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Investment Timing and Eco(nomic)-Efficiency of Climate-Friendly Investments in Supply Chains

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Abstract:

Emission trading schemes like the European Union Emissions Trading System (EUETS) try to reconcile economic efficiency and ecological efficiency by creating financial incentives for companies to invest in climate-friendly innovations. Using real options methodology we demonstrate that under uncertainty economic and ecological efficiency are still mutually exclusive. This problem is even tightened if a climate-friendly project depends on investments of a whole supply chain. We model a sequential bargaining game in a supply chain where the parties negotiate about the implementation of a carbon dioxide (CO_2) saving investment project. We show that the outcome of their bargaining is not economic efficient and even less ecological efficient. Furthermore, we can show that a supply chain is getting less economic efficient and less ecological efficient with every additional chain link. Finally, we give recommendations how managers or politicians could improve the situation and thereby increase the economic as well as the ecological efficiency of supply chains.

Keywords: Emission trading; Optimal investment timing; Real options; Game theory; Supply chain management; Eco-efficiency;
JEL Code: G34, D81, M11

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1. Introduction

In analogy to economic-efficiency, i.e. to produce a given output with a minimal (financial) input the World Business Council for Sustainable Development (WBCSD) coined the term eco-efficiency in 1992, which the literature nowadays defines as the ability to create "more value with fewer environmental resources resulting in less environmental impact" (Guenster et al., 2011, p. 680f.). Since then the concept of corporate eco-efficiency has become an important component of corporate social responsibility (CRS). Regarding the emissions of carbon dioxide (CO_2) which has been identified as a key driver of global warming economic efficiency and eco-efficiency have traditionally been mutually exclusive to a wide extant.[1] As the reduction of carbon dioxide emissions usually does not generate a financial benefit but requires investment costs companies which have to maximize their shareholder value have not invested in carbon dioxide saving innovations and therefore have not yet become eco-efficient (Walley and Whitehead, 1994). Instead, carbon dioxide savings mostly occur as an external benefit, for example as a consequence of economic-motivated energy-savings or a more efficient organization of production, logistics and warehousing in supply chains. With the introduction of world-wide Emissions Trading Systems it was expected to allow firms to combine economic efficiency with eco-efficiency. For example, companies in the European Union (EU) have to hand over emission allowances to the authorities in an amount that is equivalent to their CO_2 emissions. The emission allowances are issued by the European Union's member states and are generally scarce, i.e. the total sum of the allowed emissions is lower than the expected amount of emissions the industry would produce in absence of

[1] See, e.g. Lin et al. (2007) and Pindyck (2002).

the European Union Emission Trading System (EUETS). As a consequence, the emission allowances which can be traded at a stock exchange have a value. The concept behind EUETS is that companies are expected to invest voluntarily into projects which help to reduce their CO_2 emissions if the investment costs I are lower than the saved emissions costs S. Thus, it should be economic efficient to the companys to increase their eco-efficiency.

However, the spot market price of the allowance to emit one ton of CO_2 is varying stochastically over time, because it is subject to various sources of uncertainty.[2] First, there is political uncertainty about the total amount of emission allowances that will be issued in the next years and about the industries that will have to participate in the EUETS. Second, the economies total demand of emissions allowances is subject to market uncertainty and technological uncertainty. Consequently, the exact amount of the saved emissions costs is uncertain, too. Therefore, a company's possibility to invest into a climate-friendly project has to be regarded as a real option. Hence, upon investing a company has to give up a flexibility value f, thus it pays to wait with the investment. Instead of investing as soon as $S > I$ companies will optimally invest later, i.e. as soon as $S > I + f$. Due to this, economic efficiency is still counteracting eco-efficiency in some extant. Another problem arises in a supply chain, if a climate-friendly project which could reduce the CO_2 emissions (costs) of a chain link depends on investments of the whole supply chain. As we will show, the outcome of this situation will not even be economic efficient. Thus, the CO_2-saving project will be accomplished inefficiently late in an economic and ecological sense.

[2] See, e.g. chapter 15 of Stern (2007).

The remainder of the paper is organized as follows: Section 2 provides a brief overview of related literature in the field of supply chain management and game theory with particular focus on real options. Section 3 presents an n-echelon supply chain model under the assumption that the costs saved by investing in a CO_2 saving project are proportional to a random spot price for emission allowances and that investment timing is a result of a sequential bargaining game. Section 4 summarizes the numerical results of the comparative-static analysis while Section 5 discusses possible management policies that further improve the economic and ecological efficiency of the supply chain. Finally, Section 6 concludes.

2. Literature Review

Over the last few years, the research domain in operations management and supply change management, in particular, has lively been enriched by two central themes, namely game theory and real options. By definition, a supply chain is a network of different agents, e.g. suppliers, distributors, and retailers that participate in the sale, delivery and production of a specific good or service. As such, the profitability of a supply chain depends strongly on the individual actions of each agent and makes game theory obviously suited (Nagarajan and Sošić, 2008). In recent years, two strains of literature have emerged. The first strain considers the fact that the outcome in a supply chain is the result of a cooperative decision making process. Here, the agents jointly maximize the supply chain's profit in a cooperative game-theoretical manner.[3] Contrarily, the second strain of literatures allows the agents of a supply chain to individually maximize their profits leading to an application of non-cooperative game theory.[4]

However, not only is the question on *how* profits are shared in a supply chain a critical issue with strong strategic relevance in the field. Of central importance is also the question *when* to invest in a supply chain. Recent literature has acknowledged that the classical net present value is static in the sense that it requires the agents to make investment decisions immediately (e.g. Chevalier-Roignant et al., 2011). In contrast, interpreting an investment as an option right, i.e. the right to invest but not being obliged to puts great stress on the optimal timing of an investment and a supply chain, in particular.[5] These real options have been successfully integrated in different supply chain settings (e.g. Triantis and Hodder, 1990; Goh et al., 2007; Alvarez and Stenbacka, 2007). The other partners' action set, however, has been neglected indicating that the single firm possesses all of the bargaining power in the supply chain. Moreover, the managerial flexibility associated with investment decision becomes manifested in the strategy to switch between suppliers or production locations in response to uncertain exchange rates (e.g. Huchzermeier and Cohen, 1996; Kogut and Kulatilaka, 1994; Kazaz et al., 2005). Only a few attempts exist that focus on the

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[3] The literature sometimes refers to this cooperative approach as a centralized supply chain (Giannaccaro and Pontrandolfo, 2004). In particular, the situation of joint profit maximization is identical to a situation where decision-making is centralized by a global planner.

[4] Cachon and Netessine (2004) and Li and Whang (2002) provide a profound overview on game theoretical applications in the supply chain management literature. The flat panel industry, however, has shown, that cooperation and competition represent not the only way to manage supply chains. Rather, a mixture of competition and cooperation is also rational. These co-opetion supply chains have gained special attention lately bridging non-cooperative and cooperative game theory. See, e.g. Gurnani et al. (2007).

[5] For a comprehensive view see e.g. Dixit and Pindyck (1994), Schwartz and Trigeorgis (2004), Smit and Trigeorgis (2004), Trigeorgis (1996).

modeling of option games in supply chains. For example, Cvsa and Gilbert (2002) consider a situation where a monopolistic supplier offers two competing external distributers, i.e. two downstream buyers early purchase commitments. All individuals face primarily demand uncertainty and due to this operational flexibility exist such that the downstream firms face a trade-off between early commitment and postponement when making the decisions. The authors show that such advanced ordering opportunities tend to benefit the supply chain as a whole. Furthermore, low demand uncertainty corresponds to a high gain due to strategic leadership advantage while high demand uncertainty erodes these advantages and increases the cost for the supplier to induce such policies. Here, the distributers' profit from managerial flexibility. In particular, it is advantageous for them to wait for new demand information and this opportunity value impacts the supplier's offered per-unit price for a committed order negatively.

Contrarily, Burnetas and Ritchken (2005) neglect a multiple supplier setting and focus on a two echelon supply chain where a manufacturer grants the retailer two real option rights. First, the retailer can make advantage of a reorder right, i.e. he can order additional products at a predetermined time for a fixed prices. Second, the retailer can exercise a return right, i.e. he can return unsold goods at a predetermined salvage price. Due to the fact that the manufacturer is assumed to act as a monopolist, the introduction of such option contracts will considerably affect the wholesale and retail price of the particular good when demand is uncertain. The authors demonstrate that a counterintuitive effect exists: although the investment set for the retailer is improved due to the flexibility the supply chain options provide, he is generally worse off. Only when the volatility of demand curve is low, the retailer benefits from the reorder and return contracts. Chen (2012) focuses on the economics of cooperative decision making in a supply chain. Likewise, he models a two-echelon supply chain consisting of one supplier and one retailer. The optimization problem is a two-stage problem. In the first stage, both individuals maximize jointly the net present value of the future profits of the supply chain by negotiating optimal quantities while in the second stage supplier and retailer coordinately determine the optimal timing of investing in the supply chain. The results show that uncertainty has an ambiguous effect on timing, i.e. for low values of uncertainty it is profitable to wait with investing in the supply chain while for higher levels of uncertainty the propensity to invest earlier increases. Furthermore, sunk costs, i.e. costs for establishing the supply chain have a negative impact on investment timing. The investment costs, however, are merely allocated for setting up the supply chain and do not cover costs in association with emission saving strategies.

The aim of this paper is to bridge real option and game theory in a supply chain context, thereby taking emission saving investment policies explicitly into account. To our best knowledge, the closest model in the literature to our approach is the one presented by Chen (2012). However, our model differs in several ways. First, Chen (2012) focuses solely on a cooperative real option game setting and neglects individual profit maximization. Consequently, timing the investment is not triggered by a single individual in the chain. Second, the author uses a two-echelon setting to model the dynamic supply chain why we present a solution for more general supply chain network, i.e. an N-echelon supply chain. Finally, the focus is on raw material markets and consumer markets only and production takes place emission-free. Consequently, we explicitly allow for CO_2 emissions during the production of a final good and link the game-theoretic real option model to carbon markets in order to discuss the effects on emission reduction policies.

3. The Model

Let A be an industrial company which under the European Union Emissions Trading System is obliged to hand over an amount of emission allowances to the authorities that is equivalent to its CO_2 emissions. A is assumed to be risk neutral and discounts with the riskless interest rate $r \in \mathbb{R}^+$. Let $x \in \mathbb{R}^+$ be the amount of emissions (in production units) the company produces a year and let $p \in \mathbb{R}^+$ be the spot market price of the allowance to emitate one production unit of CO_2. We assume that this price is uncertain and that its time-varying pattern can be formally expressed by a geometric Brownian motion (gBM) process:

$$dp(t) = \alpha p dt + \sigma p dW, \qquad p(0) = p_0, \tag{1}$$

with $\alpha, \sigma \in \mathbb{R}^+$ and dW as the increment of a standard Brownian motion. For simplicity, assuming infinite operations the present value of A's future costs of CO_2 emission at time $t \geq t_0$ can be expressed as follows

$$C(t) = \mathbb{E}\left[\int_t^\infty xp(s)e^{-r(s-t)}ds\right] = \frac{xp(t)}{r-\alpha}. \tag{2}$$

Let $I \in \mathbb{R}^+$ be the total investment costs of a climate-friendly investment opportunity which enables A to reduce its emissions by $\theta \in \mathbb{R}^+$ production units every year. Hence, the present value of the saved emission costs at the time $\tau \geq t_0$ of the investment can be expressed as

$$S(\tau) = \mathbb{E}\left[\int_{\tau}^{\infty} \theta p(s) e^{-r(s-\tau)} ds\right] = \frac{\theta p(\tau)}{r-\alpha}. \tag{3}$$

Hence,

$$\tau_{eco}^{*} = inf\{t \geq t_0 \mid p(t) > p_{eco}^{*}\} \tag{4}$$

with

$$p_{eco}^{*} = \frac{I(r-\alpha)}{\theta}, \tag{5}$$

is the earliest possible time the company A could invest in the project while in expectancy the project would be self-efficient. Therefore, we call τ_{eco}^{*} the eco-efficient investment time.

In the following we will distinguish between three different cases: In the first case A is able to carry out the climate-friendly investment project on its own. In a second case the climate-friendly investment project requires investments of a neighboring chain link in the supply chain. In a third case the climate-friendly investment project requires investments of the whole supply chain.

3.1 The Single Company Case

At time τ of the investment A gains

$$\pi(\tau) = S(\tau) - I = \frac{\theta p(\tau)}{r-\alpha} - I. \tag{6}$$

Following real option theory (e.g. Dixit and Pindyck, 1994; Trigeorgis, 1996) the possibility to invest in the project contains a flexibility value and can be regarded as an invest-option for A. Hence, A should optimally invest as soon as the price $p(t)$ of the emission allowances reaches an optimal threshold p^*_{eff}. For the optimal and economic efficient investment time τ^*_{eff} we get

$$\tau^*_{eff} = inf\{t \geq t_0 \mid p(t) > p^*_{eff}\}. \tag{7}$$

Let f be the value of the invest option, then we get

$$f(p) = \max_{\tau \geq t_0} \mathbb{E}\left[\left(\frac{\theta p(\tau)}{r-\alpha} - I\right) e^{-r\tau}\right]. \tag{8}$$

Solving equation (8) yields[6]

$$f(p) = \begin{cases} \left(\frac{\theta p^*_{eff}}{r-\alpha} - I\right)\left(\frac{p}{p^*_{eff}}\right)^{\beta} & p < p^*_{eff} \\ \frac{\theta p}{r-\alpha} - I & p \geq p^*_{eff} \end{cases}, \tag{9}$$

with

$$\beta = \frac{1}{2} - \frac{\alpha}{\sigma^2} + \sqrt{\left(\frac{\alpha}{\sigma^2} - \frac{1}{2}\right)^2 + \frac{2r}{\sigma^2}} > 1, \tag{10}$$

and

$$p^*_{eff} = \frac{\beta}{\beta - 1}\frac{(r-\alpha)I}{\theta}. \tag{11}$$

Thus, the value of the option to invest is

[6] See, e.g. Dixit and Pindyck (1994).

$$f_{eff}(p) := f(p) = \begin{cases} \left(\frac{1}{\beta - 1} I\right) \left(\frac{p}{\frac{\beta}{\beta - 1} \frac{(r-\alpha)I}{\theta}} \right)^{\beta} & p < \frac{\beta}{\beta - 1} \frac{(r-\alpha)I}{\theta} \\ \frac{\theta p}{r - \alpha} - I & p \geq \frac{\beta}{\beta - 1} \frac{(r-\alpha)I}{\theta}. \end{cases} \tag{12}$$

Because of $\boldsymbol{p}^*_{\boldsymbol{eff}} > \boldsymbol{p}^*_{\boldsymbol{eco}}$, we can state the following proposition:

Proposition 1: *Under uncertainty it is economic efficient to invest later than the eco-efficient investment time.*

3.2 The Two Company Case

Now, let's assume, that the project depends on the cooperation of a neighbored chain link B in the supply chain, which has to bear a share $\xi \in (0,1)$ of the investment costs I. Hence, A only has to bear investment costs of $(1-\xi)I$. Obviously, A has to compensate B which has no direct benefit of the investment. We assume a non-cooperative setting in which A and B maximize their individual profits.[7] In particular, A and B have to negotiate about the timing of the investment and about the compensation of B.[8] At time t_0 A can offer B a fraction $\psi \in (0,1)$ of the saved emission costs. Therefore, at time τ of the investment A gains

$$\pi_A(\tau) = (1 - \psi) \frac{\theta p(\tau)}{r - \alpha} - (1 - \xi)I, \tag{13}$$

and B gains

$$\pi_B(\tau) = \psi \frac{\theta p(\tau)}{r - \alpha} - \xi I. \tag{14}$$

[7] There are several examples in practice why a supply chain is non-cooperatively rather than cooperative managed. See, e.g. Yue et al. (2006).

[8] For a general treatment see for example Lukas and Welling (2012).

B can accept the offer or reject it, but it has not to decide immediately. It also has the possibility to postpone the decision. Thus, in every point of time B has the action set $\{accept, wait\}$. This managerial flexibility of B can be interpreted as a real option. Therefore, the optimal timing decision of B is to initiate the deal as soon as the price $p(t)$ of the emission allowances reaches an optimal threshold $p_2^*(\psi)$ which depends on the offered fraction ψ. For the optimal investment time τ_2^* of B we get

$$\tau_2^* = inf\{t \geq t_0 \mid p(t) > p_2^*(\psi)\}. \tag{15}$$

Let f_B be the value of B's option to accept the offer, then we get

$$f_B(p) = \max_{\tau \geq t_0} \mathbb{E}\left[\left(\frac{\psi\theta p(\tau)}{r-\alpha} - \xi I\right) e^{-r\tau}\right]. \tag{16}$$

Solving equation (14) yields

$$f_B(p) = \begin{cases} \left(\frac{\psi\theta p_2^*(\psi)}{r-\alpha} - \xi I\right)\left(\frac{p}{p_2^*(\psi)}\right)^{\beta} & p < p_2^*(\psi) \\ \frac{\psi\theta p}{r-\alpha} - \xi I & p \geq p_2^*(\psi) \end{cases} \tag{17}$$

and

$$p_2^*(\psi) = \frac{\beta}{\beta - 1}\frac{(r-\alpha)\xi I}{\theta\psi}. \tag{18}$$

Taking into account B's optimal reaction function $p_2^*(\psi)$ A will choose ψ in t_0 such that it maximizes

$$f_A(p) = \max_{\psi \in (0,1)} \mathbb{E}\left[\left(\frac{(1-\psi)\theta p_2^*(\psi)}{r-\alpha} - (1-\xi)I\right) e^{-r\tau_2^*}\right]. \tag{19}$$

Thus, the total value of the option to invest in the project is $f(p) := f_A(p) + f_B(p)$. Solving equation (17) yields

$$f_A(p) = \begin{cases} \left(\frac{(1-\psi)\theta p_2^*(\psi)}{r-\alpha} - (1-\xi)I\right)\left(\frac{p}{p_2^*(\psi)}\right)^\beta & p < p_2^*(\psi) \\ \frac{(1-\psi)\theta p}{r-\alpha} - (1-\xi)I & p \geq p_2^*(\psi) \end{cases}. \quad (20)$$

Then, the optimal offered fraction ψ^* of A equals

$$\psi^* = \frac{\xi(\beta-1)}{\beta-1+\xi}. \quad (21)$$

Hence, we get

$$p_2^*(\psi) = \frac{\beta}{\beta-1}\frac{(r-\alpha)I}{\theta}\left(1+\frac{\xi}{\beta-1}\right) = \left(1+\frac{\xi}{\beta-1}\right)p_{eff}^* > p_{eff}^*. \quad (22)$$

Thus, we can state the following proposition.

Proposition 2: *If the climate-friendly project depends on the cooperation of a neighbored chain link in the supply chain, investment will not just happen inefficiently late from an eco-efficiency view but also from the economic efficiency view.*

3.3 The n-Company Case

Now, we consider a supply chain $(n, \theta, I, \xi = (\xi_1, \dots, \xi_n))$ consisting of $n > 2$ companies $A_1, A_2, \dots, A_n$. Company A_1 can reduce its CO_2 emissions by the amount of θ production units a year if it invests into the climate friendly project, but the investment depends on the cooperation of the other companies in the supply chain who also have to pay investment costs. Let I still denote the total sum of the investment costs and ξ_i the share of the investment costs company i

has to bear. Obviously, it is $\sum_{i=1}^{n} \xi_i = 1$. We assume that the companies negotiate sequentially about the timing of the investment and the compensations paid. Thus, company A_1 offers a premium ψ_1 to A_2 which itself offers ψ_2 to A_3, …, finally A_{n-1} offers a premium ψ_{n-1} to A_n which then can decide about the timing of the investment. Therefore, at time τ of the investment company i gains

$$\pi_i(\tau) = \begin{cases} (1-\psi_i)\dfrac{\theta p(\tau)}{r-\alpha} - \xi_i I & i = 1 \\ (\psi_{i-1}-\psi_i)\dfrac{\theta p(\tau)}{r-\alpha} - \xi_i I & 1 < i < n. \\ \psi_{i-1}\dfrac{\theta p(\tau)}{r-\alpha} - \xi_i I & i = n \end{cases} \tag{23}$$

Similarly to B in the two parties case, it is now A_n which can wait with the acceptance of the offer. Analogously, the optimal timing decision of A_n is to initiate the deal as soon as the price $p(t)$ of the emission allowances reaches the optimal threshold $p_n^*(\psi_1, \dots, \psi_{n-1})$ which depends on the fraction offered by $A_1, \dots, A_{n-1}$. For the optimal investment time τ_n^* of A_n we get

$$\tau_n^* = inf\{t \geq t_0 \mid p(t) > p_n^*(\psi_1, \dots, \psi_{n-1})\}. \tag{24}$$

Let f_n be the value of A_n's option to accept the offer, then we get

$$f_n(p) = \max_{\tau \geq t_0} \mathbb{E}\left[\left(\frac{\psi_{n-1}\theta p(\tau)}{r-\alpha} - \xi_n I\right) e^{-r\tau}\right]. \tag{25}$$

Solving the equation yields

$$p_n^*(\psi_1, \dots, \psi_{n-1}) = \frac{\beta}{\beta - 1} \frac{(r-\alpha)\xi_n I}{\theta\psi_{n-1}\left(\psi_{n-2}\left(\dots\left(\psi_2(\psi_1)\right)\right)\right)}. \tag{26}$$

Given the offered premium ψ_{i-1} of A_{i-1} and taking into account the optimal reaction functions of $A_{i+1}, \dots, A_n$ company A_i with $1 < i < n$ will choose ψ_i in t_0 such that it maximizes

$$f_i(p) = \max_{\psi_i \in (0,1)} \mathbb{E}\left[\left(\frac{(\psi_{i-1} - \psi_i)\theta p_n^*(\psi_1, \dots \psi_i, \psi_{i+1}^*(\psi_i) \dots, \psi_{n-1}^*(\psi_i))}{r - \alpha} - \xi_i I\right) e^{-r\tau_2^*}\right]. \tag{27}$$

Solving the equation yields the optimal reaction function $\psi_i^*(\psi_1, \dots, \psi_{i-1})$. By considering the optimal reaction functions of $A_2, \dots, A_n$ company A_1 will choose ψ_1 in t_0 such that it maximizes

$$f_1(p) = \max_{\psi_1 \in (0,1)} \mathbb{E}\left[\left(\frac{(1 - \psi_1)\theta p_n^*\left(\psi_1, \psi_2^*(\psi_1) \dots, \psi_{n-1}^*(\psi_1)\right)}{r - \alpha} - \xi_1 I\right) e^{-r\tau_2^*}\right]. \tag{28}$$

The total value of the option to invest in the project can be calculated by $f(p) \coloneqq \sum_{i=1}^{n} f_i(p)$. Solving equation (28) yields the optimal premium ψ_1. Then, the optimal premia $\psi_2^*, \dots, \psi_{n-1}^*$ and the optimal investment threshold p_n^* can easily been calculated recursively.

For example, for $n = 3$ we get

$$p_3^*(\psi_2) = \frac{\beta}{\beta - 1} \frac{\xi_3}{\psi_2} \frac{(r - \alpha)}{\theta} I, \tag{29}$$

$$\psi_2^*(\psi_1) = \frac{(\beta - 1)\xi_3 \psi_1}{\beta \xi_3 + (\beta - 1)\xi_2} \tag{30}$$

and

$$\psi_1^* = \frac{\beta(\beta - 1)\xi_3 + (\beta - 1)^2 \xi_2}{\beta^2 \xi_3 + \beta(\beta - 1)\xi_2 + (\beta - 1)^2 \xi_1}. \tag{31}$$

Resolved recursively, it is

$$\psi_2^* = \frac{(\beta-1)\xi_3(\beta(\beta-1)\xi_3 + (\beta-1)^2\xi_2)}{(\beta^2\xi_3 + \beta(\beta-1)\xi_2 + (\beta-1)^2\xi_1)(\beta\xi_3 + (\beta-1)\xi_2)} \tag{32}$$

and

$$p_3^* = \frac{\beta(\beta^2\xi_3 + \beta(\beta-1)\xi_2 + (\beta-1)^2\xi_1)(\beta\xi_3 + (\beta-1)\xi_2)}{(\beta-1)^2(\beta(\beta-1)\xi_3 + (\beta-1)^2\xi_2)} \frac{(r-\alpha)}{\theta} I. \tag{33}$$

Generally, for a supply chain $\left(n, \theta, I, \xi = (\xi_1, \dots, \xi_n)\right)$ we get

$$p_n^* = \frac{\beta}{\beta-1}\frac{(r-\alpha)}{\theta}\xi_n I \prod_{i=1}^{n} \frac{\sum_{j=1}^{i}\left(A_{n+1-j}\sum_{k=1}^{j}\binom{j-1}{k-1}\beta^{i-k}(-1)^{k+1}\right)}{\sum_{j=1}^{i-1}\left(A_{n+1-j}\sum_{k=1}^{j+1}\binom{j}{k-1}\beta^{i-k}(-1)^{k+1}\right)}, \tag{34}$$

$$\psi_{n-1}^* = \prod_{i=1}^{n} \frac{\sum_{j=1}^{i-1}\left(A_{n+1-j}\sum_{k=1}^{j+1}\binom{j}{k-1}\beta^{i-k}(-1)^{k+1}\right)}{\sum_{j=1}^{i}\left(A_{n+1-j}\sum_{k=1}^{j}\binom{j-1}{k-1}\beta^{i-k}(-1)^{k+1}\right)} \tag{35}$$

and

$$\psi_{n-l}^* = \prod_{i=2}^{l} \frac{\sum_{j=1}^{i}\left(A_{n+1-j}\sum_{k=1}^{j}\binom{j-1}{k-1}\beta^{i-k}(-1)^{k+1}\right)}{\sum_{j=1}^{i-1}\left(A_{n+1-j}\sum_{k=1}^{j+1}\binom{j}{k-1}\beta^{i-k}(-1)^{k+1}\right)} \times \prod_{i=1}^{n} \frac{\sum_{j=1}^{i-1}\left(A_{n+1-j}\sum_{k=1}^{j+1}\binom{j}{k-1}\beta^{i-k}(-1)^{k+1}\right)}{\sum_{j=1}^{i}\left(A_{n+1-j}\sum_{k=1}^{j}\binom{j-1}{k-1}\beta^{i-k}(-1)^{k+1}\right)}. \tag{36}$$

for all $l \in \{2, \dots n-1\}$, with $\binom{a}{b} := \frac{a!}{b!(a-b)!}$ as the binomial coefficient.

4. Comparative Static Results

Unless noted otherwise we will assume the following values: $r = 0.1$, $\alpha = 0.05, \sigma = 0.2, I = 24, \theta = 1, p_0 = 1$. Furthermore, we assume that the investment costs are split equally in the supply chain, i.e. $\xi_i = \frac{1}{n}$ for all $i \in \{1, \dots, n\}$. From equation (5) we get $p_{eco}^* = 1.2$.

Table 1: The results of the model.

	$n = 1$	$n = 2$	$n = 3$	$n = 4$	$n = 5$
p^*	3.17	5.78	11.24	23.08	49.44
$\mathbb{E}\Delta x$	32.38	52.4	74.57	98.55	123.95
f	6.16	5.45	4.1	2.81	1.82
f_1/f	1.0	0.78	0.7	0.66	0.64
f_2/f	-	0.22	0.24	0.24	0.24
f_3/f	-	-	0.07	0.08	0.09
f_4/f	-	-	-	0.02	0.03
f_5/f	-	-	-	-	0.01

Table 1 contains the results of our model for the single company case, the two-company case and for supply chains of length 3 till 5. $\mathbb{E}\Delta x$ represents the expected amount of CO_2 emissions that could have been avoided if the companies would invest at the eco-efficient investment time, i.e.:

$$\mathbb{E}\Delta x_n = \mathbb{E}\theta(\tau_n^* - \tau_{eco}^*) = \frac{\theta \ln\left(\frac{p_n^*}{p_{eco}^*}\right)}{\alpha - \frac{\sigma^2}{2}}. \tag{37}$$

It can be seen that with an increasing length of the supply chain the total value f of the option to invest is decreasing and that longer supply chains will invest later and therefore produce more avoidable CO_2. Thus, we can state the following proposition:

Proposition 3: *A supply chain is getting less economic and less ecological efficient with every additional chain link.*

Furthermore, table 1 reveals that the share $\boldsymbol{f_i/f}$ of the surplus a company $\boldsymbol{i}$ gains is the higher the nearer its position in the supply chain is to the company which can save the CO_2 emissions.

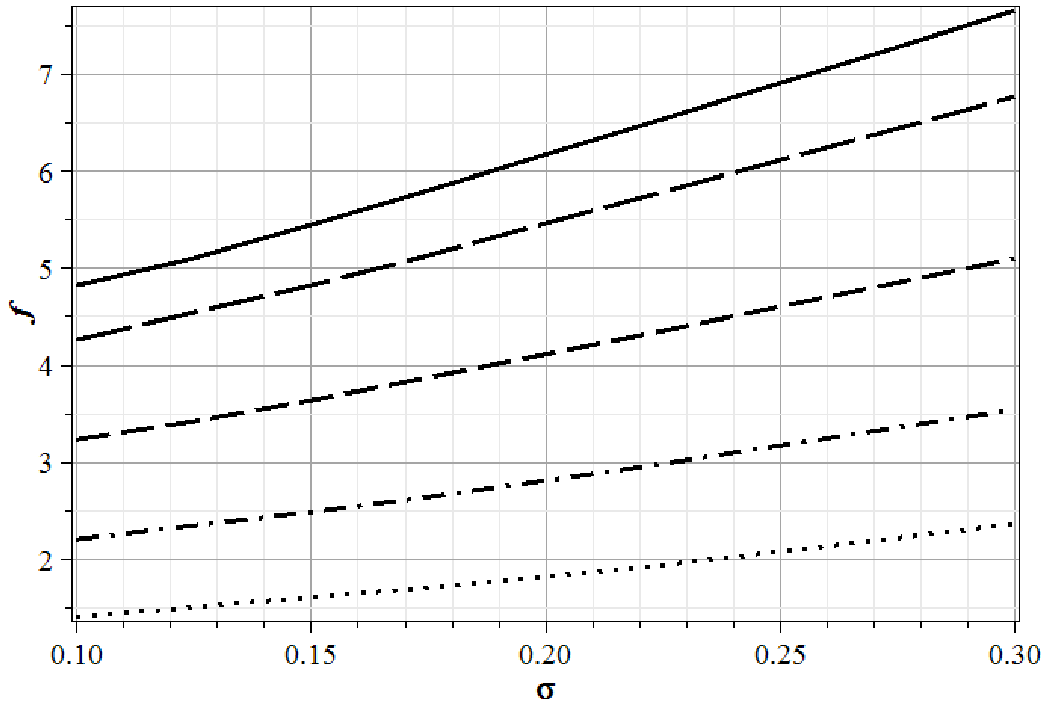

Figure 1: The expected amount of produced CO_2 $\mathbb{E}\Delta\boldsymbol{x}$ that could have been avoided if the investment would be eco-efficient in dependence of uncertainty and the length of the supply chain ($\boldsymbol{n} = \mathbf{1}$: solid line; $\boldsymbol{n} = \mathbf{2}$: long dash; $\boldsymbol{n} = \mathbf{3}$: dash; $\boldsymbol{n} = \mathbf{4}$: dash dot; $\boldsymbol{n} = \mathbf{5}$: dot).

Figures 1 and 2 demonstrate the summarized findings of our propositions. The ecological efficiency of a supply chain is getting less efficient with increasing uncertainty and with an increasing length of the supply chain (Figure 1), while the economic efficiency is increasing with uncertainty but is also decreasing with an increasing length of the supply chain (Figure 2).

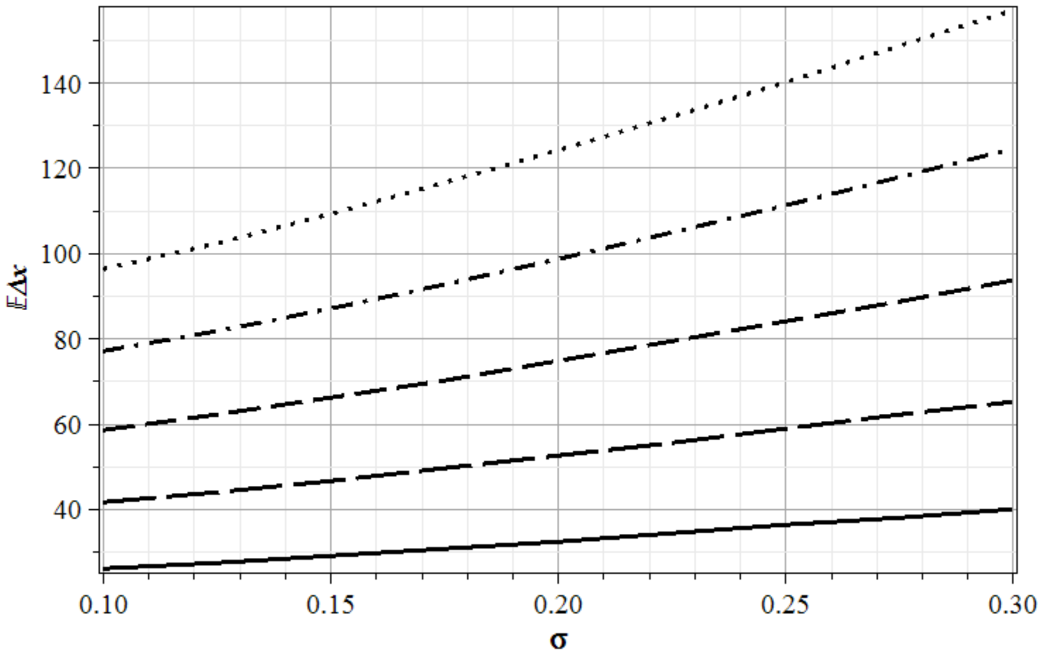

Figure 2: The total option value $\boldsymbol{f}$ of the possibility to invest in the climate-friendly project in dependence of uncertainty and the length of the supply chain ($\boldsymbol{n} = \mathbf{1}$: solid line; $\boldsymbol{n} = \mathbf{2}$: long dash; $\boldsymbol{n} = \mathbf{3}$: dash; $\boldsymbol{n} = \mathbf{4}$: dash dot; $\boldsymbol{n} = \mathbf{5}$: dot).

5. Management Strategies

First, a centralized managed supply chain seems to be the best solution to avoid economic inefficiency and partially ecological inefficiency, too. If all parties would act cooperatively instead of negotiating sequentially they could agree on the economic efficient investment time τ^*_{eff}. Following the asymmetric Nash-bargaining solution the surplus generated by the investment would be shared between the parties according to their relative bargaining power, which is exogenously given (Nash, 1950; Harsanyi and Selten, 1972). Let $\gamma_i \in [0,1]$ denote the relative bargaining power of the i-th company in the supply chain, whereby $\sum_{i=1}^{n} \gamma_i = 1$, with n as the length of the supply chain. Then, the expected gain of i after cooperative bargaining is $\gamma_i f_{eff}(p_0)$, with $f_{eff}(p_0)$ given by equation (12) as the total surplus after cooperative bargaining. However, cooperation of the supply chain requires the willingness of every member of the supply chain to cooperate. But a party i can only be expected to cooperate if its gain $\gamma_i f_{eff}(p_0)$ after cooperation is higher than its gain $f_i(p_0)$ after sequential bargaining. Thus, it can be emphasized that cooperation is the best strategy if it is possible, but cooperation is only possible if

$$\gamma_i f_{eff}(p_0) \geq f_i(p_0), \tag{38}$$

for all $i \in \{1, \dots, n\}$. The expected amount $\mathbb{E}\Delta \mathrm{x}_{\mathrm{n,C}}$ of CO_2 that could be saved by means of cooperation equals

$$\mathbb{E}\Delta \mathrm{x}_{\mathrm{n,C}} = \mathbb{E}\Delta \mathrm{x}_{\mathrm{n}} - \mathbb{E}\Delta \mathrm{x}_{1}. \tag{39}$$

As an example we consider the supply chain$\left(3, 1{,}24, \left(\frac{1}{3}, \frac{1}{3}, \frac{1}{3}\right)\right)$ with the remaining variables defined as in Section 4. The total surplus after sequential bargaining is $f = 4.1$. After cooperation the total surplus would be $f_{eff} = 6.16$. Therefore, company 1 is only willing to cooperate if

$$\gamma_1 f_{eff} = 6.16\,\gamma_1 \geq f_1 = \frac{f_1}{f} f = 0.7 \cdot 4.1, \tag{40}$$

or in other words if

$$\gamma_1 \geq \frac{0.24 \cdot 4.1}{6.16} \approx 0.47 =: \gamma_{1,min}. \tag{41}$$

Similarly, company 2 only cooperates if

$$\gamma_2 \geq \frac{0.07 \cdot 4.1}{6.16} \approx 0.16 =: \gamma_{2,min}, \tag{42}$$

and company 3 only cooperates if

$$\gamma_3 \geq \frac{0.7 \cdot 4.1}{6.16} \approx 0.05 =: \gamma_{3,min}. \tag{43}$$

Figure 3 depicts for every possible combination $\gamma = (\gamma_1, \gamma_2, \gamma_3)$ of relative bargaining powers whether a cooperative solution is possible (white triangle) or not (grey area). In the latter case at least one company is not willing to cooperate. As can been deduced from Table 1 the amount of CO_2 that can be saved in the given example by means of cooperation equals

$$\mathbb{E}\Delta \mathrm{x}_{3,\mathrm{C}} = 74.57 - 32.38 = 42.19. \tag{44}$$

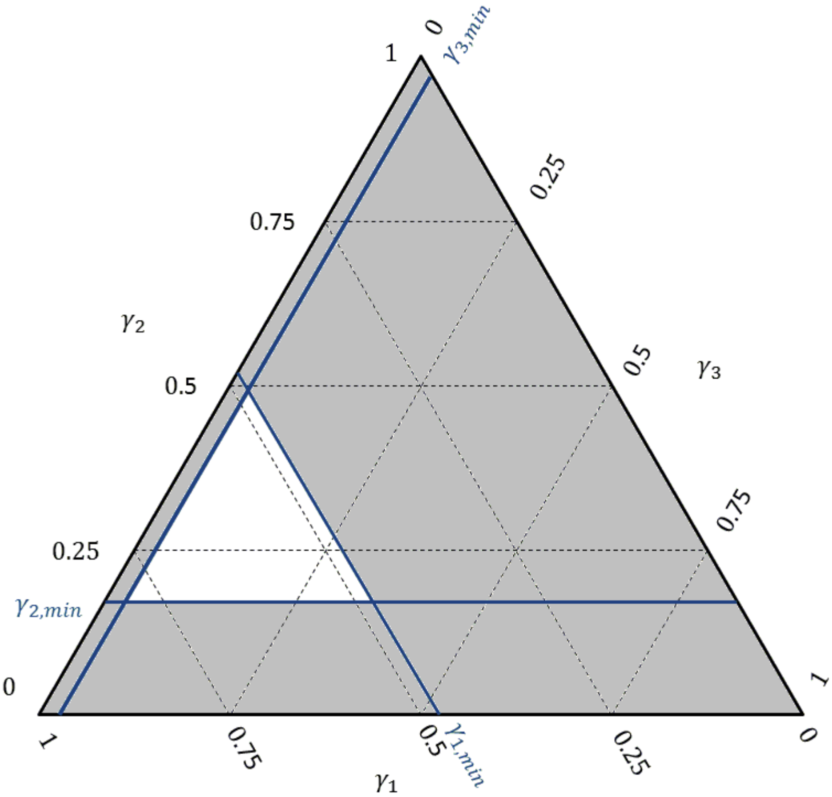

Figure 3: The combinations of bargaining power where cooperation of the supply chain is possible (white triangle) and where cooperation is not possible (grey area).

If cooperation of the supply chain is not possible the next best strategy the managers of company 1 can pursue is vertical integration, i.e. company 1 can acquire company 2 . As a consequence the supply chain changes from

$(n, \theta, I, \xi = (\xi_1, \xi_2, \xi_3, \dots, \xi_n))$ to $(n-1, \theta, I, \xi = (\xi_1 + \xi_2, \xi_3, \dots, \xi_n))$ leading to an increase of the total surplus of the possibility to invest, to an earlier investment time and therefore to less economic and less ecological inefficiency. Let $I_P \in \mathbb{R}^+$ be the purchase price of company 2, let $I_T \in \mathbb{R}^+$ be the transaction costs of the acquisition and let $V \in \mathbb{R}^+$ be the value of company 2 if it is managed by company 1, then it is recommendable for company 1 to acquire company 2 if and only if

$$\tilde{f}_1(p_0) + V - I_P - I_T \geq f_1(p_0), \tag{45}$$

with $f_1(p_0)$ as the option value of company 1 before the acquisition and with $\tilde{f}_1(p_0)$ as the option value of company 1 after the acquisition. The expected amount $\mathbb{E}\Delta x_{n,A}$ of CO_2 saved by means of the acquisition can be calculated by

$$\mathbb{E}\Delta x_{n,A} = \frac{\theta \ln\left(\frac{p_n^*}{p_{eco}^*}\right)}{\alpha - \frac{\sigma^2}{2}} - \frac{\theta \ln\left(\frac{\tilde{p}_n^*}{p_{eco}^*}\right)}{\alpha - \frac{\sigma^2}{2}}, \tag{46}$$

with $\tilde{p}_n^*$ as the investment threshold of the new supply chain. If we again consider the same example, then the acquisition of company 2 by company 1 transforms the supply chain from $\left(3, 1, 24, \left(\frac{1}{3}, \frac{1}{3}, \frac{1}{3}\right)\right)$ to $\left(2, 1, 24, \left(\frac{2}{3}, \frac{1}{3}\right)\right)$ which is identical to the two-party case. Again we have that $f_1 = 0.7 \cdot 4.1 = 2.87$ and with equation (20), (21) and (22) we get that $\tilde{p}_3^* = 4.91$ and that $\tilde{f}_1 = 4.72$. Hence, company 1 should acquire company 2 if and only if

$$V - I_P - I_T \geq -1.85. \tag{47}$$

The expected amount of CO_2 that could be saved in the given example by means of acquisition equals

$$\mathbb{E}\Delta x_{3,A} = 74.57 - 45.65 = 28.92. \tag{48}$$

Figure 4 compares the amount of CO_2 that could be saved by cooperation of the supply chain and by acquisition of company 2 by company 1. It can be seen that from the ecological view cooperation should be preferred to an acquisition for every length n of the supply chain, if it is possible.

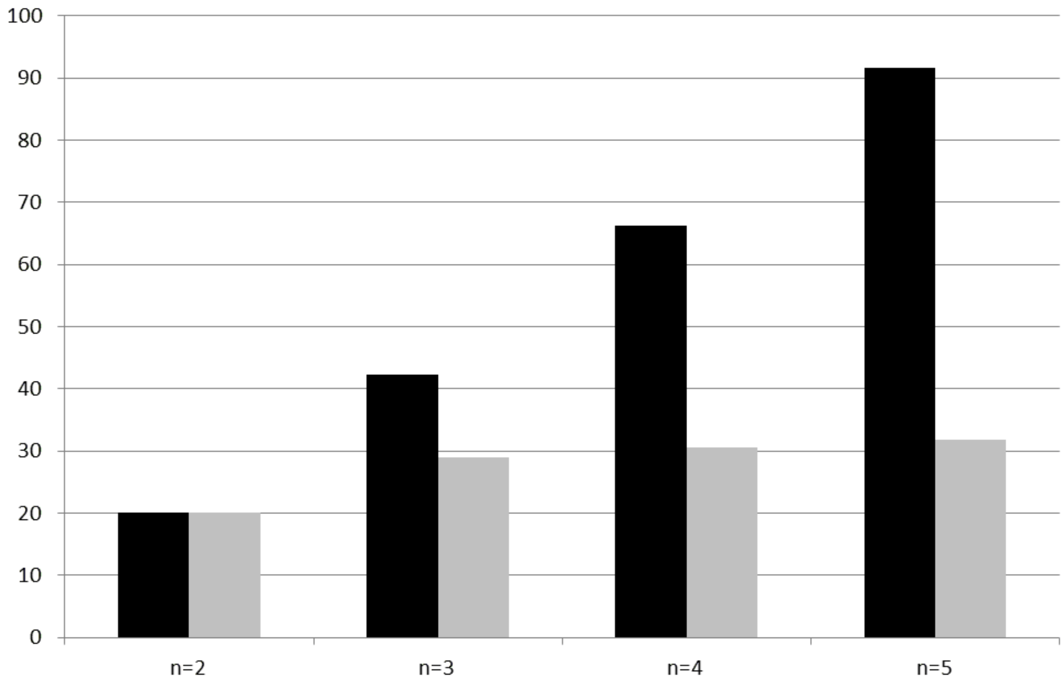

Figure 4: The amount of CO_2 (in production units) that can be saved by means of cooperation (black) and by means of acquisition (grey).

6. Conclusion

The paper considers the problem of a supply chain where the parties negotiate about the implementation of a carbon dioxide (CO_2) saving investment project.

Specifically, we employ a game-theoretic real options model in continuous time to investigate the impact of uncertainty on investment timing and the size of emission savings. The findings reveal that high volatility in carbon prices has a negative (positive) impact on ecological (economic) efficiency. Most supply chains in manufacturing and pollution intensive industries in particular, however, are far more complex than a two echelon supply chain often used in the literature. Hence, we extend the base case scenario to a more general supply chain network, i.e. an N-echelon supply chain. The results show that a supply chain is getting less economic efficient and less ecological efficient with every additional chain link. Irrespectively of the length of the supply chain, the results support recent findings in the literature that the outcome of decentralized bargaining is not economic efficient and even less ecological efficient. Hence, another concern of the paper is to give recommendations on how managers could improve the situation and thereby increase the economic as well as the ecological efficiency of supply chains. By contrasting two promising strategies to improve economic and ecological efficiency in a n-echelon setting, i.e. coordination and vertical integration, we show that vertical integration is less efficient in CO_2 emission saving than cooperation.

One direction in which this work may be extended would be to consider more explicitly the modeling of regulatory shocks on carbon prices by means of e.g. a time-varying volatility or by adding jumps to the carbon price dynamics. Another dimension that warrants further investigation is to relax the assumption of equally share investment cost associated with the implementation of emission saving technologies. Finally, other extensions include to drop the assumption of a constant emission-production relationship and to introduce demand uncertainty more explicitly. Here, a promising route would be to introduce a second stochastic process that reflects demand uncertainty and enables closer links with the existing literature.

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