de_{1_L1_F}}{r - \mu_X - \mu_E} & \varphi \geq \varphi_F \end{cases} \tag{A1.5}$$

1.2.2 Investment Trigger Value

$$\left(\frac{\varphi_L}{\varphi_F}\right)^{\beta_1}\frac{de_{1_L1_F}-de_{1_L0_F}}{r-\mu_X-\mu_E}\varphi_F+\frac{\varphi_L\left(de_{1_L0_F}\right)}{r-\mu_X-\mu_E}-I-A(\varphi_L)^{\beta_1}-\frac{\varphi_L\left(de_{0_L1_F}\right)}{r-\mu_X-\mu_E}=0 \qquad \text{(A1.6)}$$

A2. Derivation of Model II

2.1 The Follower

2.1.1 Value Function

$$\tilde{F}_{F_{21}}(\varphi)=\begin{cases} A_{21}\varphi^{\beta_1}+C_{21}\varphi^{\beta_3} & \varphi<\tilde{\varphi}^*_{F_{21}} \\ D_{21}\varphi^{\beta_4}+\dfrac{\varphi\left(de_{2_F1_L}\right)}{(r-\mu_X-\mu_E)}\dfrac{\lambda}{(r-\mu_X-\mu_E)+\lambda}-\dfrac{\lambda I}{r+\lambda} & \varphi\geq\tilde{\varphi}^*_{F_{21}} \end{cases} \qquad \text{(A2.1)}$$

Where,

$$A_{21}=\left(\tilde{\varphi}^*_{F_{21}}\right)^{-\beta_1}\left(\frac{\tilde{\varphi}^*_{F_{21}}\left(de_{2_F1_L}\right)}{r-\mu_X-\mu_E}-I\right) \qquad \text{(A2.2)}$$

$$C_{21}=\frac{\left(\tilde{\varphi}^*_{F_{21}}\right)^{-\beta_3}\left[r\left(r-\mu_X-\mu_E\right)\beta_4+\left(r-(\mu_X+\mu_E)\beta_1\right)\lambda\beta_4-\left(r-\mu_X-\mu_E\right)\left(r+\lambda\right)\beta_1\right]I}{\left(r+\lambda\right)\left(r+\lambda-\mu_X-\mu_E\right)\left(\beta_1-1\right)\left(\beta_3-\beta_4\right)} \qquad \text{(A2.3)}$$

$$D_{21}=\frac{\left(\tilde{\varphi}^*_{F_{21}}\right)^{-\beta_4}\left[r\left(r-\mu_X-\mu_E\right)\beta_3+\left(r-(\mu_X+\mu_E)\beta_1\right)\lambda\beta_3-\left(r-\mu_X-\mu_E\right)\left(r+\lambda\right)\beta_1\right]I}{\left(r+\lambda\right)\left(r+\lambda-\mu_X-\mu_E\right)\left(\beta_1-1\right)\left(\beta_3-\beta_4\right)} \qquad \text{(A2.4)}$$

$$\beta_{3(4)}=\frac{1}{2}-\frac{\left(\delta_E-\delta_X\right)\lambda}{\sigma_m^2}+(-)\sqrt{\frac{2\delta_E+\lambda}{\sigma_m^2}+\left[\frac{\left(\delta_E-\delta_X\right)\lambda}{\sigma_m^2}-\frac{1}{2}\right]^2} \qquad \text{(A2.5)}$$

$\sigma_m=\sqrt{{\sigma_X}^2+{\sigma_E}^2+2\rho_{XE}\sigma_X\sigma_E}$, $\delta_X=r-\mu_X$ and $\delta_E=r-\mu_E$.

2.1.2 Investment Trigger Value

$$\tilde{\varphi}^*_{F_{21}} = \frac{\beta_1}{\beta_1 - 1} \frac{(r - \mu_X - \mu_E)}{\left(de_{2_F 1_L}\right)} I \tag{A2.6}$$

2.2 The Leader

2.2.1 Value Function

$$\tilde{F}_{L_{12}}(\varphi) = \begin{cases} E_{12}\varphi^{\beta_3} + B_{12}\varphi^{\beta_1} + \dfrac{\varphi\left(de_{1_L 0_F}\right)}{(r - \mu_X - \mu_E)} - I & \varphi < \tilde{\varphi}^*_{F_{21}} \\ G_{12}\varphi^{\beta_4} + \dfrac{\varphi\left(de_{1_L 0_F}\right)}{(r - \mu_X - \mu_E + \lambda)} + \dfrac{\varphi\left(de_{1_L 2_F}\right)}{(r - \mu_X - \mu_E)} \dfrac{\lambda}{(r - \mu_X - \mu_E + \lambda)} - I & \varphi \geq \tilde{\varphi}^*_{F_{21}} \end{cases} \tag{A2.7}$$

$$B_{12} = \left(\tilde{\varphi}^*_{F_{21}}\right)^{1-\beta_1} \frac{\left(de_{1_L 2_F} - de_{1_L 0_F}\right)}{r - \mu_X - \mu_E} \tag{A2.8}$$

$$E_{12} = \frac{\left(\tilde{\varphi}^*_{F_{21}}\right)^{1-\beta_3} \left[(r - \mu_X - \mu_E)(\beta_1 - \beta_4) + \lambda(\beta_1 - 1)\right]\left(de_{1_L 0_F} - de_{1_L 2_F}\right)}{(r - \mu_X - \mu_E + \lambda)(r - \mu_X - \mu_E)(\beta_3 - \beta_4)} \tag{A2.9}$$

$$G_{12} = \frac{\left(\tilde{\varphi}^*_{F_{21}}\right)^{1-\beta_4} \left[(r - \mu_X - \mu_E)(\beta_1 - \beta_3) + \lambda(\beta_1 - 1)\right]\left(de_{1_L 0_F} - de_{1_L 2_F}\right)}{(r - \mu_X - \mu_E + \lambda)(r - \mu_X - \mu_E)(\beta_3 - \beta_4)} \tag{A2.10}$$

2.1.2 Investment Trigger Value

$$\tilde{\varphi}^*_{F_{21}} = \frac{\beta_1}{\beta_1 - 1} \frac{(r - \mu_X - \mu_E)}{\left(de_{2_F 1_L}\right)} I \tag{A2.11}$$

A3. Derivation of Model III

A3.1 Simultaneous Adoption:

3.1.1 The Follower

3.1.1.1 Value Function

$$F^{Sq}_{F_{12,12}}(\phi_2) = \begin{cases} \dfrac{\gamma_1 C\left(ds_{1_F 12_L}\right)}{r - \mu_C - \mu_{I_1}} - I^*_{1_F} + A_{12}\phi_2^{\beta_1} & \phi_2 < \phi^*_{1+2_F} \\ \dfrac{(\gamma - \gamma_1) C\left(ds_{12_F 12_L}\right)}{r - \mu_C - \mu_{I_2}} - I^*_{1_F} - I^*_{2_F} & \phi_2 \geq \phi^*_{1+2_F} \end{cases} \tag{A3.1}$$

$$A_{12} = \frac{\left(\phi^*_{1+2_F}\right)^{(1-\beta_1)}}{\beta_1} \frac{(\gamma - \gamma_1)\left(ds_{12_F 12_L}\right)}{r - \mu_C - \mu_{I_2}} \tag{A3.2}$$

$$\beta_{1(2)} = \frac{1}{2} + \frac{\mu_{I_2} - \mu_C}{\sigma_{m_2}} + (-)\sqrt{\left(\frac{1}{2} + \frac{(\mu_{I_2} - \mu_C)}{\sigma_{m_2}}\right)^2 + \frac{2(r - \mu_{I_2})}{\sigma_{m_2}}} \tag{A3.3}$$

$$\sigma_{m_2} = \sqrt{\sigma_C^2 + \sigma_{I_2}^2 - 2\rho_{CI_2}\sigma_C\sigma_{I_2}}\ .$$

3.1.12 Investment Trigger Value

$$\phi^*_{1+2_F} = \frac{\beta_1}{\beta_1 - 1} \frac{(r - \mu_C - \mu_{I_2})}{(\gamma - \gamma_1)\left(ds_{12_F 12_L}\right)} \tag{A3.4}$$

3.1.2 The Leader

3.1.2.1 Value Function

$$F^{Sq}_{L_{12,12}}(\phi_2) = \begin{cases} \dfrac{\gamma C\left(ds_{12_L 1_F}\right)}{r - \mu_C - \mu_{I_1+I_2}} - I^*_{1_L} - I^*_{2_L} + \left(\dfrac{\phi_2}{\phi^*_{1+2_F}}\right)^{\beta_1} \dfrac{\gamma C\left(ds_{12_L 12_F} - ds_{12_L 1_F}\right)}{r - \mu_C - \mu_{I_1+I_2}} & \phi_2 < \phi^*_{1+2_F} \\ \dfrac{\gamma C\left(ds_{12_L 12_F}\right)}{r - \mu_C - \mu_{I_1+I_2}} - I^*_{1_L} - I^*_{2_L} & \phi_2 \geq \phi^*_{1+2_F} \end{cases} \tag{A3.5}$$

3.1.2.2 Investment Trigger Value

$$\frac{\gamma C\left(ds_{12_L1_F}\right)}{r-\mu_C-\mu_{I_1+I_2}}-I_{1_L}^{*}-I_{2_L}^{*}+\left(\frac{\phi_2}{\phi_{1+2_F}^{*}}\right)^{\beta_1}\frac{\gamma C\left(ds_{12_L12_F}-ds_{12_L1_F}\right)}{r-\mu_C-\mu_{I_1+I_2}}-\frac{\gamma_1 C\left(ds_{1_F12_L}\right)}{r-\mu_C-\mu_{I_1}}+I_{1_F}^{*}-A_{12}\phi_2^{\beta_1}=0 \quad \text{(A3.6)}$$

A3.2 Sequential Adoption:

3.2.1 The Follower

3.2.1.1 Value Function

$$F_{F_{1,1}}(\phi_1)=\begin{cases} A_1\left(\dfrac{\phi_1}{\phi_{1_F}^{*}}\right)^{\beta_1} & \phi_1<\phi_{1_F}^{*} \\ \dfrac{\gamma_1 C\left(ds_{1_F1_L}\right)}{r-\mu_C-\mu_{I_1}}-I_{1_F}^{*} & \phi_1\geq\phi_{1_F}^{*} \end{cases} \quad \text{(A3.7)}$$

$$A_1=\frac{\phi_{1_F}^{*\,(1-\beta_1)}}{\beta_1}\frac{\gamma_1\left(ds_{1_F1_L}\right)}{r-\mu_C-\mu_{I_1}} \quad \text{(A3.8)}$$

$$\beta_1=\frac{1}{2}+\frac{\mu_{I_1}-\mu_C}{\sigma_{m_1}}+\sqrt{\left(\frac{1}{2}+\frac{(\mu_{I_1}-\mu_C)}{\sigma_{m_1}}\right)^2+\frac{2(r-\mu_{I_1})}{\sigma_{m_1}}} \quad \text{(A3.9)}$$

3.2.1.2 Investment Trigger Value

$$\phi_{1_F}^{*}=\frac{\beta_1}{\beta_1-1}\frac{(r-\mu_C-\mu_{I_1})}{\gamma_1\left(ds_{1_F1_L}\right)} \quad \text{(A3.10)}$$

3.2.2 The Leader

3.2.2.1 Value Function

$$F_{L_{1,1}}(\phi_1)=\begin{cases} \dfrac{\gamma_1 C\left(ds_{1_L0_F}\right)}{r-\mu_C-\mu_{I_2}}-I_{1_L}^{*}+\left(\dfrac{\phi}{\phi_{1_F}^{*}}\right)^{\beta_1}\dfrac{\beta_1}{\beta-1}\left(ds_{1_L1_F}-ds_{1_L0_F}\right) & \phi_1<\phi_{1_F}^{*} \\ \dfrac{\gamma_1 C\left(ds_{1_L1_F}\right)}{r-\mu_C-\mu_{I_2}}-I_{1_L}^{*} & \phi_1\geq\phi_{1_F}^{*} \end{cases} \quad \text{(A3.11)}$$

3.2.2.2 Investment Trigger Value

$$\frac{\gamma_1 C\left(ds_{1_L 0_F}\right)}{r-\mu_C-\mu_{I_2}} - I^*_{1_L} + \left(\frac{\phi}{\phi^*_{1_F}}\right)^{\beta_1} \frac{\beta_1}{\beta-1}\left(ds_{1_L 1_F} - ds_{1_L 0_F}\right) - A_1\left(\frac{\phi_1}{\phi^*_{1_F}}\right)^{\beta_1} = 0 \qquad \text{(A3.12)}$$

A4. Estimation of the Efficiency Volatility

Mean	90.445
Standard Error	0.154
Median	90.925
Mode	88.877
Standard Deviation	2.497
Sample Variance	**6.672**
Kurtosis	- 0.163
Skewness	- 0.724
Range	11.258
Minimum	83.141
Maximum	94.398
Count	262.000
Largest(1)	94.398
Smallest(1)	83.141
Confidence Level (95.0%)	0.304

Table A4.1 – Data Series Analysis.