Interactive web-based simulations for strategy and sustainability: The MIT Sloan *LearningEdge* management flight simulators, Part I

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Abstract

The MIT Sloan School of Management has created a set of interactive, web-based management flight simulators to teach key ideas in business, strategy, sustainability and related fields. The simulations are freely available through the MIT Sloan *LearningEdge* portal (mitsloan.mit.edu/LearningEdge). In these notes I describe six simulations available as of 2014. Part I describes *Salt Seller* (a multiplayer commodity pricing simulation); *Eclipsing the Competition* (learning curves, using the solar photovoltaic industry as the example); and *Platform Wars* (competition in the presence of network externalities using the video game industry as the context). Part II describes *Fishbanks* (the Tragedy of the Commons in the context of renewable resource management, updating the classic game by Dennis Meadows); *CleanStart* (building a startup firm, with clean tech as an example); and *World Climate* (an interactive role play of global climate negotiations). Each simulator enables participants to learn experientially about important concepts in management, strategy and/or sustainability. Each is grounded in a particular industry or firm, and comes with original case studies or briefing material describing the strategic challenges in these settings. Through these simulations, students, executives, policymakers and others can explore the consequences of different strategies so they can learn for themselves about the complex dynamics of difficult issues. I describe their purpose and use, illustrate their dynamics and outline the instructor resources available for each.

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Flight simulators for management education

Simulations are now an essential element in training for pilots, power plant operators, doctors, the military and many others who work in complex, high-risk settings. Management flight simulators (MFS)—simulations of complex operational and strategic issues in businesses and other organizations—also have a long history, going back at least to the Beer Distribution Game (Sterman, 1989; Jarmain, 1963), a board game based on the supply chain model developed by Forrester (1958, 1961).

Flight simulators in aviation and other high-risk settings are used to train personnel not merely in routine operations but in how to handle emergencies. "'Pilots don't spend their training time flying straight and level,' says airline pilot Lynn Spencer .... 'In simulator training, we're doing nothing but flying in all sorts of emergencies. Even emergencies become just another set of procedures when repeatedly trained'" (Newman, 2009).

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Management flight simulators also serve that function, but have a deeper purpose as well: many scholars and studies suggest that the traditional modes of instruction in colleges, universities and professional schools, based on lecture and discussion, in which teachers play the role of "the sage on the stage" (King, 1993), are ineffective, specifically in overcoming common conceptual errors, building actionable knowledge, enhancing problem solving skills and developing systems thinking abilities (the literature is massive: see, for example, King, 1993; Papert, 1993; Dori and Belcher, 2005; Mazur, 1997; Lasry *et al.*, 2008; Kim and Pak, 2002; Sterman, 2000). Some scholars argue that management education, whether based on lectures or the case study method, is particularly prone to these failures (Pfeffer and Fong, 2002; Mintzberg, 2005).

Alternatives to the transmission model of learning are variously known as constructionism, interactive learning, learner-directed learning or action learning, in which teachers play the role of "the guide on the side" (King, 1993). Many make the case that learning and innovation in business and other organizations require similar approaches, emphasizing experimentation, simulations and "serious play" (Pfeffer and Sutton, 2000; Schrage, 2000; Thomke, 2003; Aldrich, 2009). Despite some differences, all argue that learning (only) occurs when learners (re)construct their mental models, beliefs and habits through active engagement with a system. Constructionists stress the importance of interaction between learners and the issues through experience and experimentation, not merely (though not entirely instead of) the presentation of facts, theory, formulae and examples. Just as one can't become a skilled carpenter only by studying wood and tools but must actually build things, so too one can't become a skilled pilot, surgeon or executive without actually flying, operating, or managing. The reason is clear: from basic motor skills such as catching a baseball to sophisticated cognitive skills such as designing a circuit, there is no learning without feedback, without knowledge of the results of our actions. Transmission models provide no such feedback, while interactive, constructionist methods stress experimentation that provides rich feedback from close engagement with the material.

However, constructionist approaches face a formidable problem: we cannot directly gain experience or experiment with many important systems. In many settings the time delays in the impacts of our decisions are far longer than the time available for learning, training, or even our career or lifespan. In others, experimentation is simply impossible—we have only one planet and cannot run experiments to determine what the impact of alternative pathways for greenhouse gas emissions will be. Even when experimentation is possible and lags are short, experience, as the saying goes, is an expensive school: in many settings (e.g. aviation, surgery, business), the consequences of mistakes can be fatal (e.g. crashes, medical errors, violations of safety procedures that lead to plant accidents). More subtly, in many systems, the local and distal, and short- and long-term impacts of decisions differ: what

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works here and now often harms the system elsewhere and later (Forrester, 1969; Repenning and Sterman, 2001, 2002; Sterman, 2011). Settings, including constructionist classrooms, in which we only experience the local, immediate consequences of our decisions may bias what we learn towards actions that may appear to be sensible, but in fact work against our own goals and values. Thus educators face a dilemma: on the one hand, one can lecture about the long-term, system-wide impacts of policies, but lecture is ineffective; on the other hand, peer instruction, demonstrations, role plays and similar action-learning experiences that can be carried out within the physical and temporal constraints of the classroom or field project may systematically teach ineffective or harmful lessons.

Simulations offer a resolution to the dilemma. Simulations can compress or expand time and space, allowing learners, for example, to simulate decades in the life of an airline or a century of climate change in a few minutes (Sterman, 1988; Sterman *et al.*, 2012, 2013). Management flight simulators in the system dynamics tradition have tended to address issues with long time delays and broad-scale impacts rather than real-time tasks such as flying an aircraft or operating a power plant (e.g. Graham *et al.*, 1992; Morecroft and Sterman, 1994; see also the simulations available from Forio.com, iSee Systems and Strategy Dynamics, among others).

When experimentation is too slow, too costly, unethical or just plain impossible, when the consequences of our decisions take months, years or centuries to manifest, that is, for most of the important issues we face, simulation becomes the main—perhaps the only—way we can discover *for ourselves* how complex systems work and where high leverage points may lie.

The MIT Sloan Management flight simulators

Although some system-dynamics based MFS are freely available (e.g. the Beer Game), others are available for a fee, and some are proprietary. Simulators that are freely available can promote diffusion, particularly in the K-12 and college sectors, where funds are limited. The MIT Sloan School of Management, in keeping with the open access philosophy embodied in MIT's OpenCourseware (ocw.mit.edu) and MITx initiatives (mitx.mit.edu), established the MIT Sloan *LearningEdge* website (mitsloan.mit.edu/LearningEdge) as a portal to provide case studies, simulations and other materials to teach management principles. All materials provided on *LearningEdge* are freely available for individual and academic use. At present (2014), *LearningEdge* hosts a set of six system dynamics-based MFS, designed to teach core principles of economics, strategy, dynamics and sustainability. More are under development.

In this and the subsequent note I describe six simulations: *Salt Seller* (a multiplayer commodity pricing simulation); *Eclipsing the Competition* (learning

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curves and scale economies in the solar photovoltaic industry); *Platform Wars* (competition in the presence of network externalities using the video game industry as the context); *Fishbanks* (the Tragedy of the Commons in the context of renewable resource management, updating the classic game by Dennis Meadows), *CleanStart* (building a startup business in cleantech), and *World Climate* (an interactive role play of global climate negotiations). Each simulator teaches important general concepts in management, strategy, entrepreneurship or sustainability. Each is also grounded in a specific example, such as a particular industry, firm or public policy issue, and comes with original case studies, video users' guides and briefing materials describing the strategic challenges faced by managers and executives in these settings.

Together the simulators span an array of the core concepts relevant to managers, management students and anyone interested in the substantive issues, from pricing to competitive strategy to resource management to multi-sided markets and more. Table 1 lists the simulators together with the industry and case study upon which they are based, the key concepts they address and typical courses in which they might be used. The simulators can be used alone, or together in a sequence (as we have done at MIT Sloan, where they have been used in the core MBA strategy course, and in executive education).

The most basic simulator, *Salt Seller*, gives participants the opportunity to set prices for a commodity in an important industry, but one whose cost structure and competitive dynamics are relatively straightforward: marginal production costs are constant, the product is not differentiated and the industry is generally stable (little entry or exit, slow demand growth, slow technological change, few opportunities for cost reductions). While understanding the basic dynamics of such markets is fundamental, many products are highly differentiated, so competition takes place on other dimensions besides price. Demand is often highly dynamic, growing dramatically as new products are introduced, and as endogenous cost reductions and functionality improvements enhance the attractiveness of the products relative to alternatives. Radical, disruptive new technologies can arise and threaten the franchise of existing players. Further, many markets are characterized by various externalities, both positive and negative. Environmental damage caused by production is a negative externality; for example, emissions of CO_2 produced by firms harm human welfare by contributing to climate change, but CO_2 emitters (at present) do not pay the costs of that damage. Positive externalities arise when a firm generates benefits to others for which it is not paid: a firm's investment in fire protection to protect its assets also reduces the risk of fire for neighbors. Externalities can change the nature of competition and the optimal strategy for individual firms. The other simulators address different classes of important externalities. *Eclipsing the Competition*, based on the solar photovoltaic industry, considers competition in the presence of learning curves (also known as experience curves). In such cases, the future costs of production fall as cumulative production experience and/or investment in process improvement

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Table 1. *LearningEdge* simulators with key attributes and uses

	Salt Seller	Eclipsing the Competition	Platform Wars	Fishbanks	CleanStart	World Climate
Strategic issues addressed:	Pricing dynamics in imperfectly competitive markets	Strategy in the presence of learning curves and scale economies	Strategy in multi-sided platform markets; direct and indirect network externalities	The Tragedy of the Commons; strategy for open-access renewable resources	Entrepreneurship; marketing, product development, financing, employee ownership	Climate policy; negotiations; collective action and the Tragedy of the Commons
Industry focus	Salt industry	Solar photovoltaic industry	Video game industry	Fisheries	Clean tech	Global climate change
Accompanying case study:	Compass Minerals	SunPower	Sony PS3	Multiple examples	Multiple examples	IPCC publications and related scientific literature
Single or multiplayer:	Multiplayer or play against the computer	Play against the computer	Play against the computer	Multiplayer	Play against the Computer	Multiplayer
Simultaneous players:	1–8 players in each market; multiple, simultaneous markets supported	Unlimited	Unlimited	1–10 fishing companies per ocean; multiple simultaneous oceans supported	Unlimited	Teams of various sizes divided into 3 or 6 delegations representing different nations and regions
Useful in courses:	Economics, strategy, decision-making, game theory, system dynamics	Economics, strategy, technology policy, energy policy, environmental policy, sustainability, system dynamics	Economics, strategy, technology policy, system dynamics	Economics, strategy, negotiations, sustainability, environmental studies, public policy, resource economics, system dynamics	Entrepreneurship, human resources, economics, strategy, sustainability, system dynamics	Economics, strategy, negotiations, sustainability, environmental studies, public policy, resource economics, system dynamics

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grow: current production generates a positive externality affecting future costs, for the firm and, when knowledge is not privately appropriable, for its rivals. As discussed below, the presence of such learning processes can dramatically change the nature of effective strategy.

Platform Wars expands the scope of externalities treated in the model to include direct and indirect network externalities. A direct network externality exists when the attractiveness of a product depends on the number of product users (the installed base), for example the telephone, fax and World Wide Web. An indirect network externality arises when the attractiveness of a product depends significantly on the stock of complementary products or services that make the product more useful, for example apps for smartphones, software for the Windows operating system and Blu-Ray compatible DVDs. Competition in such markets is multi-sided; for example, a video game hardware producer such as Sony competes not only for a share of console purchases by the public but in the market for game development as it seeks to build the largest and best stock of game titles available for its platform.

The experience curve and network effects are examples of positive externalities. *Fishbanks* addresses a pervasive negative externality: resource depletion. Fishbanks simulates competition for an open-access renewable resource. Such resources are subject to the Tragedy of the Commons (Hardin, 1968); fisheries, unfortunately, offer many examples. Fishbanks offers participants an opportunity to experience the self-inflicted destruction of the resource, and the chance to negotiate and enforce self-regulation to preserve the resource and yield sustainable business success.

World Climate extends the issue of negative environmental externalities to global climate change. Participants are divided into delegations representing different nations and negotiate international agreements to limit greenhouse gas emissions. Their proposals are then evaluated using the C-ROADS climate policy simulation, a model that is used by real-world climate negotiators and policymakers (Sterman *et al.*, 2012, 2013, 2014).

CleanStart examines the dynamics of entrepreneurship, with the clean tech industry as the context. Participants build a business, starting with a great idea, a garage and a little startup capital, and must win customers, hire and motivate people, improve the product and finance their growth. Participants can choose external financing from venture capitalists or seek to build a fully employee-owned firm. Parameters can be varied to capture different industry conditions, including whether externalities such as environmental damage from greenhouse gases are captured by a carbon price.

The simulators are all implemented in Forio Simulate (forio.com) as interactive web-sims, accessible via any standard web browser. Users can play as individuals or as part of a "class"—a scenario created by an instructor or workshop facilitator in which many people can play under the same conditions. The ability to create "classes" enables instructors to design a sequence of scenarios that guide participants through a structured learning sequence.

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For example, one can design a sequence of classes for the solar simulator that begin with the classic conditions discussed in learning curve strategy: a strong learning curve with highly elastic industry demand, myopic competitors, no knowledge spillovers (i.e. all cost reductions from learning are privately appropriable and specific to the individual firm) and no possibility for the entry of radical new technologies. Later scenarios can relax these assumptions, individually or cumulatively, for example, allowing knowledge spillovers, entry of new players with radical new technologies, and/or more aggressive competitors. Instructors can also decide whether players can see the settings for a given class/scenario and, if so, whether they can change them or not. Instructors can also access the results of the games in any class they establish, in real time as play unfolds or afterwards, to monitor and control play, present results and download results for other purposes including research, grading or prizes. Instructors who register with *LearningEdge* also receive free access to all teaching materials for the simulations, for example teaching notes, debrief guides or short videos explaining how to set up and run classes and use the simulations.

Salt Seller: pricing in imperfectly competitive markets

Pricing is one of the most basic decisions firms must make. Managers, management students, consumers—everyone—should understand the dynamics of pricing. Some, particularly managers and management students, have taken economics courses, mostly at the introductory level. However, few markets approximate the perfect competition described in introductory economics texts, and few firms are simple price-takers. Imperfect, or monopolistic, competition is more typical: demand at the firm level is not perfectly elastic and many markets are dominated by a small number of firms. Price not only influences the purchasing decisions of consumers but signals important information to the firm's rivals. Consequently, pricing is one of the most basic strategic decisions firms must make. In imperfectly competitive markets producers have some ability to extract rents from customers, if they can signal to their rivals their willingness to focus on margin rather than market share; if successful, firms can earn abnormal returns at the expense of consumers. However, firms always face the temptation to undercut their rivals to gain market share, possibly leading to a price war.

The Salt Seller simulation provides an interactive multiplayer environment in which participants experience the challenge of setting prices in an imperfectly competitive market. Participants play the roles of salt producers in a region of North America, and bid for contracts to supply salt to customers such as counties, towns and municipalities who use salt to de-ice roadways in winter. The simulator is coupled with an original case study (Henderson *et al.*, 2009) to illustrate the strategic issues facing producers. The case describes

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the salt industry, production methods, demand and market dynamics, using the case of Compass Minerals, a salt producer on the eve of its initial public offering.

The structure and dynamics illustrated in Salt Seller are relevant to a wide range of industries, where price is a major determinant of product attractiveness and where there is either no ability to differentiate (as in pure commodities) or where imitation limits the ability to differentiate on quality, features, functionality or other attributes. Examples include agricultural commodities, minerals, fossil fuels such as coal and natural gas, and even high-tech products such as DRAM (dynamic random access memory).

Salt is well suited as a focal case to illustrate the dynamics of pricing in imperfectly competitive markets. Salt is necessary for life and, until the 20th century, was scarce and expensive—often more valuable than gold. Indeed, Roman soldiers were paid in salt, and the Latin word for salt—*sal*—is the root of the words "soldier" and "salary" (Kurlansky, 2002). Salt has played important roles in geopolitics, exemplified by the 1930 salt march, in which Ghandi and his supporters marched to the sea and made salt from evaporation of brine, in defiance of the British salt monopoly and taxes Britain imposed on salt production in India. In the 20th century, with the development of technology to mine salt from massive salt domes, the real price of salt fell and its use increased dramatically (Figure 1). Salt today is used in a wide range of

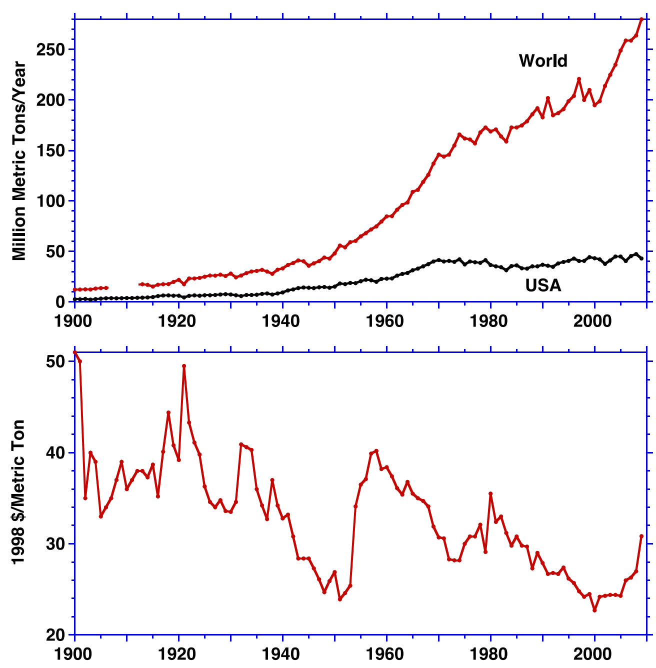

Fig. 1. Top: U.S. and world salt production, million metric tons per year. Bottom: real U.S. salt price, average of all production methods, 1998 dollars per metric ton. Source: U.S. Geological Survey (http://minerals.usgs.gov/ds/2005/140/); see also Henderson *et al.* (2009)

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applications, including roadway de-icing, water treatment, food processing, and industrial processes in chemicals, textiles, pulp and paper and oil refining. Among these, industry and roadway de-icing are by far the largest end-users, together accounting for roughly three-quarters of all U.S. salt consumption (Henderson *et al.*, 2009). The largest sources of salt are rock salt and brine produced from salt domes (together approximately 80 percent of total production). The chemical industry predominantly uses brine, while the ice control sector is overwhelmingly dependent on rock salt.

As technology improved, real prices fell from roughly \$40–50 per ton around 1900 to about \$25–30 per ton in recent years (1998 dollars). However, production and especially prices vary substantially from year to year. The variations arise from both external changes in weather and economic activity and from the internal responses of producers as they compete against one another.

In the de-icing market, municipalities, towns and counties responsible for highway de-icing conduct auctions each year to source rock salt in preparation for winter. As a commodity, there is little product differentiation in the salt itself. However, transportation costs constitute a large fraction of the total delivered price. Figure 2 shows the location of major salt mines in North America. There are major mines in, for example, Michigan, Ohio, Pennsylvania, Kansas and Saskatchewan. Clearly, producers in Michigan and Ohio have an advantage relative to others with respect to municipalities in, say, Illinois, while producers in Kansas can offer lower delivered prices to cities and towns in the central states. Consequently, the market is not perfectly competitive; producers have some degree of local monopoly power based on proximity to end-users.

The economic theory underlying such markets is well known. The salt market is an example of Bertrand competition, in which producers set prices (the bids they submit to end-users) and then customers choose quantities from each supplier given those prices. The textbook account of Bertrand competition assumes that capacity is perfectly flexible, so that producers can supply whatever customers demand, given prices—a reasonable assumption for the rock salt industry, where mines have the capacity to meet typical variations in year-to-year demand. The classic Bertrand model can be illustrated with the example of two identical producers (with the same marginal cost). For simplicity, assume firm-level demand is infinitely price-elastic (industry-level demand has finite elasticity). If the firms could collude and had perfect information, the optimal price would be the monopoly level, which, because industry demand is not perfectly elastic, is above marginal cost; each firm would take half the market and earn the maximum margin on each ton sold, extracting rents from consumers. However, if one firm prices just below its rival, it would win the entire market and increase its profits. The other firm faces the identical incentive to undercut its rival. Consequently, each firm will undercut the other until prices fall to marginal cost, the unique Nash equilibrium for the non-cooperative case.

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Fig. 2. Major salt deposits and production sites in North America. Source: The Salt Institute; Henderson *et al.* (2009)

Explicit collusion to set prices is, in the U.S.A. at least, illegal. But implicit, tacit collusion can arise through signaling. A producer may signal its willingness to maintain high prices by posting prices for its rivals to see, and by retaliating with temporary price cuts if others cut their prices. When imperfect information on costs, signaling, retaliation and other strategic moves are introduced into the Bertrand model, pricing becomes a dynamic, multiplayer game, with outcomes including prices sustained above marginal cost, price wars that drive price down to or even below marginal cost, or periods of high prices punctuated by temporary price wars as means of retaliation to discipline producers who attempt to undercut their rivals (Green and Porter, 1984).

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The Salt Seller simulator creates the opportunity for participants to learn about these dynamics experientially. Salt Seller is a multiplayer simulation in which participants play the role of salt producers. Each round (simulated year), each participant enters a bid—the price at which they are willing to supply salt to end-users. Participants enter their bids independently and without knowing what the bids of others will be. After all bids are in, the simulator determines the quantity ordered from each producer and displays industry demand, market share, firm demand, revenue, costs, profits and other key industry and financial data. Participants update their beliefs about the likely behavior of their rivals and then enter their bids for the next round.

The simulator can be played as an individual, in which case rivals are simulated by the computer using behavioral decision rules for price-setting, or in a multiplayer version, with between two and eight players (firms) competing in the market. Demand is simulated by the computer using a standard logit choice model. For simplicity, there is no entry of new firms (players) and no exit of existing firms. There are no capacity constraints and marginal production costs are constant—plausible assumptions for the salt industry over the range of variation in demand that can arise in the game.

Administrators can set a variety of parameters when creating a "class" (see above), including the industry demand elasticity, the firm-level demand elasticity (the sensitivity of market share to price in the logit choice model), the trend in industry demand and whether demand is stochastic or deterministic (Figure 3). Instructors can select a "mystery scenario" option in which the trends in the underlying demand for salt and other parameters are not known to the players in advance.

Administrators can also set the length of the game, choosing either a fixed length or selecting a random end time (between 5 and 20 rounds). The random end time is designed to eliminate horizon effects that may arise when participants know the game is drawing to a close. For example, participants may undercut their rivals when they know there are only one or two rounds left in the belief that the game will end before their rivals can retaliate.

Finally, administrators choose how long players have to make their decisions. The default is 2 minutes per decision round. Testing showed 2 minutes to be long enough for people to deliberate and to consult with teammates (when playing in groups), but short enough to make for an exciting and fast-paced game when played in a classroom or workshop. The next round begins either when all players have submitted their decisions or when the timer expires, whichever comes first. Play typically speeds up after the first few rounds. If a player does not submit a decision before the timer expires, the prior period's price for that player is used.

Figure 4 shows typical results for a two-firm game. In the top panel, the focal player, screen name "Salty Dog", repeatedly attempts to signal an interest in higher prices, but the competitor consistently prices lower and does not respond. Salty dog is successfully exploited by the competitor: while both are

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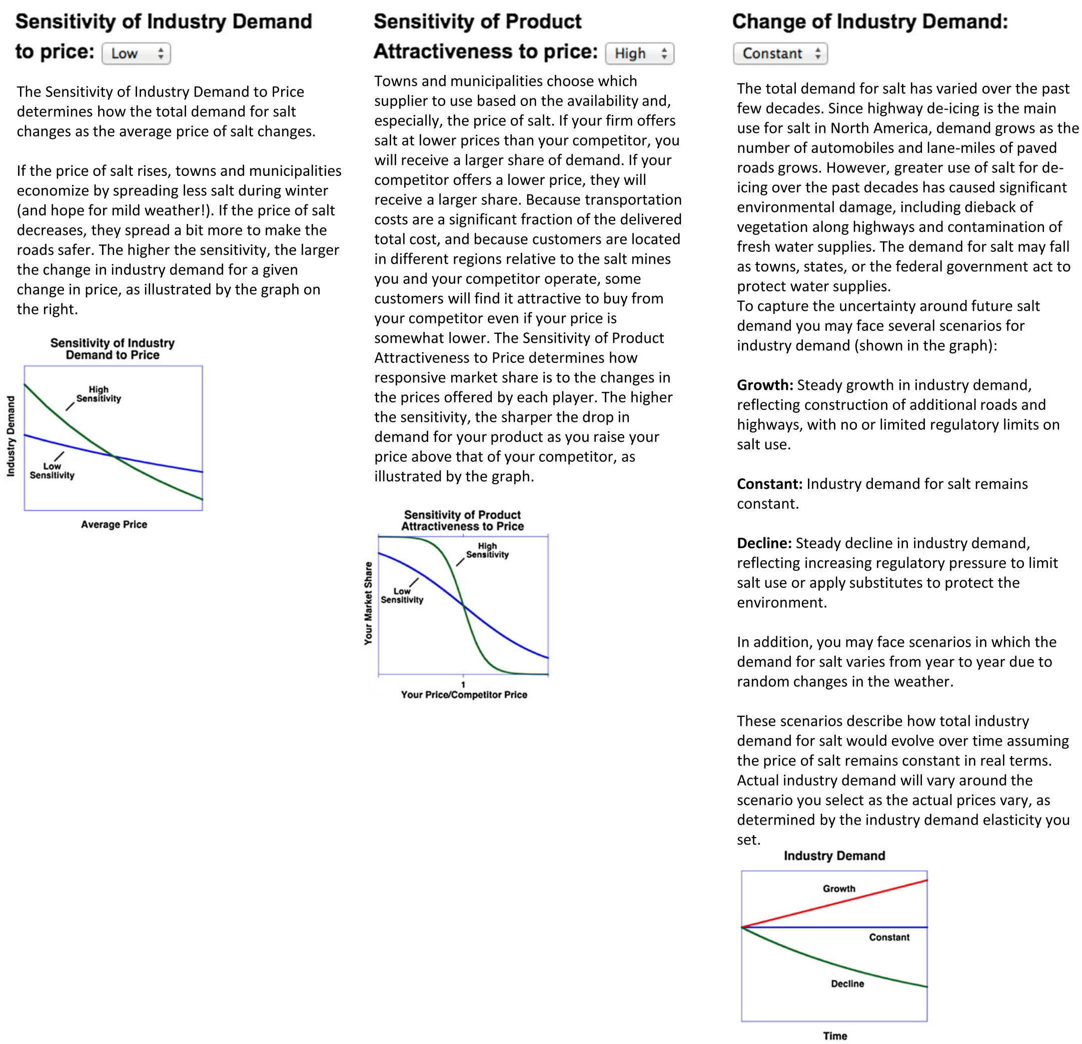

Fig. 3. Scenario settings in the Salt Seller simulator. Administrators can choose a variety of values for key parameters to capture a wide range of market conditions. Administrators can also add random variation to the trend in demand

profitable in the first few years, the competitor earns substantially more. In year 8, Salty Dog punishes the competitor by pricing at $19 per ton, below marginal cost. The competitor responds by pricing even lower the next year, while Salty Dog raises prices to about $25 per ton. As the game ends in year 10, Salty Dog has lost a cumulative total of about $150 million, with the competitor losing roughly $300 million from year 7 to 10. In the bottom panel, the players reach a collusive equilibrium in which prices are close to equal and

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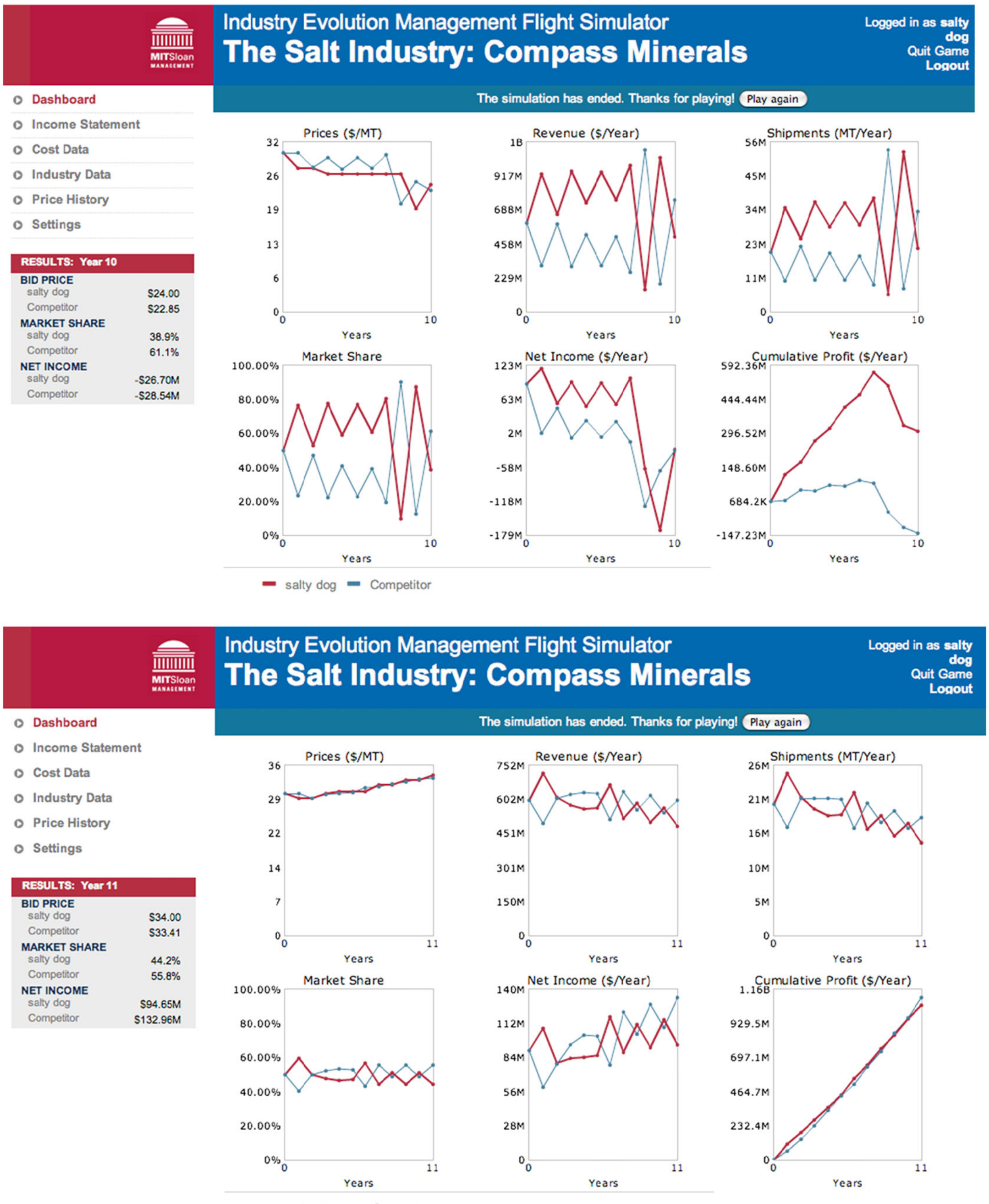

Fig. 4. Top: example game illustrating price war. Bottom: example game illustrating successful signaling and tacit collusion to achieve high profits

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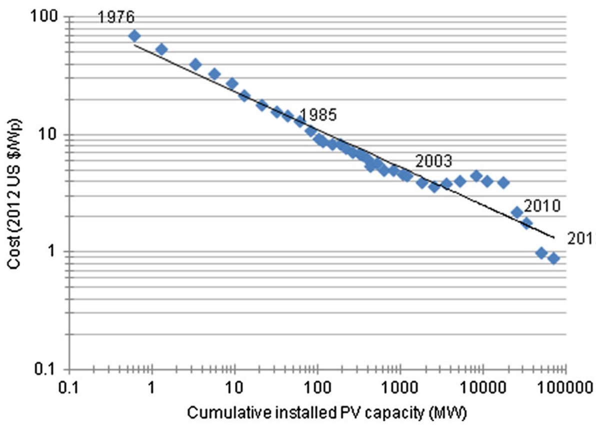
rise slightly each year. Market share remains approximately 50 percent for each, and the players resist the temptation to undercut their rival. Cumulative profits by year 11 are over $1 billion each. In the live class sessions we run, price war is far more common. One student commented, "I knew what I was supposed to do, but when [the rival firm] undercut me, I had to retaliate."

Eclipsing the Competition: learning curves in the solar photovoltaic industry

Competition in many of the most important industries around the world is more complex than the standard textbook model illustrated by Salt Seller. An important class of positive externality arises from so-called increasing returns, in which costs and product attractiveness increase with the scale of production, forming positive feedbacks that can confer cumulative advantage to the market leader (Sterman, 2000, Ch. 10, provides a summary). Learning curves and scale economies are a particularly common class of such positive feedbacks. Eclipsing the Competition creates an interactive simulator around competition in the presence of learning curves and scale economies. Learning curves are common in a wide range of industries and create a reinforcing feedback that can potentially confer competitive advantage on the first mover or firms that expand aggressively through low initial pricing and rapid capacity expansion.

Eclipsing the Competition focuses on the solar photovoltaic industry. The solar industry illustrates the dynamics of learning and scale well: unit costs are falling on a roughly 20 percent experience curve (20 percent cost reduction per doubling of cumulative production experience), while industry volume has been growing at 30 percent per year or more, doubling in less than 3 years (Figures 5 and 6). The industry is also vital to the creation of a

Fig. 5. Solar Photovoltaic experience curve. Source: Martínez-Duart J, Hernández-Moro J. 2013. *Journal of Nanophotonics* **7**(1): 078599–078599. doi: 10.1117/1.JNP.7.078599



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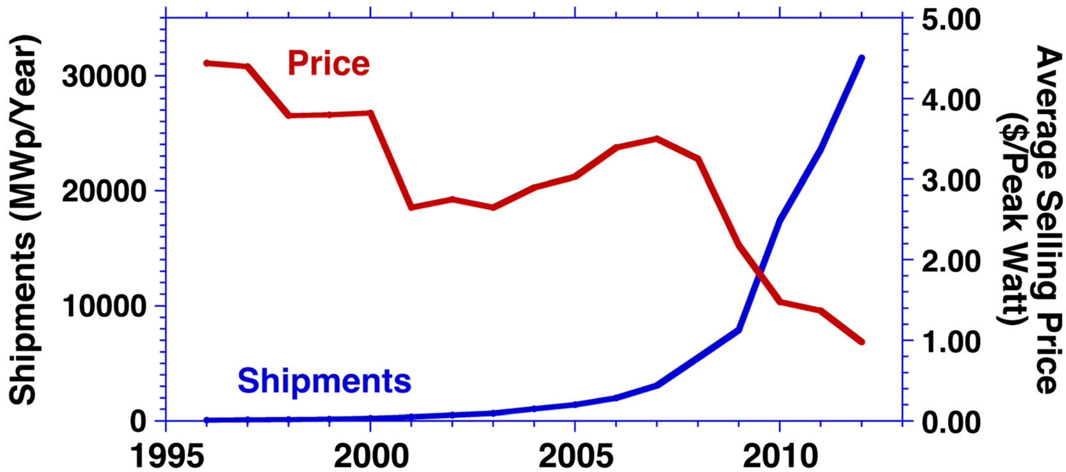

Fig. 6. World solar photovoltaic shipments (MW peak capacity per year) and average selling prices (dollars per peak watt). Source: http://www.renewableenergyworld.com/rea/news/article/2012/11/the-solar-pv-ecosystem-a-brief-history-and-a-look-ahead

low-carbon renewable energy system and involves significant issues of industrial policy, competition for green jobs and industry dominance among major nations, and the development of radical new technologies. Further, the solar PV industry is still in the early stages of evolution. Unlike many cases used to teach strategy, the role of solar in future energy systems, and future winners and losers within the industry, have yet to be determined. The "right" strategy for producers and for governments seeking to promote their own solar industry is neither obvious nor subject to hindsight bias.

The simulator is coupled with an original case focusing on SunPower, a leading PV producer founded in the U.S.A. (Henderson *et al.*, 2007). Participants take the role of senior executives at SunPower and seek strategies for success in the presence of learning curves and scale economies. Simulation administrators can select from a wide range of settings so that participants can explore the robustness and vulnerabilities of different strategies to issues including technology spillovers, aggressive competitor pricing and the entry of new, superior technologies.

The conventional wisdom in the popular management literature is that the presence of learning curves and scale economies favors a "Get Big Fast" (GBF) strategy. As one management book breathlessly put it, "By slashing prices below costs, winning the biggest share of industry volume, and accelerating its cost erosion, a company [can] get permanently ahead of the pack … [and build] an unchallengeable long-term cost advantage" (Rothschild, 1990, p. 181). Similarly, in 1996 the *Wall Street Journal* noted the popularity of "the notion of increasing returns, which says that early dominance leads to near monopolies as customers become locked in and reluctant to switch to

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competitors. Now, dozens of companies are chasing market share" (Hill *et al.*, 1996). Aggressive strategies appear to have led to durable advantage in industries with strong learning curves such as synthetic fibers, chemicals and disposable diapers (Shaw and Shaw, 1984; Lieberman, 1984; Ghemawat, 1984; Porter, 1984), and in markets such as personal computers and e-commerce (Sterman, 2000; Oliva *et al.*, 2003).

The logic is captured by the feedbacks shown in Figure 7. A firm's sales (and hence production) are given by industry demand and the firm's share of that market. The greater the sales, the greater is the scale of operations, leading to lower unit costs through a variety of processes, from engineering scale efficiencies to greater market power in labor and factor markets (Sterman, 2000, Ch. 10, notes over three dozen positive feedbacks that can lead to self-reinforcing growth of sales). Lower unit costs allow the firm to lower prices while maintaining profitability, increasing both its market share and total industry demand (the Economies of Scale loop, R1). In addition, increasing sales and production speed the accumulation of production experience, widely associated with cost reduction through learning (Argote, 1999), leading to further price cuts and still greater sales (the Learning Curve loop, R2). Not all cost reduction comes from the tacit learning associated with production experience. Many cost reductions arise from investment in process improvement including quality programs, better tooling and systems, partnerships with suppliers, and so on. Higher sales (and revenue) allow the firm to increase its investment in process improvement, lowering costs and prices, and further increasing sales (the Process Improvement loop, R3). To gain the initial advantage and drive these feedbacks faster than its rivals, a firm can lower price, even below

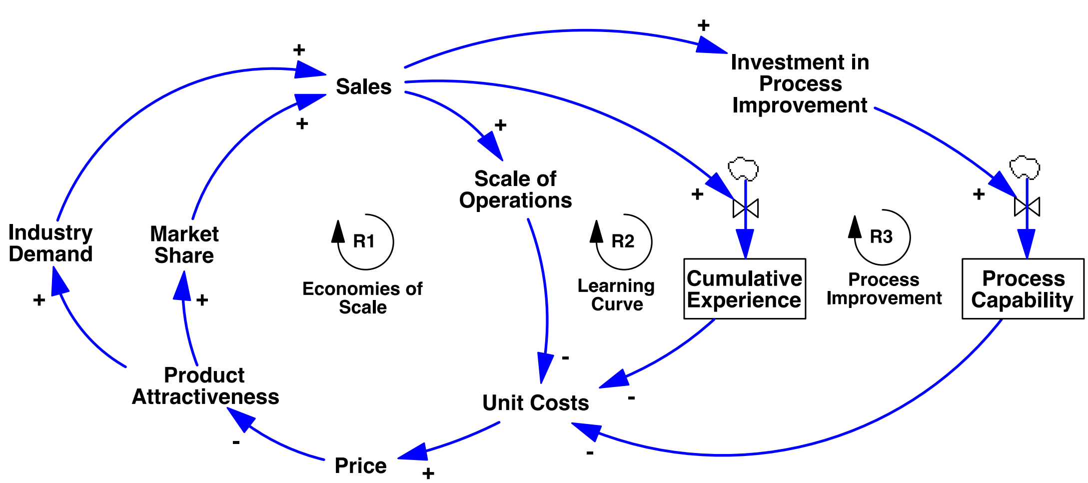

Fig. 7. Principal positive feedbacks created by scale economies and learning

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initial cost; indeed, Spence (1979) famously showed that the optimal, profit-maximizing policy for a monopolist in the presence of a learning curve is to price initially at the final cost, entailing an initial period of losses. A large literature (see Sterman *et al.*, 2007, for a summary) extends this insight to more complex situations.

However, the literature has also identified a variety of limits to the GBF strategy (Sterman *et al.*, 2007). If know-how is not privately appropriable, spillovers from imitation, reverse engineering of rivals' products and so on allow laggard firms to benefit from the cost advantage of larger rivals, dissipating the advantages aggressors pay so dearly (through process investment and low prices) to acquire (Ghemawat and Spence, 1985). Similarly, uncertainty, including the possibility of entry by new players with better, disruptive technologies, reduces the advantage of the GBF strategy. Finally, long capacity adjustment delays and forecasting errors can lead to capacity overshoot and losses that overwhelm the cost advantage of aggressive strategies (Paich and Sterman, 1993; Sterman *et al.*, 2007). These processes create negative feedbacks that undermine the effectiveness of the reinforcing feedbacks created by scale and learning.

Eclipsing the Competition offers the ability to examine all these issues. Players take the role of the senior executives of SunPower and seek to maximize their profits over a 20-year time horizon, competing against simulated rivals, including potential new entrants. Participants set the price for their solar modules and the budget for process improvement (as a fraction of their gross revenue).

The simulator includes settings that enable players or instructors to create scenarios spanning a wide array of conditions for the market, competitor behavior, cost reduction and industry demand (Figure 8). In individual mode, the player can choose the settings. When playing as part of a class, the class administrator sets these values. The settings in the box at the bottom of the list are available only to administrators when setting up a class, and determine whether players can see and/or change the settings in that scenario.

The settings provide control over the assumed price of grid power over time, including the possibility of phasing in a carbon tax, along with any subsidy available for solar PV (subsidies may be direct rebates or tax credits). The settings also provide control over competitor strategy. Each competitor sets prices based on their unit costs, adjusted by their local demand/supply balance and by the prices of the other players (see Sterman *et al.*, 2007, and Paich and Sterman, 1993, for the pricing heuristics used). The competitor price policy can be set with a goal of matching the player ("neutral"), or from Very Low, to Low, to High, to Very High relative to the player's price. Setting the competitor price policy Low or Very Low simulates the case where the competitors always seek price leadership in an attempt to pursue the GBF strategy. In addition, choosing "Competitor Always Prices Lower" ensures

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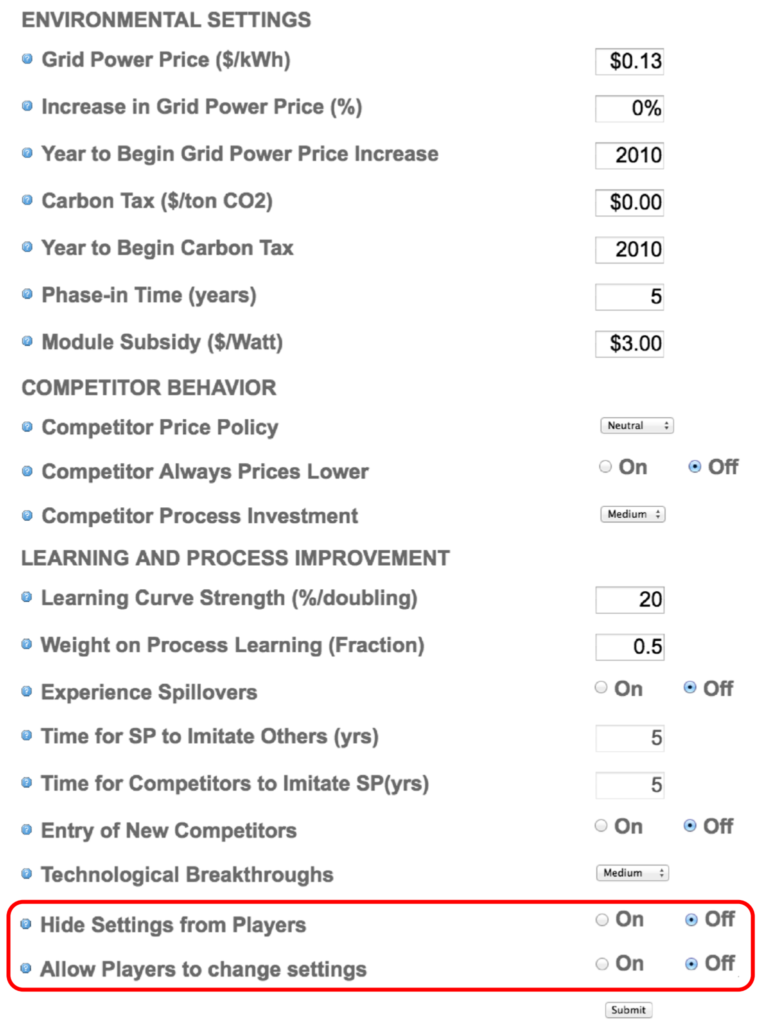

Fig. 8. Settings available in the solar simulator. In individual mode, the individual player controls the settings. The settings in the box at the bottom of the list are available only to administrators when setting up a class, and determine whether players can see and/or change the settings in that scenario

that the competitor always offers the lowest price, no matter what the player chooses—a useful setting to illustrate one failure mode for the GBF strategy. One can also choose the level of process investment for the competitor, (High, Medium or Low); to simulate the GBF strategy one might select High to capture settings in which competitors aggressively pursue cost reduction through heavy investment in process improvement. Settings also include the strength of the experience curve, how much of the cost reduction arises from process improvement (which requires investment) versus tacit learning arising from cumulative production experience (which has no direct costs),

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and the existence of, and lags in, knowledge spillovers (which need not be symmetric). One can also enable the entry of new players and the magnitude of the technical breakthroughs leading to new competitors, either Low, Medium, High or Very High.

Finally, when creating a class, instructors have the option of allowing players to view the settings or not and, if allowed to view them, whether the players can change the settings. Typically, players would be allowed to view but not change settings in their initial scenarios. In later scenarios, it is useful to hide the settings since the strength of the learning curve, the strategy used by the competitor and other key parameters are never known in advance in realistic situations.

People can play as an individual or as part of a "class" in which the faculty member chooses the settings so that all participants in the class play under the same conditions. By setting up multiple classes, a faculty member can create a sequence of scenarios that illustrate different lessons. A typical sequence for Eclipsing the Competition might begin with the default settings, in which there are no knowledge spillovers, the competitors play conservatively and do not pursue the aggressive GBF strategy and there are no technical breakthroughs that lead to entry of new firms with radical new solar technologies: these settings capture the classic case in which an aggressive strategy leads to durable competitive advantage. Next, instructors can add knowledge spillovers, or have the competitors play aggressively, or allow entry of new firms, alone or in combinations, to explore the limits to the GBF strategy. One can also examine scenarios with different paths for the price of grid power, for solar PV subsidies, and for a carbon price to explore how the market as a whole responds to changes in the overall competitiveness of solar compared to conventional power. Finally, one can challenge the robustness of player strategies to uncertainty in market and competitive conditions by choosing settings but hiding them from the players, or by enabling the "Mystery Scenario", in which the key settings are chosen randomly.

As detailed in the case study, SunPower's competitive advantage rests on their proprietary technology, which (as of the date of the case, 2006–2007) allowed them to produce the highest-efficiency modules on the market. However, competitors, including Chinese producers, were pricing lower and rapidly scaling up. SunPower (and the player) must decide how aggressively to price and how much to invest in further process improvement to continue to build advantage in the performance/price ratio for their modules.

The case study not only examines the strategic challenges facing firms in the industry, but also describes the PV industry, including its value chain, cost structure, electricity pricing and the role of government incentives for solar installation. Module prices are typically given in dollars per peak watt of capacity, but consumers are interested in the cost of solar per kilowatt hour (kWh) compared to the cost per kWh of conventional grid power. Players learn how to determine the effective cost per kWh from module prices together with

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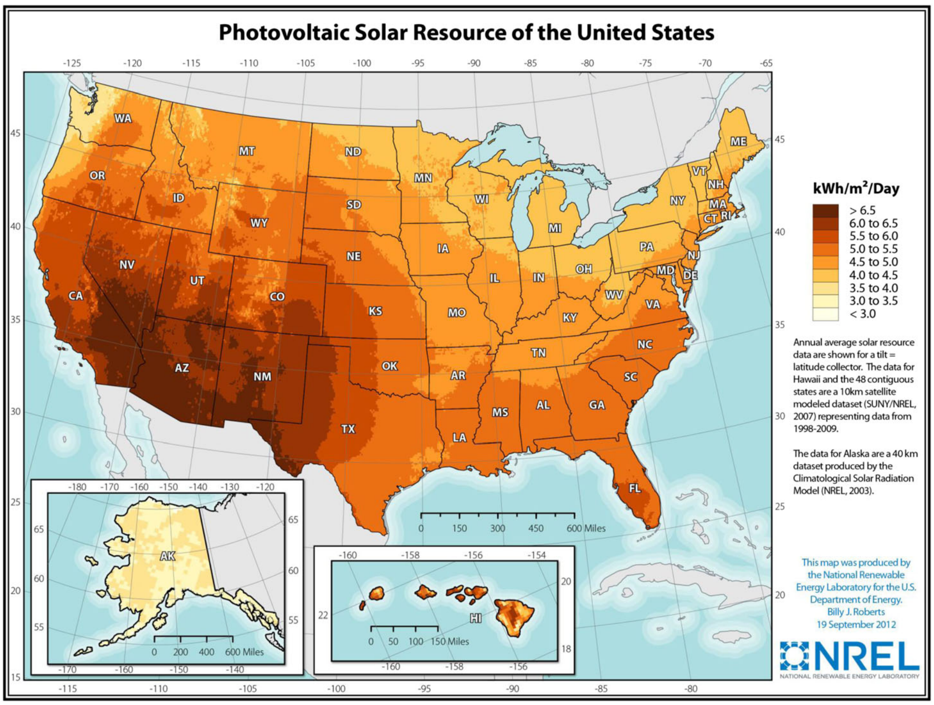

Fig. 9. Heterogeneity in solar resource in the U.S.A. Source: National Renewable Energy Lab, http://www.nrel.gov/gis/solar.html

available hours of sunlight in any location, module efficiency, installation/system integration costs, subsidies and other factors. Further, the case and accompanying slides and introductory video document the heterogeneity in both the solar resource (based on latitude and local climate), in the price of grid power and in the patchwork of national, state and other subsidies, feed in tariffs, renewable performance standards and tax credits that affect the final price consumers face (Figures 9 and 10). That heterogeneity means that there are regions in the U.S.A., and other parts of the world, in which solar PV offers a lower price to consumers than conventional grid power, even when the average cost is higher than the average grid price. The goal for solar producers is "grid parity": the point at which the cost of solar per kWh becomes equal to the cost of conventional power from the grid. At that point, solar moves from a niche technology, useful in sunny locations with high power costs or solar subsidies, to a mainstream source of electric power.[1]

[1]As an intermittent power source, widespread adoption of solar PV also require a solution to the load-balancing problem, either by coupling solar with complementary power sources such as hydro or gas turbines whose output can be adjusted rapidly to compensate for variations in solar inputs to the grid, through real-time pricing that can adjust demand, and/or through storage technologies to buffer the difference between solar output and load.

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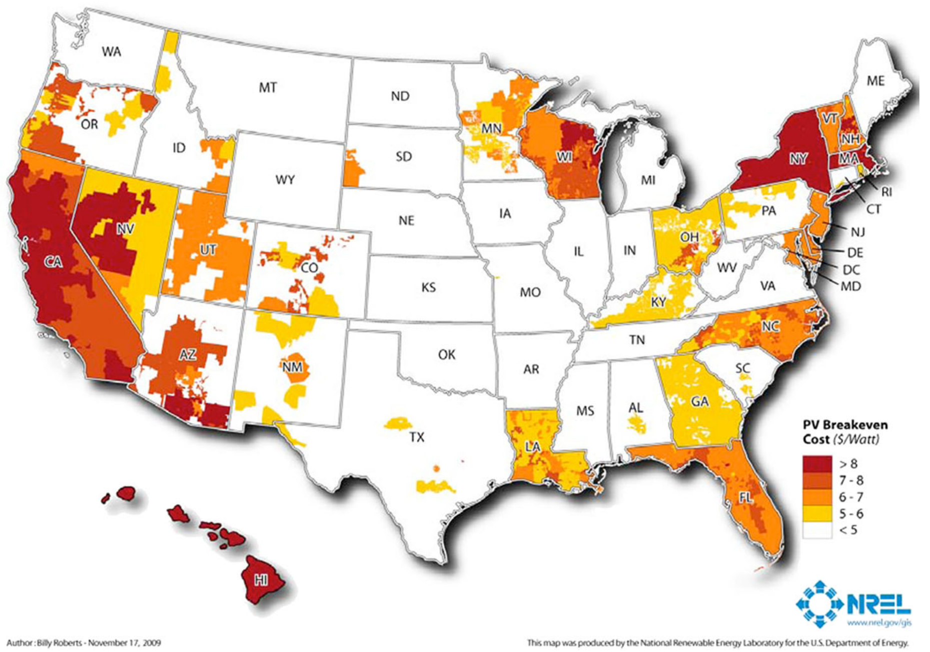

Fig. 10. Heterogeneity in solar PV breakeven cost per peak watt in the U.S.A. due to variations in solar resource, local grid power prices and subsidies and tax credits for solar installation, as of 2008 (around the start date for the simulation). Source: Denholm *et al*. (2009)

Figure 11 shows the main screen, with a successful strategy for SunPower in the default settings. In the default settings, learning and cost reductions are perfectly privately appropriable—there are no knowledge spillovers from one firm to another. The competitors play conservatively and do not pursue the GBF strategy, allowing SunPower to exploit their myopia. There is no entry of new players with radical new solar technologies. These are the classic conditions in which a GBF strategy is optimal and, as illustrated in Figure 11, by consistently pricing below its competitors and investing a higher fraction of revenue in process improvement, the player "Helios" is able to drive costs, initially higher than the competitors, down the learning curve faster and become the cost leader by 2023, while gaining market share and earning high profits. Cost reductions and aggressive pricing lead solar PV as a whole to reach grid parity by approximately 2017, triggering explosive growth in total demand, which further speeds cost reduction.

Of course, the model is not intended to be predictive, and the default settings, while helping participants learn about the classic learning curve strategy, are not realistic. Figure 12 shows a scenario in which (1) knowledge spillovers allow high-cost players to lower their costs towards those of the cost leader, with a lag specified by the administrator, here set to 2 years; (2) the competitors also pursue the learning curve GBF strategy by pricing low relative to their costs and investing heavily in process improvement; and

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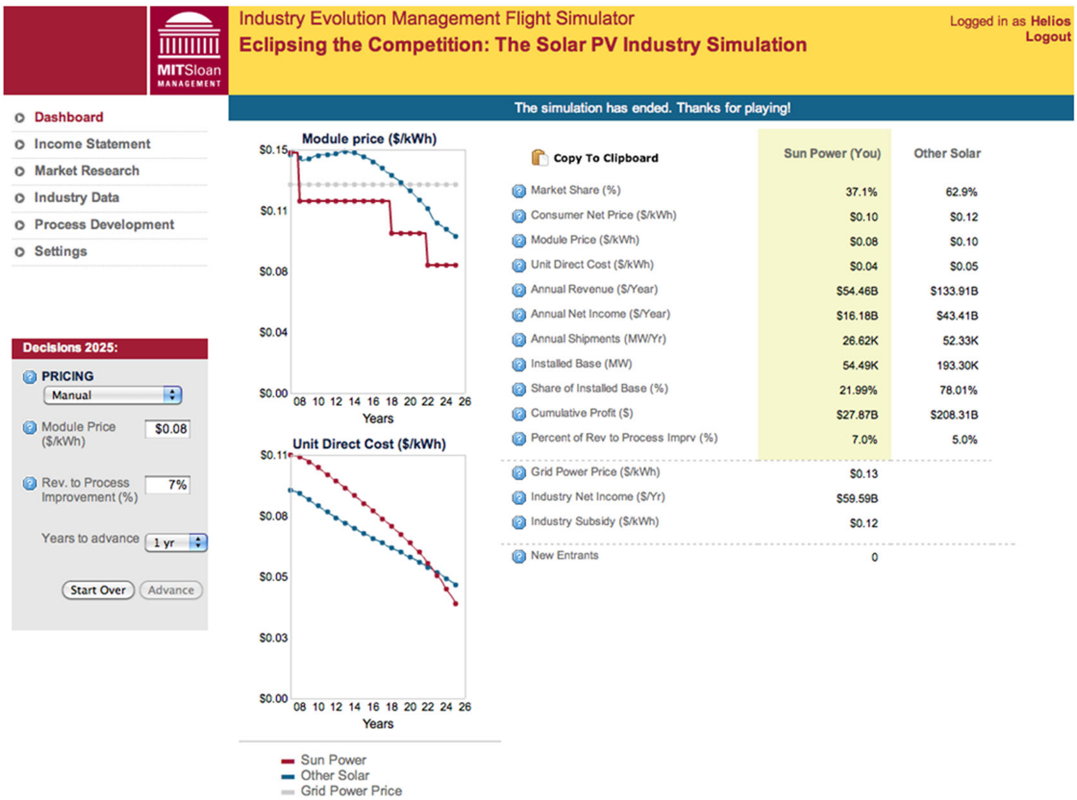

Fig. 11. Main screen for Eclipsing the Competition, showing a successful strategy using the default settings. In this simulation, the player has elected to use the Manual pricing mode, in which players set prices directly, in dollars per kWh, each period

(3) new players, with radical new technologies, can enter the market.[2] Under these conditions the GBF strategy is not effective: Although the player pursues a strategy of price leadership, using the Competitive Discount mode of price setting to offer prices that are always a certain percentage lower than the average of the competitors' prices, the competitors are also pursuing the GBF strategy and so lower their prices in response, leading to an industry-wide price war that destroys profitability for both the player and the industry as a whole. Further, despite the low prices, eventually six new firms with radical new technologies enter the market. These new firms can offer prices far below those of the player and its

[2]The entry of new players (when enabled) is stochastic and endogenous: each period there is some chance that ongoing research carried out by universities, governments or private firms will yield a new technology with costs far enough below current prices to form a new firm. Thus the higher the price of solar, the more likely that any new innovation will be competitive and be able to attract the funding needed to enter the market. New innovations also benefit, with a lag, from knowledge spillovers from incumbents.

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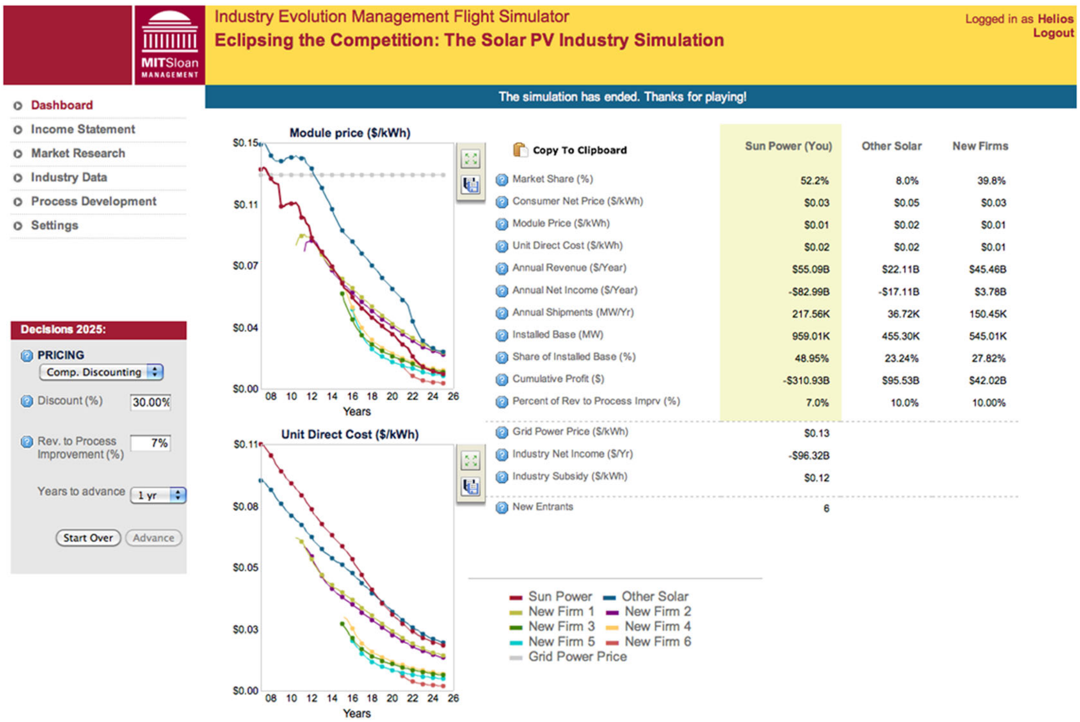

Fig. 12. Failure of the Get Big Fast strategy in the presence of knowledge spillovers, aggressive competitor pricing, and entry of new firms with new technologies. In this example, the player has chosen to use the Competitor Discounting mode to enter prices. By the end of the game, the player is setting prices 30 percent below the average price offered by its competitors in an attempt to gain market share

conventional rivals. Despite aggressive pursuit of the GBF strategy, SunPower experiences massive losses (cumulatively $311 billion by 2025; obviously, SunPower would have gone bankrupt long before then), while the solar industry grows rapidly. These examples provide only two examples of the rich variety of scenarios that can be explored with the simulator.

***Platform Wars*: competition in the presence of network externalities**

Platform Wars explores competition in the video game industry. Participants play the role of senior executives of a video game hardware maker, and seek success as they compete against other producers by setting prices for their gaming console, and by influencing the number of games design firms will

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produce for their platform by setting the royalty rates game designers must pay, and possibly choosing to subsidize game production.

The simulator is built on an original case, "Sony's Battle for Video Game Supremacy" (Sterman *et al*., 2011), which begins on the eve of the launch of Sony's PlayStation 3 in late 2006:

> As Sir Howard Stringer, CEO of Sony Corporation, settled in for his flight back to Japan from New York, a number of pressing issues occupied his mind about Sony's future. At the forefront, Sony's next generation video game console, the PlayStation 3 (PS3), was set to launch worldwide on November 17, 2006, a mere week away. Despite PlayStation 2's (PS2) dominance in the last generation of gaming consoles, Stringer understood that past successes were no guarantee of future success in the intensely competitive game industry.
>
> Microsoft had launched the first volley in the last console war by releasing the Xbox 360 in the fall of 2005. Within one year, almost 4 million Xbox 360 s had been sold worldwide, giving Microsoft a significant head-start in the race for market dominance. Meanwhile, Nintendo, a competitor thought to be dead due to the lackluster sales of its previous console, the Nintendo Gamecube, had generated significant "buzz" around its new entry, the Nintendo Wii (pronounced "we").

The video game industry is an example of a multi-sided market (Parker and van Alstyne, 2005) with demand-side increasing returns, specifically direct and indirect network externalities. The direct network externality is created by the desire of gamers to have systems compatible with those of their friends: gaming is highly social, and people like to be able to play with others, either in person or online. The indirect externality is created by the desire of gamers to buy systems compatible with the widest selection of the most popular games, and the desire of game designers to write for the platforms with the largest (expected) installed base of customers. Such dynamics are critical to a wide range of technologies, such as personal computer platforms (e.g. Macintosh vs. Wintel), home video players (e.g. Blu-Ray vs. HD-DVD), mobile phones (e.g. iPhone vs. Android), MP3 players, news media, social media such as Facebook and Twitter, and many others, including current efforts to replace automobiles powered by internal combustion engines fueled by gasoline with alternative-fuel vehicles such as battery electrics, plug-in hybrids and others (Struben and Sterman, 2008).

The presence of direct and indirect network externalities means success in the marketplace depends as much or more on the size of the installed base and the number and scope of complementary products for each platform as it does on price, quality, functionality and other traditional attributes of product

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attractiveness. Much of the literature stresses the importance of building an initial lead in installed base and complements (Arthur, 1989; Katz and Shapiro, 1994; Shapiro and Varian, 1999; Fudenberg and Tirole, 2000; Parker and van Alstyne, 2005).

Consider the battle for the home VCR market (Sterman, 2000, Ch. 10). Sony's proprietary Betamax technology was the first cassette-based home video technology to reach the market, some 18 months ahead of its principal rival, the VHS standard, launched by a consortium of Matsushita, JVC and RCA (Cusumano *et al.*, 1992). Though Betamax and VHS technologies cost about the same, the tapes and machines were not compatible. Consumers had to choose which standard to adopt. The attractiveness of each format depended on factors including price, picture quality, play time and machine features such as programmability, ease of use, size and remote control, among others.

However, the most important determinant of product attractiveness was compatibility. To swap tapes with their friends and families people had to have compatible machines. As the installed base of machines of a given format increased, the attractiveness of that format to potential new buyers increased, which in turn increased the market share of that format and boosted the installed base even further. Even more importantly, people tended to buy machines compatible with the broadest selection of pre-recorded tapes. Video rental shops, in turn, chose to stock tapes in the most common format since these would rent more often and yield

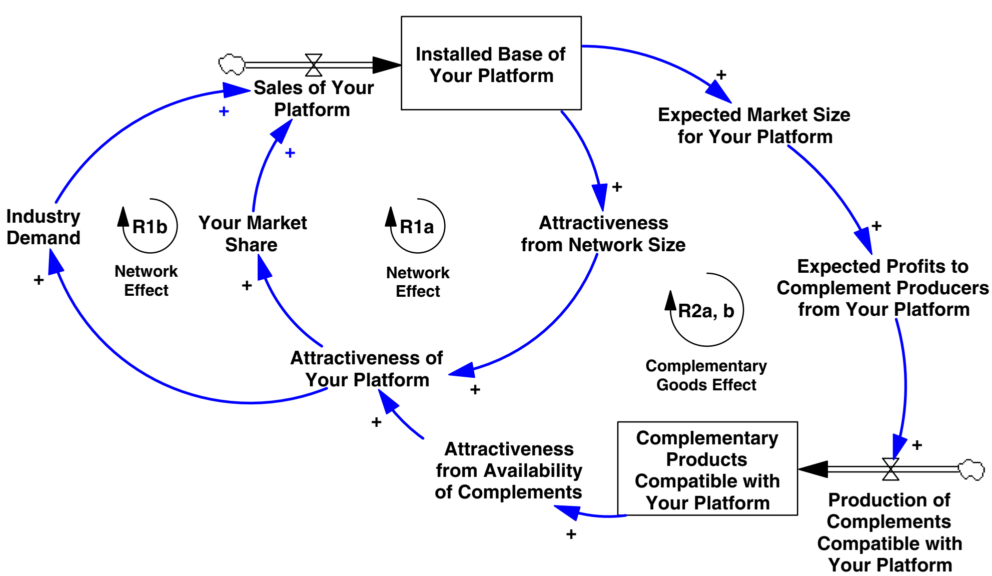

Fig. 13. Positive feedbacks created by direct and indirect demand-side externalities

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more profit. And movie studios chose to offer their films for the most widely held format.

Sterman (2000, Ch. 10) analyzes the feedback structure of the direct and indirect network externalities and links them to dozens of other positive feedbacks that can confer cumulative competitive advantage. The key feedbacks created by direct and indirect network externalities are shown in Figure 13. Sales of any firm's product are determined by industry demand and the firm's market share. Higher sales speed the growth of the installed base of the firm's product (for simplicity, discards and obsolescence are not shown). In multi-sided platform markets with a direct network externality, the attractiveness of the product to potential customers depends not only on traditional factors such as price, quality and functionality but also on the number of others who also own that product. Thus the larger the installed base, the more attractive is that firm's product, the greater market share will be, and the faster the installed base will grow (the Network Effect loops R1a and R1b). In addition, the larger the installed base of a firm's product, the larger the expected size of the market for that platform will be, as judged by producers of complementary products (video rental stores and movie studies in the VCR case, app developers in the smartphone industry, game producers in the video game industry). The larger the expected market for a particular platform, the greater the expected profits to complement producers who build for that platform, and, after a delay, the larger the installed base of complements for that platform will be. As the scope and availability of complements grow, the attractiveness of that platform rises further, leading to still greater sales (the Complementary Goods Effect loops R2a and R2b).

Competition in platform markets is rarely as simple as in the battle between Betamax and VHS, with two incompatible, proprietary platforms. In many current platform battles, complementors have the option of producing content that can be ported over to multiple platforms, with costs and production delays that can vary from case to case. If costs are low and the delays short, the indirect network externality is weakened. Similarly, hardware makers can choose to offer versions of their product that can run the software of rivals, weakening the direct network effect. The ability to run Microsoft Windows on Apple Macintosh computers through Boot Camp or third-party Windows emulators such as VMWare Fusion or Parallels provides a recent example: those purchasing Macs can, at low cost, run both the Mac OS and Windows, obviating much of the installed base advantage of Windows in the PC market.

Administrators may choose settings to create a wide range of scenarios (Figure 14). The settings include determining the order of entry for the player and simulated competitor. The default is simultaneous entry with an initially level playing field, but one can allow either the player or simulated

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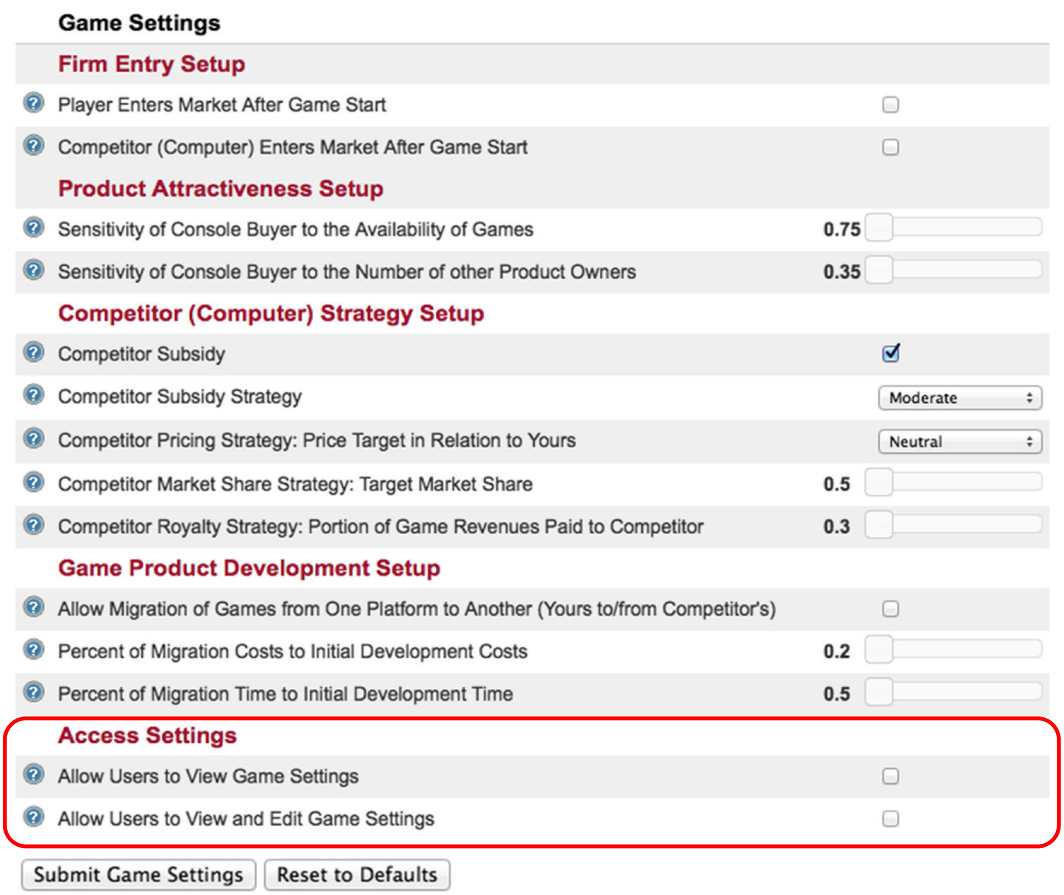

Fig. 14. Settings available in the Platform Wars video game simulator. In individual mode, the individual player can set these. The settings in the box at the bottom of the list are available only to administrators when setting up a class, and determine whether players can see and/or change the settings in that scenario

competitor to enter first. Administrators can also set the strength of the direct and indirect network effects by controlling the sensitivity of product attractiveness to the installed base of consoles and to the availability of games. Parameters governing the strategy used by the simulated competitor include whether the competitor chooses to subsidize the production of games produced for its platform and, if so, the magnitude of the subsidy, how aggressively the competitor prices its hardware relative to the player's price, the competitor's target market share (which affects competitor pricing and other decisions) and the initial royalty the competitor charges game producers for the right to produce for its platform. Parameters governing

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the strategy followed by game developers include whether developers can migrate their games from one platform to the other, and what the costs and delays of such migration are relative to developing a new game. If migration is not enabled the situation is much like that characterizing VCRs or Blu-Ray vs. HD-DVD, with incompatible proprietary formats. If migration is enabled and the costs and delays are low enough, then all content produced by complementors rapidly becomes available for both platforms, weakening the indirect network effect. Finally, administrators, in setting up a scenario, have the option of hiding the settings from players (the realistic case) or allowing them to see the settings for pedagogical purposes, and, if so, whether players can modify the settings themselves to encourage sensitivity analysis and experimentation.

Figure 15 shows a typical game with the default settings. The player pursues an aggressive strategy to jump start the direct and indirect network externalities by setting the console price lower than the initial $250 per unit, by cutting the royalty charged game designers from 30 percent to 20 percent, and by subsidizing the production of 20 games per year. The competitor responds by undercutting the player on console prices, but subsidizes fewer games and only slowly cuts the royalty rate. Although the competitor has a slight market share advantage for the first 2 years, soon the number of game titles available for the player's platform outstrips the number available for the competitor. The broader scope of titles further increases the attractiveness of the player's platform to consumers, and market share begins to rise. By year 4 the player stops lowering console prices and then cuts the number of games subsidized to zero. Although the competitor continues to undercut the player on console prices and eventually even on royalty rates, the large advantage in game titles and in the installed base of the player's platform tips the market in favor of the player, who achieves 95 percent market share by year 10. The player ultimately earns cumulative profits of $2.8 billion, while the competitor cumulatively loses money. The dynamics are quite similar to the results for the battle between Betamax and VHS in the home VCR market, illustrating the power of the positive feedbacks created by the direct and indirect network effects.

Competitive conditions are more complex in many platform wars today, including the video game industry. Figure 16 shows the result of the same strategy when the settings are changed to enable complementors (game producers) to migrate their games quickly and at low cost from one platform to another, and where the competitor pursues an aggressive strategy, including low console pricing relative to the player, aggressive game subsidies and an initial royalty rate of 20 percent (matching that of the player). Now the market tips the other way, with the competitor winning 90 percent of the market and earning cumulative profits of $6 billion, while the player loses $2.3 billion.

A good pedagogical sequence of "classes" (scenarios) begins with the default parameters, representing the classic case of proprietary, incompatible

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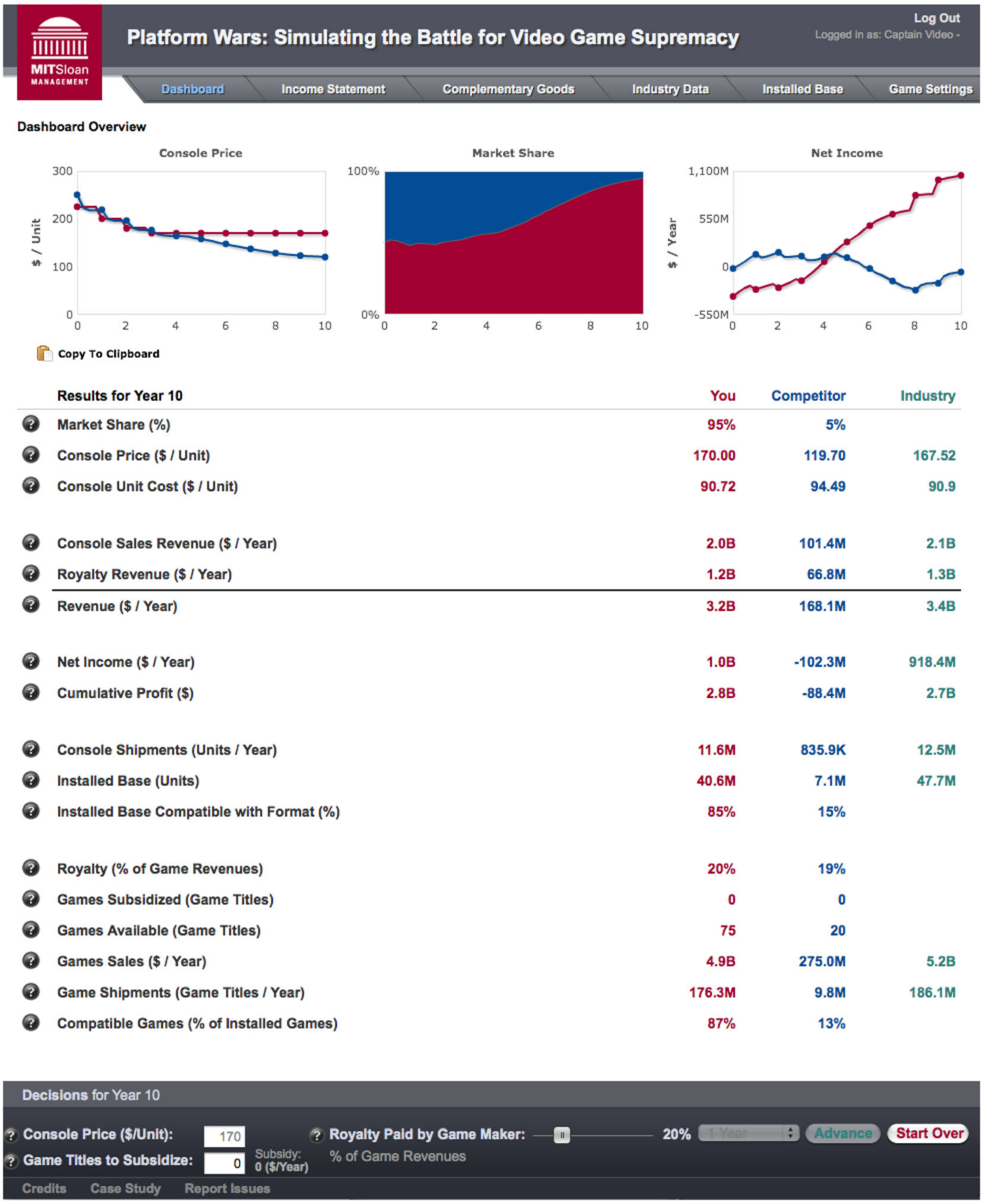

Fig. 15. Main screen for Platform Wars, showing a successful strategy with the default settings

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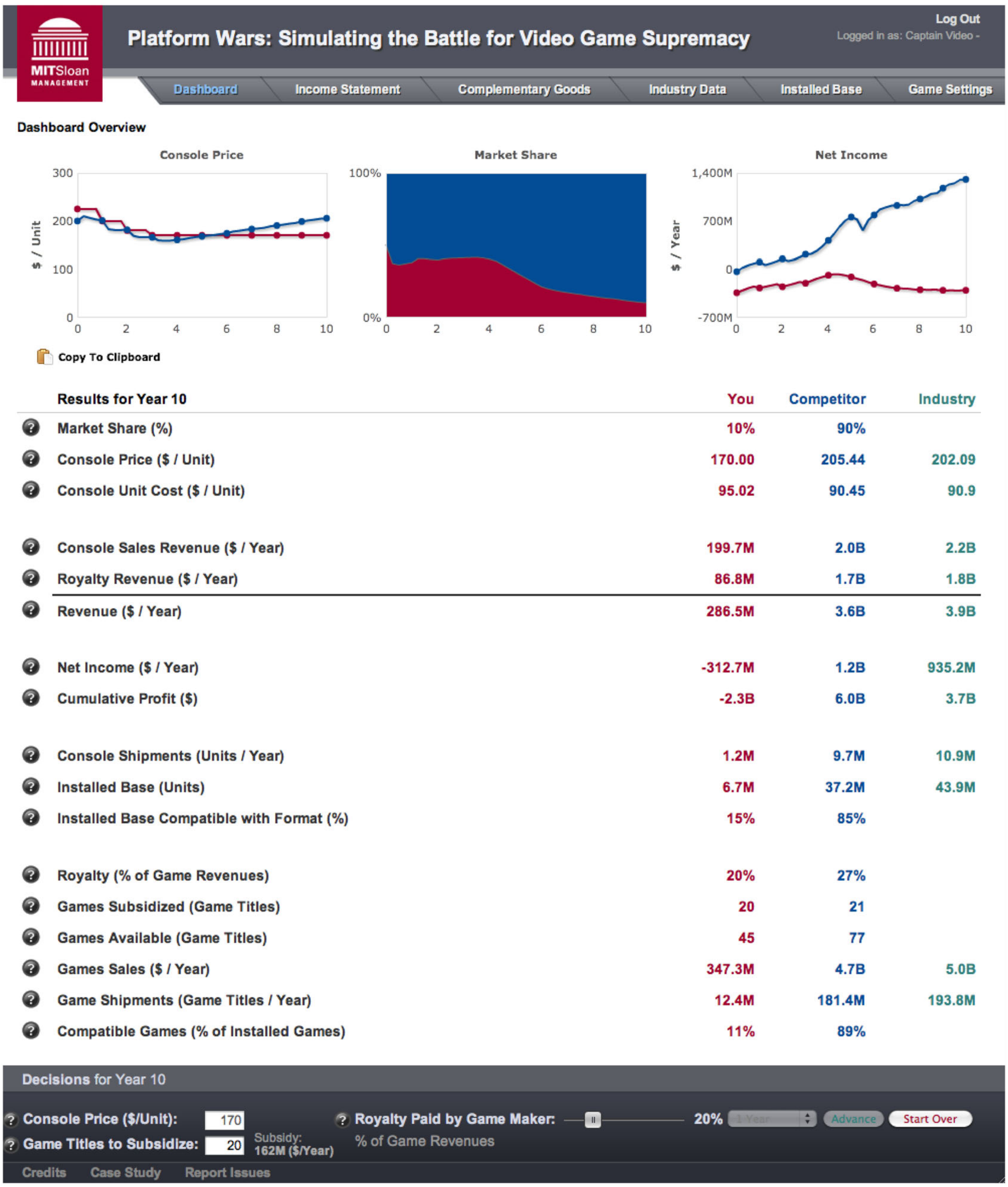

Fig. 16. Main screen for Platform Wars, showing the same strategy as in Figure 15 but where games can be migrated quickly and at low cost from one platform to another, and where the competitor pursues an aggressive strategy. The competitor wins the market and profits, while the player loses $2.3 billion

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formats without the ability to migrate content from one platform to another. Subsequent scenarios can relax these assumptions, introducing more realistic behavior for complementors, more aggressive competitor behavior and variations in the strengths of the direct and indirect network effects, so that participants not only learn how the market tends to tip towards the most aggressive player, but also what the limits to such aggressive strategies are as the feedback structure of the market varies.

Flight simulators for sustainability

Part II of this Note describes *Fishbanks*, *CleanStart* and *World Climate*. All are freely available through the MIT Sloan *LearningEdge* portal.

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References

Aldrich C. 2009. The Complete Guide to Simulations and Serious Games. Pfeiffer: San Francisco, CA.

Argote L. 1999. Organizational Learning: Creating, Retaining and Transferring Knowledge. Kluwer: Norwell, MA.

Arthur WB. 1989. Competing technologies, increasing returns, and lock-in by historical events. *Economic Journal* **99**: 116–131.

Cusumano M, Mylonadis Y, Rosenbloom R. 1992. Strategic maneuvering and mass-market dynamics: the triumph of VHS over Beta. *Business History Review* **66**(1): 51–94.

Denholm P, Margolis R, Ong S. 2009. Break-even cost for residential photovoltaics in the United States: key drivers and sensitivities NREL/TP-6A2-46909 (December 2009). Available: http://www.nrel.gov/docs/fy10osti/46909.pdf [13 June 2014].

Dori Y, Belcher J. 2005. How does technology-enabled active learning affect undergraduate students' understanding of electromagnetism concepts? *Journal of the Learning Sciences* **14**(2): 243–279.

DOI: 10.1002/sdr

Forrester JW. 1958. Industrial dynamics: a major breakthrough for decision makers. *Harvard Business Review* **36**(4): 37–66.

Forrester J. 1961. Industrial Dynamics. Productivity Press: Portland, OR.

Forrester J. 1969. Urban dynamics. MIT Press: Cambridge, MA.

Fudenberg D, Tirole J. 2000. Pricing a network good to deter entry. *Journal of Industrial Economics* **48**(4): 373–390.

Ghemawat P. 1984. Capacity expansion in the titanium dioxide industry. *Journal of Industrial Economics* **33**: 145–163.

Ghemawat P, Spence M. 1985. Learning curve spillovers and market performance. *Quarterly Journal of Economics* **100**: 839–852.

Graham A, Morecroft J, Senge P, Sterman J. 1992. Model supported case studies for management education. *European Journal of Operational Research* **59**(1): 151–166.

Green E, Porter R. 1984. Noncooperative collusion under imperfect price information. *Econometrica* **52**(1): 87–100.

Hardin G. 1968. The tragedy of the commons. *Science* **162**: 1243–1248.

Henderson R, Conkling J, Roberts S. 2007. SunPower: focused on the future of solar power (case study). Available: http://mitsloan.mit.edu/LearningEdge/sustainability/SunPower [13 June 2014.

Henderson R, Sterman J, Nanda R. 2009. Ventures in salt: Compass Minerals International. MIT Sloan School of Management: Cambridge, MA. Available: http://mitsloan.mit.edu/LearningEdge/strategy/VenturesInSalt [13 June 2014].

Hill G, Hardy Q, Clark D. 1996. Behind the plunge: bloody price wars and strategic errors hammer high tech. *Wall Street Journal* 12 July.

Jarmain WE (ed.). 1963. Problems in Industrial Dynamics. MIT Press: Cambridge, MA.

Katz M, Shapiro C. 1994. Systems competition and network effects. *Journal of Economic Perspectives* **8**(2): 93–115.

Kim E, Pak S. 2002. Students do not overcome conceptual difficulties after solving 1000 traditional problems. *American Journal of Physics* **70**: 759–765.

King A. 1993. From sage on the stage to guide on the side. *College Teaching* **41**(1): 30–35.

Kurlansky M. 2002. Salt: A World History. Penguin: New York.

Lasry N, Mazur E, Watkins J. 2008. Peer instruction: from Harvard to the two-year college. *American Journal of Physics* **76**(11): 1066–1069.

Lieberman M. 1984. The learning curve and pricing in the chemical processing industries. *RAND Journal of Economics* **15**: 218–228.

Mazur E. 1997. Peer Instruction: A User's Manual. Prentice Hall: Upper Saddle River, NJ.

Mintzberg H. 2005. Managers, Not MBAs. Berrett-Koehler: San Francisco, CA.

Morecroft J, Sterman J (eds). 1994. Modeling for Learning Organizations. Productivity Press: Portland, OR.

Newman R. 2009. How Sullenberger really saved US Airways Flight 1549. Available: http://money.usnews.com/money/blogs/flowchart/2009/02/03/how-sullenberger-really-saved-us-airways-flight-1549 [13 June 2014].

Oliva R, Sterman J, Giese M. 2003. Limits to growth in the new economy: exploring the 'get big fast' strategy in e-commerce. *System Dynamics Review* **19**(2): 83–117.

Paich M, Sterman J. 1993. Boom, bust, and failures to learn in experimental markets. *Management Science* **39**(12): 1439–1458.

Papert S. 1993. Mindstorms (2nd edn). Basic Books: New York.

Parker G, van Alstyne M. 2005. Two-sided network effects: a theory of information product design. *Management Science* **51**(10): 1494–1504.

DOI: 10.1002/sdr

Pfeffer J, Fong C. 2002. The end of business schools? Less success than meets the eye. *Academy of Management Learning and Education* **1**(1): 78–95.
Pfeffer J, Sutton R. 2000. The Knowing–Doing Gap. Harvard Business School Press: Boston, MA.
Porter M. 1984. Strategic Interactions: some lessons from industry histories for theory and anti-trust policy. In Competitive Strategic Management, Lamb RB (ed.). Prentice Hall: Englewood Cliffs, NJ.
Repenning N, Sterman J. 2001. Nobody ever gets credit for fixing problems that never happened: creating and sustaining process improvement. *California Management Review* **43**(4): 64–88.
Repenning N, Sterman J. 2002. Capability traps and self-confirming attribution errors in the dynamics of process improvement. *Administrative Science Quarterly* **47**(2): 265–295.
Rothschild M. 1990. Bionomics. Henry Holt: New York.
Schrage M. 2000. Serious Play. Harvard Business School Press: Boston, MA.
Shapiro C, Varian H. 1999. Information Rules: A Strategic Guide to the Network Economy. Harvard Business School Press: Boston, MA.
Shaw R, Shaw S. 1984. Late entry, market shares, and competitive survival: the case of synthetic fibers. *Managerial Decision Economics* **5**: 72–79.
Spence AM. 1979. Investment strategy and growth in a new market. *Bell Journal of Economics* **10**: 1–19.
Sterman J. 1988. People Express Management Flight Simulator (updated version). Available: http://www.strategydynamics.com/microworlds/people-express [13 June 2014].
Sterman J. 1989. Modeling managerial behavior: misperceptions of feedback in a dynamic decision making experiment. *Management Science* **35**(3): 321–339.
Sterman J. 2000. Business Dynamics: Systems Thinking and Modeling for a Complex World. Irwin/McGraw-Hill: New York.
Sterman J. 2011. Communicating climate change risks in a skeptical world. *Climatic Change* **108**: 811–826.
Sterman J, Henderson R, Beinhocker E, Newman L. 2007. Getting big too fast: strategic dynamics with increasing returns and bounded rationality. *Management Science* **53**(4): 683–696.
Sterman J, Kahn J, Reavis C. 2011. Sony's battle for video game supremacy. MIT Sloan School of Management: Cambridge, MA. Available: http://mitsloan.mit.edu/LearningEdge/strategy/SonysBattle [13 June 2014].
Sterman J, Fiddaman T, Franck T, Jones A, McCauley S, Rice P, Sawin E, Siegel L. 2012. Climate Interactive: the C-ROADS Climate Policy Model. *System Dynamics Review* **28**(3): 295–305.
Sterman J, Fiddaman T, Franck T, Jones A, McCauley S, Rice P, Sawin E, Siegel L. 2013. Management flight simulators to support climate negotiations. *Environmental Modelling and Software* **44**: 122–135.
Sterman J, Fiddaman T, Franck T, Jones A, McCauley S, Rice P, Sawin E, Siegel L. 2014. World climate: a role-play simulation of global climate negotiations. *Simulation and Gaming*. Available: http://jsterman.scripts.mit.edu/docs/Sterman-World Climate.pdf [13 June 2014].
Struben J, Sterman J. 2008. Transition challenges for alternative fuel vehicle and transportation systems. *Environment and Planning B* **35**: 1070–1097.
Thomke S. 2003. Experimentation Matters. Harvard Business School Press: Boston, MA.

DOI: 10.1002/sdr