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Timing and eco(nomic) efficiency of climate-friendly investments in supply chains

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A R T I C L E I N F O

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A B S T R A C T

Emission trading schemes such as the European Union Emissions Trading System (EUETS) attempt to reconcile economic efficiency with 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 continue to be mutually exclusive. This problem is even worse if a climate-friendly project depends on investing in of a whole supply chain. We model a sequential bargaining game in a supply chain where the parties negotiate over implementation of a carbon dioxide (CO_2) saving investment project. We show that the outcome of their bargaining is not economically efficient and even less ecologically efficient. Furthermore, we show that a supply chain becomes less economically efficient and less ecologically efficient with every additional chain link. Finally, we make recommendations for how managers or politicians can improve the situation and thereby increase economic as well as ecological efficiency and thus also the eco-efficiency of supply chains.

1. Introduction

The emission of greenhouse gases (GHG), for example, CO_2, NO_x, or CH_4, has been identified as a key driver of global warming. As global warming is expected to have fatal consequences at economic, ecologic, and social levels, it is necessary to reduce GHG emissions so as to prevent or at least reduce global warming. To date, several companies and states have set themselves the goal of reducing their own CO_2 emissions. For example, Wal-Mart recently announced its goal to eliminate 20 million metric tons of GHG emissions from its global supply chain by 2015 and the U.S. retailer Tesco plans to have its carbon–neutral supply chain in place by 2050 (Caro et al., 2011). Moreover, some firms explicitly attempt to offset not only their own emissions but also the emissions from all other firms involved in the supply chain.[1] The concept of eco-efficiency as an operational measure allows reporting a supply chain's economic performance per unit of environmental impact and thus makes it possible to compare companies and entire supply chains (Schaltegger, 1998). For example, the British low-cost-carrier EasyJet has successfully increased its eco-efficiency from 8.9 passenger-kilometers per emitted kilogram of CO_2 in 2001 to 11.8 passenger-kilometers per emitted kilogram of CO_2 in 2010.[2] Nevertheless, its Irish competitior Ryanair still shows a higher eco-efficiency of approximately 13.8 passenger kilometers per emitted kilogram of CO_2.[3] However, such proactive environmental awareness is rare and predominately driven by the threat of being punished by either customers or the government. Most companies need direct financial incentives to invest in climate-friendly projects. To this end, governments use different environmental policies, for example, cap-and-trade systems like the European Union Emission Trading System (EUETS) or environmental taxes to induce firms to mitigate emissions and thus improve their eco-efficiency.

The above examples make it abundantly clear that greening the supply chain is only possible through the joint efforts by multiple parties, rather than by single companies. Presently, however, there is a lack of in-depth research on two highly pertinent issues. First, when do firms optimally invest in emission mitigating strategies given uncertainty in emission allowance prices? And, second, how is timing affected by the structure of the supply chain?

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

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[1] For example, the Brazilian company Natura Cosméticos has a zero-emission strategy and offsets not only its own emissions, but also any remaining emissions of all supply chain participants (Caro et al., 2011).

[2] http://2011annualreport.easyjet.com/corporate-responsibility/environment.aspx.

[3] http://www.ryanair.com/doc/about/ryanair_brighter_planet_2011.pdf.

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project are proportional to a random spot price for emission allowances and that investment timing is the result of a sequential bargaining game. Section 4 summarizes the numerical results of the comparative-static analysis; Section 5 discusses possible coordination policies that can further improve the economic and ecological efficiency of the supply chain. Section 6 concludes.

2. Literature review

2.1. Green supply chain management

As illustrated by the reviews of Seuring and Müller (2008), Schaltegger and Csutora (2012), and Dekker et al. (2012), the management of green supply chains is becoming a ''hot'' topic. It is now taken for granted that the management of green supply chains goes beyond classic supply chain management. Issues such as product life extension, product end of life, and recovery processes at product end of life, to name just a few, are critical to the success of greening a supply chain.[4] As noted by Benjaafar et al. (2010, p. 3), however, ''there is a need for model-based research that extends quantitative models.'' To date, attempts to guide the decision-making processes of managers focus on single firm decisions that are affected by different environmental policies, specifically, for example, the optimal decision when emissions may be subject to an environmental tax or an emission cap, and the literature discusses how these factors influence operational decisions (see, e.g., Letmathe and Balakrishnan, 2005; Elhedhli and Merrick, 2012; Song and Leng, 2012; Chaabane et al., 2012; Ruiz-Femenia et al., 2012). By definition, however, a supply chain is a network of different agents—suppliers, distributors, retailers, and the like—that participate in the sale, delivery, and production of a specific good or service. As such, the profitability of a supply chain depends heavily on the individual actions of each agent, thus making game theory well suited to studying this topic (Nagarajan and Sošić, 2008).

2.2. Game theory

Over the last few years, research in operations management and, most recently, green supply chain management has been enlivened and enriched by the application of game theory. Two strands of literature have emerged. The first strand deals with 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.[5] In contrast, the second strand of literature allows the agents in a supply chain to individually maximize their profits, leading to an application of non-cooperative game theory.[6]

In the context of sustainable management, however, only a few quantitative models apply game theory to discover optimal emission-mitigating strategies to guide operational decision making in supply chains. For example, Benjaafar et al. (2010) use a multiple-firm lot-sizing model to model a supply chain consisting of N firms where each firm is confronted with certain environmental policies. Decisions about ordering and production are made either independently or jointly. In a two-firm setting, the results show that under carbon constraints, that is, a strict emission cap imposed on each firm individually, the value of the supply chain is higher for joint decision making than for non-cooperative decision making. Thus, meeting the emission targets is less costly if firms in the supply chain collaborate, indicating that collaborative decision making outperforms individual decision making. However, in this same scenario of emission caps, there are circumstances when overall emissions increase if firms decide jointly. Changing the emission policy rules such that emission caps are imposed supply-chain-wide yields significant improvements, that is, the supply chain produces the least emissions at lower costs. Although the emission cap policy dominates, there are other alternatives for limiting emissions, of which the cap-and-trade policy yields the most significant cost reduction in a collaborative setting. This occurs when the cap is very high and as a consequence the supply chain can make additional profits from selling emission savings on the carbon exchange market. Notably, the results are based on the assumption that the market price for carbon is fixed. Consequently, market price uncertainty, which is the real-world situation, is completely ignored.

The impact of a cap-and-trade policy on a two-stage emission-dependent supply chain is also investigated by (Du et al., 2012).[7] In contrast to Benjaafar et al. (2010), market risk is explicitly considered and the authors use a sequential game to investigate the firms' individual decision making. A single manufacturer has to decide on its optimal production quantity given demand uncertainty and an assigned emission quota. If it emits too much, extra permits can be acquired from a permit supplier. As a result, first the seller must decide on an optimal price for its permits, after which the manufacturer decides whether to accept or reject the offer. The results show that the bargaining power of the permit supplier (manufacturer) increases (decreases) if the government imposes a stricter environmental protection policy. Consequently, the value of the supply chain decreases. Moreover, an increase in market risk, that is, higher demand uncertainty, also affects the bargaining power of both parties. The findings reveal that higher demand uncertainty increases the permit supplier's propensity to lower carbon permit prices in order to induce the manufacturer to raise production. In a related article, the authors expand the analysis to account for the perspective of authorities (Du et al., 2012). Here, the authors endogenize the choice of the emission cap size set by a policy decision maker. The results show that this also affects the bargaining power of the participants, that is, the optimal emission cap will either strengthen or weaken (weaken or strengthen) the bargaining power of the manufacturer (supplier) depending on whether the social optimum calls for a tighter or relaxed environmental policy.

Zhang and Liu (2013) consider a three-level green supply chain where a manufacturer is responsible for the launch of a green product. Raw materials are purchased from a suppler and the final product is sold to a retailer who brings the product to market. It is only implicitly assumed that the greener product reduces supply chain emissions. Different from the above-discussed papers, however, the derived non-cooperative and cooperative solutions are supplemented by different coordination mechanisms—revenue sharing, the Shapley value coordination method, and the Nash negotiation mechanism—in order to achieve cooperation among the members. The findings reveal that the Nash negotiation mechanism outperforms non-cooperative decision making and is the perfect coordinated situation compared to all other methods. Also noteworthy is that allowing for vertical integration, such that firms

[4] See, e.g., Linton et al. (2007) for a discussion.

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

[6] Cachon and Netessine (2004) and Li and Whang (2002) provide an excellent overview of game-theoretical applications in the supply chain management literature. The flat panel industry, however, has shown that cooperation and competition are not the only way to manage supply chains; rather, a mixture of competition and cooperation is also rational. These co-opetition supply chains are the focus of work that bridges non-cooperative and cooperative game theory. See, e.g. Gurnani et al. (2007).

[7] A two-stage emission-dependent supply chain consists of a single emission-dependent manufacturer and a single permit supplier. See Du et al. (2012).

in the supply chain may enter into alliances, can act as a substitute for the analyzed coordination mechanisms.

2.3. Real options theory

However, the question of *how* profits are shared in a supply chain is not the only critical one; also of central importance is *when* to invest in a supply chain. Recent literature acknowledges that the classical net present value is static in the sense that it requires agents to make investment decisions immediately (e.g., Chevalier-Roignant et al., 2011). In contrast, viewing investment as an option right, that is, one has the right to invest but is not obliged to, makes it highly important to discover the optimal timing of an investment, particularly in the case of a supply chain investment.[8] 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 ignored, indicating that the single firm has all the bargaining power in the supply chain. Moreover, in the extant literature, managerial flexibility in investment decision making is represented by switching 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). There are very few attempts to model option games in supply chains. Cvsa and Gilbert (2002) consider a situation where a monopolistic supplier offers two competing external distributers, that is, two downstream buyers, early purchase commitments. All individuals face demand uncertainty and, due to this, operational flexibility exists such that the downstream firms face a trade-off between early commitment and postponement when making the decision. The authors show that such advance 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, whereas high demand uncertainty erodes these advantages and increases the supplier's cost of offering such policies. Here, the distributers profit from managerial flexibility; it is advantageous for them to wait for new demand information and this opportunity value has a negative impact on the supplier's offered per-unit price for a committed order.

Burnetas and Ritchken (2005) focus on a two-echelon supply chain where a manufacturer grants the retailer two real option rights. First, the retailer can take advantage of a reorder right—he can order additional products at a predetermined time for a fixed price. Second, the retailer can exercise a return right—he can return unsold goods at a predetermined salvage price. Because the manufacturer is assumed to be a monopolist, introduction of such option contracts has a considerable effect on 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 provided by the supply chain options, he is generally worse off. Only if the volatility of the demand curve is low will the retailer benefit from the reorder and return contracts. Chen (2012) focuses on the economics of cooperative decision making in a supply chain. He also 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; in the second stage, the 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, that is, for low values of uncertainty, it is profitable to wait before investing in the supply chain, whereas higher levels of uncertainty increase the propensity to invest earlier. Furthermore, sunk costs—the costs of establishing the supply chain—have a negative impact on investment timing. However, in this scenario, the investment costs are completely allocated for setting up the supply chain and do not cover costs associated 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 the best of our knowledge, the model most similar 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 even though, as our model shows, cooperative solutions are not always possible and depend on relative bargaining power. Second, Chen uses a two-echelon setting to model the dynamic supply chain, while we present a solution for more general supply chain network, specifically an N-echelon supply chain. Finally, in Chen's model, the focus is on raw material and consumer markets only and production is emission-free. 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 mitigating policies.

3. The model

Let A be an industrial company that, under the EUETS, is obliged to hand over to the authorities emission allowances in an amount 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 emit 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 stochastic process. As the appropriate stochastic approximation of the emissions allowance price is still an open question,[9] we assume, in line with the pertinent modeling literature, that $p(t)$ follows a geometric Brownian motion (gBM) process

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

with $\alpha, \sigma \in \mathbb{R}^+$, and dW as the increment of a standard Brownian motion.[10]

For simplicity, assuming infinite operations, the present value of A's future costs of CO_2 emission at time $t \geqslant t_0$ can be expressed as follows[11]:

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

Let $I \in \mathbb{R}^+$ be the total investment cost of a climate-friendly investment opportunity that 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 time $\tau \geqslant t_0$ of the investment can be expressed as

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

[9] Under consideration are the geometric-Brownian motion, the geometric-Brownian motion with jumps, mean-reverting processes, or GARCH models (which allow the volatility to change over time). However, to date, most of the empirical studies contradict each other. Yun and Baker (2009), Daskalakis et al. (2009), and Tang et al. (2011) observe no mean-reversion effect in the historic data of the EUETS emissions allowance price, but one is observed by Chang et al. (2012). Furthermore, Tang et al. (2011) determine that the geometric-Brownian motion best fits the historic data, whereas Daskalakis et al. (2009) state that a geometric-Brownian model with jumps is preferred.

[10] See, e.g., Abadie and Chamorro (2008), Cetin and Verschuere (2009), and Yun and Baker (2009).

[11] See Majd and Pindyck (1987) for a detailed proof.

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

From a net present value (NPV) logic, it follows that investment is profitable if $\theta p^*_{eco}/(r-\alpha) - I \geqslant 0$. Consequently, investment takes place when $p(t) > p^*_{eco}$ with

$$p^*_{eco} = \frac{I(r-\alpha)}{\theta}. \quad (4)$$

We call $\tau^*_{eco} = inf\{t \geqslant t_0 | p(t) > p^*_{eco}\}$ the corresponding ecologic efficient investment time, that is, τ^*_{eco} is the earliest possible time A could invest in the project with the expectations that the project will be self-efficient. This leads to the first proposition:

Proposition 1. *A single firm will invest ecologically efficiently in an emission mitigating investment as soon as the price per emission permit $p(t)$ exceeds an optimal threshold p^*_{eco}, i.e., $p(t) > p^*_{eco}$, with:*

$$p^*_{eco} = \frac{I(r-\alpha)}{\theta},$$

where I denotes the total investment cost, θ denotes the amount of emissions saved, r equals the risk-free interest rate, and α equals the growth rate of emission permit price.

In the following, we distinguish between three different cases. In the first case, A is able to carry out the climate-friendly investment project on its own. As we will see, this case corresponds to a centralized supply chain. In the second case, the climate-friendly investment project requires investment from a neighboring link in the supply chain. In the third case, the climate-friendly investment project requires investment from the whole supply chain.

3.1. The single-company case

As mentioned in the previous section, at an arbitrarily investment time τ A gains

$$\pi(\tau) = S(\tau) - I = \frac{\theta p(\tau)}{r-\alpha} - I. \quad (5)$$

Following real option theory (e.g., Dixit and Pindyck, 1994; Trigeorgis, 1996), there is some flexibility when it comes to investing in the project, which can be regarded as an invest option for A. Hence, optimally, A should invest as soon as the price $p(t)$ of the emission allowances reaches an optimal threshold p^*_{eff}.[12] Similarly, we refer to $\tau^*_{eff} = inf\{t \geqslant t_0 | p(t) > p^*_{eff}\}$ as the optimal economically efficient investment time for the single-firm case. Let f be the value of the invest option. Then

$$f(p(t)) = \max_{\tau \geqslant t} \mathbb{E}\left[\left(\frac{\theta p(\tau)}{r-\alpha} - I\right) e^{-r(\tau - t)}\right]. \quad (6)$$

Following Karatzas and Shreve (2001, p. 63),

$$\mathbb{E}\left[\left(\frac{\theta p(\tau)}{r-\alpha} - I\right) e^{-r\left(\tau^*_{eff} - t\right)}\right] = \left(\frac{\theta p^*_{eff}}{r-\alpha} - I\right)\left(\frac{p(t)}{p^*_{eff}}\right)^{\beta} \quad (7)$$

for $t < \tau^*_{eff}$, whereby

$$\beta = \frac{1}{2} - \frac{\alpha}{\sigma^2} + \sqrt{\left(\frac{\alpha}{\sigma^2} - \frac{1}{2}\right)^2 + \frac{2r}{\sigma^2}} > 1, \quad (8)$$

and p^*_{eff} is the solution of

$$\frac{\partial}{\partial p^*_{eff}}\left(\frac{\theta p^*_{eff}}{r-\alpha} - I\right)\left(\frac{p(t)}{p^*_{eff}}\right)^{\beta} = 0, \quad (9)$$

which yields

$$p^*_{eff} = \frac{\beta}{\beta - 1} \frac{(r-\alpha)I}{\theta}. \quad (10)$$

For $t \geqslant \tau^*_{eff}$, it is optimal for A to invest immediately, thus there is no flexibility value, that is, NPV calculation applies

$$f(p(t)) = \pi(t) = \frac{\theta p(t)}{r-\alpha} - I. \quad (11)$$

Hence, the value of the option to invest is

$$f_{eff}(p(t)) := f(p) = \begin{cases} \left(\frac{\theta p^*_{eff}}{r-\alpha} - I\right)\left(\frac{p}{p^*_{eff}}\right)^{\beta} & p < p^*_{eff}, \\ \frac{\theta p}{r-\alpha} - I & p \geqslant p^*_{eff}. \end{cases} \quad (12)$$

Inserting Eq. (10) in Eq. (12) yields

$$f_{eff}(p) = \begin{cases} \left(\frac{1}{\beta-1} I\right)\left(\frac{p}{\frac{\beta}{\beta-1}\frac{(r-\alpha)I}{\theta}}\right)^{\beta} & p < \frac{\beta}{\beta-1}\frac{(r-\alpha)I}{\theta}, \\ \frac{\theta p}{r-\alpha} - I & p \geqslant \frac{\beta}{\beta-1}\frac{(r-\alpha)I}{\theta}. \end{cases} \quad (13)$$

The following proposition summarizes the findings with respect to investment timing.

Proposition 2. *A single firm will invest economically efficiently in an emission mitigating investment as soon as the price per emission permit $p(t)$ exceeds an optimal threshold p^*_{eff}, i.e., $p(t) > p^*_{eff}$ with:*

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

with β as provided in Eq. (8).

Comparing Propositions 1 and 2 and Eqs. (4) and (10), two more results are particularly noteworthy, as summarized by the following propositions.

Proposition 3a. *When taking managerial flexibility explicitly into account, the single firm will postpone the investment, i.e.*

$$p^*_{eff} > p^*_{eco}.$$

Consequently, an economically efficient investment is no longer an ecologically efficient investment.

Because when $\sigma = 0$, β becomes r/α and, hence, $\lim_{\sigma \to 0 \wedge \alpha \to 0} \frac{\beta}{\beta-1} = 1$, the ecologic-efficient investment threshold p^*_{eco} becomes a limiting case for economically efficient decision-making situations.[13] This leads to the following proposition:

Proposition 3b. *An economically efficient solution becomes eco-efficient if the price per emission permit $p(t)$ becomes constant, i.e., $p^*_{eco} = p^*_{eff} \forall \sigma = 0 \wedge \alpha = 0$.*

3.2. The two-company case

Now let us assume that the project depends on the cooperation of a neighbor link B in the supply chain, which has to bear a share $\xi \in (0, 1)$ of the investment costs I. Hence, A has to bear investment costs of only $(1 - \xi)I$. Obviously, A has to compensate B, which receives no direct benefit from the investment. We assume a non-cooperative setting in which A and B maximize their individual profits.[14] A and B have to negotiate over the timing of the investment and B's compensation.[15] At time t_0, A can offer$B$ a fraction $\psi \in (0, 1)$

[12] For a graphic illustration of this interconnection, see Fig. 7.

[13] See, e.g., Lukas and Welling (2012) for a derivation of $\lim_{\sigma \to 0} \beta = r/\alpha$.

[14] There are several real-life examples of supply chains being non-cooperatively rather than cooperatively managed. See, e.g. Yue et al. (2006).

[15] For a general treatment, see, e.g., Lukas and Welling (2012).

of the saved emission costs. Therefore, at time τ of the investment A gains

$$\pi_A(\tau) = (1-\psi)\frac{\theta p(\tau)}{r-\alpha} - (1-\xi)I, \qquad (14)$$

and B gains

$$\pi_B(\tau) = \psi\frac{\theta p(\tau)}{r-\alpha} - \xi I. \qquad (15)$$

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

$$\tau_2^* = inf\{t \geqslant t_0 | p(t) > p_2^*(\psi)\}. \qquad (16)$$

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

$$f_B(p(t)) = \max_{\tau \geqslant t}\mathbb{E}\left[\left(\frac{\psi\theta p(\tau)}{r-\alpha} - \xi I\right)e^{-r(\tau-t)}\right]. \qquad (17)$$

In analogy to Eq. (10),

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

and

$$f_B(p(t)) = f_B(p) = \begin{cases} \left(\frac{\psi\theta p_2^*(\psi)}{r-\alpha} - \xi I\right)\left(\frac{p}{p_2^*(\psi)}\right)^\beta & p < p_2^*(\psi), \\ \frac{\psi\theta p}{r-\alpha} - \xi I & p \geqslant p_2^*(\psi), \end{cases} \qquad (19)$$

respectively. Taking into account B's optimal reaction function $p_2^*(\psi)$, A will choose ψ^* in t_0 such that it maximizes its expected present value as expressed by Equation (14), i.e.

$$f_A(p) = \max_{\psi \in (0,1)}\mathbb{E}\left[\left(\frac{(1-\psi)\theta p_2^*(\psi)}{r-\alpha} - (1-\xi)I\right)e^{-r\tau_2^*}\right]. \qquad (20)$$

Solving

$$\frac{\partial}{\partial\psi^*}\left(\frac{(1-\psi^*)\theta p_2^*(\psi^*)}{r-\alpha} - (1-\xi)I\right)\left(\frac{p(t)}{p_2^*(\psi^*)}\right)^\beta = 0, \qquad (21)$$

and considering the boundary case $p_2^* < p(t)$, i.e. a static ultimatum game, yields:

$$\psi^* = min\left\{\frac{\xi I(r-\alpha)}{\theta p_0}, \frac{\xi(\beta-1)}{\beta-1+\xi}\right\} \qquad (22)$$

and

$$f_A(p) = \begin{cases} \left(\frac{(1-\psi)\theta p_2^*(\psi^*)}{r-\alpha} - (1-\xi)I\right)\left(\frac{p}{p_2^*(\psi^*)}\right)^\beta & p < p_2^*(\psi^*), \\ \frac{(1-\psi^*)\theta p}{r-\alpha} - (1-\xi)I & p \geqslant p_2^*(\psi^*). \end{cases} \qquad (23)$$

Thus, the total value of the option to invest in the project is $f(p) := f_A(p) + f_B(p)$. These results lead to the following proposition:

Proposition 4a. *If the climate-friendly project depends on the cooperation of a neighbor link in the two-echelon supply chain, investment will occur as soon as $p(t)$ exceeds the economically efficient investment threshold p_2^*, i.e., $p(t) > p_2^*$ with*

$$p_2^* = \frac{\beta}{\beta-1}\frac{(r-\alpha)I}{\theta}\left(1+\frac{\xi}{\beta-1}\right),$$

where ξ denotes B's share of the total investment costs.

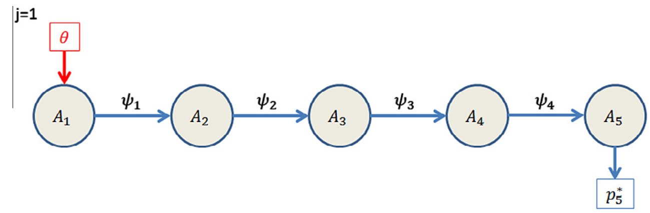

Fig. 1. Pattern of a supply chain of length 5, where A_1 is the CO_2-saving company.

Furthermore, because

$$p_2^*(\psi^*) = \frac{\beta}{\beta-1}\frac{(r-\alpha)I}{\theta}\left(1+\frac{\xi}{\beta-1}\right) = \left(1+\frac{\xi}{\beta-1}\right)p_{eff}^* > p_{eff}^*, \qquad (24)$$

we can state the following proposition.

Proposition 4b. *If the climate-friendly project depends on the cooperation of a neighbor link in a two-echelon supply chain, investment will not occur inefficiently late simply from an ecologic efficiency view but also from a economic efficiency view, i.e.:*

$$p_2^* = \left(1+\frac{\xi}{\beta-1}\right)p_{eff}^* > p_{eff}^*.$$

3.3. The n-company case

Now, we consider a supply chain ($n, j, \theta, I, \xi = (\xi_1, \ldots, \xi_n)$) consisting of $n > 2$ companies $A_1, A_2, \ldots, A_n$. Company A_j, $j \in \{1, \ldots, n\}$ can reduce its CO_2 emissions by the amount of θ production units a year if it invests in the climate-friendly project, but the investment depends on the cooperation of all other companies in the supply chain, which will also incur investment costs. Let I continue to denote the total sum of the investment costs and ξ_i the share of the investment costs to be borne by company i. 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 compensation to be paid. Without loss of generality, we assume that $j \leqslant n/2$.[16]

We first take the case of $j = 1$, that is, company A_1, which can reduce its emissions costs, is located at an end of the supply chain. Based on the sequential negotiation setting, A_1 offers a premium ψ_1 to A_2. Then, A_2 offers ψ_2 to $A_3, \ldots,$ and finally A_{n-1} offers a premium ψ_{n-1} to A_n, which then can decide about the timing of the investment (see Fig. 1).

Therefore, at time τ of the investment, company i gains

$$\pi_i(\tau) = \begin{cases} (1-\psi_i)\frac{\theta p(\tau)}{r-\alpha} - \xi_i I & i = 1, \\ (\psi_{i-1} - \psi_i)\frac{\theta p(\tau)}{r-\alpha} - \xi_i I & 1 < i < n, \\ \psi_{i-1}\frac{\theta p(\tau)}{r-\alpha} - \xi_i I & i = n. \end{cases} \qquad (25)$$

Similar to B in the two-party case, it is now A_n that can wait to accept 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^*, which depends on the fraction offered by $A_1, \ldots, A_{n-1}$, i.e., $p_n^*(\psi_1, \ldots, \psi_{i-1})$. For the optimal investment time τ_n^* of A_n we obtain

$$\tau_n^* = inf\{t \geqslant t_0 | p(t) > p_n^*(\psi_1, \ldots, \psi_{n-1})\}. \qquad (26)$$

Let f_n be the value of A_n's option to accept the offer. Then

$$f_n(p(t)) = \max_{\tau \geqslant t}\mathbb{E}\left[\left(\frac{\psi_{n-1}\theta p(\tau)}{r-\alpha} - \xi_n I\right)e^{-r(\tau-t)}\right]. \qquad (27)$$

Solving the equation in the same way as in Section 3.1 yields

$$p_n^*(\psi_1, \ldots, \psi_{n-1}) = \frac{\beta}{\beta-1}\frac{(r-\alpha)\xi_n I}{\theta\psi_{n-1}(\psi_{n-2}(\ldots(\psi_2(\psi_1))))}. \qquad (28)$$

[16] Otherwise, we need only change the direction of numbering in the supply chain.

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

$$f_i(p) = \max_{\psi_i \in (0,1)} \mathbb{E}\left[\left(\frac{(\psi_{i-1}-\psi_i)\theta p_n^*(\psi_1,\ldots,\psi_i,\psi_{i+1}^*(\psi_i),\ldots,\psi_{n-1}^*(\psi_i))}{r-\alpha} - \xi_i I\right)e^{-r\tau_n^*}\right]. \quad (29)$$

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

$$f_1(p) = \max_{\psi_1 \in (0,1)} \mathbb{E}\left[\left(\frac{(1-\psi_1)\theta p_n^*(\psi_1,\psi_2^*(\psi_1),\ldots,\psi_{n-1}^*(\psi_1))}{r-\alpha} - \xi_1 I\right)e^{-r\tau_n^*}\right]. \quad (30)$$

The total value of the option to invest in the project can be calculated by $f(p) := \sum_{i=1}^{n} f_i(p)$. Solving Eq. (30) yields the optimal premium ψ_1. Then, the optimal premiums $\psi_2^*,\ldots,\psi_{n-1}^*$ and the optimal investment threshold p_n^* can easily be calculated recursively. For example, for $n = 3$ we obtain
Here, we have always assumed that waiting is optimal, i.e. $p_0 < p_n^*$. Otherwise, immediate excercise is optimal and the results equal a n-person ultimatum game where the first person gets all the surplus and the remaining agents get nothing.

$$p_3^*(\psi_2) = \frac{\beta}{\beta-1}\frac{\xi_3}{\psi_2}\frac{(r-\alpha)}{\theta}I, \quad (31)$$

$$\psi_2^*(\psi_1) = \frac{(\beta-1)\xi_3\psi_1}{\beta\xi_3+(\beta-1)\xi_2}, \quad (32)$$

and

$$\psi_1^* = \frac{\beta(\beta-1)\xi_3+(\beta-1)^2\xi_2}{\beta^2\xi_3+\beta(\beta-1)\xi_2+(\beta-1)^2\xi_1}. \quad (33)$$

Resolved recursively, it is

$$\psi_2^* = \frac{(\beta-1)\xi_3\left(\beta(\beta-1)\xi_3+(\beta-1)^2\xi_2\right)}{(\beta^2\xi_3+\beta(\beta-1)\xi_2+(\beta-1)^2\xi_1)(\beta\xi_3+(\beta-1)\xi_2)}, \quad (34)$$

and

$$p_3^* = \frac{\beta(\beta^2\xi_3+\beta(\beta-1)\xi_2+(\beta-1)^2\xi_1)(\beta\xi_3+(\beta-1)\xi_2)}{(\beta-1)^2(\beta(\beta-1)\xi_3+(\beta-1)^2\xi_2)}\frac{(r-\alpha)}{\theta}I. \quad (35)$$

We can generalize these findings. Thus, for a supply chain (n, θ, I, $\xi = (\xi_1, \ldots, \xi_n)$),

$$p_n^* = \frac{\beta}{\beta-1}\frac{(r-\alpha)}{\theta}\xi_n I \prod_{i=2}^{n} \frac{\sum_{j=1}^{i}\left(\xi_{n+1-j}\sum_{k=1}^{j}\binom{j-1}{k-1}\beta^{i-k}(-1)^{k+1}\right)}{\sum_{j=1}^{i-1}\left(\xi_{n+1-j}\sum_{k=1}^{j+1}\binom{j}{k-1}\beta^{i-k}(-1)^{k+1}\right)}, \quad (36)$$

$$\psi_{n-1}^* = \prod_{i=2}^{n} \frac{\sum_{j=1}^{i-1}\left(\xi_{n+1-j}\sum_{k=1}^{j+1}\binom{j}{k-1}\beta^{i-k}(-1)^{k+1}\right)}{\sum_{j=1}^{i}\left(\xi_{n+1-j}\sum_{k=1}^{j}\binom{j-1}{k-1}\beta^{i-k}(-1)^{k+1}\right)}, \quad (37)$$

and

$$\psi_{n-l}^* = \prod_{i=2}^{l} \frac{\sum_{j=1}^{i}\left(\xi_{n+1-j}\sum_{k=1}^{j}\binom{j-1}{k-1}\beta^{i-k}(-1)^{k+1}\right)}{\sum_{j=1}^{i-1}\left(\xi_{n+1-j}\sum_{k=1}^{j+1}\binom{j}{k-1}\beta^{i-k}(-1)^{k+1}\right)} \times \prod_{i=2}^{n} \frac{\sum_{j=1}^{i-1}\left(\xi_{n+1-j}\sum_{k=1}^{j+1}\binom{j}{k-1}\beta^{i-k}(-1)^{k+1}\right)}{\sum_{j=1}^{i}\left(\xi_{n+1-j}\sum_{k=1}^{j}\binom{j-1}{k-1}\beta^{i-k}(-1)^{k+1}\right)}, \quad (38)$$

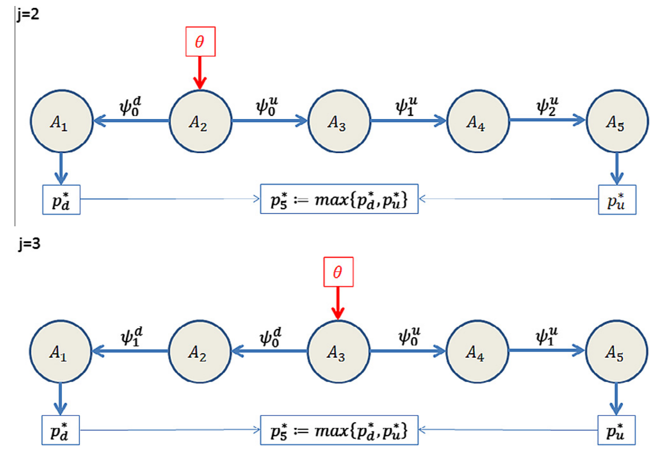

Fig. 2. Pattern of a supply chain of length 5, where A_2 or A_3 are the CO_2-saving companies, respectively.

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

Proposition 5. *If the climate-friendly project depends on the cooperation of a neighbor link in the n-echelon supply chain, investment will occur as soon as p(t) exceeds the economically efficient investment threshold* p_n^**, i.e.,* $p(t) > p_n^*$ *with*

$$p_n^* = \frac{\beta}{\beta-1}\frac{(r-\alpha)}{\theta}\xi_n I \prod_{i=2}^{n} \frac{\sum_{j=1}^{i}\left(\xi_{n+1-j}\sum_{k=1}^{j}\binom{j-1}{k-1}\beta^{i-k}(-1)^{k+1}\right)}{\sum_{j=1}^{i-1}\left(\xi_{n+1-j}\sum_{k=1}^{j+1}\binom{j}{k-1}\beta^{i-k}(-1)^{k+1}\right)}.$$

Now, we discuss the case of $j > 1$. In this case, company A_j, which can save the CO_2 emissions, has two neighboring chain links, A_{j-1} and A_{j+1}. Therefore, on the one hand, A_j has to offer a premium ψ_0^d to A_{j-1} and, on the other hand, it has to offer a premium ψ_0^u to A_{j+1}. Then A_{j-1} offers a fraction ψ_1^d to A_{j-2}, which itself offers a fraction ψ_2^d to $A_{j-3}, \ldots$, and finally A_2 offers a premium ψ_{j-2}^d to A_1, which then chooses an optimal investment threshold p_d^* and thereby can co-decide about the timing of the investment. Likewise, A_{j+1} offers a fraction ψ_1^u to A_{j+2}, which itself offers a fraction ψ_2^u to $A_{j+3}, \ldots$. Finally, A_{n-1} offers a premium ψ_{n-j-1}^u to A_n, which then chooses an optimal investment threshold p_u^* and thereby can co-decide about the timing of the investment, too (see Fig. 2).

The resulting investment threshold is

$$p_n^* = max\{p_d^*, p_u^*\}. \quad (39)$$

To solve the problem, we divide the supply chain into three parts: (1) the first $j-1$ chain links, (2) company j, and (3) the last $n-j$ chain links. The first j chain links can be regarded as a supply chain $\left(j-1, 1, \psi_0^d, \sum_{i=i}^{j-1}\xi_i I, \xi^d = \frac{1}{\sum_{i=1}^{j-1}\xi_i}(\xi_{j-1}, \xi_{j-2}, \ldots, \xi_1)\right)$, where ψ_0^d acts as a fictional amount of CO_2 emissions that can be saved by company $j-1$. Similarly, the last $n-j$ chain links can be regarded as a supply chain $\left(n-j, 1, \psi_0^u, \sum_{i=j+1}^{n}\xi_i I, \xi^u = \frac{1}{\sum_{i=j+1}^{n}\xi_i}(\xi_{j+1}, \xi_{j+2}, \ldots, \xi_n)\right)$, where ψ_0^u acts as a fictional amount of CO_2 emissions that can be saved by company $j+1$. Hence, we can calculate $p_d^*\left(\psi_0^d\right)$ and $p_u^*(\psi_0^u)$ with the help of Eq. (36).[17] For the resulting investment threshold we obtain

[17] If $j \leqslant 3$ or $n - j \leqslant 3$, we can use Eq. (10) or (24) instead.

$$p_n^*\left(\psi_0^d,\psi_0^u\right)=max\left\{p_d^*\left(\psi_0^d\right),p_u^*\left(\psi_0^u\right)\right\}. \tag{40}$$

Company A_j can use this optimal reaction function to determine its optimal offered premiums $\psi_0^{d,*}$ and $\psi_0^{u,*}$. Obviously, for optimal $\psi_0^{d,*}$ and $\psi_0^{u,*}$ the condition

$$p_n^*\left(\psi_0^{d,*},\psi_0^{u,*}\right)=p_d^*\left(\psi_0^{d,*}\right)=p_u^*\left(\psi_0^{u,*}\right), \tag{41}$$

must hold. Otherwise, company A_j could reduce one of the premiums without increasing the investment threshold p_n^*. Together with Eq. (36) we get from Eq. (41) that

$$\psi_0^{d,*}=\kappa\psi_0^{u,*}, \tag{42}$$

with

$$\kappa:=\left(\frac{\xi_1}{\xi_n}\right)\frac{\left[\prod_{i=2}^{j-1}\frac{\sum_{m=1}^{i}\left(\frac{\xi_m}{\sum_{l=1}^{j-1}\xi_l}\sum_{k=1}^{m}\binom{m-1}{k-1}\beta^{i-k}(-1)^{k+1}\right)}{\sum_{m=1}^{i-1}\left(\frac{\xi_m}{\sum_{l=1}^{n}\xi_l}\sum_{k=1}^{m+1}\binom{m}{k-1}\beta^{i-k}(-1)^{k+1}\right)}\right]}{\left[\prod_{i=2}^{n-j}\frac{\sum_{m=1}^{i}\left(\frac{\xi_{n+1-m}}{\sum_{l=j+1}^{n}\xi_l}\sum_{k=1}^{m}\binom{m-1}{k-1}\beta^{i-k}(-1)^{k+1}\right)}{\sum_{m=1}^{i-1}\left(\frac{\xi_{n+1-m}}{\sum_{l=j+1}^{n}\xi_l}\sum_{k=1}^{m+1}\binom{m}{k-1}\beta^{i-k}(-1)^{k+1}\right)}\right]}. \tag{43}$$

Hence, $\psi_0^{d,*}$ can be interpreted as a function of $\psi_0^{u,*}$ without loss of generality, that is, we obtain $\psi_0^{d,*}(\psi_0^{u,*})=\kappa\psi_0^{u,*}$. Furthermore, company A_j chooses ψ_0^d and ψ_0^u in a way that maximize its expected gain

$$\pi_j\left(\psi_0^{d,*}(\psi_0^{u,*}),\psi_0^u\right)=\pi_j(\psi_0^{u,*})$$
$$=\left(\left(\theta-\psi_0^{d,*}(\psi_0^{u,*})-\psi_0^u\right)\frac{p_n^*\left(\psi_0^{d,*}(\psi_0^{u,*}),\psi_0^u\right)}{r-\alpha}-\xi_j I\right)$$
$$\times\left(\frac{p_0}{p_n^*\left(\psi_0^{d,*}(\psi_0^{u,*}),\psi_0^u\right)}\right)^{\beta}. \tag{44}$$

Thus, for the optimal premiums $\psi_0^{d,*}(\psi_0^{u,*})$ and $\psi_0^{d,*}$ the condition

$$\pi_j(\psi_0^{u,*})=\max_{\psi_0^u\in\mathbb{R}}\{\pi_j(\psi_0^u)\}, \tag{45}$$

must hold. Therefore, the optimal premium $\psi_0^{u,*}$ can be determined by

$$\frac{\partial}{\partial\psi_0^{u,*}}\pi_j(\psi_0^{u,*})=0, \tag{46}$$

whereby

$$\pi_j(\psi_0^{u,*})=\left(\left(\theta-\kappa\psi_0^{u,*}-\psi_0^{u,*}\right)\frac{p_n^*(\kappa\psi_0^{u,*},\psi_0^{u,*})}{r-\alpha}-\xi_j I\right)\left(\frac{p_0}{p_n^*(\kappa\psi_0^{u,*},\psi_0^{u,*})}\right)^{\beta}. \tag{47}$$

4. Comparative static results

From Eqs. (4), (8), and (10) it is obvious that an increase of the investment size I and the risk-free interest rate r, respectively, raise the ecologically efficient investment threshold p_{eco}^* as well as the economically efficient investment threshold p_{eff}^*, that is, the emission mitigating strategy will be initiated later. On the contrary, increasing the amount of emissions saved due to the investment θ as well as a higher growth rate of the permit prices α will accelerate investment, that is, lower the optimal investment threshold.

In the following, we discuss the influence of uncertainty and the structure of the supply chain. Unless noted otherwise, we 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, that is, $\xi_i=\frac{1}{n}$ for all $i\in\{1,\ldots,n\}$. From Eq. (4), we find that $p_{eco}^*=1.2$.

Table 1
The results of the model.

	$n = 1$ $j = 1$	$n = 2$ $j = 1$	$n = 3$ $j = 1$	$n = 3$ $j = 2$	$n = 4$ $j = 1$	$n = 4$ $j = 2$	$n = 5$ $j = 1$	$n = 5$ $j = 2$	$n = 5$ $j = 3$
p^*	3.17	5.78	11.24	6.61	23.08	9.96	49.44	21.15	12.84
$\mathbb{E}\Delta x$	32.38	52.4	74.57	56.87	98.55	70.55	123.95	95.64	79.01
f	6.16	5.45	4.10	5.19	2.81	4.34	1.82	2.95	3.84
f_1/f	1.00	0.78	0.69	0.12	0.66	0.06	0.64	0.02	0.03
f_2/f	–	0.22	0.24	0.76	0.24	0.68	0.24	0.68	0.12
f_3/f	–	–	0.07	0.12	0.08	0.20	0.09	0.21	0.69
f_4/f	–	–	–	–	0.02	0.06	0.03	0.07	0.12
f_5/f	–	–	–	–	–	–	0.01	0.02	0.03

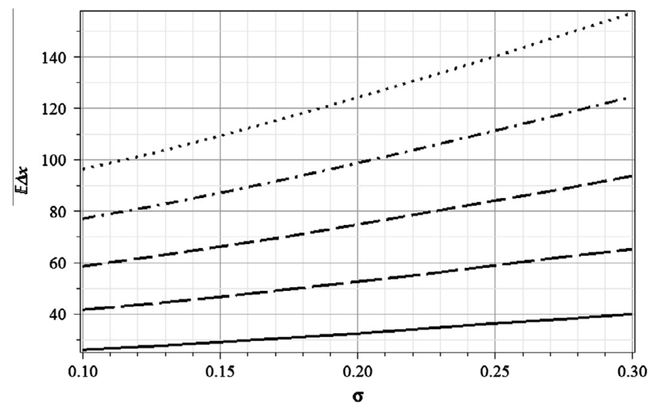

Fig. 3. The expected amount of produced CO_2 $\mathbb{E}\Delta x$ that could have been avoided if the investment was ecologically efficient in dependence on uncertainty and the length of the supply chain ($n = 1$: solid line; $n = 2$: long dash; $n = 3$: dash; $n = 4$: dash dot; $n = 5$: dot). It is always assumed that $j = 1$.

Table 1 contains the results of our model for the single-company case, the two-company case, and for supply chains of lengths 3 to 5, respectively, and for each position j of the CO_2-saving company in the supply chain. $\mathbb{E}\Delta x$ represents the expected amount of CO_2 emissions that could be avoided if the companies invest at the eco-efficient investment time, i.e.[18]:

$$\mathbb{E}\Delta x_n=\mathbb{E}\theta(\tau_n^*-\tau_{eco}^*)=\frac{\theta ln\left(\frac{p_n^*}{p_{eco}^*}\right)}{\alpha-\frac{\sigma^2}{2}}. \tag{48}$$

The table reveals that with an increasing length of the supply chain, the total value f of the option to invest decreases and that longer supply chains will invest later and therefore produce more avoidable CO_2. Hence, the following hypothesis holds:

Hypothesis 1. A supply chain becomes less economically efficient and less ecologically efficient and thus less eco-efficient with every additional chain link, i.e.,

$$p_{eco}^*<p_{eff}^*<p_2^*<\cdots<p_n^*,$$

with p_n^* given by Equation (39).

However, it is not only the length of the supply chain, but also the position of the CO_2-saving company in the supply chain, that influences economic and ecologic efficiency. Table 1 shows that a supply chain becomes more economically and ecologically efficient the more centered in the chain the CO_2-saving company is. This leads to the second hypothesis:

[18] See, e.g., Wong (2007).

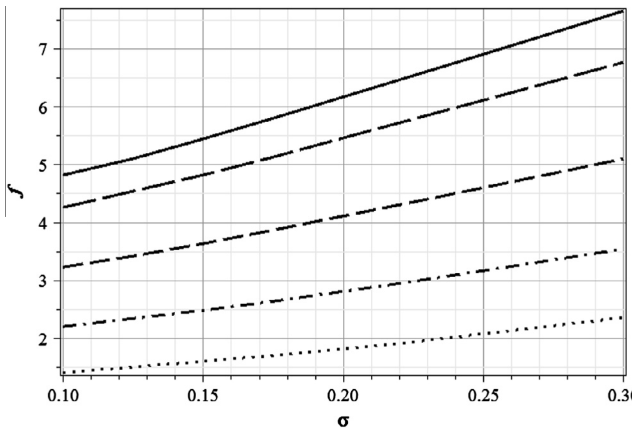

Fig. 4. The total option value f of the possibility to invest in the climate-friendly project in dependence on uncertainty and the length of the supply chain ($n = 1$: solid line; $n = 2$: long dash; $n = 3$: dash; $n = 4$: dash dot; $n = 5$: dot). It is always assumed that $j = 1$.

Hypothesis 2. A supply chain becomes more economically and ecologically efficient and thus more eco-efficient the more centered the emission-saving firm is in the supply chain.

Furthermore, Table 1 reveals that the share f_i/f of the surplus a company i gains will increase the closer company i is located to the company that is saving CO_2 emissions.

Figs. 3 and 4 summarize the findings. The ecological efficiency of a supply chain becomes less with increasing uncertainty and with an increasing length of the supply chain (Fig. 3), whereas economic efficiency increases with uncertainty but decreases with an increasing length of the supply chain (Fig. 4).

5. Coordination strategies to improve eco-efficiency

How can managers effectively increase the eco-efficiency of their supply chains? Following Zhang and Liu (2013), we discuss two major coordination mechanisms—the asymmetric Nash bargaining solution and vertical integration—and their impact on eco-efficient decision making. As the results of the previous sections show, $p^*_{eff} > p^*_{eco}$, a centralized managed supply chain seems the best way of avoiding economic inefficiency and, to some extent, ecological inefficiency as well. If all parties act cooperatively instead of negotiating sequentially, they should be able to agree on the economically efficient investment time τ^*_{eff}. Following the asymmetric Nash bargaining solution, the surplus generated by the investment would be shared by the parties based on 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 ith 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 A_i after cooperative bargaining is $\gamma_i f_{eff}(p_0)$, with $f_{eff}(p_0)$ given by Eq. (13) as the total surplus after cooperative bargaining. Cooperation, by definition, requires the cooperation of every member in the supply chain. However, a party A_i can be expected to cooperate only if its gain $\gamma_i f_{eff}(p_0)$ after cooperation is higher than its gain $f_i(p_0)$ after sequential bargaining. Thus, cooperation is the best strategy, but cooperation is possible only if

$$\gamma_i f_{eff}(p_0) \geqslant f_i(p_0), \quad (49)$$

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

$$\mathbb{E}\Delta x_{n,C} = \mathbb{E}\Delta x_n - \mathbb{E}\Delta x_1. \quad (50)$$

As an example we consider the supply chain $(3, 1, 1, 24, (\frac{1}{3}, \frac{1}{3}, \frac{1}{3}))$ with the remaining variables defined as in Section 4. The total surplus after sequential bargaining is $f = 4.1$. After cooperation, the total surplus is $f_{eff} = 6.16$. Therefore, company A_1 is willing to cooperate only if

$$\gamma_1 f_{eff} = 6.16\gamma_1 \geqslant f_1 = \frac{f_1}{f} f, \quad (51)$$

or in other words, if

$$\gamma_1 \geqslant \frac{0.69 \cdot 4.1}{6.16} \approx 0.47 =: \gamma_{1,min}. \quad (52)$$

Similarly, company A_2 cooperates only if

$$\gamma_2 \geqslant \frac{0.24 \cdot 4.1}{6.16} \approx 0.16 =: \gamma_{2,min}, \quad (53)$$

and company A_3 cooperates only if

$$\gamma_3 \geqslant \frac{0.07 \cdot 4.1}{6.16} \approx 0.05 =: \gamma_{3,min}. \quad (54)$$

Fig. 5 shows, 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 (gray area). In the latter case, at least one company is not willing to cooperate.

As can be deduced from Table 1, the amount of CO_2 that can be saved in the given example in the presence of cooperation equals

$$\mathbb{E}\Delta x_{3,C} = 74.57 - 32.38 = 42.19. \quad (55)$$

If cooperation is not possible, the next best strategy the managers of company A_1 can pursue is vertical integration, that is, company A_1 can acquire company A_2. As a consequence, the supply chain changes from $(n, 1, \theta, I, \xi = (\xi_1, \xi_2, \xi_3, \ldots, \xi_n))$ to $(n - 1, 1, \theta, I, \xi = (\xi_1 + \xi_2, \xi_3, \ldots, \xi_n))$, leading to an increase in the total surplus possible from investing and an earlier investment time and therefore to less economic and less ecological inefficiency and hence to more eco-efficiency. Let $I_P \in \mathbb{R}^+$ be the purchase price of company A_2, $I_T \in \mathbb{R}^+$ be the transaction costs of the acquisition, and $V \in \mathbb{R}^+$ be the value of company A_2 if it is managed by company A_1. Then, it is reasonable for company A_1 to acquire company A_2 if and only if

$$\tilde{f}_1(p_0) + V - I_P - I_T \geqslant f_1(p_0), \quad (56)$$

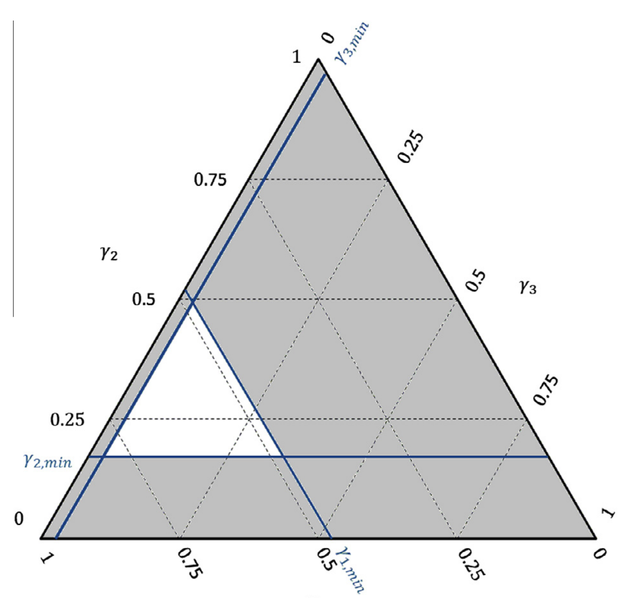

Fig. 5. The combinations of bargaining power making cooperation of the supply chain possible (white triangle) or not (gray area).

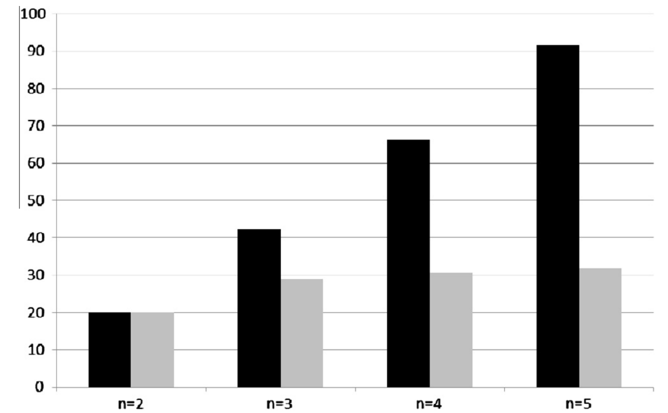

Fig. 6. The amount of CO_2 (in production units) that can be saved by means of cooperation (black) and by means of acquisition (gray).

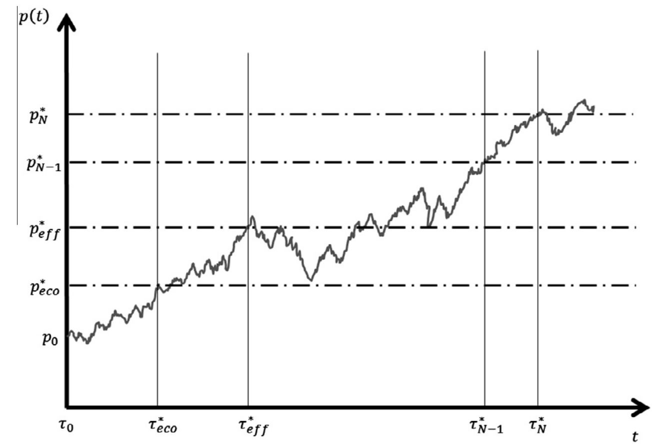

Fig. 7. Overview of the different investment times thresholds.

with $f_1(p_0)$ as the option value of company A_1 before the acquisition and $\tilde{f}_1(p_0)$ as the option value of company A_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

$$\mathbb{E}\Delta x_{n,A} = \frac{\theta ln\left(\frac{p_n^*}{p_{eco}^*}\right)}{\alpha - \frac{\sigma^2}{2}} - \frac{\theta ln\left(\frac{\tilde{p}_n^*}{p_{eco}^*}\right)}{\alpha - \frac{\sigma^2}{2}}, \tag{57}$$

with $\tilde{p}_n^*$ as the investment threshold of the new supply chain. If we again consider the same example, the acquisition of company A_2 by company A_1 transforms the supply chain from $\left(3,1,1,24,\left(\frac{1}{3},\frac{1}{3},\frac{1}{3}\right)\right)$ to $\left(2,1,1,24,\left(\frac{2}{3},\frac{1}{3}\right)\right)$, which is identical to the two-party case. Again we have $f_1 = 0.7 \cdot 4.1 = 2.87$ and using Eqs. (22)–(24), we obtain $\tilde{p}_3^* = 4.91$ and $\tilde{f}_1 = 4.72$. Hence, company A_1 should acquire company A_2 if and only if

$$V - I_P - I_T \geqslant -1.85. \tag{58}$$

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

$$\mathbb{E}\Delta \mathrm{x}_{3,A} = 74.57 - 45.65 = 28.92. \tag{59}$$

Fig. 6 compares the amount of CO_2 that could be saved by cooperation of the supply chain and by acquisition of company A_2 by company A_1. The figure reveals that from an ecological view, cooperation is preferred to acquisition for every length n of the supply chain, *if* cooperation is possible.

To conclude, four different ways of calculating the optimal investment time of a climate-friendly project are introduced in this article. First, τ_{eco}^*, the familiar NPV method that ignores the flexibility value of the investment option; second, τ_{eff}^*, the single-firm case that takes into account the flexibility value and equals a centrally managed and thus cooperative supply chain; third, τ_n^*, the non-cooperative sequentially bargaining supply chain that also takes into account the flexibility value; and finally, τ_{n-1}^*, the non-cooperative and sequentially bargaining supply chain after vertical integration of company A_2 into company A_1. As Fig. 7 depicts, because of $p_n^* \geqslant p_{n-1}^* \geqslant p_{eff}^* \geqslant p_{eco}^*$, we have $\tau_n^* \geqslant \tau_{n-1}^* \geqslant \tau_{eff}^* \geqslant \tau_{eco}^*$.

As shown by Proposition 3b, economic and ecologic efficiency are mutually exclusive as long as the emissions allowances price is not constant over time. Consequently, the four different optimal investment times have different ecologic and economic efficiency. From an ecologic perspective, τ_{eco}^* is the efficient investment time, whereas investments at τ_{eff}^*, τ_{n-1}^*, or τ_n^* would be inefficiently late. τ_n^* is an even less ecologically efficient investment time than τ_{n-1}^*, which itself is less ecologically efficient than τ_{eff}^*. From an economic perspective, τ_{eff}^* is the efficient investment time, whereas investments at τ_{eco}^* would be inefficiently early and investments at τ_{n-1}^* or τ_n^* would be inefficiently late. Again, τ_n^* is a less efficient investment time than τ_{n-1}^*. These findings are summarized in Table 2. However, although economic and ecologic efficiency are still mutually exclusive, investing at τ_{eff}^* instead of at τ_{n-1}^* or τ_n^*, as well as investing at τ_{n-1}^* instead of at τ_n^*, increases ecologic and economic efficiency and hence eco-efficiency.

Table 2
Economic and ecologic efficiency of the different investment times.

	Case	From economic efficiency view	From ecologic efficiency view
τ_{eco}^*	No real option, i.e. NPV	Investment inefficiently early	Efficient investment time
τ_{eff}^*	Real option: single firm and centrally managed supply chain	Efficient investment time	Investment inefficiently late
τ_N^*	Real option: sequential bargaining in supply chain of length	Investment inefficiently late	Investment inefficiently late
τ_{N-1}^*	Real option: sequential bargaining in supply chain of former length after vertical integration	Investment inefficiently late	Investment inefficiently late

6. Conclusion

The paper considers the problem of a supply chain in which the parties negotiate over implementation of a carbon dioxide (CO_2) saving investment project under a cap-and-trade system. 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 particularly in pollution-intensive industries, however, are far more complex than the two-echelon supply chain often used in the literature. Hence, we extend the base case scenario to a more general supply chain network, an n-echelon supply chain. The results show that a supply chain becomes less economically efficient and less ecologically efficient and thus less eco-efficient with every additional chain link. Irrespective of the length of the supply chain, the results support recent findings that the outcome of decentralized bargaining is not economically efficient and even less ecologically efficient. Hence, another aim of the paper is to make recommendations for how managers can improve the situation and thereby increase eco-efficiency, that is, both the economic as well as the ecological efficiency of a supply chain. By contrasting two promising strategies for improving economic and ecological efficiency in a *n*-echelon setting—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 could be extended is to model more explicitly the impact of regulatory shocks on carbon prices by means of, for example, time-varying volatility or by adding jumps to the carbon price dynamics. Another aspect worth further investigation is the assumption of equally shared investment costs; relaxation of this assumption could lead to further practical recommendations. Other extensions include dropping the assumption of a constant emission-production relationship and introducing demand uncertainty more explicitly. Here, a promising route would be to introduce a second stochastic process that reflects demand uncertainty.

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