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JEL classifications: L15, L26, L50, O31
Keywords: Network effects, innovation, compatibility

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This article analyses the relationship between compatibility and innovation in markets with network effects using a model of competition with endogenous R&D, commercialization and compatibility. Incumbent acquisition of an innovation or profit from entry provides entrepreneurs with an incentive for developing technological improvements. Entrepreneurs receive greater returns for the innovation if larger incumbents offer compatibility with their installed base. As a result, entrepreneurs must innovate strategically to pre-empt an incompatibility response from incumbents. Similarly, small incumbents also bid strategically to block entry or rival acquisition if it also avoids an incompatibility response from a larger incumbent. A credible threat of incompatibility reduces the entrepreneur's reserve to sell an innovation, but can also increase offers to acquire the innovation from smaller incumbents attempting to avoid incompatibility. This leads to a complex relationship between the strength of network effects, innovation incentives, the entrepreneur's ambition for improvement and potentially disrupting the compatibility regime. For weak to moderate network effects entrepreneurs are likely to target more substantial, but improbable innovations such that their network is sufficiently attractive for incumbents to offer compatibility. For a small range of sufficiently strong network effects, entrepreneurs target incremental innovations to avoid the incumbent threatening incompatibility.

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1 Introduction

Innovative entry and compatibility are typically explored individually in the economic literature regarding network effects (Katz and Shapiro, 1985; Economides, 1996; Malueg and Schwartz, 2006; Farrell and Klemperer, 2007; Norbäck et al., 2014), but the dynamic combination of these two mechanisms implys that entrepreneurs strategically target investments in technology improvement that also achieve a favourable compatibility regime. In particular, if network effects are sufficiently weak, entrepreneurs are discouraged from undertaking incremental innovations with a high likelihood of success because incumbents will not offer compatibility to an insufficiently innovative entrant. If an incumbent withdraws compatibility to protect itself from intra-network competitive pressure by an entrant, it creates a barrier to innovative entry. For example, anti-trust cases against Microsoft found that anti-competitive actions to effectively exclude competing internet browsers from the installed base of customers using the Windows operating system, hindered innovative competition (Economides, 2001). In response to such entry barriers, entrepreneurs are incentivised to target more ambitious but improbable innovations that sufficiently improve on existing products that their expanding customer base is attractive enough for an incumbent to offer compatibility. However, if network effects are sufficiently strong then entrepreneurs also face a trade off between the ambition of technological improvement and disrupting the compatibility regime offered by incumbents. Existing research hints at the complex relationship between innovation and compatibility but focuses on one or the other mechanism thereby failing to consider the dynamic interaction between the two. This article develops a model of this relationship between innovation and compatibility decisions and examines how the characteristics of innovation are affected by the market position of incumbents and the strength of network effects.

Firms in industries with network effects are able to increase demand for their own product by expanding their installed base or strategically offering or removing compatibility with rivals. That is, for sufficiently strong network effects, offering compatibility increases demand for a product by increasing the size of the network, but for sufficienlty weak network effects a large autarkic network increases demand for its own product by reducing size of the network its rivals can access. Innovating firms in markets with network effects increase demand for a product by improving quality or reducing costs, but their return to innovation depends crucially on their ability to access the compatible installed base of incumbents. Compatibility is a mutual decision by rival firms to share the demand externalities of their customers with rivals' customers. Compatibility can be interpreted in a number of ways depending upon the sources of network effects. For more traditional sources of network effects, the definition of compatibility is clear, such as interconnection between telephone networks or the compatibility of software with different computer operating systems. With more subtle sources of network effects, the definition of compatible might relate to product standards. In any case, the impact of network strength on compatibility and demand is well understood, with compatibility offered when the strength of network effects exceeds a threshold that is dependent on relative market share (Economides, 1996). However, the impact of dynamic changes to compatibility on innovation has not previously been examined. Incorporating an innovation mechanism into a model of competition with network effects and compatibility offers insights into this unique interaction.

Commercialization of an innovation offers an incentive for innovation. Innovations are often commercialized by founding a new firm or division or established firms acquiring a start-up. Rivalry for these acquisitions, the need for incumbents to avoid falling behind their rivals technologically and the incentive to block entry can drive acquisition prices for start-up firms to extraordinary levels, providing substantial incentives for innovators. For example, recent technology industry mergers and acquisitions documented in the business press have proven to be very lucrative for entrepreneurs and angel investors. In 2014, Google purchased Nest, which produce smart thermostats, for $3.2 billion.[1] In March 2016, Cisco acquired Jasper for $1.4 billion which had developed an Internet of Things (IoT) service platform that enables even small companies to establish, manage and commercialize IoT services globally.[2] Another example with an even more exorbitant price tag was Intel's acquisition of Altera, a manufacturer of programmable logic devices, for $16.7 billion in 2015.[3] Even very early stage startups are attracting substantial investments from established firms with 55% of the 70 deals (worth $846 million) in IoT firms recorded in the first quarter of 2016 considered early stage investments including from investors such as Intel, Qualcomm, General Electric and Cisco among other venture capital investors.[4] Network effects add to the incentive for innovation by leveraging an existing installed base, but the realization of network effects and the payoff to entrereneurs depends critically on each firm's decision to offer compatibility or not, both if an acquisition is successful or if it fails. The interaction between rivalry for acquisition and the compatibility regime offered by incumbents has the potential to both increase the incentive for innovation, but also weaken the barganing power of incumbents that threaten incompatibility. This article explores the nature of the relationship between innovation and compatiblity by also including acquisition by auction as a commercialization strategy.

Network effects and compatibility have been studied extensively but theoretical models have drawn contradicting conclusions about the impact on innovation or entry. When network effects are strong, incumbents are incentivised to invite entry because they gain access to the larger network that is available when rivals and entrants use their "standard" (Economides, 1996). On the other hand, when a firm has a large existing network, it will prefer incompatibility even when welfare would be higher with compatibility (Katz and Shapiro, 1985). While Katz and Shapiro (1994) suggest that compatibility often reduces product variety or restrains innovation, Farrell and Klemperer (2007) emphasize how installed bases and incompatibility can be a barrier to entry. Alternatively, Gans et al. (2002) consider compatibility as a technological decision by entrepreneurs rather than a strategic decision by incumbents with various options for commercialization, but compatibility decisions require cooperation by both incumbents and entrants. More recently, Norbäck et al. (2014) show how alternative routes to commercialization through sale of an innovation to incumbents, still provides entrepreneurs with a strong incentive for innovation, despite incompatibility posing a barrier to entry. However, the barrier to entry caused by incompatibility and installed bases, also reduces the reserve that an innovative entrepreneur would be willing to accept in return for an incumbent acquiring the innovation, so the impact of compatibility on innovation incentives is ambiguous. Alternatively, compatible installed bases are attractive for entry and strong network effects incentivize incumbents to offer compatibility and even invitations for entry (Economides, 1996). In any case, standard models either focus on the effect of compatiblity on entry (ignoring innovation) or examine innovation given a predetermined compatibility regime. These models maintain simplicity for analytical purposes, but are not sufficient to examine the relationship between dynamic compatibility decisions and innovation, leading to contradictory conclusions. Therefore, it is not clear in existing models how network effects influence the incentive for innovation or the extent of improvements targeted by entrepreneurs when the compatibility regime is dynamic. This article extends and combines elements of these standard models of network effects (Katz and Shapiro, 1985; Economides, 1996; Norbäck and Persson, 2012; Norbäck et al., 2014) to understand the interaction between compatibility choices and innovation. The model finds that the threat of incompatibility disincentivises incremantal innovations if the strength of network effects is not sufficiently strong, implying that entrepreneurs will sacrifice a higher probability of successfully innovating in order to retain a favourable compatibility regime if the innovation is achieved. Furthermore, for a small range of sufficiently strong network effects, entrepreneurs are disincentivised from selecting substantial innovations where an incumbent may punish innovative entry by removing compatible access to its installed base.

All the mechanisms in this model are standard and accepted components of competition models with network effects, yet their interaction causes entrepreneurs to face troubling incentives for the ambition of technological improvement. The purpose of this article is to identify this unique relationship between innovation and compatibility, demonstrating it's impact with calibrated examples and discussing the implications for innovation in markets with network effects. The relationship between innovation and compatibility requires understanding three mechanisms: (1) auction or entry to incentivise innovation, (2) decisions regarding compatibility between rivals' installed bases and (3) decisions about the extent and probability of improvement targeted by innovation effort. Complexity requires that analytical results are conditional on the compatibility choices of incumbents such that full analytical results become unweildly and are considered beyond the scope of the article. Greater insight can be gained from analysing numerical examples that provide a useful tool for exploring these combined conditional results. The model shows how the interaction between compatibility decisions and technological improvement creates an interesting and discontinuous relationship between the size of innovation and the incentive to develop those innovations, due to the compatibility responses of incumbents. As a result, an entrepreneur's optimal strategy is to avoid an unfavorable compatibility regime by choosing characteristics of its innovation effort where their incentive for innovation is maximized by inducing a large incumbent to offer compatibility. The threat of losing compatibility may offer entrepreneurs a greater incentive to target disruptive by less likely innovations as incumbent firms compete to acquire the innovation and block entry or offer compatibility to an innovative entrant. The threat of losing compatibility is a disincentive for incremental innovation such that these markets would likely be characterized by more moderate but less frequent innovations. However, when network effects are sufficiently strong, entrepreneurs have an incentive to maintain a favourable compatibility regime by investing in innovations that target only incremental technology improvements as entrepreneurs wish to avoid losing compatibility with the largest incumbent. These entrepreneurial responses may reinforce the dominance of incumbents as entrepreneurs innovation efforts are distorted in ways that protect incumbents from incremental competition and disruptive innovation. The vastly different impact on innovation incentives according to the strength of network effects and the strategic responses of a dominant incumbent makes the possible range of outcomes highly complex, despite the well understood mechanisms that drive these results.

To develop these ideas further, the article proceeds as follows. Section 2 outlines the model and determines the equilibrium results, conditional on the dominant incumbent's compatibility decision. Section 3 examines the relationship between innovation incentives and the strength of network effects for two calibrated examples: a market served by an incumbent monopoly and a market served by two incumbents.Section 4 discusses the many implications of the model including recommendations for policy analysis and Section 5 provides concluding remarks.

2 The model

The model combines elements of competition models with network effects to include compatibility (Malueg and Schwartz, 2006), installed-base customers (Cremer et al., 2000) and commercialization of innovations by either entry or acquisition (Norbäck and Persson, 2012; Norbäck et al., 2014), deriving results that depend on the compatibility condition (Economides, 1996). The model identifies how incentives for innovation are impacted by the strategic compatibility responses of incumbents according to the strength of network effects and the ambition of innovation effort.

2.1 Model description

One or more incumbent firms sell products in a market with network effects where consumers have greater demand for varieties with higher quality and access to a larger installed network of consumers. Incumbents have an installed base of existing customers and compete for new customers. Firms have possibly compatible products where consumer demand is also proportional to the size of the installed base of compatible varieties. For simplicity, analysis compares two regimes: full compatibility versus autarky by the largest firm. Other regimes are not examined but would be an extension of the approach here. Competition proceeds in three stages: innovation, commercialization and market competition.

In stage 1, entrepreneurs undertake effort to discover an innovation. Innovation is the process of developing a product that earns a profit through commercialization. As there is greater demand for higher quality products, innovation in this model involves developing a quality improvement in order to attract customers away from existing varieties. It is assumed that demand externalities are the source of network effects. Variations of the model could incorporate other sources of network effects but results would be similar. The entrepreneur chooses both a quality target and a probability of successfully discovering an innovation. Greater innovative effort results in either a greater quality improvement (or cost-reduction), a greater probability of discovery or both but greater innovative effort involves a greater investment cost. Cost-reducing innovations are not examined but would proceed in a similar way by lower manufacturing costs enabling lower prices to attract customers away from existing varieties. The equivalent for a model with cost-reducing innovations is to think of the quality variable as the productivity factor for producing the final product. The process of innovation also involves attracting an initial small user-base of "locked-in" consumers, prior to full commercialization. The cost of attracting an initial base is treated as part of the entrepreneur's innovation cost but the mechanism for attracting this initial base is not examined. Greater innovation effort requires a greater cost to the entrepreneur.

In stage 2 the innovation is commercialized, either by sale to an incumbent at auction or by the entry of a new firm. An incumbent may acquire an innovation to attract new customers if the profit from doing so exceeds both the cost of acquisition and the opportunity cost of grandfathering the incumbent's existing variety. Grandfathering refers to keeping the existing variety for the installed base of locked-in customers but offering the new version to new customers with access to the network benefits of existing customers. Price discrimination by incumbents on the basis of quality by offering both an old and new variety at different prices would allow incumbents to make strategic choices to limit this opportunity cost. For simplicity, this additional strategic response is left out of the model and beyond the scope of the article as it does not offer additional insights. Incumbents make offers at auction to acquire the innovation and its small installed base and the entrepreneur chooses whether to accept an offer. Alternatively, the entrepreneur can establish an entrant firm with its small initial installed base and compete with incumbents.

Also at stage 2, each firm reviews the compatibility regime that it offers and would offer for alternative auction outcomes. Compatibility between varieties is made on the basis of no payments for compatibility, the consent of both firms and is either full or incompatible. It is assumed that if a firm offers compatibility, it offers it to all rivals. If compatibility is offered, analysis implies that smaller rivals are themselves compatible. In this way, analysis of compatibility can proceed stepwise by considering whether the largest firm offers compatibility, and if not, the largest firm is autarkic and compatibility for the second largest firm can analysed and so on. For the purpose of this analysis, we consider two regimes: (1) Firm 1 autarky with all rivals offering compatibility; and (2) all firms offering compatibility to all rivals. In the case of acquisition, the grandfathered variety and consumers of the new innovative variety are compatible. Each firm and the entrepreneur also correctly predict the compatibility decisions of competitors for all possible auction outcomes. As a result, bids in stage 2 are made on the basis of correct expectations about the compatibility regime when market competition commences and the counterfactual compatibility regimes of alternative auction outcomes.

In stage 3, competition to acquire new customers occurs between participating firms. Following acquisition or entry, the quality improvement is applied to products consumed by new customers of the firm that owns the innovation. New customers refers to the pool of potential customers who are joining the market. These may be thought of as entirely new customers or as customers that are recently "off contract". Each incumbent has an installed base which represents locked-in consumers that cannot switch to other firms. The installed base can be thought of as customers already "under contract" and pricing to those customers is already set by prior contracts. For simplicity, it is assumed that existing installed base customers do not benefit from quality improvements until they are off-contract and free to choose a new supplier so that customers do not have to forecast the future and additional competive periods are not modelled. This could be considered similar to mobile phone contracts whereby a customer does not receive a better quality phone with additional features until they sign up to a new contract. It may be possible to relax this assumption with the inclusion of a switching cost made up of termination fees plus an adaptation cost, but this aspect is covered by other research (Farrell and Klemperer, 2007). Equilibrium is found by reverse deduction, starting with stage 3.

2.2 Stage 3: Competitive equilibrium

Demand is adapted from Economides (1996) and Norbäck et al. (2014) such that consumers have a preference for quality (A_i), the industry has constant strength of network effects ($0 < \alpha < 1$) and firms offer either full-compatibility or incompatibility ($\beta_i = 1$ or $\beta_i = 0$ respectively) with all rivals' varieties. Networks are considered compatible when both firms' offers agree to offer compatibility (i.e. $\beta_i = 1$ and $\beta_j = 1$). Consumers of each variety receive a benefit proportional to the size of the compatible installed bases accessed by consuming that variety. The inverse demand by new consumers for variety i out of n available varieties is

$$p_i = A_i + \alpha \left(s_i + b_i + \beta_i \left(\left(\sum_{j=1}^{n} \beta_j \left(s_j + b_j \right) \right) - \left(s_i + b_i \right) \right) \right) - \sum_{j=1}^{n} q_j \tag{1}$$

where $q_j \geq 0 \forall j \epsilon n$ is new consumption of each variety, A_i is the quality of variety i, s_i represents consumer expectations of new consumption of variety i and b_i is the installed base of non-switching consumers of variety i. Consumers have a higher willingness to pay for varieties with higher quality and larger compatible installed bases, but it is assumed that the demand function is a result of customer heterogeneity or otherwise, such that even a variety with lower quality could still have some share of residual demand at a lower willingness to pay. Similarly consumers may have a preference for a lower quality variety if consumption of that variety accesses a larger compatible installed base.

Firms have a constant symmetric marginal cost c. Firms compete over unattached customers after choosing the compatibility regime. Firm i's profit is given by

$$\pi_i = \left(p_i - c \right) q_i = \left(A_i + \alpha \left(s_i + b_i + \beta_i \left(\left(\sum_{j=1}^{n} \beta_j \left(s_j + b_j \right) \right) - \left(s_i + b_i \right) \right) \right) - \sum_{i=1}^{n} q_i - c \right) q_i \tag{1a}$$

Taking consumers expectations of market share as given, i.e. output does not affect expectations of market share (s_i), differentiation finds the first order conditions for profit maximization by all firms

$$\begin{aligned} \frac{\partial \pi_i}{\partial q_i} &= A_i + \alpha \left(s_i + b_i + \beta_i \left(\left(\sum_{j=1}^{n} \beta_j \left(s_j + b_j \right) \right) - \left(s_i + b_i \right) \right) \right) - q_i - \sum_{i=1}^{n} q_i - c \\ &= p_i - c - q_i = 0 \end{aligned} \tag{1b}$$

Using this condition and correct consumer expectations for market share under a fulfilled expectations equilibrium ($s_j = q_j$), each firm's output in Cournot competition is given by

$$q_i = \frac{A_i + \alpha \left(b_i + \beta_i \left(\left(\sum_{j=1}^{n} \beta_j \left(q_j + b_j \right) \right) - b_i \right) \right) - \sum_{i=1}^{n} q_i - c}{\left(1 - \alpha + \alpha \beta_i \right)} \tag{1c}$$

Comparing profit (Equation 1a) to output (Equation 1c) under fulfilled expectations equilibrium ($s_j = q_j$), finds profits are quadratic in output

$$\pi_i = q_i^2 \tag{1d}$$

Aggregating output (Equation 1c) across all varieties and solving for aggregate output ($\sum_{i=1}^{n} q_i$) completes the equilibrium.

$$\sum_{i=1}^{n} q_i = \left(n\left(1-\alpha\right)+\sum_{j=1}^{n}\alpha\beta_j\right)\sum_{i=1}^{n}\left(\frac{A_i+\alpha\left(b_i+\beta_i\left(\left(\sum_{j=1}^{n}\beta_j\left(q_j+b_j\right)\right)-b_i\right)\right)-c}{\left(1-\alpha+\alpha\beta_i\right)\left(1+\sum_{j=1}^{n}\left(1-\alpha+\alpha\beta_j\right)\right)}\right)$$

The equilibrium is simplified by the relevant compatibility regimes of firms. The largest incumbent firm (Firm 1) has the largest base b_1. Starting with the assumption that any firm must offer the same compatibility regime to all rival firms and since smaller rivals always offer compatibility if the larger firm offers compatibility, the largest incumbent has a choice between *full compatibility* or *autarky*. Under full compatibility all firms compete in intra-network competition. Under autarky, if the second largest firm offers compatibility, other firms compete in intra-network competition with firms on the same network and inter-network competition with the largest incumbent.

If the calculated equilibrium results in negative production for a firm, it is assumed that the firm produces zero output but the firm's installed base is still interconnected with relevant compatible networks and the output of rival firms is recalculated. For the purpose of this analysis, it is assumed that if more than one firm has negative output in the initial equilibrium, zero output and recalculation of equilibrium occurs hierarchically based on the initial equilibrium, first setting output to zero for the firm that has the most negative production.[5]

For descriptive purposes, only two regimes are examined: (1) Compatibility - where all firms are compatible with all rivals; and (2) autarky - where Firm 1 is autarkic, but all rivals are compatible. The next two subsections examine equilibrium specifically under these two compatibility regimes.[6]

Equilibrium under compatibility

Under full compatibility all firms compete on the same network. Inverse demand for any firm's variety is

$$p_i = A_i + \alpha\sum_{j=1}^{n}\left(s_j+b_j\right) - \sum_{i=1}^{n} q_i \tag{2}$$

and profit from new customers is given by

$$\pi_i = \left(p_i - c\right) q_i = \left(A_i + \alpha\sum_{j=1}^{n}\left(s_j+b_j\right) - \sum_{i=1}^{n} q_i - c\right) q_i \tag{2a}$$

Using the first order condition for profit maximization (Equation 1b) and correct consumer expectations for market share ($s_j = q_j$), each firm's output in Cournot competition is given by

$$q_i = A_i + \left(\alpha - 1\right)\sum_{j=1}^{n} q_j + \alpha\sum_{j=1}^{n} b_j - c. \tag{2b}$$

Substituting output into profit finds profits are quadratic in output

$$\pi_i = \left(p_i - c\right) q_i = \left(A_i + \left(\alpha-1\right)\sum_{j=1}^{n} q_j + \alpha\sum_{j=1}^{n} b_j - c\right) q_i = q_i^2. \tag{2c}$$

Aggregating the output of all varieties (Equation 2b) and rearranging, total industry output is given by

$$\sum_{j=1}^{n} q_j = \frac{\sum_{i=1}^{n} A_j + n\alpha\sum_{j=1}^{n} b_j - nc}{1+n-n\alpha}. \tag{2d}$$

Equations 2b and 2d define each firm's output as a function of the parameters.

The effect of additional compatible entrants on a firm's output depends upon a balance of increasing competition and increases in the overall attractiveness of the network due to network expansion through entry. As output is positive and profits are quadratic in output the same observations apply to firm profits. Prices can be calculated from the inverse demand function (Equation 2).

Equilibrium under autarky

If Firm 1 chooses autarky, its inverse demand from new customers is given by

$$p_1 = A_1 + \alpha (s_1 + b_1) - \sum_{i=1}^{n} q_i \tag{3}$$

and inverse demand for new customers of any rival firm is given by

$$p_i = A_i + \alpha \sum_{j=2}^{n} (s_j + b_j) - \sum_{i=1}^{n} q_i \tag{3a}$$

The autarky regime may be extended for additional autarkic firms by replicating Equation 3 for each of the next largest firms $i = 2, 3, ...$ and increasing j by one each time. Profit for Firm 1 is given by

$$\pi_1 = \left(A_1 + \alpha (s_1 + b_1) - \sum_{i=1}^{n} q_i - c \right) q_1 \tag{3b}$$

and for any rival firm by

$$\pi_i = \left(A_i + \alpha \sum_{j=2}^{n} (s_j + b_j) - \sum_{i=1}^{n} q_i - c \right) q_i. \tag{3c}$$

Using the first order condition for profit maximization (Equation 1b) and correct consumer expectations for market share ($s_j = q_j$), Firm 1 and its rivals' outputs in Cournot competition are given by[7]

$$q_1 = \frac{A_1 + \alpha b_1 - \sum_{i=2}^{n} q_i - c}{(2 - \alpha)} \tag{3d}$$

$$q_i = A_i + (\alpha - 1) \sum_{j=2}^{n} q_j + \alpha \sum_{j=2}^{n} b_j - q_1 - c \tag{3e}$$

Substituting into the profit functions

$$\begin{gathered} \pi_1 = \left(A_1 + \alpha (q_1 + b_1) - \textstyle\sum_{i=1}^{n} q_i - c\right) q_1 = \left((2-\alpha) q_1 - (1-\alpha) q_1\right) q_1 = q_1^2 \\ \pi_i = \left(A_i + (\alpha - 1) \textstyle\sum_{j=2}^{n} q_j + \alpha \sum_{j=2}^{n} b_j - q_1 - c \right) q_i = q_i^2 \end{gathered} \tag{3f}$$

finds profit is again quadratic in quantities. Aggregating the output of all *rival* firms (Equation 3e), substituting Firm 1 output (Equation 3d) and rearranging completes the equilibrium

$$\sum_{j=2}^{n} q_j = \frac{(2-\alpha)\left(\sum_{i=2}^{n} A_i + (n-1)\alpha \sum_{j=2}^{n} b_j - (n-1) c \right) - (n-1)(A_1 + \alpha b_1 - c)}{(2-\alpha)(n - n\alpha + \alpha) - (n-1)} \tag{3g}$$

Equations 3d, 3e and 3g define each firm's output as a function of the parameters.

The denominator in the last equation causes a limit on the range of the strength of network effects under autarky that we can examine with this model, but because of the endogenous compatibility regime decision, there is no loss of generality in the result. At high network externalities the denominator in Equation 3g becomes negative, but at high network externalities, the dominant incumbent (Firm 1) also has an incentive to offer compatibility to benefit from the entrant's large customer base, negating its impact on the autarky regime. The endogenous compatibility regime decision means the denominator is typically never in effect. In any case, such strong network effects are considered unlikely and are outside a range relevant for the purpose of this analysis.

The effect of additional entrants on a rival network always reduce demand for the autarkic variety. As output is positive and profits are quadratic in output the same observations regarding quantity apply to firm profits. Prices for unattached customers can again be calculated from inverse demand (Equations 3 and 3a).

2.3 Regime choice: To be or not to be (compatible)

Prior to determining whether the innovation is acquired at auction or a new firm enters, each incumbent firm determines the compatibility regime if their bid results in acquiring the innovation and the compatibility regime if their bid fails. For descriptive purposes only the regimes where Firm 1 is autarkic or where all firms are compatible with all rivals are examined, but analyses of further compatibility regime options follows a similar fashion. It is assumed that smaller firms always maintain compatibility with each other and accept compatibility from the largest firm if it is offered. Other regimes with autarkic rivals are not examined but are a simple extension of the approach applied here, proceeding to an autarkic Firm 2 and so on. Following the auction, the appropriate regime choice applies to subsequent market competition.

Network strength threshold

Holding rivals total output at the equilibrium levels under compatibility (denoted as $\sum_{j=2}^{n} q_i = Q_C$) and autarky (denoted as $\sum_{j=2}^{n} q_i = Q_A$),[8] Firm 1's output under compatibility and autarky is given by

$$\begin{aligned} q_{1C} &= \tfrac{A_1+(\alpha-1)Q_C+\alpha\sum_{j=1}^{n} b_j - c}{2-\alpha} \\ q_{1A} &= \tfrac{A_1+\alpha b_1 - Q_A - c}{2-\alpha} \end{aligned} \tag{4}$$

respectively. The difference in output between the two regimes for Firm 1 is

$$q_{1C} - q_{1A} = \frac{(\alpha-1)\,Q_C + \alpha\sum_{j=2}^{n} b_j + Q_A}{2-\alpha} \tag{4a}$$

Observe the increase in demand due to a larger network of installed base customers if Firm 1 chooses compatibility $(+\frac{\alpha}{2-\alpha}\sum_{j=2}^{n} b_j)$, but the effect on demand for Firm 1's variety due to competition in a compatible network compared to autarky is ambiguous $(\frac{(\alpha-1)Q_C+Q_A}{2-\alpha})$ because increased intra-network competition reduces profit for Firm 1 yet access to a competitors' network of new customers increases profit for Firm 1. As profits are quadratic in output and output must be positive, Firm 1 will choose compatibility if and only if Equation 4a is positive. That is,

$$q_{1C} - q_{1A} > 0. \tag{4b}$$

Rearranging, Firm 1 will choose compatibility if and only if network effects for variety 1 are sufficiently high that

$$\alpha > \frac{Q_C - Q_A}{Q_C + \sum_{j=2}^{n} b_j}. \tag{4c}$$

As Q_C and Q_A are both functions of α, numerical analysis in the following section is required to show how compatibility is affected by the strength of network effects. Full analytical results are

Economides (1996) also finds that with high enough network effects even the largest firm will prefer to invite entry, but does not consider how this compatibility decision affects innovators. Notably, Firm 1's profit is increasing with network effects whether there is a compatibility or autarky regime, but it increases at a greater rate for compatibility than autarky. The result is the crucial condition upon which entrepreneurs' innovation decisions are based, leading to the key results of this article.

Upon entry, the profit for the innovative entrepreneur (or any rival to the largest incumbent) is therefore

$$\pi_i = \begin{cases} q_{iC}^2 = \left(A_i + (\alpha-1)\,(Q_C + q_{1C}) + \alpha\sum_{j=1}^{n} b_j - c\right)^2 & if\ \alpha > \frac{Q_C - Q_A}{Q_C+\sum_{j=2}^{n} b_j} \\ q_{iA}^2 = \left(A_i + (\alpha-1)\,Q_A + \alpha\sum_{j=2}^{n} b_j - q_1 - c\right)^2 & if\ otherwise. \end{cases}$$

Similarly, the profit for the largest incumbent is

$$\pi_1 = \begin{cases} q_{1C}^2 = \left(\frac{A_1+(\alpha-1)Q_C+\alpha\sum_{j=1}^{n} b_j - c}{2-\alpha}\right)^2 & if\ \alpha > \frac{Q_C - Q_A}{Q_C+\sum_{j=2}^{n} b_j} \\ q_{1A}^2 = \left(\frac{A_1+\alpha b_1 - Q_A - c}{2-\alpha}\right)^2 & if\ otherwise. \end{cases} \tag{4a}$$

The profit and output of any firm can be calculated from here.

Example: Incumbent monopoly

Analytical results can be found from the above, although useful simplifications require calibration of the number of firms and their relative size. The simplest example is a market with a single incumbent. In this market the entrant's profit (and the entrepreneur's reserve) is and the incumbent's profit are $\pi_i = q_i^2$. If entry occurs, quantity supplied to the market by the entrant is

$$q_e = \begin{cases} \frac{1}{2}\left(A_i + \alpha\left(b_1 + b_e\right) + \left(\alpha - 1\right) q_{1C} - c + \alpha\right) & if\ \alpha > \frac{q_{eC} - q_{eA}}{q_{eC} + (b_1 + b_e)} \\ \frac{1}{2}\left(A_i + \alpha\left(b_1 + b_e\right) - q_{1A} - c + \alpha\right) & if\ otherwise. \end{cases} \tag{5}$$

and quantity supplied by the incumbent is

$$q_1 = \begin{cases} \frac{1}{2}\left(A_1 + \alpha\left(b_1 + b_e\right) + \left(\alpha - 1\right) q_{eC} - c + \alpha\right) & if\ \alpha > \frac{q_{eC} - q_{eA}}{q_{eC} + (b_1 + b_e)} \\ \frac{A_1 + \alpha b_1 - q_{eA} - c}{(2-\alpha)} & if\ otherwise. \end{cases} \tag{5a}$$

By substitution and rearrangement

$$q_e = \begin{cases} \frac{2(\alpha-1)(A_i+\alpha(b_1+b_e)-c+\alpha)+A_1+\alpha(b_1+b_e)-c+\alpha}{3(\alpha-1)} & if\ \alpha > \frac{q_{eC} - q_{eA}}{q_{eC} + (b_1 + b_e)} \\ \frac{(2-\alpha)(A_i+\alpha(b_1+b_e)-c+\alpha)-A_1-\alpha b_1+c}{(2(2-\alpha)-1)} & if\ otherwise. \end{cases} \tag{5b}$$

and

$$q_1 = \begin{cases} \frac{(1+\alpha)((A_i+\alpha(b_1+b_e)-c+\alpha))}{\left(4-(\alpha-1)^2\right)} & if\ \alpha > \frac{q_{eC} - q_{eA}}{q_{eC} + (b_1 + b_e)} \\ \frac{A_i+\alpha(b_1-b_e)-c-\alpha}{2(2-\alpha)-1} & if\ otherwise. \end{cases} \tag{5c}$$

Higher orders of incumbency follow in a similar manner.

2.4 Stage 2: Commercialization by sale or entry

Stage 2 is based on Norbäck et al. (2014) with an auction for incumbents to purchase an entrepreneur's innovation but adding compatibility and a regime choice by Firm 1. If an entrepreneur successfully develops an innovation in Stage 1, the idea, including associated network effects and its initial installed base, can either be sold to an incumbent or used by a new firm to enter the market. We assume that decisions regarding acquisition or entry are based on correct expectations of the compatibility regime decided by Firm 1.

During this stage, the entrepreneur determines a reserve price based on expected profit from entry and incumbents tender offers to acquire the innovation. The entrepreneur accepts bids above their reserve price with the highest bidder acquiring the innovation. If no bid exceeds the entrepreneur's reserve, then the entrepreneur chooses to enter the market as a new firm with their initial installed base. If the highest accepted bid is tied, each bid has an equal chance of acquiring the innovation. If the innovation is acquired, the installed base is added to the acquirer's installed base and when competition starts, new customers purchase at the highest quality level available to the firm.

Value of an innovation

The value of an innovation to the entrepreneur is its revenue from either the sale of the idea or its profit from a new firm entering the market. When considering entry the entrepreneur will take into account the compatibility regime that would be imposed by Firm 1 if the new firm were to enter. For the purpose of this article it is assumed that the entrepreneur and incumbents can correctly predict this regime. The entrepreneur will sell an innovation if the price it receives at auction exceeds the value the entrepreneur would earn from entry with a new firm. The entrepreneur's reserve is given by

$$v_e = \pi_{e,Regime} \tag{6}$$

The value of acquiring an innovation by an incumbent is the value of profits from the innovation, less the opportunity cost of profits from continuing to supply the market using the incumbent's existing version, taking into account that if the bid fails the innovation may be purchased by a competitor or new competition might emerge from a new entrant firm. When considering acquisition, incumbents also take into account the compatibility regime that would be determined according to Equation 4c, both if the incumbent's bid successfully results in acquisition of the innovation and if the bid fails to acquire the innovation. That is, if the incumbent expects a competitor to acquire the innovation were their bid to fail then the value of acquiring an innovation for the acquiring firm is

$$v_i = \pi_{i,Regime}\left(A_i = A_e, A_j, ..., A_n\right) - \pi_{i,Regime}\left(A_i, A_j = A_e, ..., A_n\right). \tag{6a}$$

If the incumbent expects a failed bid to result in entry by a new firm then the value of an innovation for the acquiring firm is

$$v_i = \pi_{i,Regime}\left(A_i = A_e, ..., A_n\right) - \pi_{i,Regime}\left(A_i, ..., A_n, A_e\right) \tag{6b}$$

The value of an innovation to Firm 1 is calculated in the same way as for any other incumbent.

Although Firm 1 chooses the compatibility regime after acquisition or entry, its choice is determined by other parameters as shown by Equation 4c and its expected choice can influence the outcome of the sale or entry process. It is possible that the preferred regime chosen by Firm 1 could differ with entry, rival acquisition or Firm 1 acquisition. These alternative compatibility regimes are also taken into account in the valuations by incumbents and it is assumed that potential changes in the compatibility regime are correctly predicted by firms.

Price at auction or returns from entry

The returns from either the price received at auction (P_I) or profits from entry ($\pi_{e,Regime}$) provide the entrepreneur with the incentive for investing in innovation. If the innovation is not sold at auction, the payoff to the entrepreneur (Π_e) is its profit upon entry

$$\Pi_e = v_e = \pi_{e,Regime}. \tag{7}$$

If the innovation is sold at auction, the price received is the greater of (just above) the second highest bid or the entrepreneur's reserve price. Although the incumbent would be willing to bid more, the incumbent only needs to bid just above the higher of the reserve or the highest bid of its rival(s).

If the incumbent expects a new firm to enter were their bid to fail at acquiring the innovation, then the incumbent would only have to bid just above the reserve in order to win the auction. The price of the innovation for the acquiring incumbent firm i (P_I), the payoff to the entrepreneur and the entrepreneur's incentive for innovation is given by the entrepreneur's reserve

$$P_I = \Pi_e = v_e = \pi_{e,Regime}. \tag{7a}$$

Similarly, if the acquiring incumbent expects a competitor to acquire the innovation were their bid to fail then the incumbent would only have to bid just above the highest value of the innovation to a rival in order to win the auction, even if the acquiring incumbent is willing to bid more. The price of the innovation for the acquiring incumbent, the payoff to the entrepreneur and the entrepreneur's incentive for innovation is given by

$$P_I = \Pi_e = \pi_{j,Regime}\left(A_i, A_j = A_e, ..., A_n\right) - \pi_{j,Regime}\left(A_i = A_e, A_j, ..., A_n\right) > v_e, \tag{7b}$$

which is greater than the reserve. As in Norbäck et al. (2014), network effects, competition between rivals and imperfect competition within the market provides entrepreneurs with a greater incentive for innovating.

The payoff to the acquiring incumbent is the value of acquiring the innovation less the price paid for the acquisition. That is, if the incumbent expects entry were their bid to fail at acquiring the innovation, the payoff to the acquiring incumbent from acquiring the innovation is given by

$$\Pi_i = v_i - P_I = v_i - v_e = \left(\pi_{i,Regime}\left(A_i = A_e, ..., A_n\right) - \pi_{i,Regime}\left(A_i, ..., A_n, A_e\right)\right) - \pi_{e,Regime} > 0. \tag{7c}$$

Similarly, if the incumbent expects a failed bid to result in a competitor acquiring the innovation then the payoff from acquiring the innovation to that incumbent is given by

$$\begin{aligned} \Pi_i = v_i - P_I = v_i - v_j \quad = \quad & \left(\pi_{i,Regime}\left(A_i = A_e, A_j, ..., A_n\right) - \pi_{i,Regime}\left(A_i, A_j = A_e, ..., A_n\right)\right) - \\ & \left(\pi_{j,Regime}\left(A_i = A_e, A_j, ..., A_n\right) - \pi_{j,Regime}\left(A_i, A_j = A_e, ..., A_n\right)\right) > 0 \end{aligned} \tag{7d}$$

The conditional results in equations 7c and 7d are the maximum bids that incumbents would be willing to make in an auction conditional on the largest incumbent's strategic compatibility response and the expected auction result, however, each incumbent only has to bid higher than its closest rival or the entrepreneur's reserve in order to win the auction. Therefore, the result of the auction depends crucially on the compatibility regime of the auction result and the compatibility regime of the counterfactual were the leading bid to fail at acquiring the innovation. As a result, the incentive to innovate also depends crucially on the compatibility regime and the counterfactual compatibility regime.

A credible threat of autarky

The compatibility regime choice of Firm 1 affects the price the entrepreneur receives at auction because compatibility affects the payoffs of entry, Firm 1 acquisition or a rival's acquisition. It is assumed that Firm 1's rivals correctly predict the regime choices of Firm 1. While Firm 1 could try to influence the bids of rivals or the entrant's reserve by threatening an autarkic regime were Firm 1 to fail to acquire the innovation, a threat is only credible if it would be followed through, as correctly predicted by rivals. That is the threat of autarky is considered "credible" if Firm 1 makes its highest profit under the autarky regime according to the threshold defined in Equation 4c were the second placed bidder to win the auction.

Firm 1 could respond to innovation by credibly threatening to impose autarky if the entrepreneur were to enter as a new firm. This threat of an autarky regime lowers the entrepreneur's reserve because customers to a new entrant firm would be unable to access the network effects of Firm 1's installed base. As a result, the entrepreneur accepts any price for its innovation that is above its expected profit under an autarky regime, which may even be zero. Alternatively, this threat of autarky could also increase the bids of rival firms to acquire the innovation, as those firms may also receive their highest profit by avoiding an autarky regime.

Similarly, Firm 1 could respond to innovation by credibly threatening to impose autarky if Firm 2 acquired the innovation. The threat is considered "credible" if Firm 1 makes its highest profit according to the threshold defined in Equation 4c under the autarky regime given that Firm 2 acquires the innovation. The threat of autarky lowers the profits that Firm 2 would achieve if it acquired the innovation because its customers would be unable to access the network effects of Firm 1's installed base. This lowers the bid Firm 2 is willing to pay to acquire the innovation.

Alternatively, the threat of autarky could also be credible if Firm 1 were to acquire the innovation, if Firm 1 makes its highest profit according to the threshold defined in Equation 4c under the autarky regime given that it acquires the innovation. This threat of autarky increases the bids offered by both Firm 1 and Firm 2. If Firm 1 makes a higher profit by acquiring the innovation and imposing autarky than it would if it did not acquire the innovation and retained compatibility, then the threat of autarky increases bids by both Firm 1 and Firm 2.

As a result, a credible threat of autarky changes Firm 1's payoff for innovation and the entrepreneur's incentive to innovate. Notably, the autarky regime does not have to be imposed, only credible, to achieve the result.

2.5 Stage 1: Innovation

In Stage 1 the entrepreneur selects the intensity of innovation effort (I) based on the reward that will come from the auction in Stage 2 and competition in Stage 3. The intensity of innovation effort is costly such that more intensive effort comes at a greater cost either via a personal cost to the entrepreneur due to greater effort or the cost of effort by partners added to the business. This could also be thought of as an opportunity cost to the entrepreneur and her partners who could otherwise seek employment and a lower risk income elsewhere. The entrepreneur and her partners would hope to be remunerated for the opportunity cost of their effort from the product's success and only undertake this effort on the basis that *expected* returns exceed this cost.

The intensity of innovation effort is a choice of both the size of innovation (size of quality improvement or cost reduction, $\varphi = \frac{A_e}{\overline{A}}$ where $\overline{A}$ represents some measure of existing technology) and the probability of successful discovery (ρ). Choosing a greater target for the innovation, a higher probability of success or both, requires greater intensity of innovation effort and its associated costs. Additional entrepreneurs attempting innovation also reduce the probability of "success" for each individual entrepreneur because only one firm can develop the intellectual property associated with a particular innovation. This leads to an equilibrium number of entrepreneurs attempting to discover an innovation and exerting a profit maximising intensity of innovation effort where the expected profit from successfully innovating is equal to the entrepreneur's opportunity cost. Ultimately, with free entry, entrepreneurs will spend the entire *expected* payoff from innovation, accounting for the probability of success and the number of other entrepreneurs attempting to develop an innovation by choosing a combination of quality improvement and probability of success that maximizes their return on investment. While it is beyond the scope of the competition model presented here, a simple extension would also allow the model to be applied to an endogenous growth general equilibrium model.

Let the intensity of innovation effort be a function of both probability and improvement with increasing marginal effort and let the cost of innovation equal the intensity of effort. That is, the cost of innovation is given by the function $I(\varphi, \rho)$ where

$$I'(\varphi, \rho) > 0 \qquad and \qquad I"(\varphi, \rho) > 0 \tag{8}$$

when differentiated with respect to either the size of quality improvement or the probability of success. The lemma from Norbäck et al. (2014) applies such that the entrepreneur's incentive to innovate and willingness to invest in innovation effort is positively correlated with the reward to innovation. This also corresponds to the free entry criteria of most models of innovation and endogenous growth, which include an additional assumption that competitive pressure will result in all expected profits being invested in innovation. Therefore, the relationship between innovation and its rewards deserves closer examination in light of the role for the compatibility regime to affect returns to innovation.

In maximising expected profits, incumbents jointly take into account the probability that an innovation destroys the value of their existing variety alongside the probability that the innovation is successful. For the purpose of this analysis it is also assumed that the Arrow effect applies where incumbents do not innovate because the opportunity cost of innovating requires the incumbent to grandfather their existing version. That is, although incumbents' profits from innovation might exceed their costs of innovating, including the opportunity cost, this assumption means that *expected* profits are maximized when incumbents maximize the probability of *not* innovating. This assumption is equivalent to results in the endogenous growth literature such as Aghion and Howitt (1992).

Profit maximising innovation

In equilibrium, the entrepreneur will receive the higher of either the profit from entry or the price achieved at auction when selling an innovation to an incumbent. That is, the payoff from innovation is given by

$$\Pi_e = \begin{cases} \pi_e & if\ P_I < v_e \\ P_I & otherwise. \end{cases} \tag{9}$$

The entrepreneur's *expected* profit ($\mathit{\Pi}_e$), is this payoff multiplied by the probability of success less the cost of innovating. That is,

$$\mathit{\Pi}_e = \rho \Pi_e - I \tag{9a}$$

Differentiating with respect to probability and size gives the first order conditions for selecting intensity of innovation effort to maximize profit

$$\frac{\partial \mathit{\Pi}_e}{\partial \rho} = \Pi_e - \frac{\partial I}{\partial \rho} = 0 \tag{9b}$$

and

$$\frac{\partial \mathit{\Pi}_e}{\partial \varphi} = \rho \left(\frac{\partial \Pi_e}{\partial \varphi} \right) - \frac{\partial I}{\partial \varphi} = 0. \tag{9c}$$

Rearranging Equation 9b gives the profit maximising relationship between probability of success and expected profit

$$\Pi_e = \frac{\partial I}{\partial \rho}. \tag{9d}$$

Intuitively, the first order condition states that to maximize expected profits, entrepreneurs should target a probability of success where the increase in cost due to increasing the probability of success is equal to the size of the payoff achieved at auction or entry. Dividing by the free entry requirement ($\mathit{\Pi}_e = \rho\Pi_e - I = 0$; $\rho\Pi_e = I$) and rearranging further, the optimal intensity of innovation effort requires a probability of success where the elasticity of effort intensity with respect to the probability of success (ε_{ρ}^{I}) is equal to one

$$\varepsilon_{\rho}^{I} = \frac{\partial I}{\partial \rho}\frac{\rho}{I} = 1. \tag{9e}$$

Rearranging Equation 9c, dividing by the free entry requirement ($\mathit{\Pi}_e = \rho\Pi_e - I = 0$) and multiplying by the size of innovation gives the profit maximising innovation target relationship with profit

$$\begin{gathered}\frac{\partial \Pi_e}{\partial \varphi}\frac{\varphi}{\Pi_e} = \frac{\partial I}{\partial \varphi}\frac{\varphi}{I} \\ \varepsilon_{\varphi}^{\Pi_e} = \varepsilon_{\varphi}^{I}\end{gathered} \tag{9f}$$

This result is equivalent to Young (1998) such that entrepreneurs should target a level of quality improvement where the elasticity of profit with respect to quality is equal to the elasticity of the investment cost with respect to quality. That is, entrepreneurs should target a quality and its corresponding intensity of innovation effort where the marginal cost of increasing quality is equal to the marginal benefit. An example of a function with these assumptions can be adapted from the innovation functions of endogenous growth models such as Young (1998). The possibility of different compatibility regimes at different levels of innovation means that Π_e can be discontinuous. In such cases, these differential equations can be analysed for each section of the discontinuous function and may result in either a corner solution (i.e. at the discontinuous point) or multiple solutions, if there is more than one local optimum, or both. If there is more than one local "optimum", these can be compared on a case by case basis.

The optimal innovation decision of the entrepreneur, presented in Equations 9e and 9f, conditional on the compatibility decision of the largest incumbent, completes the model such that results can be derived by simultaneous equations for any calibration. Deriving full analytical results that incorporate the compatibility condition is unnecessarily complex for the purpose of the article, so further analysis considers more specific calibrations to examine the relationship between innovation and compatibility.

3 The relationship between profit, compatibility, incentives and innovation

Examining the strength of network externalities required for Firm 1 to prefer compatibility (Equation 4c) in conjunction with acquisition and competition outcomes for the entrepreneur, reveals an interesting relationship between innovation, rewards and the strength of network effects. The payoff to the Entrepreneur/Entrant as a result of commercialization through either sale or entry represents the incentive for investing in innovation. In particular, this incentive for innovation depends crucially upon the compatibility regime as a result of the auction and on the counterfactual compatibility regimes if an acquisition attempt were to fail. In this section, numerical simulations are used to demonstrate the relationship between innovation and compatibility.

3.1 Incumbent monopoly

The profit function is dominated by three factors: the owner of the innovation, the level of quality improvement and the level of network effects. Other relevant dimensions include the size of competitors' installed bases and the quality of rivals' products, but by treating these as a calibration, each profit function can be represented as a three dimensional surface (improvement due to innovation, network effects and each firm's profit). This section examines numerical solutions describing the relationship between innovation and compatibility for a market with network effects with one incumbent firm. Prior to considering acquisition or entry and the innovation investment behaviour of entrepreneurs in response to the compatibility regime imposed by the incumbent, this section examines how profit varies with innovation, network effects, compatiblity and acquisition.

For the purpose of this numerical analysis, I assume that the incumbent has a quality level set to 1. The incumbent has an installed base ($b_1 = 5$) and the entrepreneur starts with a smaller installed base ($b_e = 2$). Marginal cost is normalized to zero.

3.1.1 Profits under compatibility

The figures below show the profit function under compatibility for positive output by firms for an entrant's innovation up to twice the incumbent quality level: (1) for the incumbents and the entrant; and (2) for incumbent if the it acquires the innovation.

If entry occurs and compatibility is agreed, the incumbent and entrant have the profit function:

$$\pi_i = \left(A_i + (\alpha - 1)\left(q_i + q_j\right) + \alpha\left(b_i + b_j\right) - c\right)^2 . \tag{10}$$

where j indicates the output and installed base of the firm's rival. If the innovation is acquired by the incumbent, its profit is

$$\pi_1 = \left(A_e + (\alpha - 1)\, q_1 + \alpha\left(b_1 + b_e\right) - c\right)^2 . \tag{11}$$

where e indicates the properties of the entrepreneur's innovation that the incumbent has acquired and q_1 is determined on the basis of the incumbent's acquired quality improvement. The figures show the profit function under compability for positive output by firms for an entrant's innovation up to twice the incumbent quality level: (1) for the incumbent and the entrant; and (2) for the incumbent if if acquires the innovation.

[Figure 1 here]

3.1.2 Profits under autarky

The figures below show the profit function under autarky for positive output by firms for an entrant's innovation up to twice the incumbent quality level: (1) for the incumbents and the entrant; and (2) for incumbent if the it acquires the innovation.

If entry occurs and compatibility is not agreed, the incumbent's profit function is given by

$$\pi_1 = \left(A_1 + (\alpha - 1)\, q_1 + \alpha b_1 - q_e - c\right)^2 . \tag{12}$$

and the entrant's profit function is

$$\pi_e = \left(A_e + (\alpha - 1)\, q_e + \alpha b_e - q_1 - c\right)^2 . \tag{13}$$

If the innovation is acquired by the incumbent its profits is as above in Equation 11. The figures show the profit function under compability for positive output by firms for an entrant's innovation up to twice the incumbent quality level: (1) for the incumbent and the entrant; and (2) for the incumbent if if acquires the innovation.

[Figure 2 here]

3.1.3 The relationship between profits, compatibility and innovation incentives

The incentive for innovation is the payoff that the entrant receives for its innovation. In particular, this is either the profit from entry or the return from sale at auction, subject to the compatibility regime and counterfactual compatibility regime. In the two sections above, the profit functions of an entrant and incumbent were examined in relation to the size of innovation and the strength of network effects, but the compatibility decisions of firms were not yet included. In this section, payoffs after the auction are examined for these firms including the endogenous compatibility regime choice and counterfactual regime according to Equation 4c to understand how the incentive for an entrepreneur to invest in innovation are affected by the strategic compatibility responses of incumbents.

The incumbent's payoff can be enhanced by threatening to impose autarky on the entrant, thereby lowering the entrepreneur's reserve. The red shading in Figure 3 shows the combination of network strength and quality improvement where the incumbent will threaten autarky. As a result, the entrepreneurs reserve and their payoff for innovation is less in this autarky region. In response, for sufficiently weak network effects, entrepreneurs face a trade off between targeting incremental innovations, with a high likelihood of success according to Equation 9e and losing compatibility, or targeting more substantial innovations with a lower probability of success that maintain compatibility. However, for a small range of sufficiently strong network effects, entrepreneurs face a trade off between targeting more substantial innovations and losing compatibility.

[Figure 3 here]

The auction determines ownership of the innovation and the compatibility regime of subsequent competition. The compatibility regime of subsequent competition is shown in Figure 4 with red shading for autarky and yellow for compatibility. For very drastic innovations, where autarky is not a credible threat, the innovation is acquired and the monopoly network is effectively autarkic.

[Figure 4 here]

The green shading in Figure 5 shows the combination of network strength and quality improvement where the entrepreneur would enter as a result of the auction and the grey region describes where the innovation is acquired by the incumbent. If the incumbent credibly threatening autarky, it is able to acquire the innovation. For weak to moderate network effects the entrepreneur will sell the innovation to the incumbent, as the incumbent maintains its highest profit by sustaining its monopoly and paying at least the entrepreneur's reserve, even if autarky cannot be credibly threatened. For strong network effects, the incumbent cannot credibly threaten autaky because it would benefit from it's own network accessing the network of a high quality entrant and the entrant's best response is to enter with a new firm.

[Figure 5 here]

As a result of the threatened compatibility regimes and the auction, Figure 6 shows the payoff to the entrant and incumbent. The central region with low to moderate network strength that is sloping upward with quality has a lower incentive for innovation by the entrepreneur than surrounding areas but a higher payoff to the incumbent. This area represents innovations where the incumbent would respond to innovation by credibly threatening to impose autarky if the entrepreneur were to enter as a new firm. The threat is considered "credible" because if entry occurred, the incumbent makes it's highest profit under the autarky regime according to Equation 4c. This threat of an autarky regime lowers the entrepreneur's reserve because customers to a new entrant firm would be unable to access the network effects of the incumbent's installed base. As a result, the entrepreneur accepts any price for its innovation that is above its expected profit under an autarky regime, which may even theoretically be zero. Notably, the autarky regime does not have to be imposed, only credibly threatened, to achieve the result. The charts show how entrepreneurs will avoid small innovations, in order to avoid the threat of autarky, unless network effects are sufficiently strong. Alternatively for some strong levels of network effects, entrepreneurs will avoid large innovations to avoid the threat of autarky.

[Figure 6 here]

In the following section, this numerical analysis is expanded to include two incumbent firms, followed by discussion of results for both analyses.

3.2 Multiple incumbent firms

This section examines numerical solutions to a calibrated model with two incumbents, proceeding by first examining profit for alternative acqusition results under compatibility and autarky, and then examining firm profits that take account of compatiblity choices. With additional incumbent firms, rivalry for acquisition can increase the entrepreneur's incentive for innovation by increasing the acquisition price at auction. That is, an incumbent may be willing to bid higher than the entrepreneur's reserve in order to avoid a rival incumbent acquiring the innovation. Furthermore, a smaller incumbent may be particularly willing to bid higher than the entrepreneur's reserve to avoid an unfavourable change in the compatibility regime if a rival incumbent were to acquire the innovation. As a result, the impact of compatibility on the entrepreneur's incentives for innovation can be partially reduced by incumbent rivalry for the acquisition.

For the purpose of this numerical analysis, two incumbents have symmetric quality levels set to 1 are assumed. Firm 1 has a larger installed base ($b_1 = 6$) than the other incumbent ($b_2 = 3$) and the entrepreneur starts with a small installed base ($b_e = 0.5$).[9] Marginal cost is normalized to zero. To make a fair comparison between compatibility and autarky, the range of network externalities shown in the charts are limited so that the denominator of Equation 3g under autarky is always positive.[10] The figures below show the profit function for positive output by firms for an entrant's innovation up to twice the incumbent quality level: (1) for the two incumbents and the entrant; (2) for the two incumbents if the smaller incumbent acquires the innovation; and (3) for the two incumbents if the larger incumbent acquires the innovation.

3.2.1 Profits under compatibility

Each participant has the profit function:

$$\pi_i = \left(A_i + (\alpha - 1) \sum_{j=1}^{n} q_j + \alpha \sum_{j=1}^{n} b_j - c \right)^2 \tag{14}$$

where $\sum_{j=1}^{n} q_j$ is defined by Equation 2d. The charts in Figure 7 show the profit function under compability for positive output by firms for an entrant's innovation up to twice the incumbent quality level: (1) for the two incumbents and the entrant; (2) for the two incumbents if the smaller incumbent acquires the innovation; and (3) for the two incumbents if the larger incumbent acquires the innovation.

[Figure 7 here]

As in typical models with network effects, profit is increasing with network strength for all firms. The entrepreneur's profit is increasing in the quality of its innovation. Incumbents' profits decline in the quality of an entrant's innovation, but the rate of decline reduces to zero as network externalities tend towards the theoretical maximum of one. Alternatively, if acquired by an incumbent the acquiring firm's profit is increasing in the quality of its acquired innovation whereas the other incumbent's profit is decreasing in the quality of its competitor's acquired innovation. Nonetheless, the non acquiring incumbent's profit is still higher when it only has one rival than when an entrepreneur chooses to enter, but the extent of this additional benefit diminishes with network strength.

3.2.2 Profits under autarky

Firm 1 has the profit function

$$\pi_1 = \left(\alpha q_1 + A_1 + \alpha b_1 - \sum_{i=1}^{n} q_i - c \right)^2 . \tag{15}$$

Competitors to Firm 1 have the profit function

$$\pi_i = \left(A_i + (\alpha - 1) \sum_{j=1}^{n} q_j - \alpha q_1 + \alpha \sum_{j=2}^{n} b_j - c \right)^2 . \tag{15a}$$

The charts in Figure 8 show the profit function under autarky for positive output by firms for an entrant's innovation up to twice the incumbent quality level: (1) for the two incumbents and the entrant; (2) for the two incumbents if the smaller incumbent acquires the innovation; and (3) for the two incumbents if the larger incumbent acquires the innovation.

[Figure 8 here]

As is typical in models with network effects, the profit of firms with the largest installed base increases with network strength. However, for smaller firms, profits initially increase with network strength but diminish at higher levels as network size becomes a more important factor for consumers than quality when network effects are strong. This is particularly apparent when the second largest incumbent acquires the innovation such that profit initially increases with network strength and later diminishes even when quality is substantially higher than the quality of the rival variety. Profit is always increasing with network strength for the largest incumbent (Firm 1), even if it fails to acquire the innovation because its installed base is larger than the rival network.

The entrant's profit is increasing in the quality of its innovation. Incumbents' profits decline in the quality of an entrant's innovation, but the rate of decline diminishes as network effects increase. Alternatively, the acquiring firm's profit is increasing in the quality of its acquired innovation whereas the other incumbent's profit is decreasing in the quality of its competitor's acquired innovation. The dominant incumbent's profit diminishes only slightly if the other incumbent acquires the innovation, but is still higher than if it faces an entrant.

3.2.3 The relationship between profits, compatibility and innovation incentives

In this section, anction dynamics and the payoffs after the auction are examined for these firms including the endogenous compatibility regime choice and counterfactual regime according to Equation 4c to understand how the incentive for an entrepreneur to invest in innovation are affected by the strategic compatibility responses of incumbents.

The red shading in the charts in Figure 9 show the combination of network strength and quality improvement where the incumbent will threaten autarky if following the auction entry were to occur or the innovation were acquired by Firm 2 or Firm 1 respectively. The incumbent's payoff can be enhanced by threatening to impose autarky on the entrant, thereby lowering the entrepreneur's reserve. Similarly, the subtle threat that autarky would be imposed if Firm 1 acquired the innovation incentivises Firm 2 to acquire the innovation and enhances Firm 1's payoff because it can still access the larger installed bases of both firms. As a result, the entrepreneurs reserve and their payoff for innovation is less in this autarky region.

[Figure 9 here]

The dark green shading in Figure 10 shows the combination of network strength and quality improvement where the entrepreneur would enter as a result of the auction, the grey region describes where the innovation is acquired by the largest incumbent, the light green region describes where Firm 2 acquires the innovation by bidding higher than either the reserve or Firm 1's bid and the brown region represents a tied auction between Firm 1 and Firm 2 where each is indifferent between acquiring the innovation or allowing its rival incumbent to acquire the innovation. For weak to moderate network effects the entrepreneur will sell the innovation to an incumbent, as both incumbents maintains their highest profit by sustaining its monopoly and paying at least the entrepreneur's reserve, even if autarky cannot be credibly threatened. For strong network effects, the incumbent cannot credibly threaten autaky because it would benefit from it's own network accessing the network of a high quality entrant and the entrant's best response is to enter with a new firm.

[Figure 10 here]

The shaded areas in Figure 11 describes which firm offered the 2nd highest bid. The dark green region represents the entrepreneur, such that only one bidder was willing to exceed the entrepreneur's reserve. As a result the winning bid only needs to bid the entrepreneur's reserve in order to win the auction. In this example, Firm 2 out bid the reserve, but Firm 1's bid was below the entrepreneur's reserve. In this area, the returns to the entrepreneur are equal to their reserve. The light green region represents Firm 2. Comparing with Figure 10, the region in the top left describes a bidding rivalry between Firm 1 and Firm 2 such that the acquisition price of the innovation exceeded the entrepreneur's reserve. In the other light green region, Firm 2 acquires the innovation for a price equal to the entpreneur's reserve and Firm 1's bid was below the reserve. The grey region represents Firm 1. In this example, bidding rivalry between Firm 1 and Firm 2 increased the price of the innovation above the entrepreneur's reserve, with Firm 2 winning the auction. Furthermore, Firm 2 is bidding strategically to avoid Firm 1 imposing an autarky regime were Firm 1 to win the auction. The brown region represents a tie between Firm 1 and Firm 2. Examining Figure 10, the brown region in that figure represents where the winning bid is a tie between Firm 1 and Firm 2, above the entrepreneur's reserve because of the threat of autarky that would be imposed were the entrepreneur to enter the market. The remainder of the brown region in Figure 11 represents where Firm 1 and Firm 2 had tied bids, but the entrepreneur has a higher reserve because there is no credible threat of autarky.

[Figure 11 here]

The auction determines ownership of the innovation and the compatibility regime of subsequent competition. The compatibility regime of subsequent competition is shown in Figure 12 with red shading for autarky and yellow for compatibility. For very drastic innovations, where autarky is not a credible threat, the innovation is acquired and the monopoly network is effectively autarkic.

[Figure 12 here]

Figure 13 shows the payoffs for the entrepreneur and each incumbent as a result of the auction for an entrepreneur's innovation that improves quality up to twice the incumbent quality level using the same calibration as Figure 7 and Figure 8, allowing payoffs to reflect auction results including potential changes in the compatibility regime.

[Figure 13 here]

In particular, the payoff to the Entrepreneur/Entrant represents the incentive for investing in innovation and clearly shows how this incentive can be substantially affected by the actual and counterfactual compatibility regimes. The entrepreneur's payoff at zero network strength represents the entrepreneur's incentive for innovation of various sizes in a market without network effects. Network effects may provide an additional incentive for innovation that is influenced by the compatibility regime. Under autarky, network effects may also provide a disincentive for innovation compared to a market without network effects because network size can be a stronger determinant of demand than quality when network effects are strong. T

3.3 The impact of compatibility on innovation incentives

Compatibility impacts innovation both if it is offered after the auction or if its threat of removal if the auction winner had failed to acquire/retain the innovation affects bidding behaviour. On this basis, the key relationship between innovation and compatibility can be seen by jointly examining the compatibility regime after the auction and the compatibility regime if the second placed bidder had won the auction with the auction results and second place bidding behaviour as shown in Figure 14. In the first chart, red and orange describes where autarky is credibly threatened or imposed as a result of bidding behaviour at the auction. The threat of autarky is considered credible if it is the profit maximising compatibility regime that would be imposed, if the second placed bidder were to win the auction. In the first chart, the red region represents where autarky is credibly threatened if Firm 1 were to win the auction and the orange region represents where autarky is credibly threatened if the entrepreneur were to enter. In the second row of charts, dark green represents the entrant, light green represents Firm 2, grey represents Firm 1 and brown represents a tie between Firm 1 and Firm 2.

[Figure 14 here]

From these charts the bidding behaviour for each firm in response to the threat of autarky by Firm 1 can be examined. Firm 1 threatens autarky for other innovations in order to lower the reserve, but acquisition is only successful for substantial innovations due to the strategic bidding behaviour of Firm 2.

Firm 2 bids strategically to avoid the threat of autarky that would be imposed were Firm 1 to acquire the innovation. The red region in the first chart describes that autarky would be imposed if Firm 1 were to win the auction. For these innovations Firm 2 bids strategically to block Firm 1's acquisition of the innovation and avoid the threat of autarky if Firm 1 had acquired the innovation. The orange region in the first chart describes that autarky would be imposed if the entrepreneur were to enter with a new firm. For these innovations Firm 2 bids strategically to block entry by the entrepreneur and avoid the threat of autarky that would occur if there were entry. In the lower of the red regions, autarky would also be credible if there were entry. In this lower red region, the bidding behaviour of Firm 2 mitigates the impact of autarky on the returns to innovation for the entrepreneur by increasing the entrepreneur's payoff above her reserve. Nonetheless, the threat of autarky still reduces the entrepreneur's reserve and her incentive to innovate. In the upper red region and the orange region, the bidding behaviour of Firm 2, adds to the entrepreneur's incentive to innovate, above the direct benefit of compatibility. That is, in this region compatibility indirectly increases the incentive to innovate by increasing the bids of incumbent rivals.

In the yellow regions there is no credible threat of autarky and compatibility is also offered after the auction. In these regions compatibility increases the incentive to innovate by offering the entrepreneur access to the installed base of incumbent networks, irrespective of the auction outcome.

If there were more rival incumbents, other smaller incumbents could also bid strategically to avoid autarky. In such cases, these incumbents would be indifferent between acquiring the innovation themselves and allowing another small rival to acquire the innovation, as both would either block acquisition by the largest incumbent to avoid autarky or block entry by the entrepreneur in order to avoid autarky. In such cases, the impact on bidding behaviour is similar to the incumbent duopoly case because winning bid only has to exceed bid or reserve of the relevant firm that would cause an undesirable compatibility regime. As a result, the findings from the incumbent duopoly case extend to higher orders of incumbency.

Strategic bidding behaviour, compatibility responses and autarky threats result in a discontinuous relationship between the strength of network effects, the ambition of technological improvement and the entrepreneurs incentive to innovate. Incentives for innovation are higher where the incumbent would offer compatibility to an entrant. For innovations where compatibility would not be offered to an entrant, the disincentive of autarky is mitigated if compatibility were offered to a rival incumbent that acquired the innovation. Similarly, for innovations where compatibility is offered to an entrant, but autarky would be imposed if Firm 1 acquired the innovation, the threat of autarky to rivals further adds to the entrepreneur's incentive to innovate.[11]

4 Discussion

This section discusses the implications of the interaction between compatibility and innovation incentives. In particular, entrepreneurs have an incentive to choose the characteristics of their intensity of innovation effort to avoid an unfavorable punishment of autarky if their innovation is ultimately successful. As a result, entrepreneurs will typically target innovations with greater probabilities of success along the edges of the dicontinuous payoff function where compatibility is maintained.

4.1 The impact of compatibility on innovation effort

In response to strategic bidding behaviour, the entrepreneur should be expected to target innovations where there are greater incentives. Entrepreneurs will adjust their innovation effort in order to maintain a favorable compatibility regime that allows the entrant or acquiring firm to access the network effects associated with the installed base of the largest incumbent network. Clearly, the entrepreneur should target the innovations where compatibility is offered to an entrant. Similarly, the entrepreneur may still target innovations where compatibility would not be offered to the entrant, if compatibility were offered to a smaller rival incumbent acquiring the innovation. Furthermore, the entpreneur may also be attracted to target innovations where an entrant would be offered compatibility, but compatibility would not be offered to a smaller rival incumbent acquiring the innovation.

However, where compatibility decisions cause a discontinuous relationship between innovation incentives and the ambition of technological improvement, entrpreneurs would choose characteristics of their effort along these discontinuous 'knife-edges'. The impact on effort is described by Equations 9e and 9f:

$$\varepsilon^I_\rho = \frac{\partial I}{\partial \rho}\frac{\rho}{I} = 1 \qquad \begin{array}{c} \frac{\partial \Pi_e}{\partial \varphi}\frac{\varphi}{\Pi_e} = \frac{\partial I}{\partial \varphi}\frac{\varphi}{I} \\ \varepsilon^{\Pi_e}_\varphi = \varepsilon^I_\varphi \end{array} \quad .$$

The profit maximising technology improvement target, where $\varepsilon^{\Pi_e}_\varphi = \varepsilon^I_\varphi$, conditional on compatibility, may not be possible if autarky is imposed upon entry. In response entrepreneurs maximise profit, not by choosing the profit maximising target of improvement conditional on autarky, but by choosing a so called 'knife-edge' solution where compatibility would still be offered. So long as the entrepreneur's payoff at this knife edge is higher than an incrementally lower innovation target where autarky would be imposed, this is a profit maximising innovation target even if the $\varepsilon^{\Pi_e}_\varphi = \varepsilon^I_\varphi$ condition is not satisfied. But profit maximisation still requires that the elasticity of innovation effort with respect to probability is equal to one. As a result, selecting a higher target for technology improvement also results in the entrepreneur selecting a lower probability of successfully innovating.

4.2 Tradeoffs

The ability for the largest incumbent to punish the owner of a new innovation by not offering compatibility results in two trade offs between choosing a more innovative target with lower probability of success and compatibility versus choosing a higher probability of success with a lower target and retaining compatibility. In both cases, entrants have an incentive to either reduce the disruptive improvement target for their innovations or reduce the likelihood of success, thereby allowing an incumbent to be partially protected from competitive innovative entry and maintain its dominant market position.

Between a higher probability of success and disrupting the compatibility regime

For the entire range of network effects entrepreneurs face a trade off between the probability of success and losing compatibility with the largest incumbent. The threat of punishment by an incumbent refusing compatibility is a disincentive for incremental oinnovations and, if network effects are moderately strong, also for moderate innovations because consumers are attracted to the largest network. This punishment may encourage entrants to only target highly disruptive innovations such that incumbents maintain compatibility with these very high quality entrant varieties in order to access the network benefits of what is expected to be an attractive customer base. However, entrepreneurs in these markets will also choose a lower probability of success such that Equation 9e is satisfied in order to maximise profits.

As a result, entrepreneurs face a trade off between choosing a higher probability of success for smaller improvements, but being punished with incompatibility for the resulting innovation upon entry or acquisition. As a result, markets with network effects and sufficient concentration will experience infrequent, although disruptive innovations. Incumbents are partially protected from contestability because they can use their dominant market position to discourage incremental innovation where success is likely.

Between innovation and disrupting the compatibility regime

A second trade off occurs for a short range of very strong network effects that imply a disincentive for disruptive innovation as entrepreneurs attempt to also achieve a compatible regime with the largest incumbent. Critically, when network effects are very strong, an entrant may avoid investing in innovations that introduce a moderate quality asymmetry in order to avoid the dominant incumbent removing the entrant's installed base from the compatible network, if entry would result in autarky.

As a result, entrepreneurs may be incentivized to limit the quality improvement in order to maximize the value of an innovation. If a market is in this situation, it follows a frequent, incremental innovation path. However, this particular trade off only arises when network effects are sufficiently strong such that entry is worthwhile for an entrepreneur with an incremental innovation. Incumbents are partly protected from contestability because they can use their dominant market position to discourage high quality entry.

4.3 The weak network effects "bonus"

Noticably, when network effects are weak, the largest incumbent receives an additional reward for an entrepreneur's large, disruptive innovation, because incumbents bid to block entry but rivalry doesn't ensue beyond the enterpreneur's reserve since all incumbents benefit when any incumbent acquires the innovation. Therefore, incumbents can benefit when disruptive innovations are successful.

Furthermore, if the characteristics of innovation effort are merely a target, but actual outcomes are a distribution around those targets, then incumbents could gamble on the likelihood of a highly disruptive innovation with early stage financing. Such bidding would occur well in advance of success, on the possibility of achieving this weak network effects "bonus". This "bonus" characteristic might help explain the substantial involvement of incumbent firms in early stage financing of innovations by entrepreneurs. Such support for innovation when network effects are weak, would stimulate more disruptive innovations in these markets with weak network effects. While incumbents are also indifferent between acquiring these innovations or allowing a rival to acquire them, so long as the entrepreneur is blocked from entry, provided the investment to increase the likelihood of disruptive innovation is less than the expected benefits, it would be in the interests of incumbents to stimulate this type of innovation.

4.4 Implications

Access to compatible installed bases in markets with network effects provides a substantial additional incentive for innovation above that available for markets without network effects. If an entrant can establish connectivity with a large compatible installed base it benefits from the additional demand for its product. Yet the ability for a dominant firm to impose autarky can reduce innovation incentives compared to an industry with full compatibility. When autarky is imposed, an entrepreneur can only access the compatible installed base of small rivals to the largest incumbent. In the worst case, an entrepreneur is unable to receive a return for her investment in innovation if an incumbent can use its large autarkic network to maintain an attractive product despite the improvement offered by an entrant. While entrepreneurs will choose innovation intensity to avoid the punishment of incompatibility, this distortion can allow an incumbent to maintain a dominant position with reduced threat of contestability from entrants.

Alternatively, the punishment from an incumbent to imposing autarky on an entrant is mitigated, if rival incumbents are able to block entry by acquiring the innovation themselves. In these situations, autarky in a market with network effects represents a disincentive to innovate, but compatibility if a smaller rival acquires the innovation mitigates this disincentive by providing some additional incentive to innovate.

In some ways the trade off between innovation and compatibility reflects a similar capacity trade off in Gelman and Salop (1983). In their article, entrants limit capacity, in order to be accomodated by an incumbent, but offer discount coupons to this limited capacity and discounts are then are honoured by the incumbent such that entry occurs with no output. In comparison to the model here, entrepreneurs limit either the probability of successfully innovating or the target of technological improvement according to the strength of network effects, in order to be accomodated by the incumbent. However, the trade off described by the model here requires network effects and adds to the strategic interactions of entrepreneurs and incumbents.

Despite its similarities, the model is not a special case of the hold-up problem (Williamson, 1979; Rogerson, 1992) becuase there is no uncertainty about the compatibility regime and contractual problems are solved as part of the model. That is, contractual arrangements related to the hold-up problem are agreed upon either by the incumbent acquiring the innovation, possibly at a discount due to its threat of autarky, or by the entrant choosing to limit or increase the target of technology improvement to avoid such a threat. Even so, the impact that innovation is diminished, rather than "held-up", by the potential for the incumbent to impose autarky suggesting that solutions may be similar. One option would be for a payment to occur to the incumbent, prior to innovation, to compensate the incumbent for a reduced profit, in return for a compatibility commitment. Such a commitment could be credible if the contract included significant penalties for defaulting on the deal by imposing autarky. Such a deal would enable entrants to profit maximise for innovations with greater probability of success.

A possible regulatory response would be to require incumbents to offer compatibility. This has three effects on innovation. Although regulated compatibility may increase the incentive for innovation for entrepreneurs, the threat of autarky when network effects are weak can also increase the incentive for disruptive innovation as incumbents bid competitively to acquire the innovation and avoid an autarkic regime and/or to block entry. In this way, regulated compatibility removes the solutions, where entrepreneurs target innovations that avoid an unfavorable compatibility regime. Alternatively, innovators do not always remain as entrants or smaller rivals to a dominant incumbent. In a fully dynamic model, an entrant also has an incentive for innovation to disrupt the incumbent's position and take over as the largest incumbent. The threat of regulated compatibility may therefore reduce the innovation incentive for an entrepreneur who is designing a new standard and expects to eventually be in a dominant position. In choosing an appropriate regulatory regime, competition authorities must balance these two incentives to encourage innovative entry, but not discourage long term disruptive entry.

5 Concluding remarks

As markets are increasingly affected by network effects, understanding the impact of network effects on innovation becomes a vital component of entrepreneurship, innovation, competition and regulatory policy. This article provides a useful framework to consider how an incumbent's compatibility decision interacts with entrepreneurial innovation in particular industries, even if anti-compatitive conduct is not clear from price competition. Although compatibility and acquisition may offer entrepreneurs additional incentives for innovation, previous analyses do not examine dynamic compatibility decisions, masking the trade off for entrepreneurs between the likelihood of successful innovation and potentially disrupting the compatibility regime and the trade off between the ambition of technological improvement and potentially disrupting the compatibility regime. In response, entrepreneurs are disincentivised to target particular innovations in markets with network effects. Consequently, these entrepreneurial responses to incompatibility threats by incumbents are likely to protect the competitive positions of incumbents.

This is a particularly useful finding because it implies that anti-competitive situations will often not be clearly presented in price competition or specific actions by the dominant firm. Rather, an incumbent can disincentivise innovative entrepreneurship simply by being in a dominant position where the *likely* threat of incompatibility is already clear to potential entrepreneurs and incumbent rivals. This is an important development for competition and industry regulators to take note of, because its impact on consumer welfare is substantial, yet subtle, and not observed if significant innovations are discouraged by a threat of incompatiblity and simply do not occur. Given that the impact of network effects on innovation activity is likely to be increasing due to new internet-based technologies, these findings are crucially important for regulating industries in a way that takes account of innovation. The findings of the model highlight the need for close examination of the impact of demand (and supply) externalities on innovation in specific industries and other ways that dominance in specific markets with network effects may distort market outcomes. Future empirical studies of particular industries can now proceed using this model to frame the analysis of an incumbent's compatibility decision, even if anti-competitive conduct is not clear from price competition.

Notes

[1]Source:The Economist (2016) http://econ.st/24Edsbi. Accessed November 2016.

[2]Source: Reuters (2016) http://reut.rs/1QdB2Em. Accessed November 2016.

[3]Source: Reuters (2015) http://reut.rs/1I4xiDp. Accessed November 2016.

[4]The term 'early stage investments' refers to Seed/Angel and Series A investments.
Source: CBInsights (2016) https://www.cbinsights.com/blog/iot-funding-startups-q1-2016/.

[5]Full derivation of equilibria with zero output by one or more firms is shown in Appendix A for a market with two incumbents and one entrant.

[6]In these derivations, n is defined by the final number of firms competing, such that if a new firm enters in Stage 2, n is one higher than if the innovation is acquired in Stage 2. An alternative derivation is shown in Appendix B where equilibrium is defined separately for Firm 1, rivals and the entrant with a constant definition for n, irrespective of entry or acquisition.

[7]For the purpose of this analysis, output is calculated as a function of output by firms on compatible networks ($\sum_{j=2}^{n} q_j$) to simplify finding equilibrium under autarky. Conversely, Norbäck et al. (2014) assume all installed bases are incompatible so choose to find equilibrium using aggregate output of incompatible firms. Either approach finds the correct equilibrium. For other regimes not analysed here, (e.g. Firm 2 autarky) a mixed approach could be used such as aggregate output by autarkic firms and aggregate output by compatible firms, or whatever approach is appropriate given the compatibility regime.

[8]See Appendix B for equilibrium defined by rival aggregate demand with a constant definition for n, irrespective of entry or acquisition.

[9]Note that the calibration here has changed. With more incumbent firms, the impact of compatibility is most apparent with a smaller entrant.

[10]With three firms $\alpha < 0.72$. This limit is not required for two firms or once the endogenous compatibility regime is included because strong network effects support compatibility.

[11]While theoretically possible, in this example, the effect of this last case is marginal.

Declaration of interest statement

The authors have no potential conflict of interest

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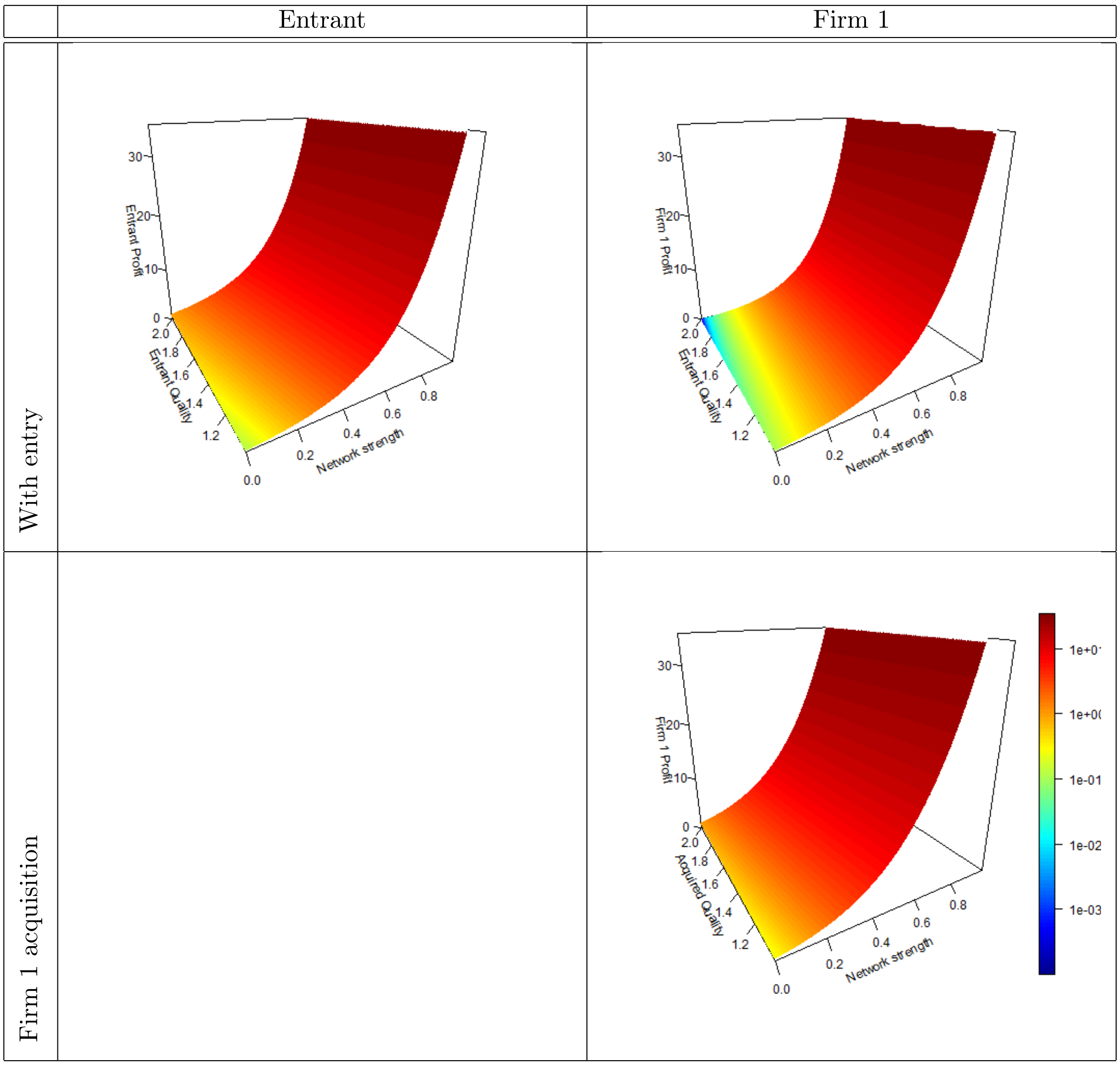


Figure 1: Profits under compatibility: with entry; and with acquisition by the incumbent

Note: Colours are all shown on the same log scale between zero and 35 to show relative changes.

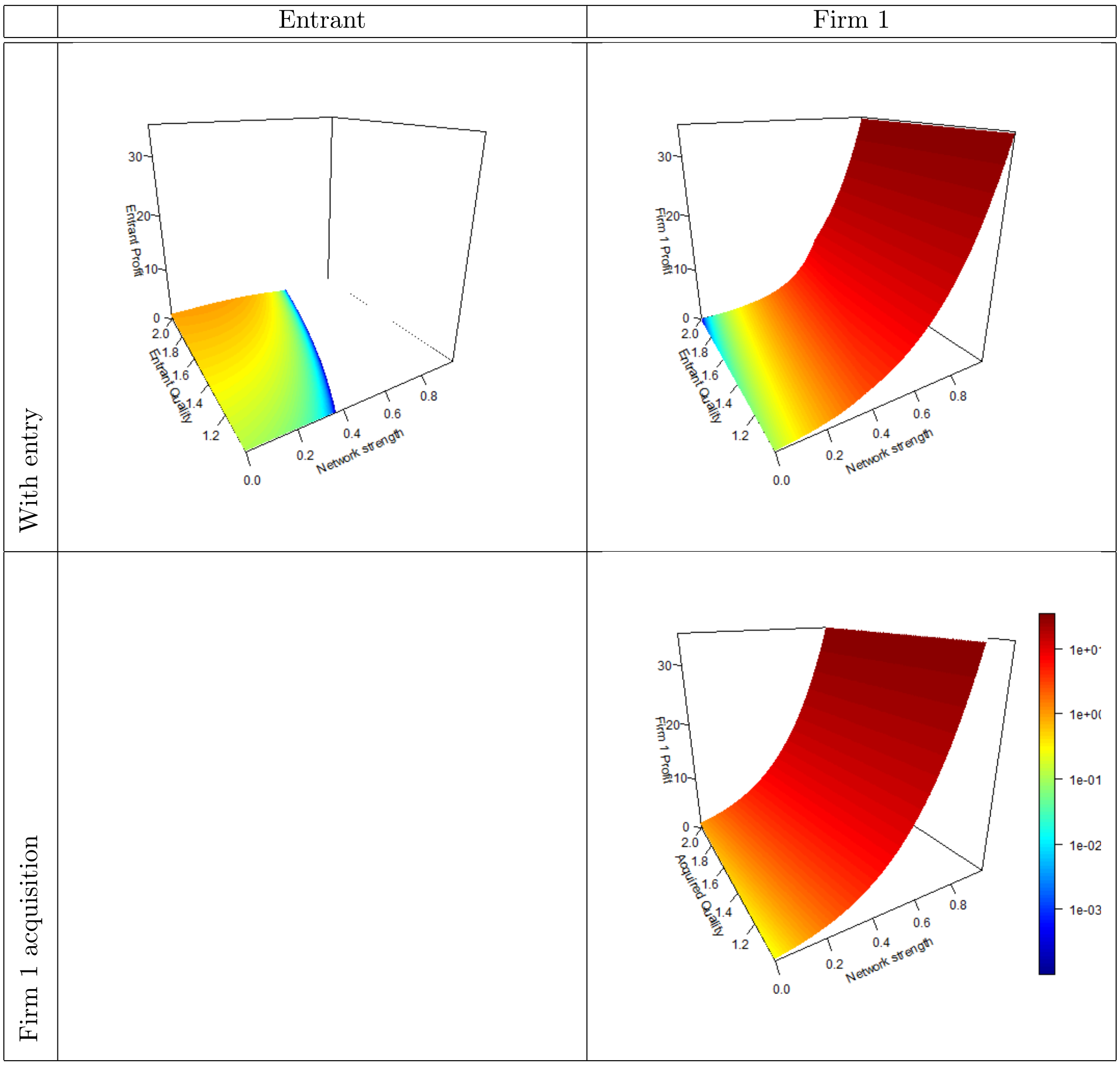


Figure 2: Profits under autarky: with entry; and with acquisition by the incumbent

Note: Colours are all shown on the same log scale between zero and 35 to show relative changes.

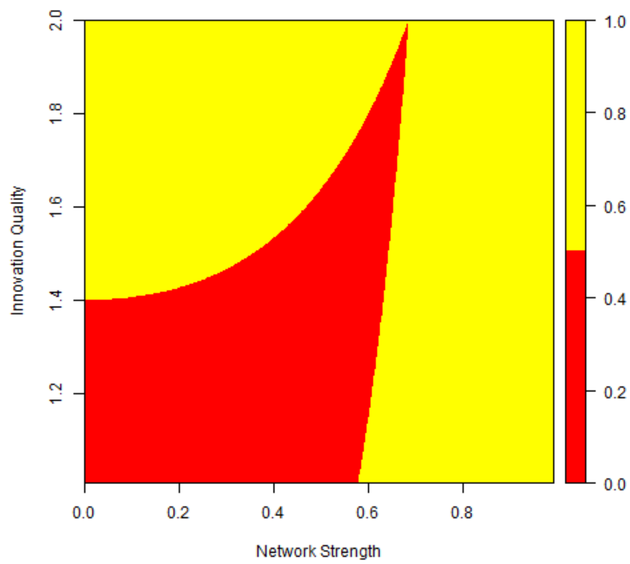


Figure 3: Credible threats of autarky

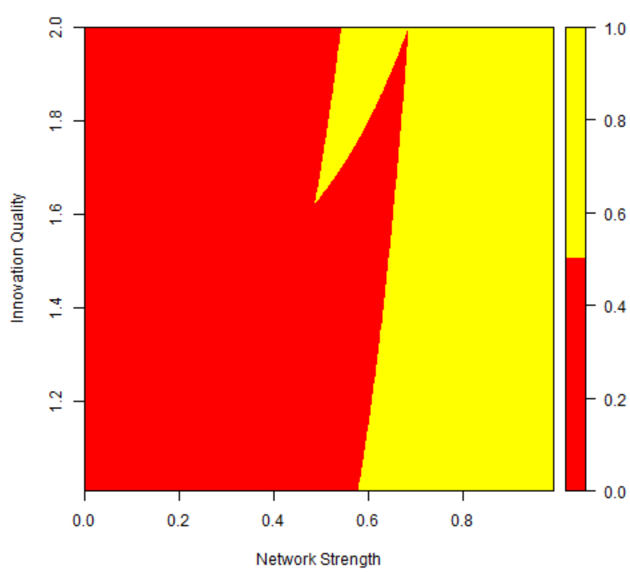


Figure 4: Compatibility regime

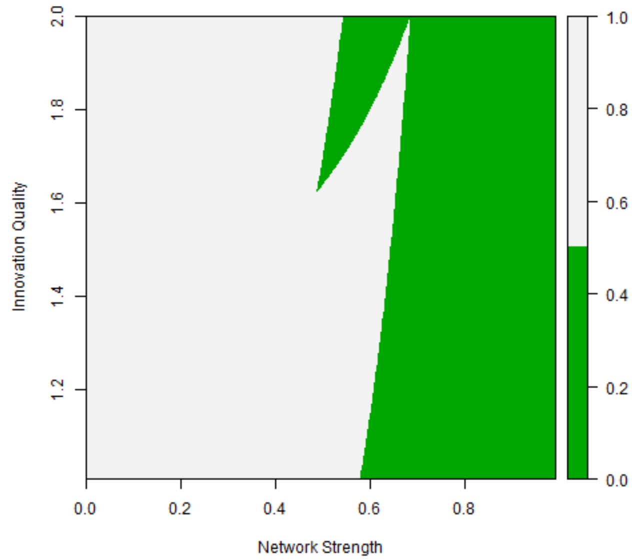


Figure 5: Ownership

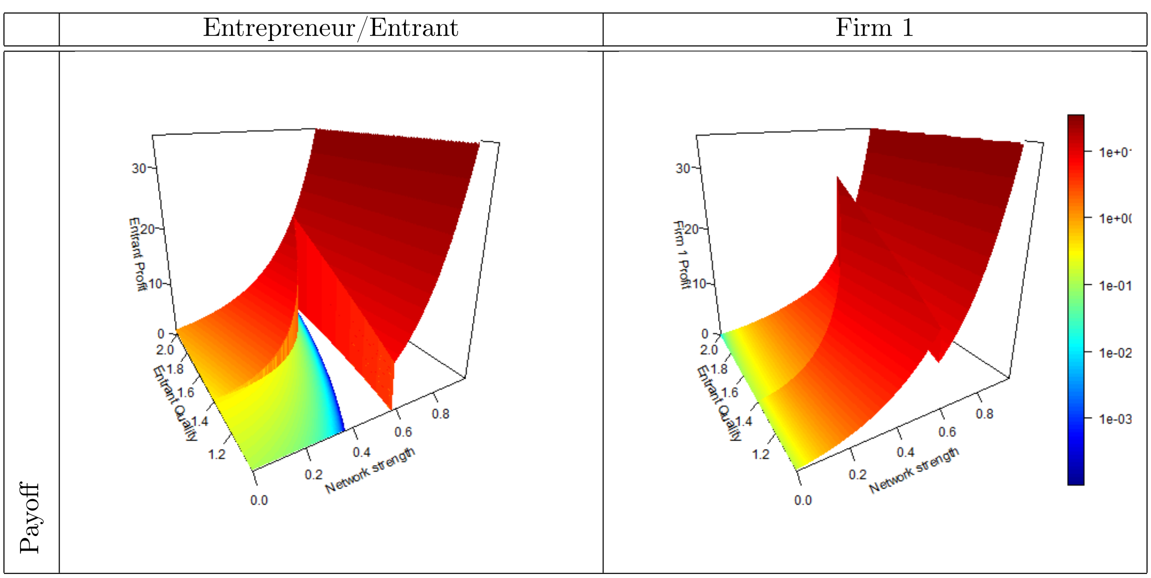


Figure 6: Payoff as a result of the auction

Note: Colours are all shown on the same log scale between zero and 35 to show relative changes.

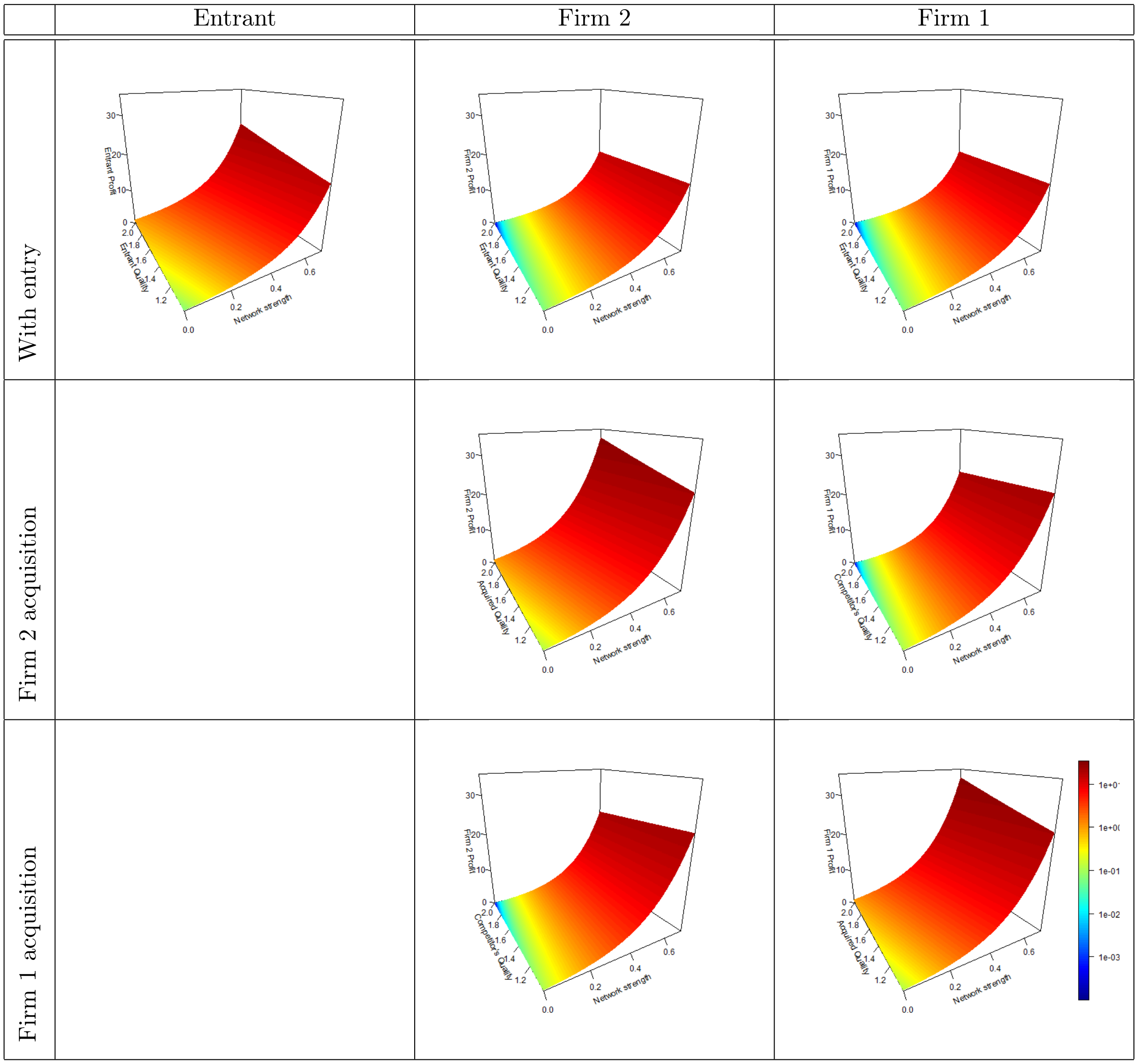


Figure 7: Profits under compatibility: with entry; with acquisition by small incumbent (Firm 2); and with acquisition by large incumbent (Firm 1)

Note: Colours are all shown on the same log scale between zero and 35 to show relative changes.

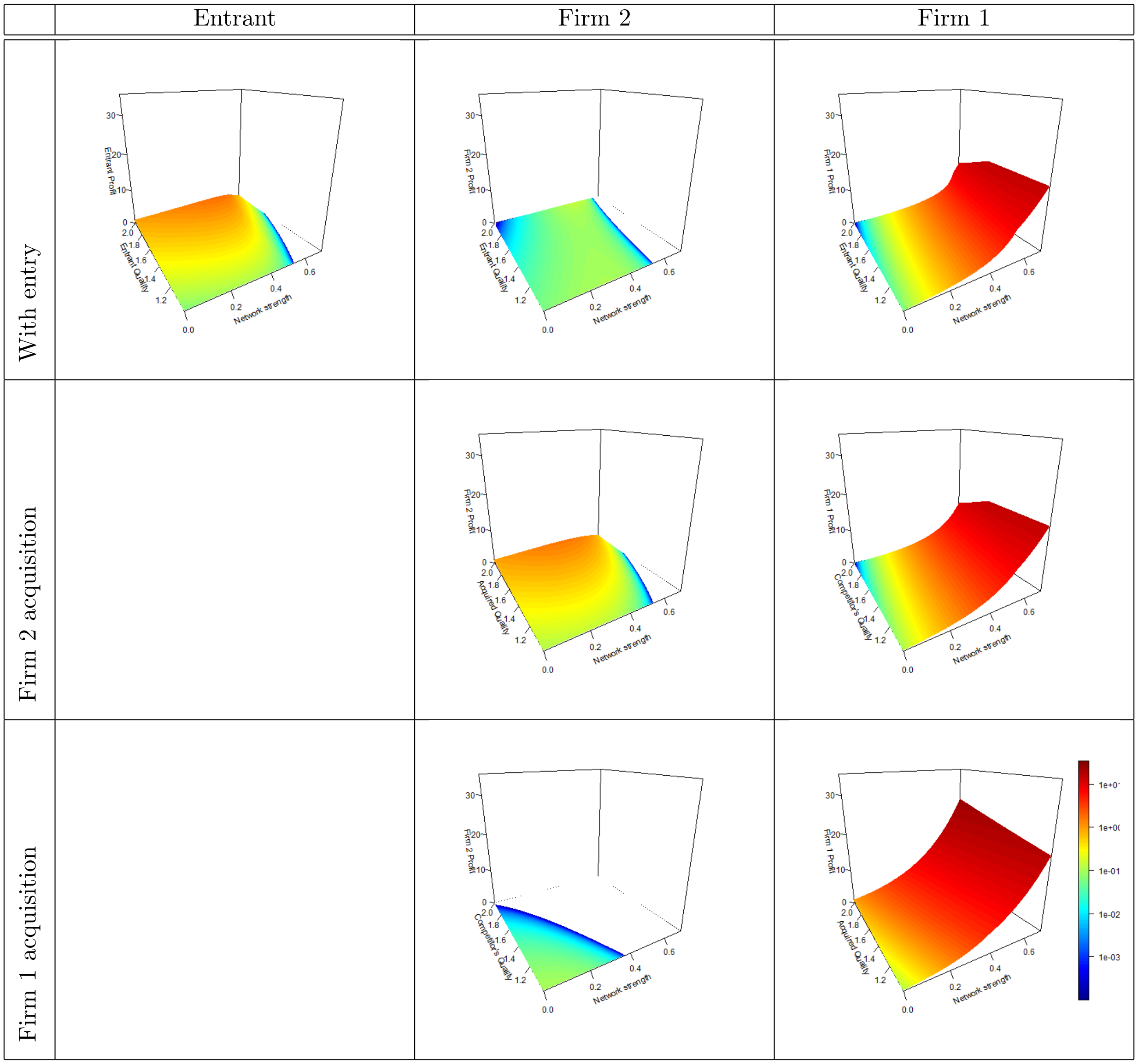


Figure 8: Profits under autarky: with entry; with acquisition by small incumbent (Firm 2); and with acquisition by large incumbent (Firm 1)

Note: Colours are all shown on the same log scale between zero and 35 to show relative changes.

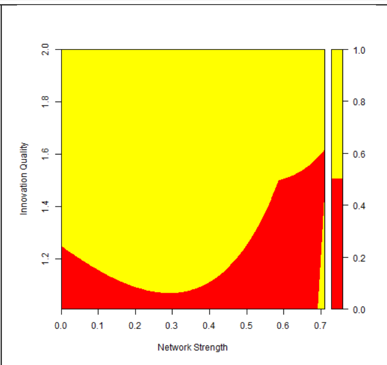
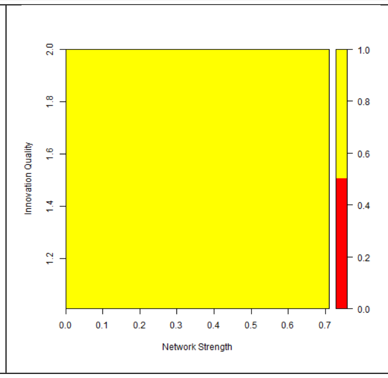
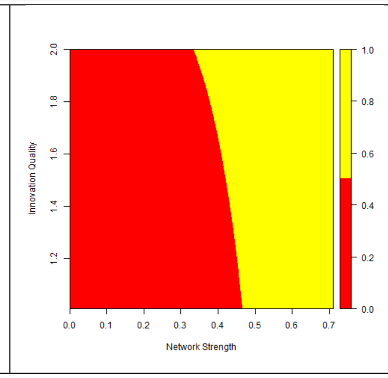
	Entry	Firm 2 acquisition	Firm 1 acquisition
Regime threat			

Figure 9: Credible threats of autarky if acquired by each firm

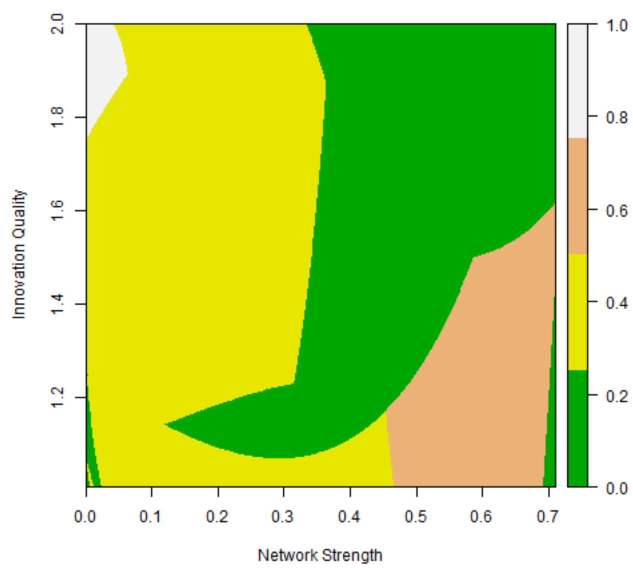


Figure 10: Ownership

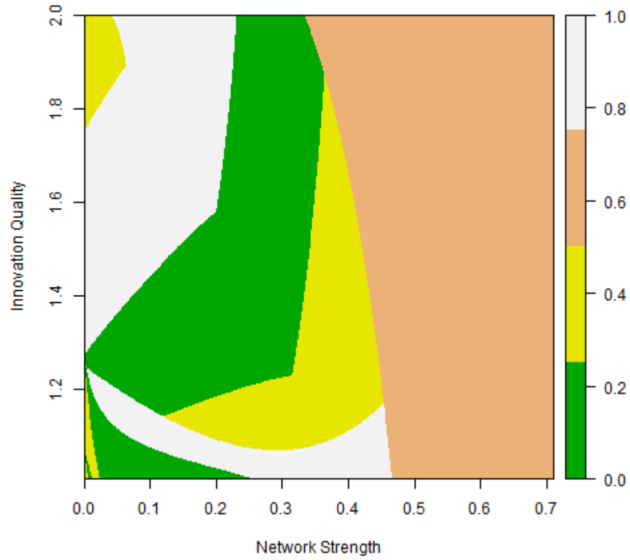


Figure 11: Losing bidder

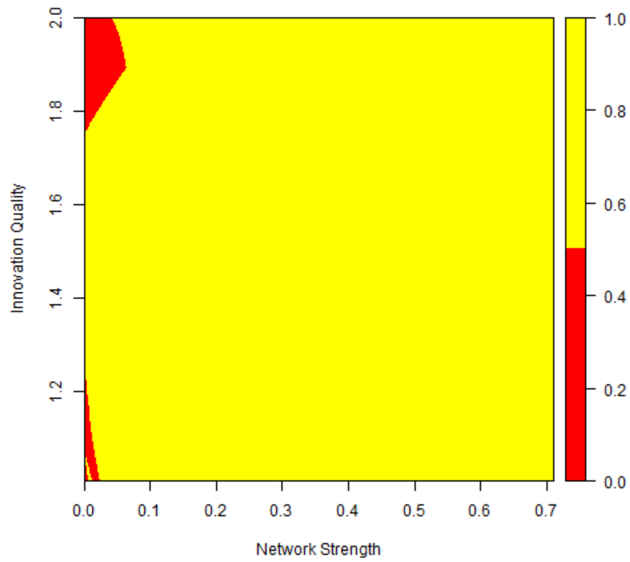


Figure 12: Compatibility regime

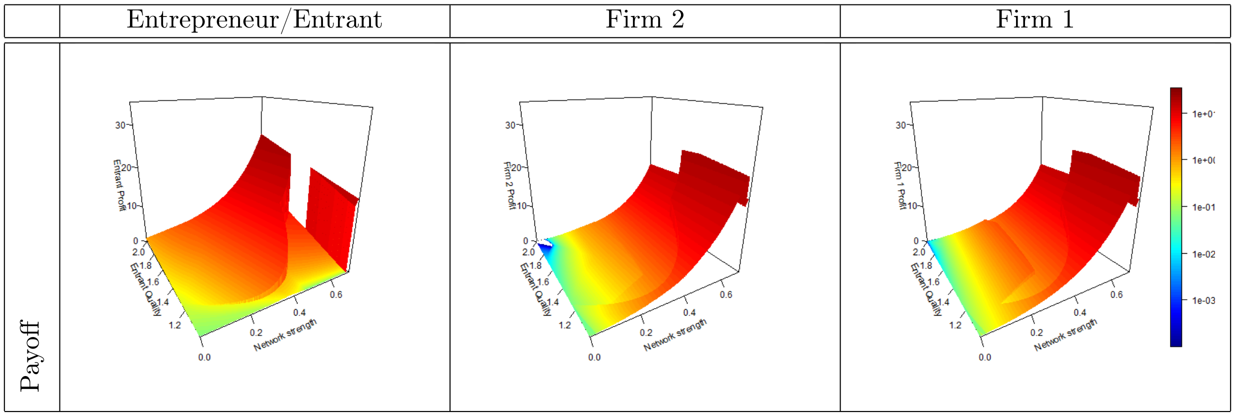


Figure 13: Payoff as a result of the auction

Note: Colours are all shown on the same log scale between zero and 35 to show relative changes.

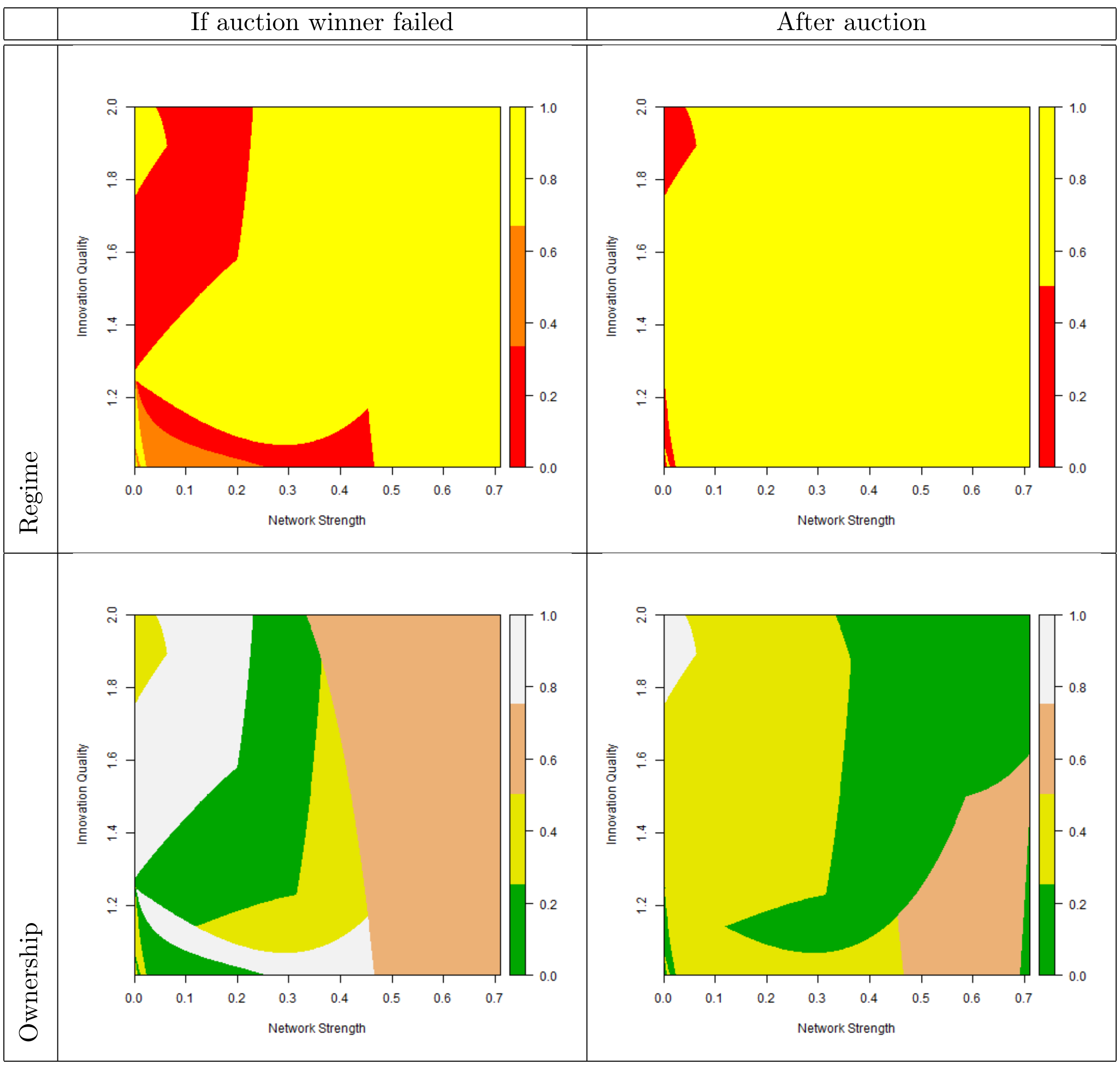


Figure 14: Credible threats of autarky and bidding behaviour

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