A Game-Theoretic Real Options Approach to the Adoption of Industry Compatibility Standards

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Abstract

We apply a game-theoretic real options approach to analyse two mechanisms for the adoption of industry compatibility standards in situations of conflict. Conflicts arise if the players agree that adoption by the industry of one particular standard is best for all, but they each have a vested interest in their own preferred standard being the industry choice. We analyse the two main mechanisms for standard adoption: one mechanism focuses on achieving consensus via negotiation and the other is via the market in which one player unilaterally adopts and expects her competitors to follow suit. A key question in the field is which mechanism performs better. Another is when should a participant take the lead and unilaterally adopt a particular standard.

We address these questions in our paper by deriving equilibrium strategies for both mechanisms. In particular, we show that by considering the problem from the unique perspective as a real option timing game, a comparison of the mechanisms to help inform the industries which performs best cannot provide a definitive answer because it depends on each of the participants' expected payoffs from unilateral adoption and concession at any given time. Furthermore, the equilibrium expected payoffs in each of the mechanisms are equivalent.

Keywords: Standardisation; Game theory; Real options; Timing games.

1 Introduction

Standards are an agreed way of doing things for the design or measurement of products and processes. The adoption and market acceptance of a particular standard is meant to reduce technological and legal uncertainty across and within industries by guaranteeing that conforming to the standard will enable interoperability and network benefits among independently manufactured products and services (Wen et al. [2022]; Deng et al. [2022]; Blind et al. [2023]; Fichman [2004]). Other benefits of standard adoption include establishing safety requirements, promoting competition in the market, and facilitating divisions of labour. However, they can also be associated with costs such as the resulting market power and higher rents that accrue to certain parties (Blind et al. [2023]). As such, conflicts can arise in the sense that all relevant parties agree that one standard should be adopted by all, but reaching agreement and consensus on which standard is difficult because each party wants their own standard to be adopted. Reasons for such conflict include: different parties plan to serve different segments of the market; a party may have a competitive advantage and experience in a particular system and, hence,

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has vested interest in their own standard; there may be a variety of opinions on which standard is best for the industry; or nations may press for certain standards to protect domestic firms (Farrell and Saloner [1988]).

The adoption of compatibility standards emerge in two main ways (Simcoe [2012]; Rysman and Simcoe [2008]). One approach is via the market in which an industry player - a potential leader - adopts a standard and the other players in the industry follow suit (Besen and Farrell [1994]). These are known as *de facto* standards. For example, iTunes was adopted originally by Apple and was initially only available on Apple devices. However, in October 2003, iTunes was updated to a more widely compatible version to support Microsoft Windows 2000 and Windows XP and was adopted and made available across a wide range of non-Apple devices. Another example is that of Google's General Transit Feed Specification (GTFS) being adopted by most of the transit systems globally to provide timetable and transit route data to the public (Blind et al. [2023]).

The other main approach is where compatibility standards are adopted through a process of explicit consensus achieved via negotiation and discussion within a committee known as a Standard Setting Organization (SSO). However, while the participants of the committee realise the benefits of setting one specific standard, they sometimes have their own vested interests in the standard that is set and, as such, reaching a consensus can be difficult and this can lead to conflict.

In some cases, governments legally mandate certain compatibility standards. For example, in recent years, environmental challenges have led to compatibility standardisation efforts to enable green technologies such as the EU mandate of electrical vehicle plug compatibility (Blind et al. [2023]; Bakker et al. [2015]). However, in our paper, we focus on situations of conflict over which standard to adopt and therefore, examine and compare de facto compatibility standard adoption with standard adoption via a SSO.

Simcoe [2012] points out that a large normative question in the area of compatibility standard adoption is over the comparison of the performance of committees and markets, especially in the context of shared technology platforms, but he finds that there is no complete answer. Fichman [2004] also notes that a central question in IS research is about when a firm should take a lead role in adopting innovative technologies. More recently, in their review of the recent literature on standards, Blind et al. [2023] call for further theoretical contributions to "highlight critical distinctions to enable researchers to better understand when and why dominant platforms become de facto standard setters and when they participate in broader standardisation efforts" (i.e., via an SSO). We attempt to shed some light on this question in our paper.

While there is plethora of research on compatibility standards in the literature, much of it is empirical. On the theoretical side, research relating to the performance of the standardisation approaches include, for example, Farrell and Saloner [1988] who use a game theoretic approach to analyse these two mechanisms described, Farrell [1996] develops a model considering the consensus via a committee mechanism with incomplete information to assess its performance, and Simcoe [2012] uses a simple model of standard setting committees based on the stochastic bargaining framework of Merlo and Wilson [1995]. What none of the contributions have addressed to date is that there is uncertainty over the payoffs that will accrue to the individual firms from adopting a standard (noted by Katz and Shapiro [1986]), as well as the inherent option like feature of the decision to adopt one.

As such, we propose to analyse the problem of adopting compatibility standards using a real options approach (see, for example, Dixit and Pindyck [1994]; Trigeorgis et al. [2022]). We deem it an appropriate methodology for our analysis because similar to most investment decisions, adopting a standard has two main features; there is uncertainty over whether the adopted standard will succeed so that waiting has value in order to resolve some of this uncertainty

(McGrath and MacMillan [2000]; Benaroch [2002]), and the decision to adopt is only partly reversible in the sense that the sunk cost of implementing the standard cannot be fully recouped. In this way, we contribute to the literature on compatibility standard adoption by introducing a new methodology under which to analyse it which accounts for uncertainty over the payoffs from adoption as well as the inherent option value. As we will discuss, this approach allows us to answer the question on which adoption mechanism performs better (Simcoe [2012]), as well as when a specific mechanism should be adhered to (Blind et al. [2023]; Fichman [2004]), from a different angle to those cited above. We also contribute to the real options literature by introducing a new application of the methodology because, to the best of our knowledge, it has not been applied in the context of compatibility standard adoption to date.

To be specific, our analysis is one of a real option *timing game* (see, for example, Smit and Trigeorgis [2004]; Trigeorgis et al. [2022]; Chevalier-Roignant et al. [2019])) because we focus on situations of conflict. In particular, we assume that all participants agree that the adoption of one particular standard is better than the case of all participants going their own way, but they cannot agree on which standard should be adopted because they all want their own standard to succeed. The game is, thus, a qualitative 'battle of the sexes' type set up (see, also Farrell and Saloner [1988] and Farrell [1987]). As mentioned above, conflicts arise for many reasons, but in essence, they arise because the benefits or payoffs to the individual participants are heterogeneous. As such, along with each wanting the market to accept and adopt their own proposed standard, they also have different stopping times over when to adopt so that their payoffs from doing so are maximised. Hence, we assume that the players' strategies are typically asymmetric over stopping times. However, the symmetric case of both players having the same stopping times is nested within our model.

To summarise, all participants want one particular standard to be adopted by the industry and they want their own standard to succeed. The payoff to adopting a particular standard is uncertain for each participant, and the optimal time to adopt a standard so that the payoff is maximised is different for each participant.

The literature on timing games has grown extensively over the last decade or so and has been applied to numerous different contexts (see Azevedo and Paxson [2014]; Chevalier-Roignant et al. [2011]). Many of the contributions to this literature have focussed on analysing games with a first mover advantage, or preemption games (see, among others, Riedel and Steg [2017]; Huisman and Kort [2015]; Thijssen et al. [2012]; Pawlina and Kort [2006] and Weeds [2002]). The literature on war of attrition timing games, or games with a second mover advantage, is less well developed, with Hoppe [2000], Murto [2004] and Steg and Thijssen [2015] being particular exceptions. Furthermore, for the most part, the literature on timing games has focussed on players with symmetric strategies, whereas in our paper, we consider players whose strategies are asymmetric; i.e., the optimal times for each of the players to choose a particular action are different. This is novel in the context of war of attrition games. Riedel and Steg [2017] have already developed an equilibrium framework for preemption games with asymmetric strategies.

We analyse the adoption of compatibility standards as a real option timing game via the two main approaches: de facto standard adoption through a market mechanism, and standard adoption through consensus agreement within a committee (SSO). Key to our analysis is the asymmetric incentives of the participants and the uncertainty over the payoffs from adoption, but the symmetric case is nested within our framework. Our main result is that by analysing the decision to adopt as a timing game, the state space can be split into regions such that when the relative expected payoff from unilaterally adopting the preferred standard over conceding to adopt the competitor's is negative, it is optimal to negotiate within a SSO. Otherwise, when the relative payoff is positive, there is a first mover advantage, an it is optimal to preempt the competitor and unilaterally adopt her preferred standard (i.e., via the Market mechanism).

The relevance of this result is as follows. It answers the question posed by Blind et al.

[2023] over when and why dominant platforms become de facto standard setters and when they participate in broader standardisation efforts (i.e., via an SSO), as well as the question posed by Fichman [2004] over when a firm should take a lead role in adopting innovative technologies (namely, as soon as they have a first mover advantage in terms of expected payoffs). Moreover, as mentioned, Simcoe [2012] points out that there is no complete answer to the question of which performs better: markets or committees. Our model shows why this is the case. For an individual player, taking one approach to adoption is optimal for certain expected payoff levels, and the other approach for different expected payoff levels. Moreover, in equilibrium, each player's expected payoff at any time during the negotiation is equivalent to her expected payoff at the earliest time it is optimal for a Market game to be played. We further discuss how our result implies that comparing the performance of the two mechanisms with respect to the likelihood of achieving coordination is not economically meaningful.

The more wide-ranging economic implication of our result is that if one of the parties has an expected payoff from adoption of a standard that is sufficiently high to give that party a first mover advantage, they should adopt the standard immediately and other players follow suit by adopting that same standard at the time that is optimal for them; i.e., when the expected payoff from doing so adequately exceeds the adoption cost. This may be substantially later than the first adopter, but they should commit to adopting the leader's standard and not go their own way. For example, in 2023, in the US electric vehicle industry, plug compatibility is an important problem and the adoption of a de facto plug is expected to be crucial in the rollout of public charging infrastructure (cf. Blind et al. [2023]; Li [2023]).

On the other hand, if there is no first mover advantage to any of the participants, they should negotiate within a committee. This absence of a first mover advantage may arise if the standard is in the early stages and there is much uncertainty over whether implementing it will increase the demand for the product or service. Nevertheless, each participant is sufficiently confident about its impact on future demand to argue for it to be adopted widely by the industry.

The remainder of the paper is organised as follows. The standard adoption model is described in Section 2 and an intuitive outline and key results are provided in Section 2.2. In Section 3 we present the equilibrium results more generally for the Market and Committee mechanisms. In Section 4 we discuss and compare the two mechanisms with respect to our results, and Section 5 concludes. All proofs, as well as an outline of the typical timing game framework, are provided in the Appendix.

2 Overview and Intuition

2.1 Model Overview and Assumptions

Consider a timing game in which two asymmetric players i and j have the choice between adopting one of two incompatible new standards. There is conflict in that the players' preferences are different: player i wants to adopt standard i and j wants to adopt standard j. Both realise that the adoption of one standard is better than going their own way by each adopting their own preferred standard.[1] It is a classic 'battle of the sexes' type set up, which appropriately represents compatibility standard adoption in situations of conflict (see, for example, Farrell and Saloner [1988]; Farrell [1987]).

The payoffs from adopting the standards are uncertain and the uncertainty is represented by a fixed filtered probability space $(\Omega, \mathcal{F}, (\mathcal{F}_t)_{t\geq 0}, P)$, such that $(\mathcal{F}_t)_{t\geq}$ is right continuous and complete. Once a player i adopts his preferred standard, hereafter referred to as Insists, the

[1] Indeed, Adner et al. [2020] find that social welfare is greater under compatibility standard adoption.

other player j Concedes (adopts i's preferred standard) or Insists (adopts his own preferred standard).

Strategies are feasible state-dependent stopping times $\tau : \Omega \to [0, \infty]$ and are pure strategies for the initial mode of the game. Let $\mathcal{T}$ denote the set of all stopping times which are pure strategies for the game. The players' strategies are asymmetric and players cannot observe the strategies of their opponents; i.e., they are *open loop*.

If the strategies of players i and j for $i \neq j$, are to Insist at τ_i and τ_j, respectively, then if $\tau_i < \tau_j$, the game will end at τ_i. The payoff to i at τ_i, if she is the Leader (i.e., the only one to Insist), is π^I_{i,τ_i}, if he is the Follower (i.e., he Concedes) at τ_i, the payoff is π^C_{i,τ_i}, and if both players Insist simultaneously at τ_i, the payoff to i is π^B_{i,τ_i}. All the payoffs at the time a move is made are right-continuous and adapted stochastic processes $\pi^I_{i,t} = (\pi^I_{i,t})_{t\geq 0}$, $\pi^C_{i,t} = (\pi^C_{i,t})_{t\geq 0}$ and $\pi^B_{i,t} = (\pi^B_{i,t})_{t\geq 0}$.

The intuition is as follows. For the Follower, adopting a standard that is compatible with that adopted by the Leader will make their products more popular than if it had adopted a totally different standard. Moreover, if the Follower adopts a different standard to the Leader, the Leader may suffer in that its products may lose some of their attractiveness relative to that of the Follower. For example, Adner et al. [2020] discuss such a scenario in the context of Apple adopting Amazon's Kindle Reader app for the iPad. In particular, they argue that if Apple had not adopted it, it would have lost to Amazon some buyers who prefer e-books on the Kindle Reader app to those on Apple's own iBooks app, and vice versa. The main reason for this, they argue, is owing to the different profit foci of the two firms,[2] and we capture this in our model by letting our players have asymmetric strategies over when to adopt. Moreover, we assume that $\pi^B_{k,t} < \pi^C_{k,t}$ for all t and $k = \{i, j\}$ to capture the preference of concession to the opponent over both going their own ways.

Returning to the technical set-up, two firms $k = \{i, j\}$have the opportunity to adopt a particular standard. If firm i Insists and adopts her preferred standard at time t and if the competing firm j Concedes and adopts that standard also, then i is the Leader and her return from Insisting is given by $D_I X_t$, where $(X_t)_{t\geq 0}$ follows a geometric Brownian motion:

$$dX = \mu X dt + \sigma X dB_t,$$

where μ and $\sigma > 0$ are the drift and volatility parameters, respectively, and $(B_t)_{t\geq 0}$ a standard Brownian motion.

If, however, j adopts his preferred standard at t and i Concedes by adopting that same standard, then the return to i from conceding is X_t.

Finally, if both i and j go their own way and adopt their own preferred standards, the return to i at the time of adoption t is $D_B X_t$, where $D_B < 1$. Since $D_B < 1$, at any time $t \geq 0$, the return from going one's own way and Insisting is lower than the return from Conceding.

There is a firm-specific sunk cost to adopting a standard, denoted by $I_k > 0$, $k = \{i, j\}$. This could, for example, be the cost of labour and/or materials required to implement the standard for their products or services.

In line with the literature on timing games, once one player plays Insist, the other player's decision over whether to Insist or Concede is instantaneous. However, if the decision is to

[2]Apple's profits from hardware sales are more important to it than royalties from e-book sales, and vice versa for Amazon. Other examples they provide of standards being adopted by parties with different profit foci include Google's Android Auto being adopted by General Motors and Microsoft Office being made available on the Apple iPad. In the former, the profit focus of GM is the car business, whereas Google's main source for profit is ad-sponsored content, and not their self-driving cars. In the latter, the profit focus of Apple is hardware sales, whereas the focus for Microsoft is software sales.

Concede, he will not actually adopt the other player's standard until some time later. In particular, at the time it would be optimal for him to adopt if he were a monopolist because once the other player adopts, he is no longer faced with any competitive pressure and chooses his optimal stopping strategy accordingly.

We also assume that profits are discounted at a common risk-free rate $r > \mu > 0$. Then let $\beta_1 > 1$ be the positive root of the quadratic equation

$$\frac{1}{2}\sigma^2\beta(\beta - 1) + \mu\beta - r = 0 \tag{1}$$

and define

$$X_k^* := X_{\tau_k^*} = \frac{\beta_1}{\beta_1 - 1}(r - \mu)I_k \tag{2}$$

with $\tau_k^* := \inf\{t \geq 0 | X_t \geq X_k^*\}$ for $k = \{i, j\}$. This is a standard result from the optimal stopping literature for the optimal real option investment threshold for a Follower in a duopoly (see Dixit and Pindyck [1994], Chapter 9).

Therefore, the expected payoff to i from adopting her preferred standard at some time t, with j Conceding at t and adopting at $\tau_j^* \geq t$ is given by

$$\begin{aligned}\pi_{i,t}^I =& \Big[\int_t^{\tau_j^*} e^{-rs} D_I X_s ds + \int_{\tau_j^*}^{\infty} e^{-rs} X_s ds - I_i \Big| \mathcal{F}_t\Big] \\ =& e^{-rt}\Big(\frac{D_I X_t}{r - \mu} - I_i\Big) + e^{-r\tau_j^*}\frac{(1 - D_I)\beta_1 I_j}{\beta_1 - 1}.\end{aligned} \tag{3}$$

Note here that j Concedes and becomes the Follower at t so that he makes his adoption decision as if he were a monopolist from that time. As such, τ_j^* denotes the optimal time for j to adopt i's preferred standard, with I_j denoting the cost to j of adopting i's standard, and so on. Moreover, as is standard in timing games of this type, we assume that once the Follower acts, the Leader loses her monopoly share of the profits and both share the market stream of payoffs (arising from the standard) between them.

On the other hand, if j adopts his preferred standard at $t \in [\tau_j, \tau_i)$, then i Concedes at t, but adopts the standard at $\tau_i^* \geq t$; in other words, she takes the role of the typical Follower. Her expected payoff from Conceding is

$$\begin{aligned}\pi_{i,t}^C =& E_t\left[\int_{\tau_i^*}^{\infty} e^{-r(s-t)} X_s ds - I_i \Big| \mathcal{F}_t\right] \\ =& e^{-r(\tau_i^* - t)}\left(\frac{X_{\tau_i^*}}{r - \mu} - I_i\right),\end{aligned} \tag{4}$$

and if she adopts her preferred standard at t and j adopts his own preferred standard at t also, the expected payoff is

$$\pi_{i,t}^B = e^{-rt}\Big(\frac{D_B X_t}{r - \mu} - I_i\Big). \tag{5}$$

Finally, we described τ_i and τ_j as the strategies (or planned times) for i and j to Insist, respectively. Therefore, one $\min(\tau_i, \tau_j)$, denoted by $\widetilde{\tau}$ is reached, the game ends. However, more particularly, we interpret them as the earliest times at which i and j are indifferent between being the Leader or Follower (i.e., unilaterally adopting her preferred standard, or conceding to her competitor). In other words,

$$\tau_k := \inf\{t \geq 0 | \pi_{k,t}^I = \pi_{k,t}^C\}. \tag{6}$$

We return to this specific example later in the paper to illustrate our findings in more detail, but the general set up in terms of payoff functions for player i is represented by Fig. 1 below.

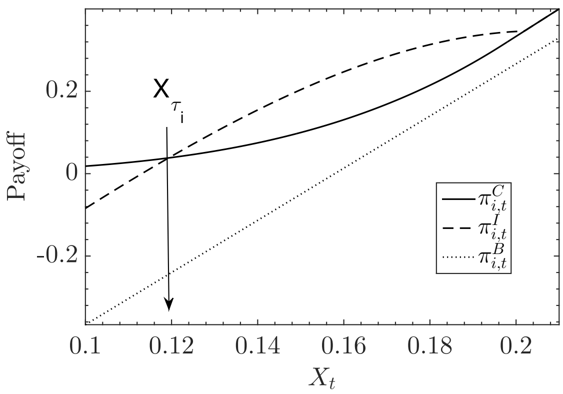

Figure 1: Payoff Functions

Lastly, it is important to point out that the geometric Brownian motion assumption is made here so that the payoff functions can be easily computed for illustrative purposes later on.[3]

To solve for the equilibria of the games described, we adopt the framework of Riedel and Steg [2017]. In Appendix A, we restate their definitions of the concepts required for understanding and solving the games.

Their approach to determining mixed strategy equilibria is that of Fudenberg and Tirole [1985] in which $G_i^\nu(t)$ is a distribution function representing the conditional probability that i has stopped before time t given that her competitor has not stopped, for the subgame starting at $\nu \in \mathcal{T}$, such that $\mathcal{T}$ is a set of pure strategy stopping times. They argue that, in continuous time, such a distribution function is insufficient to define an equilibrium strategy and, as such, $\alpha_i^\nu(t)$ is introduced as a randomisation device to replicate discrete time results that are lost when modelling in continuous time. In particular, there is no "next period" in continuous time and the randomisation device avoids situations of both trying to stop simultaneously in a dt interval when stopping unilaterally by each player is optimal, but not simultaneous stopping.

To solve for the equilibria, we must determine the probabilities of who Insists first and when that arise from a pair of extended mixed strategies (G_i^ν, α_i^ν) and (G_j^ν, α_j^ν). Let $\tau_k^\nu := \inf\{t \geq \nu : \alpha_k^\nu(t) > 0\}$ for $k = \{i, j\}$. Let $\lambda_{I,k}$ denote the probability that player k Insists first, so that the opponent Concedes, let λ_B denote the probability that both players Insist simultaneously and let λ_W denote the probability that both wait; i.e., neither Insists. These probabilities are defined in terms of G_k^ν and α_k^ν in Appendix A.

Note that the technical analysis to follow hereafter assumes asymmetric strategies of the players. However, the analysis for the symmetric strategy case proceeds along the same lines but for $\tau_i^\nu = \tau_j^\nu$ and, hence, for $\alpha_i^\nu(t) = \alpha_j^\nu(t)$. We do consider this special case within our model and, as such, the symmetric strategy solution is nested within our more general solution under these conditions.

2.2 Model Intuition and Snapshot of Key Results

Before we proceed with defining the general equilibria, to fix ideas and intuition, consider the case with only two periods: period 0 and period 1. In period 0 (the current period), there is

[3]However, our results on the economic forces driving the equilibria that emerge are generalisable to many other underlying payoff processes.

no uncertainty over the level of X; i.e., it is $X_0 = x$. However, in period 1, X_1 may be high or low; i.e., its level is unknown. The players each have a choice between adopting the standard in period 0 (Insisting) or waiting and adopting it in period 1. There are four possible scenarios at period 0, which are explained below (see also Table 1 of Section 3).

1. $\tau_i = 0$ and $\tau_j = 1$: i Insists at $\tau_i = 0$ and j Concedes. This scenario occurs with probability $\lambda_{I,i}$.

2. $\tau_i = 0$ and $\tau_j = 0$: i and j randomise over Insisting at $t = 0$.

3. $\tau_i = 1$ and $\tau_j = 0$: i Concedes and j Insists at $\tau_j = 0$ so that i adopts j's standard in period 1 with probability $\lambda_{I,j}$.

4. $\tau_i = \tau_j = 1$: Both players wait in period 0 with probability λ_W and the game is repeated.

Player i must compare these payoff values to determine what approach is optimal. If $\pi^I_{i,0} \geq \pi^C_{i,0}$, then it is optimal to Insist at period. If this holds, then $\tau_i = 0$. However, if it does not hold, then i should wait and $\tau_i = 1$. The same arguments are true for player j.

If at least one of the firms expects the demand for their device with their preferred software will be high leading to a FMA, they will be keen to adopt it quickly before the competitor adopts his (e.g., radical innovaion). Prompt adoption is key because once the competitor adopts the standard at a later date, their expected profits will decline owing to the competition in the market and, hence, the longer they have the monopoly share, the greater is their FMA. In the e-books example introduced above, Adner et al. [2020] point out that Amazon's Kindle was introduced to the market in 2007 and Apple's iPad in 2010. Therefore, for those three years, Amazon's Kindle device was the only e-reader available in the market. However, when the iPad was introduced, "Amazon cut the Kindle's price by $70 as a competitive response." In other words, before the iPad was introduced, Amazon had a FMA as the only player in the e-books market, but when the iPad was introduced, their profits declined with the competition. This is a clear example of a Market (or Bandwagon) effect and we analyse that scenario in the following subsection.

On the other hand, it could be that the idea is in the early stages, and neither firm is sufficiently convinced of a high demand so is not yet ready to adopt. Nevertheless, they still want their own preferred standard and hope to convince the competing firm to Concede and commit to adopting it. This is achieved via a SSO or committee agreement and is a classic war of attrition. With this commitment set (i.e., Leader and Follower roles agreed upon *ex ante*), then the "winner" can act as a monopolist and adopt when his expected payoff from doing so is sufficiently high (see, for example, Farrell and Simcoe [2012] who show that wars of attrition impose adoption delays when the players have vested interests). We call this scenario the Committee Case.

2.2.1 Market Case

We return to the four scenarios just described in the previous subsection and analyse them in the context of the Market Case in which one player takes the lead by unilaterally adopting their preferred standard in the hope/expectation her competitors Concede by adopting that same standard (recall, for example, Amazon's introduction of the Kindle e-Reader app which was subsequently adopted by Apple for the iPad):

1. $\tau_i = 0$ and $\tau_j = 1$ implies i Insists at $\tau_i = 0$ when $\pi^I_{i,0} = \pi^C_{i,0}$. Since $\tau_j = 1$, $\pi^I_{j,0} < \pi^C_{j,0}$ so that $\lambda_{I,j} = 0$ (since $\lambda_{I,j}$ represents the probability of j insisting.) It further implies that $\lambda_B = 0$ since both players will not Insist simultaneously. Now, i will insist for sure at

$t = 0$ so that $\lambda_{I,i} = 1$ and $\lambda_W = 0$. As such, in this scenario, the payoff to player i is given by $V_{i,0} = \pi^I_{i,0} = \pi^C_{i,0}$. This corresponds with Eq. (B.1) in our formal proof of Proposition 1 (cf. Appendix B).

2. $\tau_i = 0$ and $\tau_j = 0$ implies $\pi^I_{i,0} = \pi^C_{i,0}$ *and* $\pi^I_{j,0} = \pi^C_{j,0}$. This suggests that both Insist at $t = 0$ so that $\lambda_B = 1$ and $V_{i,0} = \pi^B_{i,0}$. However, since $\pi^B_{i,t} < \pi^C_{i,t}$, for all t, given that j Insists, i would achieve a higher payoff from Conceding at $t = 0$ instead. But, j will also have the same idea about Conceding. Hence, i may take the risk of Insisting because j may Concede by this argument. Therefore, there is a randomisation between the players over Insisting. In equilibrium, i should Insist with a probability that yields the highest expected payoff.

   Let p_i denote the probability that i Insists at period 0. This differs from $\lambda_{I,i}$ given the above because the latter corresponds with i being the only one to insist. In essence $\lambda_{I,i}$ is captured here by $\frac{p_i(1-p_j)}{p_i+p_j-p_ip_j}$ (cf. Riedel and Steg [2017] and Eq. (A.6) in Appendix A). Therefore, for this example, the expected payoff to i will be

$$\begin{aligned} V_{i,0} =& \lambda_{i,I}\pi^I_{i,0} + \lambda_{j,I}\pi^C_{i,0} + \lambda_B \pi^B_{i,0} \\ =& \frac{p_i(1-p_j)}{p_i+p_j-p_ip_j}\pi^I_{i,0} + \frac{p_j(1-p_i)}{p_i+p_j-p_ip_j}\pi^C_{i,0} + \frac{p_ip_j}{p_i+p_j-p_ip_j}\pi^B_{i,0}. \end{aligned}$$

   Maximising this expression with respect to p_i gives

$$p^*_j = \frac{\pi^I_{i,0} - \pi^C_{i,0}}{\pi^I_{i,0} - \pi^B_{i,0}}. \tag{7}$$

   This probability corresponds to α^ν_j given by Eq. (B.4). Replacing for p^*_j in $V_{i,0}$ gives

$$V_{i,0} = \pi^C_{i,0}.$$

3. $\tau_i = 1$ and $\tau_j = 0$ implies j Insists at $\tau_j = 0$ and i Concedes. Thus, $\lambda_{I,j} = 1$, $\lambda_{I,i} = 0$, $\lambda_W = \lambda_B = 0$. As such, $V_{i,0} = \pi^C_{i,0}$. This corresponds with Eq. (B.2) in Appendix B.

4. $\tau_i = 1$ and $\tau_j = 1$ implies neither Insist at $t = 0$ since $\pi^I_{k,t} < \pi^C_{k,t}$ for $k = \{i, j\}$ and the game is repeated .

Let $\widetilde{\tau} := \min(\tau_i, \tau_j)$. Then, from the above analysis, the equilibrium expected value to i for the market (preemption) game is given by

$$V^M_{i,0} = \pi^C_{i,0}\mathbb{1}_{\widetilde{\tau}=0}. \tag{8}$$

A coordinated outcome is one such that one, and only one, player plays Insist. In Scenario 4, there is no outcome, so we do not consider it. However, it is clear from the above discussion that a coordinated outcome is achieved at $t = 0$ in Scenarios 1 and 3. In Scenario 2, when both randomise over playing Insist, coordination will be achieved if, and only if, only one of the players Insist. This idea is represented by Eq. (13) in the formal analysis presented below, in which $P(i, 1)$ and $P(j, 1)$ denote respective probabilities of i or j being the only one to Insist.

2.2.2 Committee Case

The preceding analysis gave an informal description of the problem under the Market Case to explain some of the intuition underlying the more technically complicated results to follow in Section 3. We continue in this vein for the Committee Case in this subsection.

Let τ_k^* denote the optimal time for player k to adopt his preferred standard (Insist) *if he were the only player in the market.* It is well known from the literature on timing games that when there is a competitor and a FMA, there is a preemptive pressure to be the first to stop. We have defined this preemption time as $\tau_k = \inf\{t \geq 0 | \pi^I_{k,t} = \pi^C_{k,t}\}$. In the two period Market Case, we implicitly assume that $\tau_k < \tau_k^*$ so that, for example, if $\tau_k = 0$, $\tau_k^* = 1$. This means that if there was no competitive pressure for k, he would adopt at time $\tau_k^* = 1$ because this strategy would maximise his payoff from doing so. However, there is a payoff advantage to being the first mover and, as such, it is better for him to adopt earlier (i.e., at time $\tau_k = 0$) to avail of this and obtain monopoly share of the market for some time before his competitor adopts.

Recall the example above of two firms A and B wanting to adopt a new standard that is in the early stages (i.e., a new software feature for their devices). If there was no competitive pressure, k would adopt at time τ_k^*. However, the potential entry of future competitors in the market reduces the upper end of payoff distribution (see Dixit and Pindyck [1994]). Moreover, given the early stage, payoff uncertainty is high and the sunk cost of adoption cannot be recouped. Hence, even if $t \geq \tau_k^*$, the potential cap on its future profits by the adoption of the software by the competing firm means that he would rather not adopt yet but to wait until the expected payoff level is higher. The implication of this is that there is value in waiting; i.e., the players are not concerned about being preempted by their competitor and are not duelling over the Leader role (i.e., akin to incremental rather than radical innovators). Furthermore, given that negotiation within a committee is associated with substantial delays in adoption (cf. Simcoe [2012]), it is reasonable to assert that the players do not have a preemptive pressure to adopt (i.e., play Insist), but want to convince their competitors to commit adopting to their standard in the future. As such, the Committee Case is represented by a war of attrition game[4] and $\tau_k^* < \tau_k$ (see, for example, Thijssen et al. [2006]).

To give a heuristic argument, consider a two period example such that $\tau_i^* = 0$ and $\tau_i = 1$. At $t = 0$, i would adopt if she were a monopolist, but because of the potential of future entry by her competitor which reduces the potential upside of her future payoff, she would prefer to wait until $t = 1$, but having convinced her competitor to commit to her standard. However, j is of a similar mind. He too wants to wait until $t = 1$, but wants to convince i to commit at $t = 0$ to adopting his preferred standard. As such, there will be a randomisation over adopting at $t = 0$.

Let θ be the probability that j Concedes and commits to i's choice of standard at $t = 0$. In a war of attrition situation, each player wants the other player to commit at a particular time, but not adopt until some time later. Thus, if j Concedes at $t = 0$, i adopts (plays Insist) at $t = 1$.

The expected value to i of not conceding at $t = 0$ is

$$V^{NC}_{i,0} = \theta \pi^I_{i,1} + (1 - \theta) V_{i,1},$$

and if i Concedes at $\tau_i^* = 0$, her expected value is equal to

$$V^C_{i,0} = \pi^C_{i,0}.$$

In equilibrium, it must be such that player i is indifferent between not conceding or conceding at $\tau_i^* = 0$ (cf. Fudenberg and Tirole [1991]); i.e., θ must be such that $V^C_{i,0} = V^{NC}_{i,0}$. Thus,

$$\theta^* = \frac{\pi^C_{i,0} - V_{i,1}}{\pi^I_{i,1} - V_{i,1}}, \tag{9}$$

where $V_{i,1}$ denotes i's expected value at $t = 1$.

[4] See also Farrell and Saloner [1988]

Let $\gamma_{i,0}$ denote the probability that i Concedes at $t = 0$. Then, the expected value to i at $t = 0$ is given by

$$V_{i,0} = \gamma_{i,0} V_{i,0}^{C} + (1 - \gamma_{i,0}) V_{i,0}^{NC}.$$

In equilibrium, when $\theta = \theta^*$, her expected value during the war of attrition (woa) is

$$V_{i,0}^{woa} = V_{i,0}^{NC} = \pi_{i,0}^{C},$$

which implies that the equilibrium expected value to i during the war of attrition is equivalent to her equilibrium expected value at the earliest time one of the players unilaterally adopts and the game becomes one of preemption (Market Case) (see Eq. (8)).

This is a main result of our paper and may explain why the question over which approach performs better has not been fully answered (cf. Simcoe [2012]). By considering the problem as an option timing game, we examine it from a more sequential dynamic perspective which shows that in equilibrium, the expected payoff at some point in the Committee Case is equivalent to her expected payoff at the preemption point; i.e., when she enters the market region by obtaining a FMA. We discuss this in further detail later in Section 3.

Figure 2 below depicts the argument graphically for the $\tau_i^* = 0$ and $\tau_i = 1$ example. In the top left plot, $\pi_{i,0}^{I} < \pi_{i,0}^{C}$ implying the expected payoff from Conceding is actually higher than the expected payoff from insisting at $t = 0$. In the top right plot, the equilibrium probability θ^* of j Conceding is shown as increasing over time. The bottom left plot depicts the equilibrium situation for a particular θ^*; namely $\theta^* = 0.2$. At this value of θ^*, $x \approx 0.11$ (see top right figure) and we see that in the bottom figure, the expected payoffs from waiting and Insisting at $x \approx 0.11$ coincide.

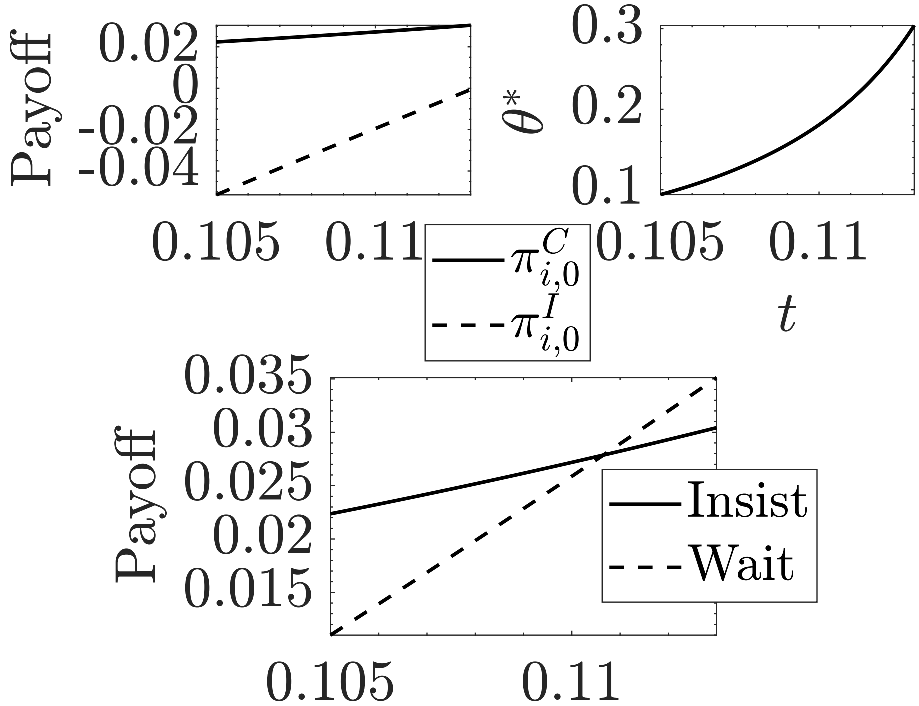

Figure 2: A graphical illustration of the attrition scenario

In the more formal analysis, we model strategies more generally as distribution functions over time such that θ^* is actually a hazard (or attrition) rate given by Eq. (15).

3 Equilibria of the Games

3.1 Market Case

Suppose that the battle of the sexes style game depicted in Table 1 below is to be played until at least one of the players play Insist and adopt their preferred standard unilaterally. This happens at $\widetilde{\tau} = \min(\tau_i, \tau_j)$. We refer to hereafter as the Market Case.

		Player j	
		INSIST	CONCEDE
	INSIST	$(\pi^B_{i,t}, \pi^B_{j,t})$	$(\pi^I_{i,t}, \pi^C_{j,t})$
Player i	CONCEDE	$(\pi^C_{i,t}, \pi^I_{j,t})$	Repeat game

Table 1: **Market Case**

We analyse this situation as a preemption game in which there is an advantage to being the first mover so that neither player wants to be preempted by their competitor. Therefore, define $\tau^\nu_k := \inf\{t \geq \nu : \alpha^\nu_k(t) > 0\} = \inf\{t \geq \nu : \pi^I_{t,k} - \pi^C_{t,k} = 0\}$, for $k = \{i, j\}$. Preemption further implies that $\tau^\nu_k < \tau^*_k$ for $k \in \{i, j\}$, where τ^*_k is the optimal time for k to adopt if not faced with preemptive pressure from a competitor. For an intuitive and simplified exposition of the the following results and discussion, see Section 2.2.1.

Proposition 1. (**Market**) *Assume that for player i, $\pi^I_{i,t} \geq \pi^C_{i,t} > \pi^B_{i,t}$ for all $t \geq \tau^\nu_i$, where $\tau^\nu_i := \inf\{t \geq \nu | \alpha^\nu_i(t) > 0\} = \inf\{t \geq \nu | \pi^I_{i,t} - \pi^C_{i,t} = 0\}$. Moreover, assume that $\widetilde{\tau} \leq \min(\tau^*_i, \tau^*_j)$.*

The pair of strategies $(G^\nu_i(t), \alpha^\nu_i(t))$, for any $t \in [\nu, \infty)$, are given by

$$G^\nu_i(t) = \mathbb{1}_{t \geq \tau^\nu_i} \tag{10}$$

and

$$\alpha^\nu_i(t) = \begin{cases} 0 & \text{if } t < \tau^\nu_i \\ 1 & \text{if } \tau^\nu_i < t < \tau^\nu_j \\ \frac{\pi^I_{j,t} - \pi^C_{j,t}}{\pi^I_{j,t} - \pi^B_{j,t}} & \text{if } \max(\tau^\nu_i, \tau^\nu_j) \leq t \end{cases} \tag{11}$$

constitute a subgame perfect equilibrium with expected payoff to player i at time t given by

$$V^M_{i,t} = \pi^C_{i,t} \left(\mathbb{1}_{t \geq \max(\tau^\nu_i, \tau^\nu_j)} + \mathbb{1}_{\tau^\nu_j \leq t < \tau^\nu_i} \right) + \pi^I_{i,t} \mathbb{1}_{\tau^\nu_i \leq t < \tau^\nu_j}, \tag{12}$$

where $\mathbb{1}_x = 1$ if x is true, otherwise $\mathbb{1}_x = 0$.

Proof. See Appendix B. ■

We call an outcome coordinated if both firms have not gone their own way by adopting their own preferred standards. Otherwise, the outcome is uncoordinated. The benefits of coordination in the context of our paper has been discussed previously.

Corollary 1. (**Market**) *The probability of coordination at time t is given by*

$$P(Coordination^M_t) = \mathbb{1}_{\min(\tau^\nu_i, \tau^\nu_j) \leq t < \max(\tau^\nu_i, \tau^\nu_j)} + (P(i, 1) + P(j, 1)) \mathbb{1}_{t \geq \max(\tau^\nu_i, \tau^\nu_j)}, \tag{13}$$

where $P(k,1)$ is given by Eq. (A.6) for $k = \{i,j\}$. Hence

$$
\begin{aligned}
P(i,1)+P(j,1) =& \frac{\alpha_i^\nu(t)+\alpha_j^\nu(t)-2\alpha_i^\nu(t)\alpha_j^\nu(t)}{\alpha_i^\nu(t)+\alpha_j^\nu(t)-\alpha_i^\nu(t)\alpha_j^\nu(t)} \\
=& \frac{\alpha_i^\nu(t)\left(\pi_{i,t}^I-\pi_{i,t}^B\right)+(1-2\alpha_i^\nu(t))\left(\pi_{i,t}^I-\pi_{i,t}^C\right)}{\alpha_i^\nu(t)\left(\pi_{i,t}^I-\pi_{i,t}^B\right)+(1-\alpha_i^\nu(t))\left(\pi_{i,t}^I-\pi_{i,t}^C\right)} \\
=& 1-\frac{(\pi_{j,t}^I-\pi_{j,t}^C)\left(\pi_{i,t}^I-\pi_{i,t}^C\right)}{\left(\pi_{j,t}^I-\pi_{j,t}^C\right)\left(\pi_{i,t}^I-\pi_{i,t}^B\right)+(\pi_{j,t}^C-\pi_{j,t}^B)\left(\pi_{i,t}^I-\pi_{i,t}^C\right)}
\end{aligned}
\tag{14}
$$

A coordinated outcome is an outcome such that one, and only one, player plays Insist. This arises with certainty if one, and only one player, has a FMA from Insisting. However, if both players have a FMA, the outcome may not be coordinated since both players play Insist with some positive probability.

The left hand plot of Fig. 3 below, depicts the payoffs to both the Insister and the Conceder when the outcome is coordinated, whereas the right hand plot depicts the same for an uncoordinated outcome.

In the left hand plot, $X_{\tau_i^\nu} \approx 0.12$ and this is the value of X_t at which i is indifferent between insisting and conceding (Leader or Follower). From the plot it is also the case that $X_{\tau_j^\nu} \approx 0.14$. As such, $\tau_i^\nu < \tau_j^\nu$ in this example and, hence, i becomes the Insister at τ_i^ν and gets payoff $\pi_{i,t}^I$ for all $t \geq \tau_i^\nu$ (solid line) and j becomes Conceder at τ_i^ν and gets payoff $\pi_{j,t}^C$ for all $t \geq \tau_i^\nu$ (dashed line). Prior to τ_i^ν; i.e., for $X_t < X_{\tau_i^\nu}$, it is not optimal for either player to Insist. Once i adopts at τ_i^ν, j Concedes to adopt i's preferred standard. As such, his payoff drops to the Conceder payoff of standard i. This is depicted by the dashed line in the plot. He will wait until τ_j^* to adopt the standard, where $X_j^* \approx 0.2$ and, at that stage, the payoffs to both i and j coincide.

The right hand plot depicts an example of an uncoordinated outcome. Both i and j Insist at the same time when $X_{\tau_i^\nu} = X_{\tau_j^\nu}$. In this sense, both go their own way and each gets payoff $\pi_{k,t}^B$ for $k = \{i,j\}$ and $t \geq \tau_k^\nu$. The dotted line in the figure depicts the payoff j would get if he instead Conceded and, it is clear, that he would have been better off doing this. Indeed, if i were to Insist and j were to Concede, the payoffs to both are depicted in the left hand plot and, as we can see from the values on the vertical axes, both are definitely better off if they coordinate. An example of an uncoordinated outcome is that one of the firms adopts its own unique standards which are incompatible with the other firm's products or services.

A coordinated outcome is only achieved with certainty if only one player has a FMA from adopting unilaterally. Otherwise, the outcome is coordinated with probability $P(i,1)+P(j,1)$, which is the probability that only i plays Insist *or* only j plays Insist. From Eq. (14), it is clear that the probability of coordination is low when the FMA of both players ($|\pi_{i,t}^I - \pi_{i,t}^C|$ and $|\pi_{j,t}^I - \pi_{j,t}^C|$) is high, which is intuitive and provides support for the empirical observation that a number of leading radical innovators opt to go their own way and adopt their own preferred standard rather than coordinating with their competitors (e.g., see Foucart and Li [2021]; Lieberman and Montgomery [1988]).

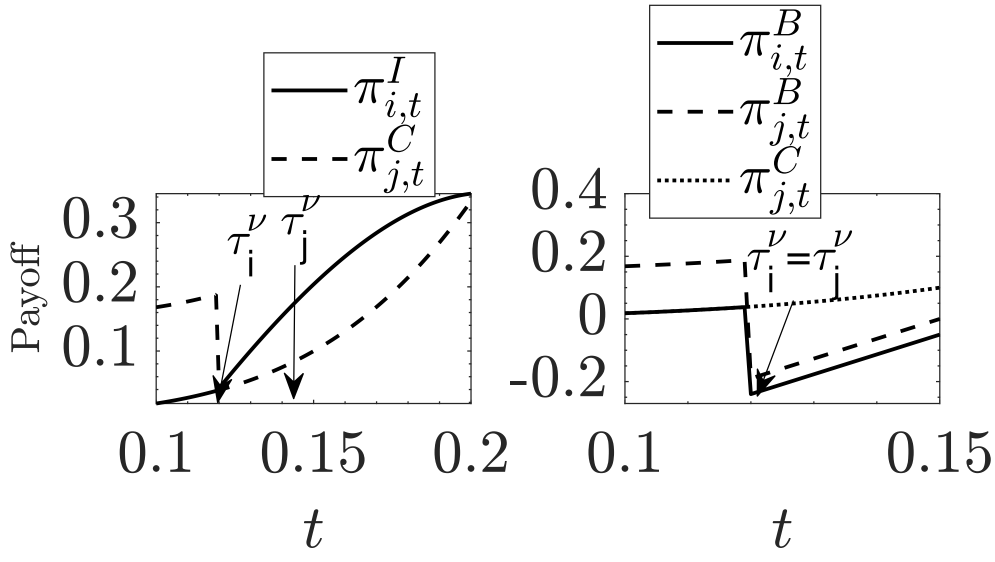

Figure 3: Market Case Example for Coordinated versus Uncoordinated Outcomes.

3.2 Committee Case

In this subsection, we consider a game within a SSO where there is conflict. We call this the Committee Case and, since unilateral adoption does not arise while the game is still in play (i.e., during the negotiation), it is therefore the case that there is no FMA for any of the players in the committee; i.e., $\pi^C_{k,t} > \pi^I_{k,t}$ implying $t < \widetilde{\tau} := \min(\tau^\nu_i, \tau^\nu_j)$. This further implies that since τ^ν_k has been defined above as $\tau^\nu_k := \inf\{t \geq \nu | \alpha^\nu_k(t) > 0\}$, then $\alpha^\nu_k(t) = 0$ for all $t < \widetilde{\tau}$ and $k = \{i, j\}$.

The payoff from Conceding in this region is higher than the payoff from Insisting. However, for each player, the cost of Conceding to her opponent is the giving up on her preferred standard and, thus, the expected payoff from being the market leader in that. A player is willing to bear that cost if there is a chance her competitor will Concede. The chance is only reasonable if the opponent is also arguing for their standard. Thus, it is reasonable to assume that $t \geq \tau^*_k$ for $k = \{i, j\}$; in other words, for each player, he would adopt the standard at t if he were a monopolist, but owing to the potential adoption of the standard by his competitor at a later date, the upside potential of his future expected payoff is lower than in the monopoly case. To compensate for this, he does not want to adopt until he will have at least a FMA. Thus, the committee region in our model is defined by $t \in [\max(\tau^*_i, \tau^*_j), \widetilde{\tau})$ (see Fig. 4).

When $\widetilde{\tau}$ is reached, the game ends and at least one of the players unilaterally adopts. In real option timing games, our committee region is typically analysed as a war of attrition in which each of the players have a second mover advantage and both want their competitor to stop first (akin to playing Insist in our framework) so they can avail of an information spillover (see, for example, Thijssen et al. [2006]). In other words, there is a war of attrition over who stops first. However, in our problem, in the SSO the players are trying to convince their opponents to Concede and not adopt as they still want to adopt their preferred standard. If they convince their opponent to Concede, then the roles of the Leader and Follower are effectively predetermined at that point and the Leader can wait until τ^ν_i when her expected payoff from adoption is higher. It is still a war of attrition in which the goal for each player is to have their

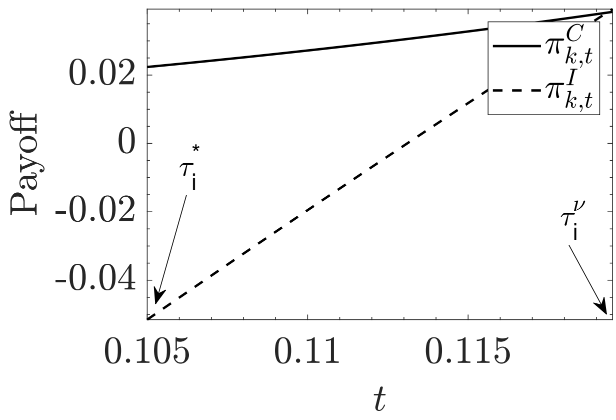

Figure 4: Committee Region for player i

opponent 'drop out', where "dropping out" is by Conceding before the player Insists (i.e., before he unilaterally adopts). Therefore, the probability of insistence by each player in t is zero; i.e., $G_k^\nu(t) = 0$ for $k = \{i, j\}$ and $t \in [\max(\tau_i^*, \tau_j^*), \widetilde{\tau})$.

If i is convinced to Concede first at t, then her expected payoff is just $\pi^C_{i,t}$. However, if j Concedes first, then i can wait until τ_i^ν to adopt and, thus, her expected payoff is π^I_{i,τ_i^ν}. But since $\pi^I_{i,\tau_i^\nu} = \pi^C_{\tau_i^\nu}$ by the definition of τ_i^ν, her expected payoff from j Conceding first is equal to her expected payoff from Conceding at τ_i^ν; i.e., π^C_{i,τ_i^ν}.

The game that is played is depicted in Table 2.

		Player j	
		Do not concede	Concede
	Do not concede	Repeat game	$(\pi^C_{i,\tau_i^\nu}, \pi^C_{j,t})$
Player i	Concede	$(\pi^C_{i,t}, \pi^C_{j,\tau_j^\nu})$	Repeat game

Table 2: **Committee Case**

To solve for the mixed strategy equilibria we introduce a distribution function $H_i^\nu(t)$ representing the conditional probability that i Concedes before time t given that her competitor has not Conceded, for the subgame starting at $\nu \in \mathcal{T}$ for which $\mathcal{T}$ is a set of pure strategy stopping times. It is an adapted and right continuous function with $H_i^\nu(t) = 0$ for $t < \nu$. In the market case above, we introduced a randomisation probability denoted by $\alpha_i^\nu(t)$ to allow for situations in which insistence by at least one player is certain, but simultaneous insistence is not. In our attrition region $t \in [\max(\tau_i^*, \tau_j^*), \widetilde{\tau})$, concession by at least one firm is not certain; i.e., $H_k^\nu(t) < 1$ and, hence, we do not require a randomisation device of this sort.

Proposition 2. (Committee) *Let $t \in [\max(\tau_i^*, \tau_j^*), \widetilde{\tau})$, such that $\widetilde{\tau} = \min(\tau_i^\nu, \tau_j^\nu)$. The strategy $H_i^\nu(t)$ for any $t \in [\nu, \infty]$ constituting a subgame perfect equilibrium is defined by*

$$\frac{dH_i^\nu(t)}{1 - H_i^\nu(t)} = -\frac{E_t[d\pi^C_{j,t}]}{\pi^C_{j,\tau_i^\nu} - E_t[\pi^C_{j,t+dt}]} \tag{15}$$

and the equilibrium expected payoff for all t in the attrition region is given by

$$V_{i,t}^{woa} = \pi^C_{i,t} = e^{-r(\tau_i^\nu - t)} \pi^C_{i,\tau_i^\nu}. \tag{16}$$

Proof. See Appendix C. ■

The cost to a player from not Conceding at a particular t is represented by the drift of $\pi^C_{i,t}$ (i.e., $E_t[d\pi^C_{i,t}]$)[5]. A player will only bear this cost if there is a chance her competitor will Concede in the $[t, t+dt)$ interval. Her compensation for waiting is represented by $\pi^C_{i,\tau^\nu_i} - E_t[\pi^C_{i,t+dt}]$. In equilibrium, the compensation for the cost of waiting makes them entirely indifferent between Conceding and not. Conceding at the rate described by (15) ensures such indifference. As such, her expected equilibrium payoff is just the expected payoff from immediate concession.

A coordinated outcome is achieved in the attrition region if one of the players Concede. This leads to the following proposition.

Corollary 2. (Committee) *The probability of a coordinated outcome at any time* $t \in [\max(\tau^*_i, \tau^*_j), \widetilde{\tau})$ *(the attrition region), is given by*

$$P(Coordination^C_t) = H^\nu_i(t) + H^\nu_j(t). \tag{17}$$

To analyse this probability of coordination, it is sufficient to consider the probability θ^* given by (9), rather than the distribution functions defined as attrition rates. The probability of coordination is equivalent to the probability that one of the players plays Concede and this increases in the likelihood of $\widetilde{\tau}$ being reached; i.e., that at least one of the players has a FMA (see also Fig. 2). This, in turn, is true if, for at least one player, the expected benefit from playing Concede over Insist is low and this will force the other player to "drop out"; i.e., to Concede (attrition rates are defined in terms of the competitor's expected payoffs). Intuitively, this likely to be true in a SSO negotiation if one of the players is nearing the stage of having a FMA from adopting unilaterally and so will be more compelled to work harder at convincing her competitors to Concede.

4 Comparison of the Mechanisms in Equilibrium

Before proceeding, we summarise the story for player i in Fig. 5 below. The diagonal solid line depicts cases in which $\pi^I_{i,t} = \pi^C_{i,t}$; i.e., when $t = \tau^\nu_i$. For all $t > \tau^\nu_i$, $\pi^I_{i,t} > \pi^C_{i,t}$ and the Market game of unilaterally playing Insist is optimal. This is depicted by the red shaded region.

The dashed line is the point at which $\pi^I_{i,t} = (\pi^I_i)^*$, in other words, when $t = \tau^*_i$. Below the solid line, when $\pi^I_{i,t} < \pi^C_{i,t}$ for all t, $\tau^*_i < \tau^\nu_i$ for some values of $\pi^C_{i,t}$ ($\pi^C_{i,t} > 0.4$ in this example) ($\tau^*_i < \tau^\nu_i$ when the dashed line is below the solid line). For those values, once τ^*_i is hit, or equivalently, when $\pi^I_{i,t}$ reaches $(\pi^I_i)^*$, i will play the Committee game (war of attrition) until τ^ν_i. This is depicted by the blue region in the plot. The white region is the Continuation region when no play is optimal.

We now address the question of which mechanism (negotiation via SSO or unilateral adoption) is best (Simcoe [2012]) or when one mechanism should dominate and be adhered to (Fichman [2004]; Blind et al. [2023]). This can be interpreted as (i) which yields the highest payoff, (ii) which is more likely to achieve coordination, or (iii) when a player should take the lead in unilaterally adopting his preferred standard.

The last question (iii) is posed by Fichman [2004] (regarding new technology adoption) and Blind et al. [2023] and we show that he should take the lead and unilaterally adopt his preferred standard as soon as he has a FMA in terms of expected payoffs.

[5]This can be calculated as $r\pi^C_{j,t}$ by applying Ito's formula to (4)

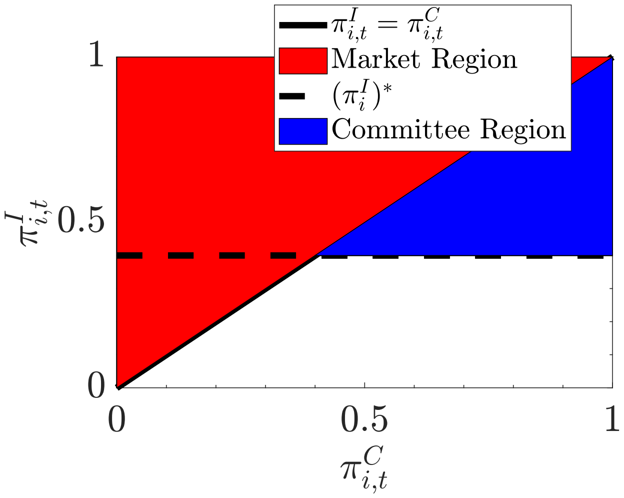

Figure 5: Market and Committee Regions for player i.

Regarding mechanism performance, negotiation via a SSO is only realistic if none of the participants have an expected FMA from adopting their preferred standard in terms of expected payoffs. As soon as one of them does have such payoffs, then she will unilaterally adopt immediately and the game ends; in other words, the game becomes a preemption game and the Market effect ensues. Since SSOs and Market (preemption) games are optimal for different relative payoffs, comparing their performance in terms of expected payoffs is not useful; at any time, either negotiation via an SSO is optimal *or* it is optimal for one player to unilaterally adopt and the others follow her lead. Nevertheless, we show that in equilibrium, the expected payoff from being in a SSO is given by her expected payoff from immediate concession which is equivalent to her (discounted) expected payoff from adopting as the conceder (i.e., adopting her competitor's choice of standard) at the later time of τ_i^ν.

If a participant in the SSO presently unilaterally adopts her preferred standard, then $\widetilde{\tau}$ will have been reached, and we see from Eq. (12) that the equilibrium expected payoff in the market case at $\widetilde{\tau}$ is also the expected payoff from immediate concession, even for the player who unilaterally adopts (plays Insist) at that time. Note that the scenario of $t \in (\widetilde{\tau}, \max(\tau_i^\nu, \tau_j^\nu))$ yielding the equilibrium payoff $\pi^I_{i,t}$ is stated in the proposition for generalisation purposes, but unilateral adoption in the context of our standardisation story tends to happen after discussion within a SSO. This rules out, in the context of conflict over compatibility standard adoption that we consider, the likelihood of a state of $t > \widetilde{\tau}$ without anyone having unilaterally adopted. This implies that the equilibrium expected payoff in the Market Case and the Committee (SSO) cases are equivalent and correspond with the expected payoff from Conceding at $\widetilde{\tau}$.

This result is key for the following reason. Simcoe [2012] points out that a large normative question in the field is about which mechanism performs better, but there is no complete answer. This is point is echoed in more recent review by Blind et al. [2023]. Our result may explain why. In particular, because we consider the problem as a real option timing game, which approach should be taken at any specific point in time to maximise the expected payoff from adopting depends on the state of payoffs at that time. Moreover, we show that in equilibrium, the expected payoff in the SSO is equivalent to her expected payoff at the time the Market effect will ensue.

Finally, regarding the performance of the two mechanisms with respect to coordination, an uncoordinated outcome is only possible in the Market Case if both players have a FMA at the same time. In the SSO, an uncoordinated outcome is ruled out since the players will not play

Insist simultaneously. However, this does not necessarily imply that the SSO performs better than the Market with respect to coordination. This is because a comparison in this context is only economically meaningful if it were to direct the players to adopt under a particular mechanism and this direction only has significance if a player could have a FMA and a higher expected payoff from concession *at the same time*, which is not possible. As such, by accounting for the dynamic aspect of the players' payoffs, we show that comparing the mechanisms under the likelihood a coordinated outcome will be achieved is economically insignificant because this likelihood depends on the players' expected payoffs from playing Insist or Concede.

5 Conclusion

In this paper, we consider the adoption of compatibility standards as a real option timing game with asymmetric strategies over players' stopping times and uncertain expected payoffs. In particular, we analyse two different mechanisms for the adoption of such standards to answer the question posed in the literature about which performs better; one in which coordination is achieved by the market without explicit collaboration and one in which it is achieved via negotiation through a SSO. The two mechanisms correspond with preemption and war of attrition games, respectively (or radical versus incremental innovations).

We find a number of novel economic implications relative to prior studies which investigated a similar question pertaining to the adoption of standards. Importantly, we find the Market effect of one player unilaterally adopting her preferred standard will only arise in equilibrium when she obtains a first mover advantage from doing so in terms of her expected payoffs and none of the other players has a FMA. When none of the players have such a FMA, there is negotiation within a SSO. It cannot be the case that players with a FMA will argue for their preferred standard in a SSO *or* that participants arguing for their preferred standard in a SSO but without a FMA will unilaterally adopt.

The relevance of our result is the following. We show that by modelling the problem as an option timing game with asymmetric strategies (the symmetric case is nested within our model as a special case) and uncertain expected payoffs from adoption, the different mechanisms are optimal under different expected payoff levels. Hence, the difficulty in answering questions over whether committees outperform markets (and vice versa), and hence when to unilaterally proceed with adoption or wait to achieve compatibility, is explained by our result that in equilibrium, at any time t, it will be optimal for one approach *or* the other, and will depend on the state of the payoffs for each player at that time.

We further show that, in equilibrium, the expected payoff to a player at any time during the negotiation phase is equivalent to her expected payoff at the earliest time at which she or one of her competitors has a FMA; i.e., when the Market mechanism becomes optimal over the SSO.

Finally, an uncoordinated outcome is only possible if more than one player has a FMA at the same time. This can never arise during the negotiation phase. Nevertheless, one should not conclude that the SSO outperforms the Market from a coordination perspective because a comparison in this context is not economically meaningful. This is because at any given time, the probability of an uncoordinated outcome depends on the players' expected payoffs from adoption via Insist or Concede (i.e., of their or their competitor's standard) which, in turn, determines whether a standard should be adopted unilaterally or via negotiation.

The takeaway from our analysis should be that if the answer to the question over which mechanism performs better is desirable as a means to direct policy or how future agents show go about adopting a standard, then it cannot be given definitively. It depends on the state of expected payoffs at a particular point. That said, in terms of expected payoffs, their equilibrium performances are equivalent.

Appendix

A The Timing Game Framework

In this section, we restate the Riedel and Steg [2017] definitions of the concepts required for understanding and solving the games.

Definition 1. (Reidel and Steg): A timing game Γ is a tuple $((\Omega, \mathcal{F}, (\mathcal{F}_t)_{t\geq 0}, P), \mathcal{T} \times \mathcal{T}, (\pi_i^I, \pi^C{}_{,i}, \pi_i^B)_{i=\{1,2\}}, (\pi_i)_{i=\{1,2\}})$ consisting of a filtered probability space $(\Omega, \mathcal{F}, (\mathcal{F}_t)_{t\geq 0}, P)$, stopping times $\mathcal{T}$ as pure strategies, adapted and right continuous processes $(\pi_i^I, \pi_i^C, \pi_i^B)_{i=\{1,2\}}$ and the expected present value of payoffs are given by

$$E^0[\pi_i(\tau_i, \tau_j)] = E[e^{-r\tau_i}\pi^I_{i,\tau_i}\mathbb{1}_{\tau_i<\tau_j} + e^{-r\tau_j}\pi^C_{i,\tau_j}\mathbb{1}_{\tau_j<\tau_i} + e^{-r\tau}\pi^B_{i,\tau_i}\mathbb{1}_{\tau_i=\tau_j=\tau}]. \tag{A.1}$$

Definition 2. (Reidel and Steg): Fix a stopping time $\nu \in \mathcal{T}$. An *extended mixed strategy* for player i for the subgame Γ^ν, starting at ν, is a pair of processes (G_i^ν, α_i^ν) taking values in $[0, 1]$, respectively, with the following properties:

1. G_i^ν is adapted, right continuous and non decreasing. It satisfied $G_i^\nu(s) = 0$ for $s < \nu$.
2. α_i^ν is progressively measurable. It is a.s. right continuous in $\mathbb{R}_+$ for which $\alpha_i^\nu(t) \in (0, 1)$ and $\alpha_i^\nu(s) = 0$ for all $s < \nu$.
3. $\alpha_i^\nu(t) > 0 \Longrightarrow G_i^\nu(t) = 1$ for all $t \geq 0$ a.s.

Definition 3. (Reidel and Steg): A time consistent extended mixed strategy for player k for $k = \{i, j\}$ for the timing game Γ is a family of strategies $(G_k^\nu, \alpha_k^\nu)_{\nu\in\mathcal{T}}$, such that for all ν, ν', τ in $\mathcal{T}$, with $\nu \leq \nu' \leq \tau$,

$$G_k^\nu(t) = G_k^\nu(\nu'-) + (1 - G_k^\nu(\nu'-))G_k^{\nu'}(t)$$

and

$$\alpha_k^\nu(\tau) = \alpha_k^{\nu'}(\tau)$$

for $t \geq \nu'$ a.s.

Definition 4. (Reidel and Steg): A subgame perfect equilibrium for the timing game is a pair $(G_k^\nu, \alpha_k^\nu)_{k=\{1,2\}}$ of time consistent extended mixed strategies such that for all $\nu \in \mathcal{T}$, $i \neq j$, and an extended mixed strategy (G_a^ν, α_a^ν), then a.s.

$$V_i(G_i^\nu, \alpha_i^\nu, G_j^\nu, \alpha_j^\nu) \geq V_i(G_a^\nu, \alpha_a^\nu, G_j^\nu, \alpha_j^\nu).$$

The probabilities of who Insists first and when are defined as follows:

1. If $\tau_i^\nu < \tau_j^\nu$, then at τ_i^ν, $\alpha_i^\nu(\tau_i^\nu) > 0$ (so that $G_i^\nu(\tau_i^\nu) = 1$) and $\alpha_j^\nu(\tau_i^\nu) = 0$ so that the conditional probability that j will Insist at τ_i^ν is given by $\Delta G_j^\nu(\tau_i^\nu)/(1 - G_j^\nu(\tau_i^\nu-))$ (Riedel and Steg [2017]), such that $\Delta G_k^\nu(t) := G_k^\nu(t) - G_k^\nu(t-)$. Thus, $\Delta G_i^\nu(\tau_i^\nu) = 1 - G_i^\nu(\tau_i^\nu-)$.

- $$\begin{aligned}\lambda_{I,i} =&(1-G_i^\nu(\tau_i^\nu-))(1-G_j^\nu(\tau_i^\nu-)) * P(\text{i Insists at } \tau_i^\nu) * P(\text{j Concedes at } \tau_i^\nu)\\ =&\Delta G_i^\nu(\tau_i^\nu)(1-G_j^\nu(\tau_i^\nu-))\alpha_i^\nu(\tau_i^\nu)\left(1-\frac{\Delta G_j^\nu(\tau_i^\nu)}{1-G_j^\nu(\tau_i^\nu-)}\right)\\ =&\Delta G_i^\nu(\tau_i^\nu)(1-G_j^\nu(\tau_i^\nu)).\end{aligned} \tag{A.2}$$

  Since $G_i^\nu(\tau_i^\nu)=1$, a move will occur at τ_i^ν with certainty. Since j Concedes in this case, then i Insists with certainty. Therefore, $\alpha_i^\nu(\tau_i^\nu)=1$.

- $$\begin{aligned}\lambda_{I,j} =&(1-G_i^\nu(\tau_i^\nu-))(1-G_j^\nu(\tau_i^\nu-)) * P(\text{i Concedes at } \tau_i^\nu) * P(\text{j Insists at } \tau_i^\nu)\\ =&(1-G_i^\nu(\tau_i^\nu-))(1-G_j^\nu(\tau_i^\nu-))(1-\alpha_i(\tau_i^\nu))\frac{\Delta G_j^\nu(\tau_i^\nu)}{1-G_j^\nu(\tau_i^\nu-)}\\ =&\Delta G_i^\nu(\tau_i^\nu)\Delta G_j^\nu(\tau_i^\nu)(1-\alpha_i(\tau_i^\nu)).\end{aligned} \tag{A.3}$$

- $$\begin{aligned}\lambda_B =&(1-G_i^\nu(\tau_i^\nu-))(1-G_j^\nu(\tau_i^\nu-))\alpha_i^\nu(\tau_i^\nu)\frac{\Delta G_j^\nu(\tau_i^\nu)}{1-G_j^\nu(\tau_i^\nu-)}\\ =&\Delta G_i^\nu(\tau_i^\nu)\Delta G_j^\nu(\tau_i^\nu)\alpha_i^\nu(\tau_i^\nu).\end{aligned} \tag{A.4}$$

- $$\lambda_W = \Delta G_i^\nu(\tau_i^\nu)(1-G_j^\nu(\tau_i^\nu))(1-\alpha_i(\tau_i^\nu)). \tag{A.5}$$

2. If $\tau_i^\nu=\tau_j^\nu=\tau^\nu$

   - If $\alpha_i^\nu(\tau^\nu), \alpha_j^\nu(\tau^\nu) > 0$, both Insist at τ^ν such that $G_k^\nu(\tau^\nu)=1$ for $k=\{i,j\}$. However, who Insists first is the question. From Thijssen et al. [2012], the probability that only one player stops and that is player i is given by

     $$P(i,1) = \frac{\alpha_i^\nu(\tau^\nu)(1-\alpha_j^\nu(\tau^\nu))}{\alpha_i^\nu(\tau^\nu)+\alpha_j^\nu(\tau^\nu)-\alpha_i^\nu(\tau^\nu)\alpha_j^\nu(\tau^\nu)} \tag{A.6}$$

     and the probability that both Insist simultaneously is given by

     $$P(i,j) = \frac{\alpha_i^\nu(\tau^\nu)\alpha_j^\nu(\tau^\nu)}{\alpha_i^\nu(\tau^\nu)+\alpha_j^\nu(\tau^\nu)-\alpha_i^\nu(\tau^\nu)\alpha_j^\nu(\tau^\nu)}. \tag{A.7}$$

     Therefore

     - $$\lambda_{I,i} = \Delta G_i^\nu(\tau^\nu)\Delta G_j^\nu(\tau^\nu)P(i,1). \tag{A.8}$$
     - $$\lambda_B = \Delta G_i^\nu(\tau^\nu)\Delta G_j^\nu(\tau^\nu)P(i,j). \tag{A.9}$$

B Proof of Proposition 1

B.1 Equilibrium Characterisation

In this case, the game depicted in Table 1 is played. Consider the following scenarios:

- Let $t < \widetilde{\tau} := \min(\tau_i^\nu, \tau_j^\nu)$. In this case, $\alpha_i^\nu(t) = \alpha_j^\nu(t) = 0$ and $G_i^\nu(t) = G_j^\nu(t) = 0$. Therefore, no player Insists at t and neither will act until some $\widetilde{\tau}$.

- Let $\tau_i^\nu \leq t < \tau_j^\nu$ so that $\alpha_i^\nu(t) > 0$, $\alpha_j^\nu(t) = 0$ and $G_i^\nu(t) = 1$. Since this is a preemption game, once τ_i is reached, the value of waiting to player i is zero so that the game ends and she Insists. Thus, the total expected payoff to player i from playing the matrix game depicted in Table 1 is given by

$$\begin{aligned} V_{i,t} =& \lambda_B \pi_{i,t}^B + \lambda_{I,i} \pi_{i,t}^I + \lambda_{I,j} \pi_{i,t}^C \\ =& G_j^\nu(t) \alpha_i^\nu(t) \pi_{i,t}^B + (1 - G_j^\nu(t)) \pi_{i,t}^I + G_j^\nu(t)(1 - \alpha_i(t)) \pi_{i,t}^C. \end{aligned}$$

  where the λ's are given by Eqs. (A.2) to (A.4).

  However, since $G_j^\nu(t) = 0$ and $G_i^\nu(t) = 1$, i Insists with certainty at t so that $\alpha_i(t) = 1$ and

$$V_{i,t} = \pi_{i,t}^I. \tag{B.1}$$

- If $\tau_j^\nu \leq t < \tau_i^\nu$, so that $\alpha_i^\nu(t) = 0$, $\alpha_j^\nu(t) > 0$ and $G_j^\nu(t) = 1$ and $G_i^\nu(t) = 0$, we get that $\alpha_j^\nu(t) = 1$ and

$$\begin{aligned} V_{i,t} =& \lambda_B \pi_{i,t}^B + \lambda_{I,i} \pi_{i,t}^I + \lambda_{I,j} \pi_{i,t}^C \\ =& \pi_{i,t}^C. \end{aligned} \tag{B.2}$$

- If $t \geq \max(\tau_i^\nu, \tau_j^\nu)$, then $\alpha_i^\nu(t) > 0$, $\alpha_j^\nu(t) > 0$ and $G_i^\nu(t) = G_j^\nu(t) = 1$. This implies that at least one player will make a move at t and, as such, the probability that both Concede is zero. The total expected payoff to player i at t is given by

$$V_{i,t} = \lambda_{B,i} \pi_{i,t}^B + \lambda_{I,i} \pi_{i,t}^I + \lambda_{I,j} \pi_{i,t}^C, \tag{B.3}$$

  where $\lambda_{I,k}$ ($k = \{i, j\}$) and $\lambda_{i,B}$ are given by Eqs. (A.8) and (A.9), respectively. Replacing for the λ's and taking the first order condition with respect to $\alpha_i^\nu(t)$, we get that the expected payoff to i is maximised for

$$\alpha_j^\nu(t) = \frac{\pi_{i,t}^I - \pi_{i,t}^C}{\pi_{i,t}^I - \pi_{i,t}^B}, \tag{B.4}$$

  which is reminiscent of the standard solution obtained by, among others, Thijssen et al. [2012] and Riedel and Steg [2017].

  This implies, therefore, that player i's maximum expected payoff in equilibrium is given by

$$V_{i,t} = \pi_{i,t}^C. \tag{B.5}$$

B.2 Subgame Perfection

To show the equilibrium is subgame perfect, let player i deviate from the equilibrium strategy in each of the scenarios described, and let player j abide by his equilibrium strategy. We argue that by deviating, he cannot achieve a higher payoff than that described above.

1. For $t < \widetilde{\tau}$ $(= \min(\tau_i^\nu, \tau_j^\nu))$, if i instead plays Insist at t rather than wait, his expected payoff is $\pi_{i,t}^I$, where $\pi_{i,t}^I < \pi_{i,t}^C$ in that region. Hence, he is better off not Insisting for $t < \widetilde{\tau}$.

2. For $\tau_i^\nu \leq t < \tau_j^\nu$, if i does not Insist at t, then his expected payoff is to Concede at τ_j^ν; i.e., $\pi_{i,\tau_j^\nu}^C < \pi_{i,t}^I$.

3. For $\tau_j^\nu \leq t < \tau_i^\nu$, if i Insists instead of Conceding at t, then the outcome is that both play Insist and i gets $\pi_{i,t}^B < \pi_{i,t}^C$.

4. For $t \geq \max(\tau_i^\nu, \tau_j^\nu)$, according to the equilibrium defined above, he plays Insist with positive probability. However, if he Insists with zero probability, he gets $\pi_{i,t}^C$. Therefore, he cannot achieve a better payoff (i.e., $\pi_{i,t}^I$) from deviating from the strategy defined above.

C Proof of Proposition 2

Let $t \in [\max(\tau_i^*, \tau_j^*), \widetilde{\tau})$. Neither player will Insist before $\widetilde{\tau}$. Each player wants the other to Concede first. Her competitor will Concede at t with probability $H_j^\nu(t)$ and the game will end. If neither player concedes before $\widetilde{\tau}$, the game will end at that point and one of the players will Insist with certainty. If j Concedes at t, i adopts at time τ_i^ν for a payoff $\pi_{i,\tau_i^\nu}^C$. Simultaneous concession is not possible. Therefore, the expected payoff to i from Conceding at some $t' \in [t, \widetilde{\tau})$ is given by $V_{i,t}^C = \pi_{i,t}^C$.

On the other hand, if she does not concede at t, her expected payoff is

$$\begin{aligned} V_{i,t}^{NC} =& \frac{dH_{j,t}}{1-H_{j,t}} \pi_{i,\tau_i^\nu}^C + \left(1 - \frac{dH_{j,t}}{1-H_{j,t}}\right) V_{i,t+dt} \\ =& \frac{dH_{j,t}}{1-H_{j,t}} \pi_{i,\tau_i^\nu}^C + \left(1 - \frac{dH_{j,t}}{1-H_{j,t}}\right) \left(V_{i,t}^{NC} + E_t[dV_{i,t}]\right) \end{aligned} \tag{C.1}$$

where $dH_{j,t}/(1 - H_{j,t})$ denotes the probability j Concedes in the $[t, t + dt]$ interval conditional on him not having conceded before this. Hence

$$\frac{dH_{j,t}}{1-H_{j,t}} = -\frac{E_t[dV_{i,t}]}{\pi_{i,\tau_i^\nu}^C - V_{i,t}^{NC} - E_t[dV_{i,t}]} \tag{C.2}$$

In equilibrium, she should be indifferent between conceding and not so that $V_{i,t}^{NC} = V_{i,t}^C = \pi_{i,t}^C$. This implies the rate of attrition of j is

$$\frac{dH_{j,t}}{1-H_{j,t}} = -\frac{E_t[dV_{i,t}]}{\pi_{i,\tau_i^\nu}^C - \pi_{i,t}^C - E_t[dV_{i,t}]} = -\frac{E_t[d\pi_{i,t}^C]}{\pi_{i,\tau_i^\nu}^C - \pi_{i,t}^C - E_t[d\pi_{i,t}^C]}. \tag{C.3}$$

However, since $t \in [\tau_i^*, \widetilde{\tau})$, she will not adopt until τ_i^ν, so her expected payoff at t is, in equilibrium, her discounted expected payoff at τ_i^ν, which is, by definition, $\pi_{i,t}^C$ (see Eq. (4)).

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