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DOI
10.1109/TEM.2020.2983352

Publication date
2020

Document Version
Accepted author manuscript

Published in
IEEE Transactions on Engineering Management

Citation (APA)
Papachristos, G., & van de Kaa, G. (2020). A System Dynamics Model of Standards Competition. *IEEE Transactions on Engineering Management*, *68*(1), 18-32. Article 9099091.
https://doi.org/10.1109/TEM.2020.2983352

Accepted Author Manuscript. Link to published article (IEEE): **https://doi.org/10.1109/TEM.2020.2983352**

A System Dynamics Model of Standards Competition

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Abstract

Standards competition is a complicated process influenced by a large number of factors and mechanisms. This paper develops a simulation model that draws on current theory of standards competition dynamics, and represents the interplay of strategic factors that firms can use to gain a competitive advantage. The model is used to reproduce four published cases of standards competition and explore alternative outcomes. Simulation results align with the published cases, and show that the competition outcome arises from the systemic effect of all the factors identified in the original studies. Further simulation tests explore under which conditions competition outcomes could have been different. The model, thus, provides a basis for further theoretical and empirical work on strategic aspects of standards competition in the respective industries of the cases.

Keywords: standards, dominant designs, platforms, competition, system dynamics, retroduction

Managerial relevance statement

This paper explores whether and how competitive advantage in standards competition can be maintained or reversed through strategic actions. The simulation model provides a tool to understand a firm's competitive position and its available strategic options. It integrates the factors that affect standards competition outcomes, and separates the endogenous factors that firms can control from the exogenous factors that are beyond firm control. Simulation results give a clear picture of which standards might dominate and why, and sensitivity analysis gives some insight about the strategic actions that can influence the outcome. This has some managerial implications for firms involved in standards development. The model provides a sense of the time window within which the strategic firm actions make sense. It can be used by platform developers and complementary goods providers to explore the range of strategic actions available to them and understand their systemic implications. Finally, the present work could be used to explore the scope of intervention by regulators or antitrust laws (Fig. 2,3).

INTRODUCTION

Technological standards facilitate platform ecosystems and act as the interface between firms in a supply and a demand network (Tassey, 2000; Gawer and Cusumano, 2014; Gawer, 2014; Jacobides *et al.* 2018). The importance of standard-based markets that support multi-party transactions in the economy is evident in the growing number of firms involved in standard development and operation (Boudreau, 2010; Eisenmann *et al.*, 2006; 2011). This growth calls for a deep understanding of standards competition processes and their inherent complexity, uncertainty and path dependent character (Hill, 1997; Schilling, 1998, 2002; Shapiro and Varian, 1999; Rochet and Tirole, 2003; Suarez, 2004; Thrane *et al*., 2010; Narayanan and Chen, 2012; Gawer, 2014; Gawer and Cusumano, 2014). This paper focuses on factors that affect standard competition outcomes. Standard competition refers to the competition between two or more standards in the market that may result in dominant standards such as in the case of VHS vs Betamax (Cusumano et al. 1992) or Blu-ray vs HD DVD (Gallagher 2012).

Understanding how the factors documented in the literature can generate a range of standards competition outcomes is a challenge. For example, a firm may enter early in a market and gain an advantage over late comers (Schilling, 1998; 2002; Eisenmann *et al*., 2006; Fosfuri *et al*., 2013). However, other competition outcomes are also possible (Lieberman and Montgomery, 1988; Katz and Shapiro, 1992; Suarez and Lanzolla, 2007; Franco *et al*., 2009; Cennamo and Santaló, 2013;

Lieberman and Montgomery, 2013). The evidence on whether early market entry and first mover advantage (FMA) may last or may be lost appears to be inconclusive and context dependent. Market pioneers may enjoy an enduring competitive advantage over late entrants (Urban et al., 1986; Lambkin, 1988; Lieberman, 1989; Makadok, 1998) but they may also lose their market leadership to late entrants (Christensen and Bower, 1996; Christensen, 1997; Freeman, 1997; Cho et al., 1998; Dowell and Swaminathan, 2006). It is also possible to have a range of outcomes other than a winner take all (WTA) (Katz and Shapiro, 1992; Windrum and Birchenhall, 1998; Suarez, 2005; Suarez and Lanzolla, 2007; Cennamo and Santalo, 2013; Vidal and Mitchell, 2013). The range of outcomes depends on the competing firms and their business environment.

The question then is how standards achieve and sustain competitive advantage in a market, and whether it can be reversed through strategic moves? This may be addressed through a dynamic, endogenous view of a firm's capability to pioneer or respond to new developments in the market environment through strategic factors (Lieberman and Montgomery, 1988; Suarez and Lanzolla, 2007; Franco *et al*., 2009; Tiwana et al., 2010; Fosfuri *et al.*, 2013; Srinivasan and Venkatraman, 2018). A suitable approach to address the large number of factors that influence standards competition is modelling and simulation (Sterman, 1994; Davis et al., 2007; Harrison et al., 2007). Simulation can demonstrate how standards competition factors generate endogenously competitive advantage (Lieberman and Montgomery, 1988), as no single factor is decisive for standards dominance (Suarez, 2004).

The model in this paper is the first step to integration and synthesis of the standards competition literature towards the development of a generalizable model. Model development draws on several theoretical frameworks as a basis (Hill, 1997; Schilling, 1998; 2002; Suarez, 2004; van de Kaa *et al.*, 2011; Gallagher, 2012; Gawer, 2014; Gawer and Cusumano, 2014). The paper adopts a retroductive method (Sayer, 1992; Wuisman, 2005) and tests the model in four cases of standards competitions detailed in van den Ende *et al*. (2012) and van de Kaa and de Vries (2015): (i) Firewire vs. USB, (ii) Wifi vs. HomeRF, (iii) MPEG vs. AC3, and (iv) Blu-Ray vs. HD DVD.

The case choice is partly informed by the aim to investigate First Mover Advantage (FMA), WTA dynamics, and whether they can be reversed. In case one, USB overturns the FMA of Firewire, while in case two Wifi maintains its FMA in the second case. In this sense, they constitute polar types of cases (Eisenhardt and Graebner, 2007). Furthermore, the case choice facilitates the tests we intend to do with the model to investigate whether it is possible to reverse the FMA or FMA loss, and WTA outcomes documented in the cases. The timing of market entry is not a differentiating factor in the rest of the cases and this an additional test to the generality of the model. This multiple case design enables a comparison to clarify whether our findings will be idiosyncratic to a single case or replicated consistently across several cases (Eisenhardt, 1991).

This paper contributes to research on standardization and standards competition dynamics in four ways. First, it develops a first model that reproduces four cases of standards competition and can claim such a high degree of generality (Weick, 1989). The paper illustrates and uses an approach that can be repeatedly applied to published studies and thus enrich the current knowledge base. Thus, the model is relevant to research on understanding standards competition dynamics in the respective industrial sectors of the case studies: consumer electronics, information technology, and telecommunications.

Second, the model integrates the theoretical factors that affect standards competition outcomes in four cases, and thus provides a bridge between rich empirical research and theoretical research (Eisenhardt and Graebner, 2007; Zhu and Iansiti, 2012). Attempts at theory integration have been made (Suarez, 2004; Murmann and Frenken, 2006; Narayanan and Chen, 2012). A careful reading of recent review articles that propose future research directions reveals that they do so without considering the potential of modelling and simulation methods to contribute to theory development on standards competition (McIntyre and Subramaniam, 2009; Tiwana et al. 2010; Narayanan and Chen, 2012; McIntyre and Srinivasan, 2017). This direction is missing and we believe it is worth using modelling and simulation as a means to an integration effort that will span current theoretical frameworks and the competition factors they consider, with the aim to develop models that can be applied to diverse case studies to reproduce their outcomes and explore alternative ones.

Third, simulation results show how the systemic interaction of factors generates the results documented in the published cases. The factors that firms can act directly upon are distinct to the exogenous factors that lie beyond a firm's control. Thus, the model offers the opportunity to explore further the original cases in depth, and vary the strength of firm-controlled factors to represent strategic actions to achieve market dominance, maintain their competitive advantage or nullify the advantage of their competitors.

Fourth, the model reproduces the competition outcomes and then it is used to explore further the case outcomes, beyond what is documented in the original publications. Results show that altering the timing of market entry is not enough to generate and sustain the FMA some standards have, and the WTA dynamics in cases i and iv. Stronger initial uncertainty on potential user preferences influences the outcome but does not reverse it. Sensitivity analysis results show that alternative combinations of factors may not generate the documented outcome. A series of "what if" scenarios explores whether the competitive advantage of standards in each case can be reversed by competitor actions, and by extension generate and explore any intermediate outcome in the cases.

The remainder of the paper is structured as follows. Section 2 discusses the factors of standards competition and the influence and nature of their interactions. Section 3 presents the research method. Section 4 presents an integrated conceptual basis for the model, and subsequently the quantitative system dynamics model. Section 5 presents and discusses simulation results and sensitivity analysis results. The paper concludes with discussion and ideas on further work in Section 6.

FACTORS OF STANDARDS COMPETITION

Several literature strands focus on the topic of technology competition leading to standards or dominant designs. Evolutionary economics stresses the inherent path dependent nature of markets that lead to certain outcomes and thus do not specifically mention factors for standards dominance (Abernathy and Utterback, 1978; Abernathy and Clark, 1985). Industrial economics stresses the importance of direct network effects that often operate in such markets (Farrell and Saloner 1985; Katz and Shapiro, 1985). Technology management scholars stress the importance of building up installed base which can trigger self-reinforcing mechanisms for technology dominance (Shapiro and Varian, 1998) and they discuss various factors that affect that installed base (Gallagher and Park, 2002; Gallagher, 2012). Research on platform competition, focuses on market settings where indirect network effects are evident (Cennamo and Santalo, 2013). Van de Kaa et al. (2011) present a list of factors for standards competition, and them in five categories: (i) standards supporter characteristics, (ii) standards characteristics, (iii) standards support strategies, (iv) other stakeholders, and (v) market characteristics. These categories are briefly summarized below to provide some background for the model developed later in the paper.

Standards supporter characteristics include complementary assets that are essential for market success (Teece, 1986): (i) the financial resources and revenue necessary to implement and pursue a strong marketing campaign (Schilling, 1999), (ii) reputation and credibility to attract other stakeholders and increase the installed base of standards (Foray, 1994), (iii) operational resources such as sufficient production capacity to meet demand (Suarez and Lanzolla, 2005), and (iv) learning orientation, or the extent to which stakeholders can learn from earlier standards competition episodes (Schilling 1998; 2002).

Standards characteristics that may confer an advantage over competitor standards include: (i) technological characteristics, (ii) compatibility with previous standards generations (Lee *et al.*, 2003), (iii) the availability of complementary goods for the standards (Schilling, 2002), and (iv) flexibility or the extent to which the standards can be adapted to changing requirements (Van den Ende *et al.*, 2012).

Standards competition strategies include: (i) low pricing strategy to quickly increase the installed base (Katz and Shapiro, 1986), (ii) appropriability strategy i.e. the extent of standards openness to adoption and development from other firms (Perrons, 2009; Alexy and Reitzig, 2013; Henkel *et al*., 2014; Felin and Zenger, 2014; Hagiu, 2014), (iii) market entry timing (Lieberman and Montgommery, 1988), (iv) marketing and communications e.g. pre-announcements of new version releases (Dranove and Gandal, 2003), (v) preemption of scarce assets to deny competitor access to them (Barney and Clark, 2007), (vi) expand the distribution network of standards and accelerate their diffusion (Wonglimpiyarat, 2005), and (vii) increase the stakeholder commitment to standards development and promotion (Tegarden, 1999).

The other stakeholders category includes, e.g.; (i) the installed base of current and previous standards versions (Farell and Saloner, 1986), (ii) the number of complementary goods suppliers and the effectiveness of the standards development process (Van de Kaa *et al*., 2011), (iii) the diversity of standards supporters (Gomes-Casseras, 1994; Boudreau, 2012), and (iv) large and powerful stakeholders (Suarez and Utterback, 1995). Finally, regulatory and anti-trust interventions may also affect the final outcome of a standards competition.

The market characteristics category includes, e.g.; (i) direct network effects that affect dominance (Farrell and Saloner, 1985; Katz and Shapiro, 1985), (ii) indirect network effects where complementary products and services provide additional utility to the user (Katz and Shapiro, 1994; Rochet and Tirole, 2003; Cennamo et al., 2018), (iii) bandwagon effects where the choice of one actor induces similar choices by others (de Vaan, 2014), and (iv) switching costs between standards (Burnham *et al.,* 2003; Capone *et al.*, 2013).

RESEARCH METHOD

Retroduction

The research method used in this paper is retroduction. It is a meta-process through which an empirical phenomenon is explained as the outcome of generative mechanisms that operate under certain conditions (Sayer, 1992; Wuisman, 2005). In this process, understanding a phenomenon involves uncovering these mechanisms and their causal factors. It is necessary to demonstrate their generative causality and show how causal mechanism ensembles tend to generate particular events that are empirically observed e.g. standards competition outcomes (Bhaskar, 1998).

Retroduction begins with an observed outcome *X* for which an explanation can be formed based on current knowledge with the aim to address a theoretical gap. In this paper*, X* is the outcome of the four standards competition cases investigated in the respective publications. The aim is to explain them from a single hypothesis *H*, formed by abduction that draws on *Existing Theory* on standards competition and the published cases. Hypothesis H is constructed using the standards competition factors presented in section 2. *H* consists of an ensemble of generative mechanisms that interact systemically with a particular intensity and timing (Collier, 1994). If *H* holds, it will generate *X* and thus provide an explanation for all four cases considered in this paper.

It is necessary to demonstrate deductively that *H* holds, and subject the outcome to empirical scrutiny to evaluate its explanatory power against alternative explanations (Wuisman, 2005). This is because different outcomes may be observed depending on which mechanisms of *H* operate i.e. the set of empirically observed outcomes is a subset of possible ones (Sayer, 1992; Archer *et al.,* 1998). Furthermore, valid, general explanations hold only to the extent that the mechanisms persist over time and are active across cases and social contexts (Sayer, 1992). This is why *H* is tested against four different cases in this paper.

The rationale behind the use of simulation

A range of approaches are used to study standard competition such as qualitative case studies, formal theoretical and econometric models (Farrell and Saloner, 1985; 1986; Gallacher and Park, 2002; Rochet and Tirole, 2003; 2006; Caillaud and Jullien, 2003; Parker and Van Alstyne, 2005; Armstrong, 2006; Gallacher, 2012; Hagiu and Spulber, 2014). However, these approaches cannot address sufficiently the large number of factors that influence standards competition, as a lot of data is necessary to get significant results and that data is often unavailable. Moreover, it is difficult to assess the combined effect these factors have on standards competition outcomes, with respect to their timing (Dew and Read, 2007), the variation of their intensity (Suarez, 2005; Zhu and Iansiti, 2012), possible delays that increase the difficulty in providing insights on managerial trade-offs (Schilling, 2002; Cenamor *et al.,* 2013), and assess the implications for standards governance (Huber et al., 2017).

Specifically, a case study research design presents its own challenges as humans face cognitive limitations in understanding complex processes where cause and effect are often separated temporally due to system feedback, delays and accumulation processes (Sterman 1989a;1989b; 1994), and factor intensity and influence on platform competition varies. For example, platform quality and price become more important to consumers as the intensity of network effects decreases (McIntyre and Subramaniam 2009). Furthermore, humans observe only the competition outcome that takes place, while a range of competition outcomes is possible in path dependent processes. The implication is that tracing the evolution of a path dependent process can reveal why certain outcomes and not others emerged, but only identifying and testing causal mechanisms can reveal why certain outcomes and not others became possible in the first place (Goldstone 1998).

In this respect, we believe that these approaches are somewhat limited in their ability to fully represent complex standards competition processes. Ex-post explanations about platform competition need to be tested through simulation to see: (i) whether explanations are internally, temporally and causally consistent, (ii) whether the proposed factor interactions can generate the documented competition outcomes, (iii) whether alternative explanations provide a better explanation of the competition outcome, and (iv) what conditions could possibly reverse the documented outcomes.

Modelling and simulation is applied in the deductive step of the process (Figure 1) because it is difficult to evaluate otherwise the numerous factor interactions documented in each case, and thus to provide a dynamically consistent story for each of the four cases. Simulation also allows the exploration of “what if” scenarios to evaluate different competition outcomes (Burton and Obel, 2011). These tests provide an additional robustness check on whether alternative explanations hold or not, thus they increase the confidence in the proposed explanatory mechanisms of *H* (Siggelkow, 2007). Retroduction thus bridges rich qualitative research and deductive research, inductive theory development from cases and deductive theory testing (Eisenhardt and Graebner, 2007).

The benefit of simulation is also illustrated in Loch and Huberman (1999) and Zhu and Iansiti (2012). In their paper, they follow initially an analytical approach, but later they use simulation because it is difficult to ascertain otherwise the effect of complementarities and other scale related factors. However, the choice of simulation as a research strategy has certain strengths and weaknesses just as case study research has (Langley, 1999). The assumption in using case-based material and modelling and simulation is that the approaches do not share the same weaknesses, and the strengths of one approach counter the weaknesses of the other (Jick, 1979; Johnson et al. 2017). For example, simulation offers certain strengths in terms of internal validity, precise specification of assumptions so that boundary conditions are clarified, and it facilitates systematic experimentation (Harrison et al., 2007; Davis et al., 2007; Epstein, 2008).

Finally, the use of a simulation model enables an appreciation of the time window within which strategic actions by either actor make sense, something that is not possible with a case study research design. In this way emphasis is placed on the need to address and document the role of delays and timing of strategic actions in all future standards competition cases. The model can be used to explore the effect that delays can have on standards competition outcomes. Delays stand in-between intermediary, strategic standards competition factors, their effect, and standards competition outcomes. Farrell and Saloner (1986) give an example of how delays may arise. A new technology, or standard, may be more competitive, offering private and social incentives for its adoption, but potential users may be committed to previous technologies for various reasons e.g. compatibility, resulting in delayed growth for the new technology.

Several theoretical simulation models of standards competition have been developed (Abrahamson and Rosenkopf, 1997; Adner and Levinthal, 2001; Lee *et al*., 2006; Almirall and Casadesus-Masanell, 2010; Ohori and Takahashi, 2012; Zhu and Iansiti, 2012; Lee *et al*., 2016).

Case specific simulation models have also been developed e.g. Microsoft Explorer vs. Netscape (Windrum, 2004), the strategic management and the diffusion of public wireless local area access services (Casey and Toyli, 2012), Xbox vs. Playstation (Zhu and Iansiti, 2012), and the effects of licensing cost on product and technology markets (Hytonen *et al*., 2012). However, it seems that the richness of the literature and frameworks comes at the cost of fragmentation, different analysis levels and modelling approaches (Narayanan and Chen, 2012; Papachristos and van de Kaa, 2018; Papachristos, 2020). Still, attempts at theory integration have been made (Suarez, 2004; Murmann and Frenken, 2006; Narayanan and Chen, 2012). A careful reading of recent review articles that propose future research directions reveals that they do so without considering the potential of modelling and simulation methods to contribute to theory development on standards competition (McIntyre and Subramaniam, 2009; Tiwana et al. 2010; Narayanan and Chen, 2012; McIntyre and Srinivasan, 2017). This direction is missing and we believe it is worth using modelling and simulation as a means to an integration effort that will span current theoretical frameworks and the competition factors they consider, with the aim to develop models that can be applied to diverse case studies to reproduce their outcomes and explore alternative ones.

STANDARDS COMPETITION DYNAMICS

The factors discussed in Section 2 are parts of causal mechanisms that influence the outcome of standards competition processes. The development of a model to generate endogenously standards competition dynamics and outcomes requires intermediary causal links drawn from the literature to complete the mechanisms. These are then developed into a causal loop diagram (CLD) where numbers on the links trace the relevant literature in Appendix B. A CLD is part of the system dynamics methodology for mapping system factor interactions (Sterman, 2000). The plus sign indicates that a factor X causes a change in Y in the same direction, ceteris paribus, and the minus sign an inverse change in the opposite direction. For transparency, the intermediary causal relations are numbered and traced back to the literature (Tables C1, C2 in Appendix B). For clarity, the CLD is broken down in two figures. Fig. 1 presents factors in categories of *standards supporter characteristics*, *standards characteristics* and *standards support strategy*. Fig. 2 presents *other stakeholders* and *market characteristics*.

Starting at the bottom of Fig. 1, *Standards_Selection_By_Users*, can lead to an increase in the *Current_Installed_Base*. Its growth creates a stock of *Past_Experience* upon which standards development firms can rely in the future and may improve their *Core_Capabilities*, and *Absorptive_Capacity* (Cohen and Levinthal, 1990) leading to greater *Effectiveness_of_ Development_Process* and to *Standards_Selection_By_Users*. Cohen and Levinthal (1989) developed the concept of absorptive capacity to capture the effect a firm's prior knowledge base has on its ability to recognize the value of new external information, and on its innovation capabilities and future strategic actions (Cohen and Levinthal, 1990; Cassiman and Veugelers, 2006).

Growth in installed base can improve the *Revenue* of standards supporter firms which may be used to influence *Customer_Expectations* or implement *Competitive_Pricing* strategies. This can encourage customers to buy products related to the standards and discourage new entrants from increasing the *Number_of_Standards_Available* in the market. Standards supporter firms can raise customer expectations through *Marketing_Communications* that reinforce customer perception of those standards features that differentiate it from its competitors, increase customer switching costs and reduce their search for alternatives (Burnham et al., 2003; Capone et al., 2013). This can eventually become a self-fulfilling prophecy (David and Greenstein, 1990). For example, in the early phase of standards competition, pre-announcements about standards characteristics or their imminent adoption by firms can discourage users from adopting rival standards and thus deny market share to competitors (Farrell and Saloner, 1986).

Revenue can be an exogenous parameter for new standards that enter into the competition, but it can also be based on current and past adopter bases. Ceteris paribus, it may also increase supporter commitment to particular standards. This counteracts the tendency of firms to commit to several standards, to hedge against uncertainty and risk in the early competition stages (Adner, 2006). High *Revenue* can enable standards supporters to acquire scarce resources to increase their *Technological_Advantage* and Superior_*Production_Capacity* that may give them an advantage in terms of quality and performance over their competitors. High *Past_ Experience_in_Setting_ Standards* can reinforce *Brand_Reputation* which may attract additional suppliers of complementary goods for the support group. *Network_Effects* depend on the magnitude of the installed customer base and can have a positive effect subject to *Backward_Compatibility* and *Open_Appropriability_Strategy*. The range of *Complementary_Goods* available can also increase *Network_ Effects*. Their effect can be influenced by the regulatory framework that might prescribe certain standards or complementary products (Axelrod *et al.*, 1995).

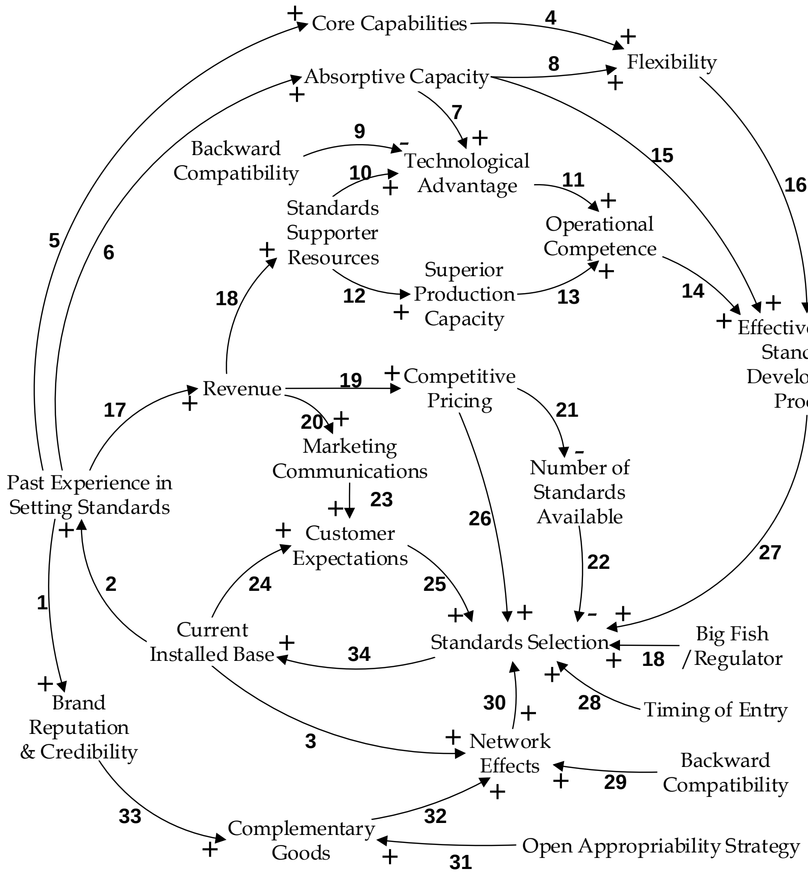

Figure 1. Causal loop diagram of: standards supporter characteristics, standards characteristics, and standards support strategy

In Fig. 2, the *Diversity_of_Stakeholder_Network* can lead to an increase in the range of *Complementary_Goods* which may raise *Switching_Costs*, and lock-in users to particular standards (David, 1985). The effect of *Switching_Costs* is influenced by the *Open_Appropriability_ Strategy* that suppliers follow to protect their standards from competitor imitation. A less open strategy can constrain the production of compatible complementary products. In this case, users that switch to other standards will also have to switch to complementary products that are compatible with the new standard. The level of *Compatibility* between standards works in the opposite direction and reduces switching costs (van de Kaa *et al.,* 2011). The *Bandwagon_Effect* influences the *Standards_Selection_By_Users*. As users provide positive feedback based on their experiences and influence potential customers by social contagion. A high *Rate_of_Tech_&_Market_Change* implies that new standards generations are introduced frequently and it may lower supporter C*ommitment* to any of them. It may also cause customers to wait for future versions. When *Market_Uncertainty* is high, firms and customers are less willing to risk, choose, and quickly commit to one standard. This can decrease the likelihood and the speed at which standards may become dominant (Arthur and Lane, 1993). *Antitrust_Laws* can prevent certain standards from becoming dominant. Finally, particularly influential firms or other actors (*Big_Fish*) or *Regulators* can promote, institutionalize, adopt or support financially standards and shift the market balance.

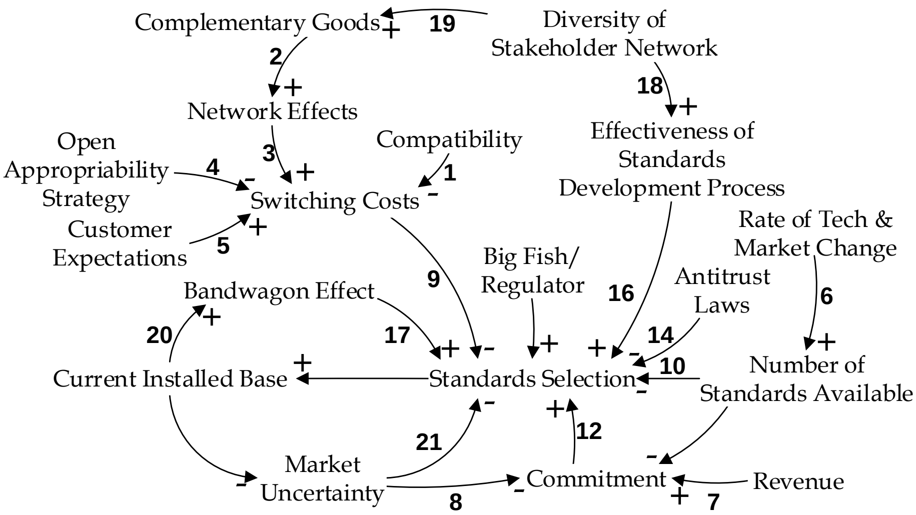

Figure 2. Causal loop diagram of: other stakeholders and market characteristics

A Simulation Model of Standards Competition

A simulation model based on Figures 1 and 2 is developed in this section following system dynamics methodology (Sterman, 2000). Additional detail for replicating the model is provided with case documentation in Van de Kaa and De Vries (2015) and Van den Ende et al. (2012). The list of model equations and the model is available from the authors upon request.

The model includes the effect of complexity on standards evaluation and choice in variable *Market_Uncertainty* (Arthur and Lane, 1993). This effect is represented by a component of uncertainty ξ that has zero mean and variance $1/\beta^2$. It has a symmetric exponential distribution with uncertainty parameter β_t and density given by (Loch and Huberman, 1999):

$$f_\xi(x) = \frac{1}{2}\beta_t e^{-\beta_t x} \text{ for } x \geq 0 \tag{1}$$

$$f_\xi(x) = \frac{1}{2}\beta_t e^{\beta_t x} \text{ for } x < 0 \tag{2}$$

Where β_t is the uncertainty magnitude that standards users face depending on standards complexity and adopter experience. Customers evaluate standards separately and independently, so the random component x across customers is an independent and identically uniformly distributed random variable. Uncertainty β_t diminishes when standards market share S_t increases as their performance is understood better, and information about the availability of future versions, upgrades, and future complementary goods and services becomes available (Padmanabhan *et al.,*1997). This effect is assumed to be linear and it is modeled in parameter β_t, where β_O is the initial value and S_t is the standards market share:

$$\beta_t = \beta_O \times (1 - S_t) \tag{3}$$

Prior customer switching experience is another relevant factor for multi-generation standards cases (e.g. Schilling, 2003). The greater the number of standards a customer has past experience of, the lower the switching costs he faces due to the experience of switching to using new products. Moreover, frequent switching implies that the customer interacts less with each supplier, and thus the benefits accrued through this relationship are smaller and easier to forego (Burnham *et al.,* 2003). The switching experience of customers has been modelled as the sum of past switching events. A switching event takes place when the standard's installed base trend changes.

Finally, user satisfaction *U* with the standards reduces the chances that customers switch between standards (Burnham *et al.*, 2003). *U* is assumed to depend on the standard's *Operational_Competence* and the range of *Complementary_Goods*. The logic is that technically superior standards with a wide range of complementary goods have a competitive advantage (Schilling, 2005). Following the definitions of Burnham *et al.* (2003) user satisfaction *U* is distinct from switching costs *C*, the one-time costs that users associate with the switch from one provider to another. If users are satisfied and switching costs are high then they are more likely to stick to their standards choice. The intention I_t of a customer to persist with a particular standards choice is modelled as:

$$I_t = U_t \times C_t \qquad (4)$$

Where $C_t = C_{p,t} + C_{f,t} + C_{r,t}$ and $C_{p,t}$ is procedural switching costs, which include time and effort required, $C_{f,t}$ is financial switching costs, $C_{r,t}$ is relational switching costs which are related to brand relationship, psychological or emotional loss. *Network_Effects* N_t are modelled as the multiplicative effect of the installed base $B_{p,t}$, *Backward_Compatibility* L_f, *Complementary_ Goods G*, and *Open_ Appropriability_Strategy A*, as the effect of these variables is not separable (Sterman, 2000, p528) e.g. without complementary goods, standards have no value so network effects should be zero:

$$N_t = B_{p,t} \times L_f \times G_t \times A \qquad (5)$$

The logic of this equation is that network effects are moderated by the appropriability strategy that standards supporters adopt, i.e. all the strategic actions that firms undertake to protect standards from competitor imitation (Lee *et al.*, 1995). If *A* is low, the development of complementary products is inevitably restricted as well. If there is no previous installed base, as in competition Cases 1, 2 and 4, then $N_t = G_t \times A$ in the model. The total standards performance P_t is given by:

$$P_t = (B_{p,t} + S_t \times N_t) \times I_t \times WoM_t \qquad (6)$$

Where S_t is the standards market share, $B_{p,t}$ is the potential installed base, and WoM_t is a word of mouth effect (Sterman, 2000). Users switch to other standards depending on their evaluation of P_t. Demand $D_{i,t}$ for standard *i* is given by multinomial logit choice models (McFadden, 1978; 2001) as the exponential function of the utility of standard *i* as judged by the user of standard *i*:

$$D_{i,t} = \exp\left(\gamma \frac{P_{i,t}}{P_i^*} - 1\right) \quad (7)$$

Where γ is the sensitivity of utility to performance. Then the share $\sigma_{i,t}$ of users that chooses standard *i* is given by:

$$\sigma_{i,t} = \frac{D_{i,t}}{\sum_i D_{i,t}} \quad (8)$$

Model Testing

The model was tested to establish confidence in its validity using established tests in system dynamics (Sterman, 2000). Boundary adequacy tests have been applied to the iterative model development process from its start, since the aim was to integrate the causal factors that influence competition so that it could produce the outcomes of the four cases endogenously. Additional tests included: dimensional consistency, extreme value testing of input parameters, numerical sensitivity to simulation time step, and sensitivity analysis which is discussed in Section 5.2.

From standards competition theory, it follows that standards with an advantage in one of the factors, ceteris paribus they should eventually capture a larger market share. This was tested with a deterministic version of the model. The value of each factor was separately increased for standard 1 keeping the rest at a value of 0.5 for both standards. For example, if the *timing of entry* of standard 1 is set a year later then standard 2 becomes dominant.

The converse test was also carried out i.e. with identical setup for the two competing standards, there was no difference in end market shares in the deterministic version of the model and no statistically significant difference in the stochastic version. Finally, we carried out numerical integration tests. Rates and constants are set in units per year so in order to set the integration time step, we progressively reduced it in half until there was no significant difference in results for a time step of 1/8 year.

RESULTS

Simulation Results

Simulation of the four published cases aims to investigate whether the factors identified in each one, are necessary and sufficient to produce the corresponding competition outcome. Only the factors identified in the original published cases are used each time to calibrate the model variables (Table 1). Their input values were based on our understanding of the cases, discussion with the authors of each published case and their supplementary documentation (Appendix B). The actual case values were used for market entry timing. Values for flexibility and diversity of stakeholder network have been included as exogenous time series for each case (data is available upon request). Initial uncertainty value is $\beta_O = 8$ for each case. No data were provided for γ in the original studies and it is conservatively set to 0.3. Each case setup is simulated 100 times for the time period outlined in the original study. Subsequently, sensitivity analysis tests whether the outcome of standards competition depends on the parameter values used in the model. Finally, alternative scenarios are explored to see the conditions under which the competition outcome could be reversed through strategic competitor actions.

Table 1 Factors relevant in each case and input values in corresponding variables

	Standard A	Standard B
Case 1 simulation time: 24 years	**Firewire**	**USB**
1.Technological Advantage - Learning	0.1	0.4
2.Technological Advantage - Initial Technical & Market Know-How	0.6	0.3
3.Timing of Entry (yr)	1	7
4.Commitment	0.1	0.6
Case 2 simulation time: 25 years	**Wifi**	**HomeRF**
1.Technological Advantage - Learning	0.2	0.1
2.Technological Advantage - Initial Technical & Market Know-How	0.4	0.3
3.Timing of Entry (yr)	1	2
4.Marketing Communication	0.2	0.1
5.Commitment	0.3	0.2

Case 3 simulation time: 24 years	MPEG	AC3
1.Brand Reputation - Past Performance in Setting Standards	0.2	1
2.Technological Advantage - Learning	0.1	0.3
3.Technological Advantage - Initial Technical & Market Know-How	0.4	0.9
4.Backward Compatibility between Standards Generations	1	0.4
5.Initial Complementary Goods Rate	0.2	0.8
6.Marketing Communication	0.1	0.4
7.Commitment	0.1	0.8
8.Previous Installed Base	12	0
Case 4 simulation time: 13 years	**Blu-Ray**	**HD DVD**
1.Brand Reputation - Past Performance in Setting Standards	1	0.4
2.Commitment	0.6	0.3

Fig. 3 (left) shows results for the Firewire vs. USB case. Despite the early entry advantage of Firewire, USB became dominant. Firewire never attains more than 33% share of the pc market[1]. The results are a reasonable reflection of this. After 2008 Firewire was slowly phased out[2]. Sensitivity analysis was carried out with uncertainty $\beta_O = \{0..18\}$, since it was set in an ad hoc manner. For β_O values greater than 8, the effect of uncertainty attenuates the advantage that standards may have to a certain extent and the end market share results of standards converge. Fig. 3 (right) shows results for the Wifi vs. HomeRF case. Simulation results are close to the actual total market share of Wifi chipsets in the market which exceeded 80% in 2001 (Vaughan-Nichols, 2002). Standards market shares converge with increasing uncertainty but they do not overlap.

[1] https://arstechnica.com/gadgets/2007/06/report-firewire-doomed-to-niche-interface-status/
[2] https://arstechnica.co.uk/gadgets/2017/06/firewire-history/

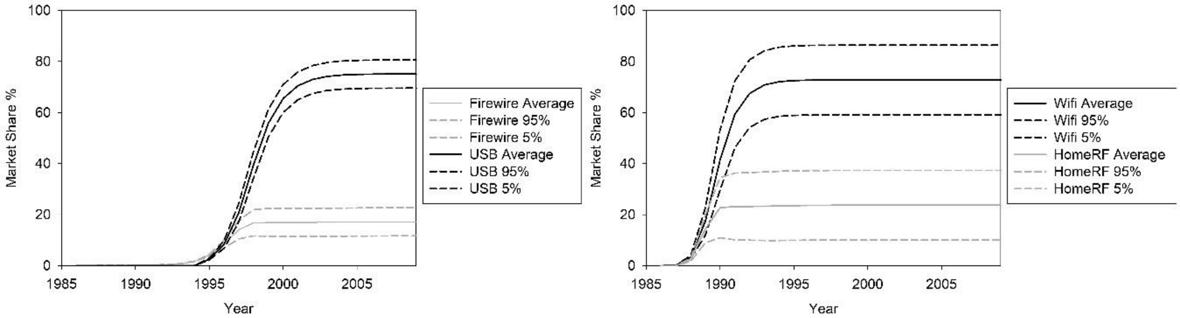

Figure 3. Simulation results for: Firewire vs. USB (left), Wifi vs HomeRF (right)

Fig. 4 (left) shows simulation results for the MPEG vs. AC3 case. Quantitative data on the case is scant, a proxy for adoption is the number of licensees for each standard[3]. Data available for 2017 show this to be 1490 for AC3 and 1066 for MPEG. Fig. 4 (right) shows simulation results for the Blu-Ray vs. HD DVD case. Two factors favor Blu-Ray over HD DVD: brand credibility and level of commitment. The result is close to reality as at the end of 2008 Blu-Ray had sold 2.2 million units, 4 times that of HD DVD (Daidj *et al*., 2010). Standards market shares converge with increasing uncertainty in both competition cases but they do not overlap.

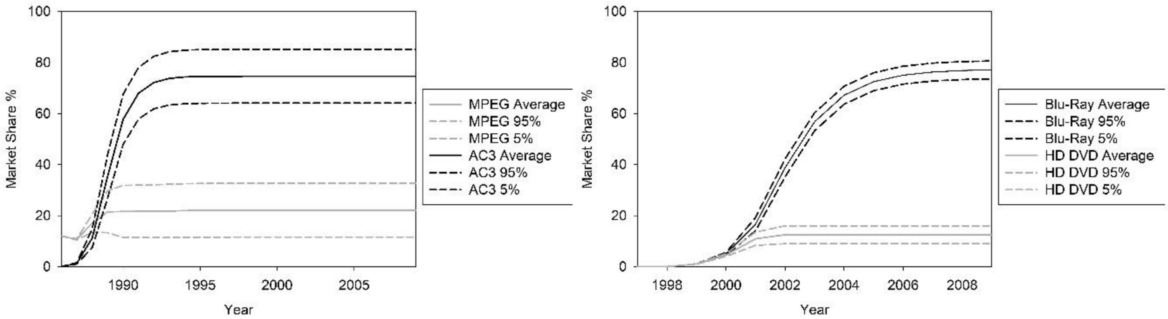

Figure 4. Simulation results for: MPEG vs. AC3 (left), Blu-Ray vs HD DVD (right)

In summary, simulation results show that the model can reproduce the outcome of the competition documented for each case, with a parameter setup based on the published case explanation. Nevertheless, the results should not be seen as numerical estimates of the real standards market shares. The results are robust with respect to the level of initial uncertainty. Uncertainty causes some users to choose inferior standards, and this dilutes the effect of factors that give a competitive

[3] Data collected from http://www.mpegla.com/main/programs/M2/Pages/Licensees.aspx
https://www.atsc.org/about-us/members/
http://web.archive.org/web/20141024183853/
https://www.dolby.com/us/en/professional/licensing/licensed-dolby-manufacturers.aspx

advantage to a standard. Nevertheless, uncertainty is not sufficient to alter the results in any of the cases as causal influences from the factors identified overcome this effect. The sensitivity analysis results in the next section show that alternative explanations do not hold, and that it is the systemic effect of all the factors identified in each case that produces the outcome of the competition. The implication is that an equivalent systemic effect is required to alter the outcome.

Sensitivity Analysis

Sensitivity analysis is necessary as all the published cases were qualitative and model calibration was based on parameter value estimates of the relative influence of each factor on each standard. Sensitivity testing for each parameter P_i where standard A or B has an advantage (Table 1), starts by setting $P_{Ai} = P_{Bi}$=min(P_{Ai}, P_{Bi}) and then increasing P_{Ai} or P_{Bi} in a stepwise manner to its maximum value (step is given in Appendix A). For the second parameter (i=2) the entire value range assigned to parameters for i=1 is explored again, and so on for the parameter range i for each case. In effect, each step in the sensitivity analysis tests an alternative explanation for the competition outcome.

Results are shown only for the limiting cases of $P_{Ai} = P_{Bi}$=min and P_{Ai} *or* P_{Bi} =max because the complete input space explored is large (see Appendix A for details). For example, for case one the results of four factors taking minimum and maximum values are shown. This results in $2^4 = 16$ setups (x-axis) and each setup was simulated for 100 runs. Figures 7–11 show average market share results and 95 percent confidence intervals for each standard. Graphs on the left include the external time series input for *flexibility* and *network diversity* (data available upon request), while graphs on the right do not. Hence, in Figures 7-11, setup one on the left shows always their effect only, and on the right shows competition results with identical parameter values for the two standards, thus no difference in market share should be observed.

The Firewire vs. USB case (Figure 5) exhibits a pattern which persists with (left) and without (right) the external time series input for flexibility and network diversity that favor USB. USB has the advantage with technological learning, flexibility and network diversity (Figure 5 left, setup 1–4). Adding the effect of Firewire early entry (setup 5–8), the significant overlap in standards market shares illustrates that it could overcome the USB advantage. This is in support of the theoretical relation between entry timing and market share (Schilling, 1998; 2002). Nevertheless, early entry was not enough for Firewire success because USB supporters were more committed, and completely countered Firewire's advantage. The effect of commitment for USB is evident in setups 9–16, when compared to setups 1–8.

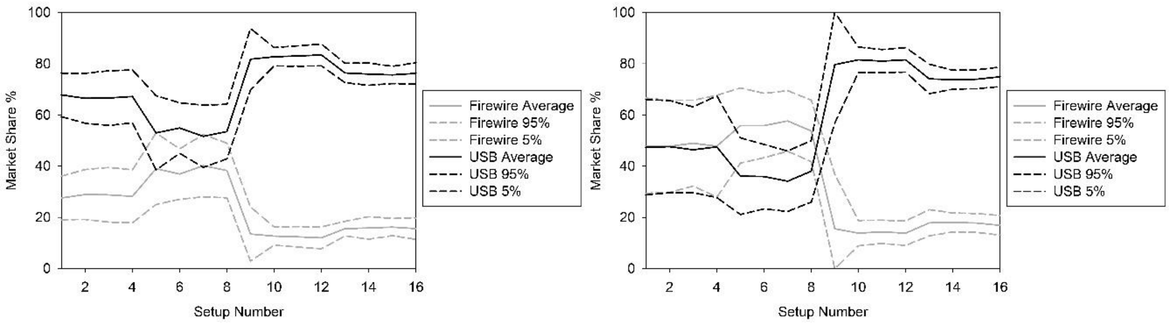

Figure 5. Sensitivity results for Case 1: Firewire vs. USB

Figure 6 shows results for Wifi vs. HomeRF. Comparison of setup one in Figure 6 left and right, shows that the effect of flexibility and network diversity is enough to determine the outcome of the competition. When more parameters are enabled to influence the competition i.e. going from setup one to 32, the market share difference increases. Removing flexibility and network diversity (Fig. 6, right), reduces Wifi's advantage and there is high market share overlap with HomeRF until setup 15. Then the added advantage of early Wifi entry is clearly shown in setup 15 market share. This shows the systemic character of standards competition. The results demonstrate that the Wifi advantage of flexibility, network diversity, and entry timing are interchangeable, thus there is a range of strategic options to achieve market dominance that the HomeRF development team could consider to reverse the outcome.

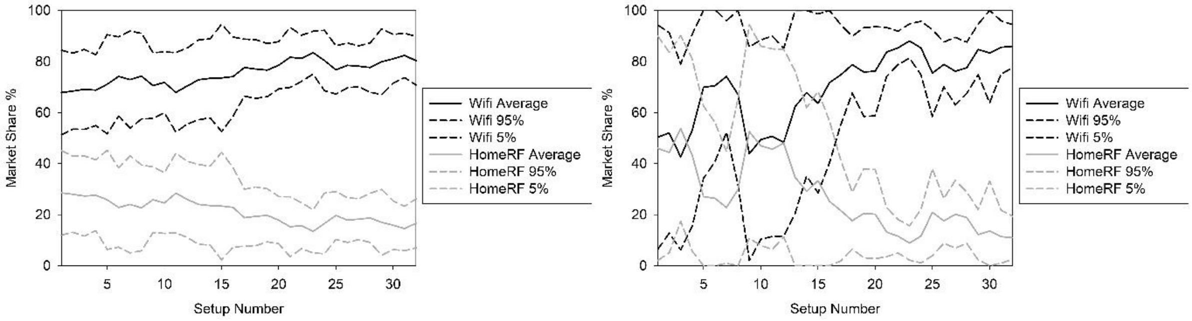

Figure 6. Sensitivity results for Case 2: Wifi vs. HomeRF

Figure 7 shows results for the MPEG vs. AC3 case. The characteristic pattern in the results suggests that some factors have an impact that is significantly higher than others. The difference between AC3 and MPEG becomes larger as each parameter takes values in a stepwise manner. The effect of removing flexibility and network diversity improves AC3 market share slightly.

Observing the alternation between higher and lower values for end market share (Figure 7, right) and tracing it back to the sensitivity setup, the large shift in values at the 17th setup is due to the increase in *Complementary Goods* for AC3. The rapid periodic pattern every two setups is caused by *Brand Reputation* that takes minimum and maximum values. This case illustrates better the effect the introduction of each parameter in the competition dynamics has on market share e.g. M*arketing_Communications* values introduced at setup 33, level of *Commitment* at setup 65, and *Previous_Installed_Base* at setup 128 (Fig. 7, left).

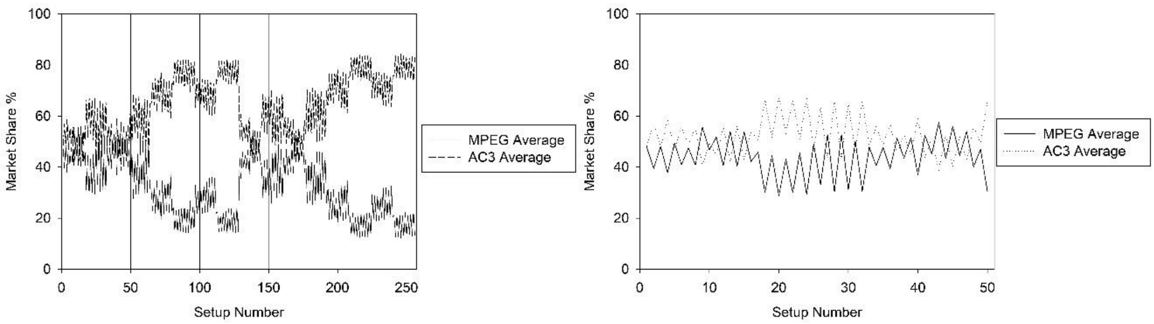

Figure 7. Sensitivity results for Case 3: MPEG vs. AC3 (left), setup 1-50 (right)

Figure 8 shows the Blu-Ray vs. HD DVD sensitivity results for uncertainty β_o values of 4, 8 and 12 in setup 1, 5, and 9. No combination of values alters the competition outcome, even when flexibility and network diversity are removed (Fig. 8, right). The outcome does not change even when testing separately for the time series of flexibility and network diversity. Either of the two confers an advantage to Blu-Ray.

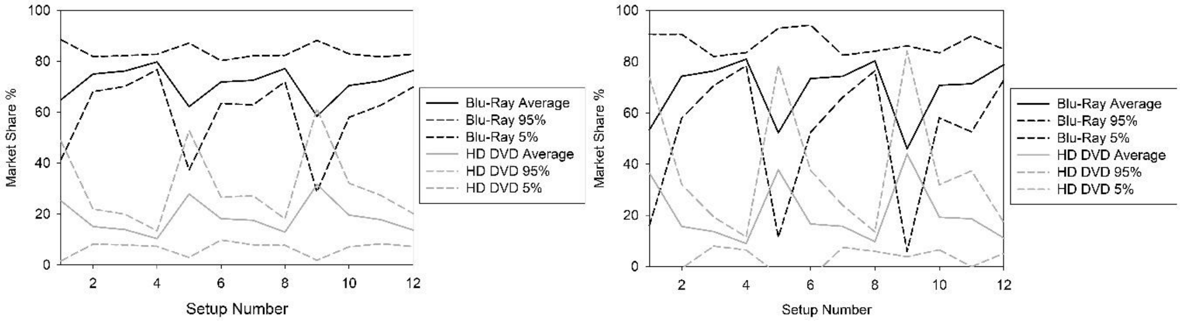

Figure 8. Sensitivity results for Case 4: Blu-Ray vs. HD DVD

DISCUSSION

The simulation model aimed to integrate factors of standards competition and test its application in four standards competition cases and explore them further. The simulation study was based on all the data available from the original published cases. The model was set up for each case by assigning parameter values only to the factors identified as influential in the original publications. The agreement between case analysis and simulation results implies that the combined effect of the factors identified in each case is sufficient to endogenously generate the end result of the competition within the time frame of each case. Simulation results and the sensitivity analysis is the kind of integrative study called for (Suarez, 2004; Narayanan and Chen, 2012).

The sensitivity results are important because they show that alternative explanations with fewer factors do not hold and any case analysis that simply adds up factor effects is unreliable. The conclusions drawn from sensitivity analysis were also checked and hold with different parameter ordering e.g. 4,3,2,1 rather than 1,2,3,4 in case 1, and with tests of the uncertainty effect which indicated that it does not have a significant effect in the case outcomes. The systemic nonlinear effect of the factors identified in each case is necessary and sufficient to produce the competition outcome.

Sensitivity analysis shows that the influence of some factors in cases one and two (Fig. 5 and 6) can overturn the outcome of the competition. For example, if the timing of market entry was different in Firewire vs. USB, or if the *Commitment* of USB supporters had not been so high, the outcome could have been different. Moreover, governance mechanisms can make the difference in situations where standards are equally competitive[4] (e.g. Figure 1: Open Appropriability Strategy, Backward Compatibility, and Figure 2: Diversity of Stakeholder Network). The effect of governance mechanisms that increase stakeholder network diversity on competition outcomes is evident most clearly in case 1 results (Figure 3 left), and case 2 results (Figure 4, left). In a setting where competitors are equally strong, governance mechanisms that influence network flexibility and diversity give the competitive edge and the advantage in terms of market competition outcome to USB in case 1 and to Wifi in case 2.

The question arises whether some strategic action in any of the cases could reverse the outcome. In order to explore alternative competition outcomes in favor of HD DVD in case four, we keep the original setup (Table 1) and vary the following additional factors the model includes: 1) *Revenue*, 2) *Technological Advantage – Learning*, 3) *Technological Advantage – Initial Technical & Market Know How*, 4) *Initial Complementary Goods Rate*, 5) *Competitive Pricing*, 6) *Marketing Communication*. The magnitude of each HD DVD factor is increased several fold (x-axis) relative to Blu-Ray and each set up is simulated 100 times. Simulation results show that the average end market share of Blu-Ray decreases most noticeably with increasing *Revenue* for HD DVD (Figure 11).

This can be explained as increasing *Revenue* activates two loops in Figure 1, and increases *Commitment* (Figure 2), thus it confers a competitive advantage to HD DVD. This counters the advantage Blu-Ray has in *Flexibility* (Figure 1) and *Stakeholder_Network_ Diversity* (Figure 2). These factors lie closer to standards selection than *Revenue* and influence it through one loop only. Increasing factors two to six does not have the same pronounced effect. This is because they lie downstream of *Revenue* and closer to standards selection (Figure 1). The results illustrates how they can be complementary to each other when taken together.

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[4] We would like to thank a reviewer for suggesting this point.

Figure 9 illustrates what Figure 4 and sensitivity results are only suggestive of. It shows that Toshiba would have stood a chance if it had invested three times more in HD DVD, relative to Sony investment in Blu Ray. Toshiba paid $150 million to two movie studios for exclusive deals on HD DVD, while Sony invested an estimated $200 million to integrate Blu-Ray in PlayStation 3 and paid an estimated $400 million to Warner for exclusive content deals (Gallagher, 2012).

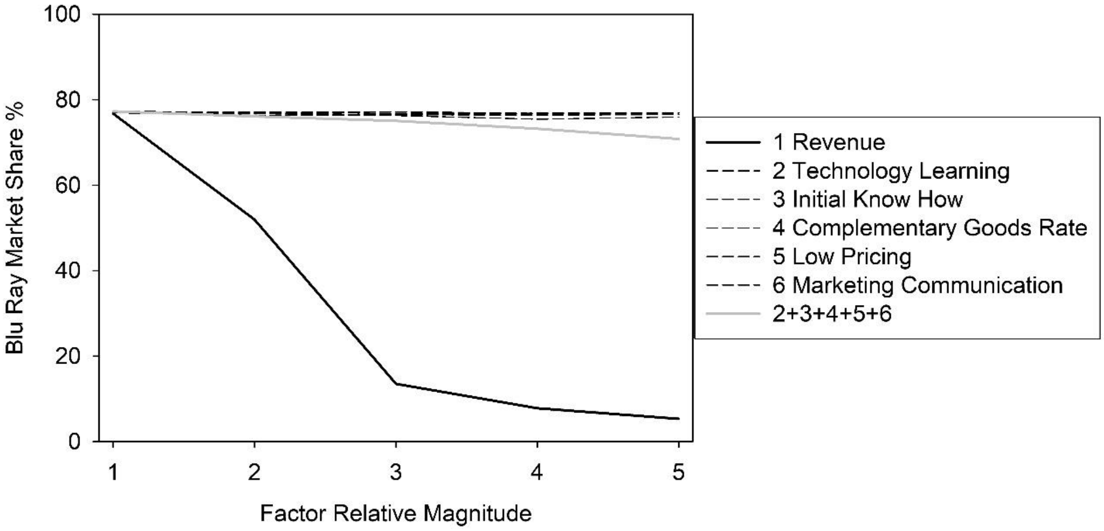

Figure 9. Alternative outcomes for Case 4: Blu-Ray vs. HD DVD

A similar approach was performed to explore the factors that may change the competition outcome in cases one to three. In case one, Firewire could dominate and maintain its advantage if it had double the initial complementary goods rate to the market, or if USB *Revenue* was 0.6 compared to 1 for Firewire. In contrast, better *Marketing_Communication* is not enough, irrespective of its relative magnitude. For case two, a 50 percent increase in *Revenue* would have given HomeRF a clear competitive advantage over Wifi, while increasing the rate at which complementary products for HomeRF reach the market does not make a difference. For case three, a 30% increase in the *Revenue* of MPEG is enough to alter the competition outcome, while a change in the appropriability strategy for MPEG does not make a difference.

The model thus illustrates the possibility to reverse a WTA outcome and a First Mover Advantage. Moreover, it offers the possibility to investigate on a case by case basis what are the factors of standards competition that can enable such a reversal of competition outcomes.

In case one, the model illustrates that it is possible to reverse the WTA outcome to favor Firewire instead of USB. This entails that Firewire maintains its FMA over USB. It is also possible to explore intermediate competition outcomes as illustrated in case four, by varying the relative strength of factors in the competition of Blu-Ray against HD-DVD.

Limitations and Future Research

One of the main limitations of the study is that model application is limited to the respective industries of the published cases: consumer electronics, information technology, and telecommunications. The reproduction and exploration of standards cases from other industrial sectors e.g. transport, would definitely require some alterations in model structure and the factors it includes. For example, most likely changes would have to account for the extent to which delays play a crucial role.

This is also a limitation in the current implementation of the model, as quantitative case data were available only on market entry timing, and thus additional delays in all four cases were assigned identical values to control for their effect. The effect of price, scale economies and up-scaling of standards characteristics on standards competition (Wilson, 2012), was also not explicitly considered as the original documented studies were qualitative and additional primary research is required for this. They could be part of the strategic options available to competing standards. The validation of the model results was also difficult and required additional research as market share data was scarce and not provided in the original studies.

A further limitation of the model conceptualization concerns standards governance, envelopment, and multihoming (Tiwana et al., 2010; Eisenmann et al., 2011; Cennamo et al., 2018). A simple dynamic bilateral relation is assumed to operate between standards firms and complementors, where the latter choose to support the standards with the larger user base. However, increased competition across standards firms and the availability of more sophisticated development tools for standards, can shift the power balance between standards providers and complementors (Srinivasan and Venkatraman, 2018). There is pressure to offer incentives for standards support to complementors because they have more alternatives. The dyadic nature of standards-based competition, implies that the challenges complementors face have repercussions for standards firms and both need to reassess their relative positions and options. Complementors are likely to support specific standards based on their resources and capabilities, and respond to the strategic actions of other complementors and standards firms. These issues are worth exploring further, through appropriate model extensions, as they become ever more salient with standards that continue to converge across industry boundaries (Kim et al., 2015).

The combination of case based and simulation research (Papachristos 2012; 2018a;2018b) allows several other extensions related to early standards adopters, user retention and switching costs as well as wait and see behavior of potential standards users in the face of increasing uncertainty. The model can be used to assess the key factors of success for standards dominance during each stage of the battle as suggested in theory (Suarez, 2004). This will expand the model scope to study multi-standards or multi-generational competition, and thus provide a further test for its generality. The application of the model in single and multi-generation standards competition cases could help identify similarities and differences between the two. Follow-up research could also examine how well the model explains technology selection in industries that are not characterized by network effects.

A frequent system dynamics practice is to disaggregate parts of the model and see how this affects the dynamic behavior of the model (Sterman, 2000). For example, studying the effect of direct versus indirect network effects on standards competition and strong vs weak ties between users (Suarez, 2005). A further model extension would involve disaggregation of customer stocks with respect to their switching experience and switching costs in order to explore targeted firm strategies for customer retention.

Customers with limited experience are likely to have high switching costs. If they perceive high switching costs for particular standards, which would potentially lock them in for some time, they may not choose it and adopt a wait and see strategy. Increasing switching costs to retain customers may result in low customer acquisition rate especially of new, inexperienced users, i.e. precisely the market segment with the greater retention potential. In contrast, lead users with frequent switching behavior, seek to have the latest, most advanced standards in the market. They have high tolerance levels to switching costs and thus it may be worth catering to this customer segment through targeted strategic actions. Lead users can be important because they can constitute a critical mass and the basis for a broader diffusion that leads to competitive advantage and rapid market share growth for a standard. In contrast, emphasis of the core standards value, engagement of current customers with defensive marketing, increasing product complexity, introduction of loyalty programs and encouragement of broader use could lead to slower, sustainable growth. This is an interesting trade-off between switching costs and customer acquisition.

The model could also be disaggregated to introduce standards diversity (Papachristos, 2017), and standards aspects that customers value in order to test different positioning strategies for standards. Customers might also try out new standards or lease them instead or buying them. Thus, there is scope to differentiate between trial and switching costs in the model as well. A concomitant issue would involve the question of complementary goods supply timing during the lifecycle of a standard.

Another future research direction is to use the model as a research guide to elaborate on the effect of delays in standards competition processes in empirical studies. The model inputs required provide a guide for data collection for future case studies and this will promote comparability and transparency. For example, it could be used to study the tension between the delay of standards release preannouncements in the market and the rest of the delays involved in the process. A direction that would utilize empirical data on delays, would be the construction of management "flight" simulators for firms (Sterman, 2000) to allow the exploration of prospective "what if" scenarios about standards competition (Burton and Obel, 2011). This would require some estimation of the relative magnitude of delays involved for a specific sector. Managers could then use such a "flight" simulator to assess various competition strategies. Seen from a different theoretical lens, it would be possible to use it to try out different business models (Casadesus-Masanell and Ricart, 2010; Zott *et al.*, 2011).

CONCLUSIONS

Considerable research on standards competition illustrates its inherent complexity and path dependent nature. Several theoretical frameworks and models have been developed to investigate the effect of the factors involved in standards competition on competitive advantage and competition outcomes. Recent research outline papers propose directions for future research but they do not consider explicitly the use of modelling and simulation as a means to future theory integration and development that will span the current theoretical frameworks and the competition factors they propose.

This paper develops a simulation model of standards competition that is applied in four standards competition cases. Model development draws and integrates current theory into a dynamic framework of standards competition factors and competitive advantage. The paper adopts retroduction and system dynamics modelling to investigate standards competition, and demonstrates its use on four published standards competition cases. The reproduction of case results with the model adds confidence to the insights of the original studies and in model generality. The simulation results and sensitivity analyses show that it is the systemic influence of factors that determines the competition outcome in each case. Moreover, explanations with alternative combinations of standards factors are shown not to hold. The model in this paper is the first step to integration and synthesis of the standards competition literature, and the development of a generalizable model. The accumulation of research that applies the approach followed in this paper should provide a test to prior research and the opportunity to take into account standards competition details beyond those of the present study.

The model enables the inference of insights from additional “what if” outcomes beyond those documented in the cases, something not possible with the case study research design used in the original publications. First, it is shown that altering the timing of market entry is not enough to generate and sustain the FMA some standards have, and the WTA dynamics in cases i and iv. Second, stronger initial uncertainty on potential user preferences influences the outcome but does not reverse it. Third, sensitivity analysis shows that alternative combinations of factors may not generate the documented outcome. Fourth, a series of “what if” scenarios explore whether the competitive advantage of standards in each case can be reversed by competitor actions, and by extension generate and explore any intermediate outcome in the cases.

The paper thus, contributes to the literature that explores the conditions under which FMA can be achieved and maintained, and WTA outcomes are possible. The work thus provides a good and reliable basis for further theoretical and empirical research on standards competition that can be expanded to address explicitly the role of delays in standards competition and find suitable competitive responses in the respective industries of the four cases. Moreover, the insight that time-based advantages may not be sufficient to secure a market-based advantage is of managerial relevance. The model can be used to help managers re-calibrate their strategic thinking as it distinguishes between standards competition factors to those that are under firm control and those that are not.

REFERENCES

Abernathy WJ, Clark KB. 1985. Innovation: Mapping the winds of creative destruction. Research Policy 14: 3-22.

Abernathy WJ, Utterback JM. 1978. Patterns of industrial innovation. Technology Review 80(7): 40-7.

Abrahamson E, Rosenkopf L. 1997. Social Network Effects on the Extent of Innovation Diffusion: A Computer Simulation. Organization Science 8: 289–309.

Adner R, Levinthal D. 2001. Demand heterogeneity and technology evolution: Implications for product and process innovation. Management Science 47(5): 611–628.

Adner R. 2006. Match your innovation strategy to your innovation ecosystem. Harvard Business Review 84(4), 98–107.
Alexy O, Reitzig M. 2013. Private–collective innovation, competition, and firms' counterintuitive appropriation strategies. Research Policy 42(4): 895–913.
Almirall E, Casadesus–Masanell R. 2010. Open versus closed innovation: A model of discovery and divergence. Academy of Management Review 35(1): 27–47
Anderson, P., Tushman, M.L. 1990. Technological discontinuities and dominant designs: A cyclical model of technological change. Administrative Science Quarterly 35(4), 604-633.
Archer M, Bhaskar R, Collier C, Lawson T, Norrie A (eds) 1998. Critical Realism: Essential Readings. Routledge: London, UK.
Armstrong M. 2006. Competition in Two–Sided Markets. RAND Journal of Economics 37: 668–691.
Arthur WB, Lane DA. 1993. Information contagion. Structural Change and Economic Dynamics 4(1): 81–104.
Axelrod R, Mitchell W, Thomas RE, Bennett DS, Bruderer E. 1995. Coalition formation in standard–setting alliances. Management Science 41(9): 1493–1508.
Baldwin, C.Y., Woodard, C.J. 2009. The architecture of platforms: A unified view. in: Gawer, A. (Eds.), Platforms, markets and innovation. Edwar Elgar Publishing, Cheltenham, UK, pp. 19-44.
Barney J, Clark DN. 2007. Resource–Based Theory: Creating and Sustaining Competitive Advantage. Oxford University Press: Oxford, UK.
Bhaskar R. 1998. Philosophy and scientific realism. In Critical realism: Essential readings, Archer MS, Bhaskar R, Collier A, Lawson T, Norrie A (eds). Routledge: London, U.K.: 16–47.
Blind K. 2004. The Economics of Standards, Theory, Evidence, Policy. Cheltenham, UK: Edwar Elgar.
Boudreau KJ. 2010. Open platform strategies and innovation: granting access vs. devolving control. Management Science 56(10): 1849–1872.
Boudreau K. 2012. Let a thousand flowers bloom? An early look at large numbers of software app developers and patterns of innovation. Organization Science 23(5): 1405–1427.
Burnham TA, Frels JK, Mahajan V. 2003. Consumer switching costs: A typology, antecedents and consequences. Academy of Marketing Science 31(2): 109–126.
Burton RM, Obel B. 2011. Computational modelling for what–is what–might be and what–should be studies and triangulation. Organization Science 22(5): 1195–1202.
Caillaud B, Jullien B. 2003. Chicken and egg: Competition among intermediation service providers. RAND journal of Economics 34(2): 309-328.
Capone G, Malerba F, Orsenigo L, 2013. Are switching costs always effective in creating first mover advantage? The moderating role of demand and technological regimes. Long Range Planning 46: 348–368.
Casadesus–Masanell R, Ricart JE. 2010. From Strategy to Business Models and onto Tactics. Long Range Planning 43(2–3): 195–215.
Casey TR, Toyli J. 2012. Dynamics of two–sided platform success and failure: An analysis of public wireless local area access. Technovation 32: 703–716.
Cassiman B, Veugelers R. 2006. In search of complementarity in innovation strategy: Internal R&D and external knowledge acquisition. Management Science 52(1): 68-82.
Cho D.S., Kim D.J., Rhee D.K. 1998. Latecomer strategies: evidence from the semiconductor industry in Japan and Korea. Organization Science 9(4): 489–505.
Cenamor J, Usero B, Fernandez Z. 2013. The role of complementary products on platform adoption: Evidence form the video console market. Technovation 33: 405–416.
Cennamo C, Santalo J. 2013. Platform competition: Strategic trade–offs in platform markets. Strategic Management Journal 34: 1331–1350.
Cennamo C, Ozalp H, Kretschmer T. 2018. Platform architecture and quality trade-offs of multihoming complements. Information Systems Research 29(2): 461-478.

Christensen C.M., Bower J.L. 1996. Customer power, strategic investment, and the failure of leading firms. Strategic Management Journal 17(3): 197–218.
Christensen C.M. 1997. The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail. Harvard Business School Press: Boston, MA.
Cohen WM, Levinthal DA. 1989. Innovation and learning: The two faces of R&D. Economic Journal 99(397): 569-596.
Cohen WM, Levinthal DA. 1990. Absorptive capacity: A new perspective on learning and innovation. Administrative Science Quarterly 35(1): 128-152.
Collier A. 1994. Critical realism: An introduction to the philosophy of Roy Bhaskar. Verson: London.
Cusumano MA, Mylonadis Y, Rosenbloom RS. 1992. Strategic maneuvering and mass-market dynamics: the triumph of VHS over Beta. Business History Review 66(1): 51-94.
Daidj, N., Grazia, C., Hammoudi, A., 2010. Introduction the non-cooperative approach to coalition formation: The case of the Blu-Ray/HD-DVD standards wars. Journal of Media Economics 23(4), 192-215.
David PA. 1985. Clio and the economics of QWERTY. American Economics Review 75(2): 332–337.
David PA, Greenstein S. 1990. The Economics of Compatibility Standards: An Introduction to Recent Research. Economics of Innovation and New Technology 1: 3–41.
Davis JP, Eisenhardt KM, Bingham CB. 2007. Developing theory through simulation methods. Academy of Management Review 32(2): 480–499.
Dew N, Read S. 2007. The more we get together: Coordinating network externality product introduction in the RFID industry. Technovation 27: 569–581.
Dowell G., Swaminathan A. 2006. Entry timing, exploration, and firm survival in the early U.S. bicycle industry. Strategic Management Journal 27(12): 1159–1182.
Dranove D, Gandal N. 2003. The DVD versus DIVX standard war: empirical evidence of network effects and preannouncement effects. Journal of Economics Management Strategy 12(3): 363–386.
Eisenhardt KM. 1991. Better stories and better constructs: The case for rigor and comparative logic. Academy of Management Review 16: 620–627.
Eisenhardt KM, Graebner ME. 2007. Theory building from cases: Opportunities and challenges. Academy of Management Journal 50(1): 25–32.
Eisenmann T, Parker G, van Alstyne M. 2006. Strategies for two–sided markets. Harvard Business Review 84: 92–101.
Eisenmann T, Parker G, van Alstyne M. 2011. Platform envelopment. Strategic Management Journal 23(12): 1270–1285.
Epstein JM. 2008. Why model? Journal of Artificial Societies and Social Simulation 11(4)
Farrell J, Saloner G. 1985. Standardization, compatibility, and innovation. Rand Journal of Economics 16, 70–83.
Farrell J, Saloner G. 1986. Installed base and compatibility: innovation, product preannouncements, and predation. American Economic Review 76(5): 940–955.
Felin T, Zenger TR. 2014. Closed or open innovation? Problem solving and the governance choice. Research Policy 43(5): 914–925.
Foray D. 1994. Users, standards and the economics of coalitions and committees. Information Economics and Policy 6(3–4): 269–294.
Fosfuri A, Lanzolla G, Suarez FF. 2013. Entry-timing strategies: The road ahead. Long Range Planning 46: 300–311.
Franco AM, Sarkar MB, Agarwal R, Echambadi R. 2009. Swift and smart: The moderating effects of technological capabilities on the market pioneering-firm survival relationship. Management Science 55(11): 1842–1960.
Freeman C. 1997. The Economics of Industrial Innovation (3rd edn). MIT Press: Cambridge, MA.

Gallagher SR, Park SH. 2002. Innovation and competition in standard-based industries: a historical analysis of the U.S. home video game market. IEEE Transactions on Engineering Management 49(1): 67-82.
Gallagher SR. 2012. The battle of the blue laser DVDs: The significance of corporate strategy in standards battles. Technovation 32(2): 90–98.
Gawer A, Cusumano MA. 2014. Industry platforms and ecosystem innovation. Journal of Product Innovation Management 31(3): 417–433.
Gawer A. 2014. Bridging differing perspectives on technological platforms: toward an integrative framework. Research Policy 43: 1239–1249.
Goldstone JA. 1998. Initial conditions, general laws, path dependence and explanation in historical sociology. American Journal of Sociology 104(3): 829 – 845.
Gomes–Casseras B. 1994. Group versus group: how alliance networks compete. Harvard Business Review 72(4): 62–74.
Hagiu A, Spulber D. 2014. First–Party Content and Coordination in Two–Sided Markets. Management Science 59: 933–949.
Hagiu A. 2014. Strategic decisions for multisided platforms. Sloan Management Review 55(2).
Harrison JR, Lin Z, Carroll GR, Carely KM. 2007. Simulation modeling in organizational and management research. Academy of Management Review 32(4): 1229–1245.
Henkel J, Schöberl S, Alexy O. 2014. The emergence of openness: How and why firms adopt selective revealing in open innovation. Research Policy 43(5): 879–890.
Hill CWL. 1997. Establishing a standard: Competitive strategy and technological standards in winner take all industries. Academy of Management Executive 11(2): 7–25.
Huber TL, Kude T, Dibbern J. 2017. Governance practices in platform ecosystems: Navigating tensions between cocreated value and governance costs. Information Systems Research 28(3): 563-584.
Hytonen H, Jarimo T, Salo A, Yli–Juuti E. 2012. Markets for standardized technologies: patent licensing with principle of proportionality. Technovation 32: 523–535.
Jacobides MG, Cennamo C., Gawer A. 2018. Towards a theory of ecosystems. Strategic Management Journal 39(8): 2255-2276.
Jick T. 1979. Mixing qualitative and quantitative methods: Triangulation in action. Administrative Science Quarterly 24: 602–11.
Johnson BR, Russo F, Shoonenboom J. 2017. Causation in mixed methods research: The meeting of philosophy, science and practice. Journal of Mixed Methods Research 13(2): 1–20.
Katz ML, Shapiro C. 1985. Network externalities, competition and compatibility. American Economic Review 75: 424–440.
Katz ML, Shapiro C. 1986. Technology adoption in the presence of network externalities. Journal of Political Economy 94(4): 822–841.
Katz ML, Shapiro C. 1992. Product introduction with network externalities. Journal of Industrial Economics 40: 55–84.
Katz ML, Shapiro C. 1994. Systems competition and network effects. Journal of Economic Perspectives 8(2): 93–115.
Kim N, Lee H, Kim W, Lee H, Suh JH 2015. Dynamic patterns of industry convergence: Evidence from a large amount of unstructured data. Research Policy 44(9): 1734–1748.
Lambkin M. 1988. Order of entry and performance in new markets. Strategic Management Journal, Summer Special Issue 9: 127–140.
Langley A. 1999. Strategies for theorizing from process data. Academy of Management Review 24(4): 691-710.
Lee J, O'Neal DE, Pruett MW, Thomas H. 1995. Planning for dominance: a strategic perspective on the emergence of a dominant design. R&D Management 25(1): 3–15.
Lee J, Lee J, Lee H. 2003. Exploration and exploitation in the presence of network externalities. Management Science 49(4): 553–570.

Lee E, Lee J, Lee J. 2006. Reconsideration of the winner take all hypothesis: complex networks and local bias. Management Science 52(12): 1838–1848.
Lee J, Song J, Yang J–S, 2016. Network structure effects on Incumbency advantage. Strategic Management Journal 37: 1632–1648.
Lieberman MB, Montgomery DB. 1988. First Mover Advantages. Strategic Management Journal 9: 41–58.
Lieberman M.B. 1989. The learning curve, technological barriers to entry, and competitive survival in the chemical processing industries. Strategic Management Journal 10(5): 431–447
Lieberman MB, Montgomery DB. 2013. Conundra and progress: Research on entry order and performance. Long Range Planning, 46: 312–324.
Loch CH, Huberman BA. 1999. A punctuated equilibrium model of technology diffusion. Management Science 54(2): 160–177.
Makadok R. 1998. Can first-mover and early-mover advantages be sustained in an industry with low barriers to entry/imitation? Strategic Management Journal 19(7): 683–696.
McFadden D., 1978. Econometric models of probabilistic choice. in (eds.) C. Manski, D. McFadden, Structural Analysis of Discrete Data with Econometric Applications. MIT Press, Cambridge, MA, pp 198-272.
McFadden D., 2001. Economic choices. American Economic Review 91(3), 351-378.
McIntyre DP, Subramaniam M. 2009. Strategy in network industries: A review and research Agenda. Journal of Management 35(6): 1494 - 1517.
McIntyre DP, Srinivasan A. 2017. Networks, platforms, and strategy: Emerging views and next steps. Strategic Management Journal 38(1): 141-160.
Murmann JP, Frenken K. 2006. Toward a systematic framework for research in dominant designs, technological innovations, and industrial chance. Research Policy 35: 925–952.
Narayanan VK, Chen T. 2012. Research on technology standards: Accomplishment and challenges. Research Policy 41: 1375–1406.
Ohori K, Takahashi S. 2012. Market design for standardization problems with agent based social simulation. Journal of Evolutionary Economics 22: 49–77.
Padmanabhan V, Rajiv S, Srinivasan K. 1997. New products, upgrades, and new releases: a rationale for sequential product introduction. Journal of Marketing Research 34(4): 456–472.
Papachristos, G, 2017. Diversity in technology competition: The link between platforms and sociotechnical transitions. Renewable and Sustainable Energy Reviews 73: 291-306.
Papachristos, G. 2012. Case study and system dynamics research: Complementarities, pluralism and evolutionary theory development. 30th International Conference of the System Dynamics Society, St Gallen, Switzerland online proceedings.
Papachristos, G. 2018a. Analytical sociology for sociotechnical transition research: Bridging case study and system dynamics. In proceedings of the 36th International System Dynamics Conference, 6th-10th August, Reykjavik, Iceland.
Papachristos, G. 2018b. A mechanism based transition research methodology: Bridging analytical approaches. Futures 98, 57-71. https://doi.org/10.1016/j.futures.2018.02.006
Papachristos, G. Van de Kaa, G. 2018. Understanding platform competition through simulation: A research outline. Technology Analysis and Strategic Management 30(12): 1409-1421.
Papachristos, G. 2020. Platform competition: A review and research outline for modelling and simulation research. Journal of Engineering and Technology Management 56: 101567.
Parker G, Van Alstyne M. 2005. Two-sided Network Effects: A Theory of Information Product Design. Management Science 51: 1494-1504.
Perrons RK. 2009. The open kimono: How Intel balances trust and power to maintain platform leadership. Research Policy 38(8): 1300–1312.
Rochet J–C, Tirole J. 2003. Platform Competition in Two–Sided Markets. Journal of the European Economic Association 1(4): 990–1029.
Rochet J-C, Tirole J. 2006. Two-Sided Markets: A Progress Report. RAND Journal of Economics 37: 645-667.

Sayer A. 1992. Method in social science: A realist approach. Routledge, UK.
Schilling MA. 1998. Technological lockout: an integrative model of the economic and strategic factors driving technology success and failure. Academy of Management Review 23(2): 267–284.
Schilling MA. 1999.Winning the standards race: Building installed base and the availability of complementary goods. European Management Journal 17(3): 265–274.
Schilling MA. 2002. Technology success and failure in winner–take–all markets: the impact of learning orientation, timing, and network externalities. Academy of Management Journal 45(2): 387–398.
Schilling MA. 2003. Technological leapfrogging: lessons from the U.S. video game console industry. California Management Review 45(3): 6–32.
Schilling MA. 2005. Strategic Management of Technological Innovation. New York: USA.
Shapiro C, Varian HR, 1999. Information Rules, a Strategic Guide to the Network Economy. Harvard Business School Press: Boston, Massachusetts.
Siggelkow N. 2007. Persuasion with case studies. Academy of Management Journal 50(1): 20–24.
Srinivasan A, Venkatraman VN. 2018. Architectural convergence and platform evolution: Empirical test of complementor moves in videogames. IEEE Transactions on Engineering Management DOI: 10.1109/TEM.2018.2881560
Sterman JD. 1989a. Misperceptions of feedback in dynamic decision making. Organizational Behaviour and Human Decision Processes 43(3)3: 301–35.
Sterman JD. 1989b. Modelling managerial behaviour: Misperceptions of feedback in a dynamic decision making experiment. Management Science 35(3): 321–39.
Sterman JD. 1994. Learning in and about complex systems. System Dynamics Review 10(2–3): 291–330.
Sterman JD. 2000. Business Dynamics: Systems Thinking and Modeling for a Complex World. Irwin McGraw–Hill: New York.
Suarez FF, Utterback JM. 1995. Dominant designs and the survival of firms. Strategic Management Journal 16(6): 415–430.
Suarez FF. 2004. Battles for technological dominance: an integrative framework. Research Policy 33(2): 271–286.
Suarez FF. 2005. Network effects revisited: the role of strong ties in technology selection. Academy of Management Journal 48(4): 710–720.
Suarez FF, Lanzolla G. 2005. The half–truth of first–mover advantage. Harvard Business Review 83(4): 121–127.
Suarez FF, Lanzolla G. 2007. The role of environmental dynamics in building a first mover advantage theory. Academy of Management Review 32(2): 377–392.
Tassey, G. 2000. Standardization in technology-based markets. Research Policy 29: 587-602.
Tegarden LF, Hatfield DE, Echols AE. 1999. Doomed from the start: What is the value of selecting a future dominant design?. Strategic Management Journal 20(6): 495–518.
Teece DJ. 1986. Profiting from technological innovation: implications for integration, collaboration, licensing, and public policy. Research Policy 15(6): 285–305.
Thrane S, Blaabjerg S, Møller RH. 2010. Innovative path dependence: Making sense of product and service innovation in path dependent innovation processes. Research Policy 39(7): 932–944.
Tiwana A, Konsynski B, Bush AA. 2010. Research Commentary–Platform evolution: Coevolution of platform architecture, governance, and environmental dynamics. Information Systems Research 21(4): 675–687.
Urban G.L., Carter T., Gaskin S., Mucha Z. 1986. Market share rewards to pioneering brands: an empirical analysis and strategic implications. Management Science 32(6): 645–659.
de Vaan M. 2014. Interfirm networks in periods of technological turbulence and stability. Research Policy 43(10): 1666–1680.

Van den Ende J, van de Kaa G, den Uijl S, de Vries HJ. 2012. The paradox of standard flexibility, The effects of co–evolution between standard and interorganizational network. Organization Studies 33: 705–736.
Van de Kaa G, van den Ende J, de Vries H, van Heck E. 2011. Factors for winning interface format battles: A review and synthesis. Technological Forecasting and Social Change 78: 1387–1411.
Van de Kaa G, de Vries HJ. 2015. Factors for winning format battles: A comparative case study. Technological Forecasting and Social Change 91: 222–235.
Van de Kaa, G, Papachristos, G, de Bruijn, H. 2018. The governance of platform development processes: a metaphor and a simulation model. Technology Forecasting and Social Change https://doi.org/10.1016/j.techfore.2018.08.021
Vaughan-Nichols, S., 2002. Bull Market for IEEE 802.11 WLAN Chipsets. Computer, vol. 35, 17-19. doi:10.1109/MC.2002.1046966.
Vidal E., Mitchell W. 2013. When do first entrants become first survivors?. Long Range Planning 46: 335-347.
Weick KE. 1989. Theory construction as disciplined imagination. Academy of Management Review 14(4): 516–531.
Wilson C. 2012. Up–scaling, formative phases, and learning in the historical diffusion of energy technologies. Energy Policy 50: 81–94.
Windrum P., Birchenhall C. 1998. Is product life cycle theory a special case? Dominant designs and the emergence of market niches through coevolutionary-learning. Structural Change and Economic Dynamics 9: 109-134.
Windrum P. 2004. Leveraging technological externalities in complex technologies: Microsoft's exploitation of standards in the browser wars. Research Policy 33: 385–394.
Wonglimpiyarat J. 2005. Standard competition: Is collaborative strategy necessary in shaping the smart card market?. Technology Forecasting and Societal Change 72(8): 1001–1010.
Wuisman JJJM. 2005. The logic of scientific discovery in critical realist social scientific research. Journal of Critical Realism 4(2): 366–394.
Zhu F, Iansiti M. 2012. Entry into platform based markets. Strategic Management Journal 33: 88–106.
Zott C, Amit R, Massa L. 2011. The Business Model: Recent Developments and Future Research. Journal of Management 37(4): 1019–1042.

APPENDIX A SENSITIVITY ANALYSIS TABLE

Case 1	Firewire (min,max)	USB (min,max)	step
5 Technological Advantage - Learning	0.1,0.1	0.1,0.4	0.1
5 Technological Advantage - Initial Technical & Market Know-How	0.2,1	0.2,0.2	0.1
11 Timing of Entry	1,1	1,10	1
15 Commitment	0.1,0.1	0.1,0.8	0.1
Case 2	**Wifi (min,max)**	**HomeRF (min,max)**	
5 Technological Advantage - Learning	0.1,0.4	0.1,0.1	0.1
5 Technological Advantage - Initial Technical & Market Know-How	0.3,0.4	0.3,0.3	0.1
11 Timing of Entry	0.5,0.5	0.5,2	0.5
12 Marketing Communication	0.1,0.4	0.1,0.1	0.1
15 Commitment	0.2,0.6	0.2,0.2	0.1
Case 3	**MPEG (min,max)**	**AC3 (min,max)**	
2 Brand reputation - Past Performance in Setting Standards	0.2,0.2	0.2,1	0.2
5 Technological Advantage - Learning	0.1,0.1	0.1,0.4	0.1
5 Technological Advantage - Initial Technical & Market Know-How	0.3,0.3	0.3,0.9	0.3
6 Backward Compatibility between Standards Generations	0.4,1	0.4,0.4	0.2
7 Initial Complementary Goods Rate	0.2,0.2	0.2,0.8	0.2
12 Marketing Communication	0.1,0.1	0.1,0.6	0.1
15 Commitment	0.1,0.1	0.1,0.9	0.2
17 Previous installed base	0,20	0,0	5
Case 4	**Blu Ray (min,max)**	**HD DVD (min,max)**	
2 Brand reputation and credibility - Past Performance in Setting Standards	0.4,1	0.4,0.4	0.2
15 Commitment	0.3,0.8	0.3,0.3	0.1

APPENDIX B LINKS OF CAUSAL RELATIONS TO THE LITERATURE

Table C1 Links of causal relations in Figure 2 to the literature

Influence	Reference	Influence	
1	Van de Kaa *et al.*, 2011.	18	Hill, 1997; Van de Kaa *et al.*, 2011.
2	Gawer and Cusumano, 2014; Suarez, 2004; Schilling, 1998	19	Van de Kaa et al., 2011.
3	Schilling, 1998; Schilling, 2002.	20	Van de Kaa *et al.*, 2011.
4	Schilling, 1998; Van de Kaa *et al.*, 2011.	21	Schilling, 1998.
5	Schilling, 1998; Van de Kaa *et al.*, 2011.	22	Van de Kaa *et al.*, 2011.
6	Schilling, 1998.	23	Katz and Shapiro, 1994; Hill, 1997; Suarez, 2004
7	Schilling, 1998; Schilling, 2002; Cohen and Levinthal, 1990	24	Katz and Shapiro, 1994.
8	Schilling, 1998; Van de Kaa *et al.*, 2011; Cohen and Levinthal, 1990	25	Zhu and Iansiti, 2012; Hill, 1997; Suarez, 2004; Schilling, 1998.
9	van de Kaa and de Vries, 2015.	26	Suarez, 2004; Van de Kaa *et al.*, 2011.
10	Hill, 1997.	27	Hill, 1997; Schilling, 1998.
11	Hill, 1997.	28	Dew and Read, 2007; Suarez, 2004; Schilling, 1998
12	Hill, 1997.	29	Suarez, 2004; Schilling, 1998; Van de Kaa *et al.*, 2011.
13	Van de Kaa *et al.*, 2011.	30	Gawer and Cusumano, 2014; Hill, 1997; Suarez, 2004; Schilling, 1998, 2000
14	Hill, 1997; Van de Kaa *et al.*, 2011.	31	Gawer, 2014; Hill, 1997; Suarez, 2004
15	Schilling, 1998; Schilling, 2002.	32	Hill, 1997; Schilling, 1998; Schilling, 2002
16	Schilling, 1998; Schilling, 2002.	33	Suarez, 2004; Dew and Read, 2007; Cenamor *et al.*, 2013.
17	Van de Kaa *et al.*, 2011.	34	Hill, 1997; Schilling, 1998.

Table C2 Links of influences in Figure 3 to the literature

Influence	Reference
1	Suarez, 2004; Schilling, 1998.
2	Hill, 1997; Schilling, 1998; Schilling, 2002; Van de Kaa *et al.*, 2011.
3	Burnham *et al.*, 2003.
4	Cennamo and Santalo, 2013; Burnham *et al.*, 2003.
5	Zhu and Iansiti, 2012; Burnham *et al.*, 2003.
6	Suarez and Lanzolla, 2007; Van de Kaa *et al.*, 2011.
7	Van de Kaa *et al.*, 2011.
8	Suarez and Lanzolla, 2007. Van de Kaa *et al.*, 2011.
9	Dew and Read, 2007; Burnham *et al.*, 2003; Schilling, 1998.
10	Suarez and Lanzolla, 2007.
11	Hill, 1997.
12	Hill, 1997.
13	Suarez and Lanzolla, 2007; Van de Kaa *et al.*, 2011.
14	Narayanan and Chen, 2012; Suarez, 2004.
15	Narayanan and Chen, 2012; Suarez, 2004.
16	Hill, 1997; Van de Kaa *et al.*, 2011.
17	Sterman, 2000; Van de Kaa *et al.*, 2011.
18	Hill, 1997; Van de Kaa *et al.*, 2011.
19	Hill, 1997; Suarez, 2004; Van de Kaa *et al.*, 2011; Cenamor *et al.*, 2013.
20	Sterman, 2000; Van de Kaa *et al.*, 2011.
21	Arthur and Lane, 1993.