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CAPABILITY-BASED GOVERNANCE PATTERNS OVER THE PRODUCT LIFE-CYCLE

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Capability-based governance patterns over the product life-cycle

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Abstract

We investigate patterns of vertical governance over the product life-cycle as function of the capability regime properties imitability and substitutability. We use a novel neo-Schumpeterian model to study emerging governance patterns. We find that, in the era of incremental change, firms prefer vertical specialization. In the era of ferment, no governance form dominates. Imitability and substitutability, in interplay, determine the governance form preferred. High imitability frustrates appropriation and thereby integration for synergistic advantages. However, firms need not vertically specialize: under low substitutability, incompatibilities reduce the advantages of specialization. When both substitutability and imitability are low, firms can appropriate the value of their inventions and there is no combinatorial advantage of specialization, so firms predominantly integrate. If substitutability is high and imitability is low, the combinatorial advantage of specialization balances with the synergistic advantage of integration.

1 Introduction

Under competition, firms seek to acquire capabilities to produce products that generate superior value for consumers. Capability value and competitiveness of firms derive not only from own capabilities, but also from capabilities of firms up- or downstream in the value network (cf. Håkansson and Snehota,

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1989). Given occasional changes to market, technological and competitive conditions, firms are likely to have to occasionally decide on their vertical scope of and linking with particular capabilities. Recent research is concerned with the *temporal patterns* in the vertical scope of firms *over the product life-cycle* (e.g. Fine, 1998; Jacobides and Winter, 2005; Cacciatori and Jacobides, 2005; Argyres and Bigelow, 2010; Argyres and Zenger, 2009). We use the eras of ferment and incremental change in the cycle of technological change (Anderson and Tushman, 1990; Tushman and Anderson, 1986) to characterize the industry conditions in product life-cycle for firms to deal with in their governance decisions. Following product life-cycle theory rationales (Utterback and Abernathy, 1975), capability-based concerns tend to dominate prior to the emergence of the dominant design, i.e. in the era of ferment, while cost-based concerns tend to dominate in the era of incremental change. However, there is disagreement on the vertical scope of firms during the era of ferment. According to Afuah (2001); Jacobides and Winter (2005); Fine (1998), firms are vertically integrated for knowledge absorption and efficient research. According to Harrigan (1985); Balakrishnan and Wernerfelt (1986), firms are vertically specialized to prevent lock-in and allow flexible recombination. During the era of incremental change, firms seek to outsource production, generally to reap scope, scale and cost advantages, although firms may integrate to horizontally differentiate their products (Argyres and Bigelow, 2010).

We argue that differences in findings on the vertical governance forms chosen may well have to do with conditions that are specific to the industry. We show that the *properties of capabilities*, notably substitutability and imitability (cf. Teece et al., 1997; Barney, 1991), determine the governance patterns over the product life-cycle.

We analyze the relationship of the capability properties and governance forms in a neo-Schumpeterian multi-agent model with agents that autonomously control their vertical scope of production. There are three types of firms: input component producers (suppliers), system producers (assemblers), and firms that produce both. Firms search a capability space (Gilbert et al., 2001, 2007) for production capabilities, and combine input and system capabilities (either in-house or by teaming up with a firm providing the complement) to produce products to compete on the end-consumer market. The research question is: what patterns of vertical governance occur over the product life-cycle and how do these patterns change with capability properties? In answering this question, we vary the imitability and substitutability of capabilities as independent variables and study the evolutionary emerging governance pattern over the product life-cycle as dependent variable. The cost structure (economies of scale in production, switching costs, research costs) is the mediating variable.

We find that the vertical governance pattern over the product life-cycle strongly depends on the basic properties of the capabilities in the technology regime. In the era of incremental change, firms prefer vertical specialization. In the era of ferment, however, no governance form dominates. High imitability frustrates appropriation and thereby integration for synergistic advantages. However, firms need not vertically specialize: under low substitutability, incompatibilities reduce the advantages of specialization. When both substitutability and imitability are low, firms can appropriate the value of their inventions and there is no combinatorial advantage of specialization, so firms predominantly integrate. If substitutability is high and imitability is low, the combinatorial advantage of specialization balances with the synergistic advantage of integration. An integrated conceptual framework containing both imitability and substitutability is required to determine whether firms vertical specialize to be able to switch to alternative component technologies or rather vertically integrate to fine-tune input component and system.

In Section 2, we derive hypotheses from the literature on the competitive challenges in the different eras of the technology cycle underlying the product life-cycle and how this affects capability and cost-based governance decisions under different capability regimes. In Section 3, we define our neo-Schumpeterian agent-based simulation model. In Section 4, we present, analyze and interpret the simulation results. In Section 5, we summarize our findings and draw conclusions.

2 The effect of capabilities on governance

We discuss the (dis)advantages of searching for competitive combinations of capabilities under vertical integration and specialization, the effect of capability properties on these search (dis)advantages in general and during the era of ferment and incremental change in particular.

2.1 Governance form and search

The competitive value of capabilities depends on the capabilities of partners in the value network (Håkansson and Snehota, 1989). To realize product competitiveness, up- and downstream capabilities need to be attuned. The vertical governance form affects the search for a combination of capabilities. Firstly, whenever a firm is vertically integrated there is a *synergistic advantage at firm level*. Communication and cross-fertilization of knowledge is efficient, and input component and system technology are closely finetuned during development such that there is high internal compatibility (cf. Schilling, 2000; Kogut and Zander, 1992; Afuah, 2001). An additional advantage is that integration excludes rivals from using the same input or system and assures that the generated value is appropriated by its (integrated) inventor. Ownership rewards the investments in discovery (cf. Grossman and Hart, 1986).

Secondly, whenever a firm is vertically specialized, there is a *combinatorial advantage at population level*. An system producer can easily and (relatively) cheaply link up with an alternative (vertically specialized) input supplier to realize a new combination of capabilities (cf. Schilling and Steensma, 2001; Dyer and Singh, 1998). In case there are many suppliers that search independently for capabilities, system producers explore more combinations than when vertically integrated. Furthermore, suppliers may trade with or be approached by more than one assembler, thus increasing their chances of sales. Vertical specialization thus constitutes a *decentralized search* of many combinations.

So, vertical integration allows attuning for high performance plus appropriation of generated value, while vertical specialization allows easy recombination and decentralized search.

2.2 Properties of the capability regime

Capabilities form a competitive advantage if they are valuable and rare, and hard to imitate and substitute (Barney, 1991). In this study, we focus on imitability and substitutability.

Imitability refers to the extent of efforts (costs, dedicated time or other resources) needed to imitate capabilities. Under high (low) imitability, limited (extensive) efforts are required. The *synergistic advantage* of being integrated reduces with imitability. If capabilities can be imitated easily and cheaply, the competitive advantage of additional performance achieved by tight vertical governance is likely to erode quickly. Furthermore, also the *combinatorial advantage* of being specialized decreases as other integrated firms can quickly imitate a high performing combination found by other firms. If imitability is high, both advantages are relatively weak. However, by specializing, firms still enjoy the decentralized searching and at least consider more combinations than when fully integrated. If imitability is low, integration is an effective exclusion and appropriation instrument (but the firm is locked in), whereas specialization allows competitors to access the same (possibly superior) upstream capabilities. Note that exclusion is less of a reason to integrate if those capabilities are of limited value for competitors: the value of arbitrary complementary capabilities drops whenever the substitutability drops. A system (input) producer does not need to exclude competing system (input) producer from accessing the same input (system) producer as they are likely to encounter compatibility issues anyhow.

Substitutability refers to the extent to which swapping one capability for another may affect overall performance (conditioned on values of both capabilities). If input component and system capabilities are complexly interwoven or finely attuned, swapping one for an arbitrary other capability is likely to lead to compatibility problems and thereby deter overall performance. If capabilities are modular, swapping one input (system) for another input (system) capability is likely to yield few compatibility issues. The more substitutable (more modular/ less complex) capabilities, the more eager firms are to specialize (cf. Argyres and Bigelow, 2006; Sanchez and Mahoney, 1996). If substitutability is low, compatibility issues are common and capabilities must be attuned closely to reach high performance. Vertical integration allows attuning upstream and downstream capabilities to arrive at an integrated, competitive product, while specialization and relying on external capabilities is likely to yield products whose performance is low due to incompatibilities. So, with a decrease in substitutability (increase in complexity), the combinatorial advantage of specialization decreases and the synergistic advantage of integration increases. However, due to these incompatibilities, integration *as exclusion instrument* is less important. As the value of decentralized search drops with a drop in substitutability, firms rely less on vertical specialization and rather pursue integrated search. We expect this effect to become stronger if imitability drops.

Table 1 contains the hypotheses. In the on-diagonal cells, there is consensus, while, in the off-diagonal cells, there is ambiguity due to conflicting implications.

		Substitutability	
		Low	High
Imitability	Low	H1: Integration for exclusion/ appropriation H2: Integration for attuning, specialization suffers incompatibilities	H1: Integration for exclusion/ appropriation vs. specialization to link w. top capabilities H2: Specialization for decentralized search
	High	H1: Specialization for decentralized search H2: Integration for attuning, specialization suffers incompatibilities	H1&2: Specialization for decentralized search

Table 1: Governance forms as predicted by imitability and substitutability. There is ambiguity on the governance form in the off-diagonal cells. In the era of incremental change,

2.3 Governance in different eras

Recent research is concerned with the *temporal patterns* in the vertical scope of firms *over the product life-cycle* (e.g. Fine, 1998; Jacobides and Winter, 2005; Cacciatori and Jacobides, 2005; Argyres and Bigelow, 2010; Argyres and Zenger, 2009). According to the cycle of technological change (Anderson and Tushman, 1990; Tushman and Anderson, 1986), the industry cycles through the eras of ferment and incremental change, punctuated by the emerge of a dominant design and a radical breakthrough. In each of these eras, the market, competitive and technological conditions differ, and so are the concerns in deciding on a governance form. Table 1 needs further specification for both eras.

During the era of ferment, entrants and incumbents compete on product technology and small scale production has firms produce in costly job shops. Firms are faced with a -what we call- 'high stakes/ high gains' governance dilemma. Integration allows firms to attune input and system and reach a high performance. However, firms also frequently discover new input and system technologies and frequently bring new products to the market. With this technological turmoil, there is a high risk that current capabilities become obsolete and the value of being able to link up with complementing capabilities increases (cf. Harrigan, 1985; Balakrishnan and Wernerfelt, 1986). If substitutability is high, flexible recombination is relatively valuable. If substitutability is low, the probability that a complement at the market yields a high performing product is low. Under low imitability, firms can effectively appropriate market value, so integration to reach a high performance is more valuable. The propensity to vertically integrate decreases with imitability.

During the era of incremental change, technological changes are unlikely or less frequent. Specialization to be able to link to alternative capabilities is only occasionally interesting. However, firms are manufacturing a relatively standardized product with relatively stationary demand, so it is probably easy to find a supplier of standard inputs or an assembler of standard systems. Governance decisions are primarily cost-based and target minimizing the production and transaction costs. Firms outsource production if there are positive economies of scale in production in an upstream sector (cf. Stigler, 1951), or if there are diseconomies of scope (Prahalad and Hamel, 1990) (or positive economies of specialization (cf. Smith, 2003)). In general, transaction costs and diseconomies of scope mediate the appeal of specialization and integration in obvious directions: e.g. existence of positive economies of scale in the upstream sector promotes vertical specialization. We expect that these factors have greater explanatory power during the era of incremental change. In the present chapter, we treat transaction and production costs as mediating variables. The governance form affects (potential) scale economies, scope economies, marginalization, dexterity, and transaction costs. We discuss actual assumptions in the model definition.

3 Neo-Schumpeterian model

3.1 Overview

We provide a neo-Schumpeterian model in which firms compete for consumer demand through product innovation and price setting. The industry has a fixed, two-tier vertical structure and firms explicitly decide to *produce systems, input components, or both.* A system producer needs to buy inputs, while an integrated firm makes both inputs and systems. Figure 1 illustrates the industry structure.

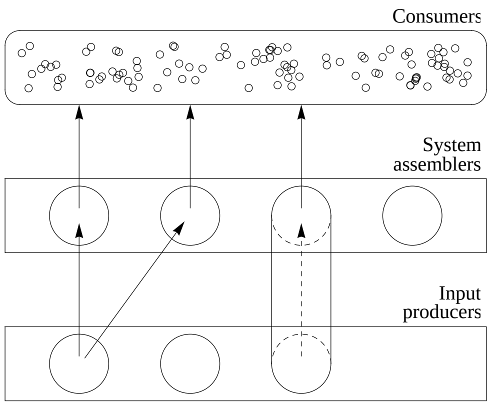


Figure 1: Graphical illustration of the industry structure. Here, one supplier provides inputs to two system assemblers, and there is one integrated firm.

In Subsection 3.2, we describe how firms search a multidimensional capability landscape for superior capabilities and how *vertically specialized* firms also look for production chain partners with superior capabilities to jointly produce a superior product. In Subsection 3.3, we describe the firm heuristics for its business strategy (mass manufacturer or entrepreneur), a product technology search strategy (exploration, imitation or radical search) and a vertical governance strategy (vertically integrate or specialize) of firms. Given that searching, producing and changing production costs money, only firms that have superior products survive and see their strategies imitated by entrants. This establishes an evolutionary 'training' of the strategy. The products are launched, dynamically priced and ultimately withdrawn from the market following the heuristics described in Subsection 3.4. In Subsection 3.5, we describe how consumers buy

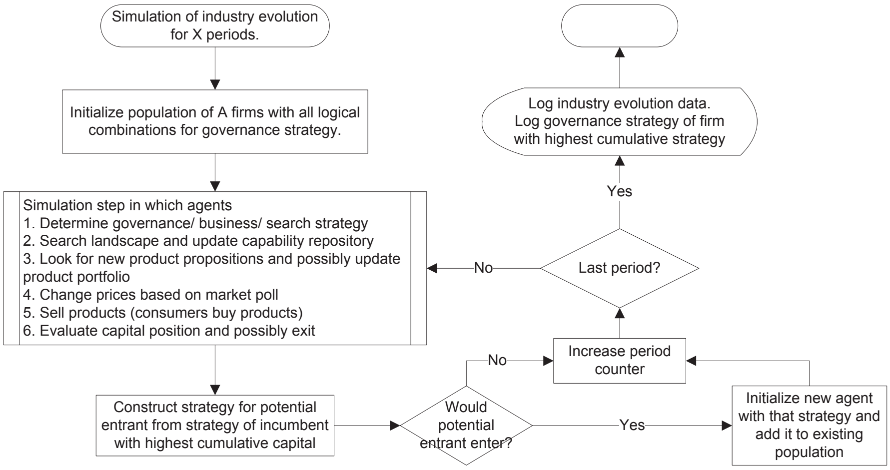


Figure 2: Flowchart of industry evolution with strategy training.

products based on price, performance, their adoption willingness and recommendations by other consumers. A flowchart of this industry evolution with strategy training is given in Figure 2.

In the present work, we train only two strategy variables: the governance form (integrated/ specialized) *before* and *after* the emergence of the dominance design. The strategy variables for business type (mass-production versus job shop production) and capability search are fixed. The industry level parameters (production costs, diffusion rate, etc) are treated as mediating variables. The other strategy decision variables (decision thresholds discussed later) are taken constant and equal for all agents. By homogenizing firms, evolution trains just the governance strategy. The values chosen for mediating variables and strategy decisions variables are given in Appendix 6. In Subsection 4.1, we discuss our parameter choices in detail. Typical simulation results (see Subsection 4) of our neo-Schumpeterian model feature distinct eras of ferment and of incremental change and reproduces the stylized facts of swarm-in/ shake-out, turbulence/ convergence in product technology, and profit erosion.

3.2 Capability search

Firms search at two levels: operational landscape search and combinatorial search. At the first level, firms search the capability landscapes (the system production capability landscape, the input production capability landscape, or both) for new viable capabilities by manipulating an experimental capability proposition. As soon as a focal firm finds a capability with non-zero performance that is new to this firm, the firm adds it to its internal capability repository.

At the second level, firms form product propositions from combinations of readily discovered input and system capabilities. An integrated firm combines system and input capabilities from its internal capability repositories, while an assembler combines its internal system capabilities with input capabilities possessed by suppliers. Whenever an integrated firm or potential value chain partner adds a capability to its repository, all possible new combinations are in-

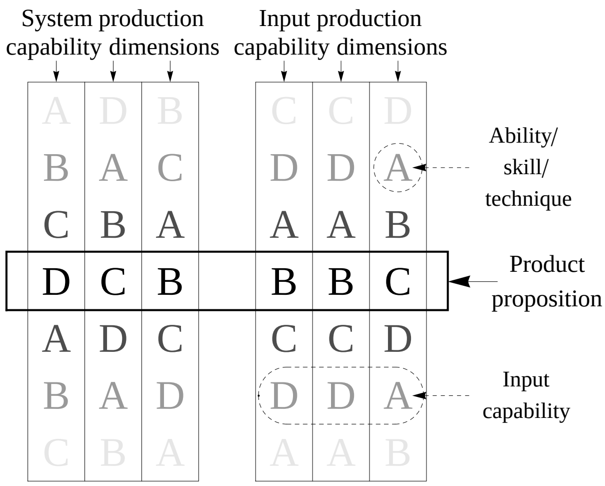


Figure 3: Graphical illustration of the two capability dimension landscapes consisting of 'reels' of abilities/ skills/ techniques.

spected for new and better performing products.
Radical search unlocks a new generation of product capabilities. Once a firm has unlocked a generation new to it, it will focus its search on that generation. A capability of a particular generation needs a complementary capability of the same generation.
Firms do not just explore the current landscape, or unlock new ones through radical search, but may also imitate product technology of competitors. In Subsection 3.3, we describe how firms decide what search strategy to follow.

Landscape search

A capability is the recipe on how to mix techniques, capital goods, and skills/ abilities to produce a certain output product. We operationally encode a capability as an alphabetic string. There are two capability landscape tiers: one for system capabilities and one for input capabilities. Each capability landscape tier is made up of a fixed number of N capability dimensions (abilities, techniques, capital goods, skills). For each of the capability dimensions, there are D options. We use the metaphor of the reels in a gambling slot machine (see Figure 3): there are N reels (capability dimensions) with D pictures (skills/ abilities/ techniques/ resources). At each tier, the firm is looking for a feasible combination in the space of size D^N possible combinations.

As R&D is done by trial-and-error (Nelson and Winter, 1982), we infer that almost all capabilities (each a unique combination of abilities, techniques, skills, etc) are technological infeasible and have zero performance. Only a few capabilities have non-zero performance. From innovation size distribution studies (e.g. Silverberg and Verspagen, 2003), we infer that combinations that are feasible have a certain performance distribution. We implement these two observations as in the island-sea landscape of Fagiolo and Dosi (2003): opportunities are randomly scattered 'islands' in a 'sea' that has to be sailed to reach those islands.

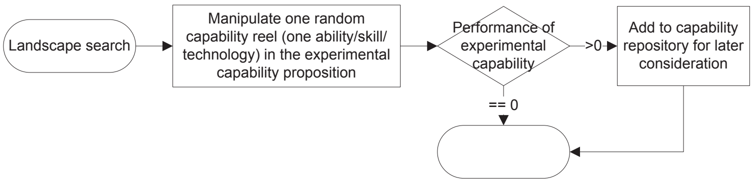


Figure 4: Flowchart of operational landscape search in which the experimental capability is manipulated to find new feasible capabilities by trial-and-error.

During initialization of the industry, we randomly select C combinations that are feasible (so we have C islands) and have a non-zero performance, and set the remaining $D^N - C$ capabilities to have a performance of zero[1].
Of the C feasible capabilities, capability i from product technology generation g has a performance q equal to $g + e^{-\alpha u^{\beta}} \in [g, g+1]$ where $u \sim U[0,1]$ is a uniform random variable. We tune this distribution with parameters $\alpha \geq 0$ and $\beta \geq 0$ to assure that a large share of the capabilities has low performance, while a small share of the capabilities has high performance (cf. Silverberg and Verspagen, 2003).
During exploration, the focal firm searches this landscape by changing one ability at a time of its experimental capability proposition, i.e. by turning one capability reel in Figure 3 up or down one step at a time. If a capability is technologically feasible, i.e. has a performance higher than zero, it is added to the capability repository and is considered during the first level combinatorial search (which is described in detail below). The process of operational landscape search is depicted in the flowchart in Figure 4. We assume that firms have fixed search costs.

Combinatorial search

Whenever an integrated firm finds a capability that is new to this firm, it is added to its repository. The focal firm then considers all combinations of this new capability with the complementary component capabilities (of the same generation) it currently possesses. Whenever an assembler discovers a new system capability or a supplier discovers a new input capability, the assembler will consider all new combinations with capabilities of suppliers by enumerative search. Whenever a supplier discovers a new capability, assemblers contact the supplier to evaluate new combinations. This procedure is depicted in the flowchart in Figure 5. We discuss the procedure to decide on whether to start the production of a new product in Subsection 3.4.

We assume that already one poorly performing capability will cause the whole product to be poorly performing. The performance of a combination of

[1] At first, we drew a performance value for each of the D^N combinations. We found that the capabilities with very low performance were used only very rarely and usually only very briefly (until replaced by capabilities with higher performance). So, the effect of the capabilities with very low performance was limited. Truncating the very low performance values of the $D^N - C$ capabilities to zero, and thereby adopting the island-sea landscape, we shortened the computation time dramatically. Switching to an island-sea structure of the capability landscape goes at the expense of having to add an additional parameter C for the number of islands.

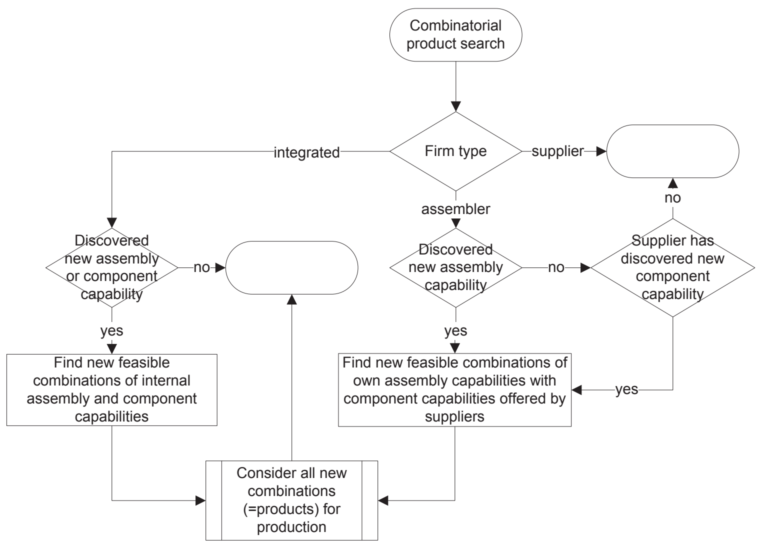


Figure 5: Flowchart of combinatorial search for products by combining capabilities already discovered.

system and input capability is low if one or both capabilities have low performance. The performance of a combination is high only if the performances of both the input and system capabilities are high. If either one is low, the overall performance is low. To operationalize this interaction, we take the *product* of the performances. As also the fit of input and system matters, we multiply this product by the compatibility value (explained in detail later). The skewed nature of the total performance due to the multiplications is corrected by taking the third root. We thus propose the following expression for the overall performance q of a product:

$$q = g + \sqrt[3]{(q_i^S - g)(q_j^I - g)c_{ij}} \tag{1}$$

Hereby, q_i^S (q_j^I) is the performance of the system i (input j), g is the generation of both input and system (which is described later when discussing radical search), c_{ij} is the compatibility j and system i.
Following the landscape metaphor for capabilities, the compatibility c_{ij} of the input and the system relates inversely to the 'distance' δ_{ij} in the codings of the input and system. We use the Lee (1958) measure $\mathcal{L}$, which is the minimum number of one-step manipulations required to change one coding into another. We assume that compatibility drops with distance and that the relative magnitude of the drop is a negative constant. As such, the compatibility is an exponential function:

$$c_{ij} = e^{-x\,\delta_{ij}} \qquad \text{with } \delta_{ij} := \tfrac{2\mathcal{L}(s_i, s_j)}{ND} \tag{2}$$

The s_i (s_j) is the (alphabetic) string for system i (input j). The distance δ_{ij} is normalized by using that $ND/2$ is the maximum Lee distance. Complexity x determines the level of substitutability of inputs (and systems) for one another in a given product. If $x = 0$, the inputs are perfectly interchangeable (as are the systems), as there is no effect on the overall product performance by doing so. The higher $x > 0$ is, the more sensitive overall product performance becomes to the compatibility (distance) of input and system. We use this complexity x as if the inverse of substitutability and treat it as one of our two independent variables.

Effect of the governance form on search

From the perspective of capability search, both governance forms (vertically integrated, specialized) have their advantages. A vertically specialized assembler has the advantage of being able to combine with all input capabilities offered by -potentially many- suppliers. As all of these suppliers are searching for and also finding input capabilities, the number of capabilities on offer also quickly grows. This is the *combinatorial* advantage as discussed in Subsection 2.2.
A vertically integrated firm has the advantage of having control over looking for input and system capabilities that are a proper fit. We model such a *synergistic* advantage by having an integrated firm look for inputs on the capability landscape tier in the alphabetic neighborhood of the system capability. The second advantage is that the integrated firm does not need to rely on suppliers that may go bankrupt after which the assembler has to switch to using possibly less compatible inputs. From the compatibility formula (2), it is apparent that the 'synergistic advantages' of integrated search are particularly great whenever substitutability is low (complexity x is high).

Multiple generations of product technology

Given economic conditions specified later, firms engage in radical search to unlock a new landscape for the next generation of products. As consumers are willing to pay more for the new generation of products, there is a potential reward for firms to engage in radical search. The performance of an input or system of generation g lies in the range $[g, g + 1]$. So, in Equation (1), we used the *normalized* performance level of input and system in computing the overall performance.

3.3 Strategies

Each firm follows three strategies: a business strategy, a capability landscape search strategy and a vertical governance strategy. Following Anderson and Tushman (1990), we have firms change their business strategy upon the technological punctuations. In line with this, we also have firms change their vertical governance strategy upon technological punctuations. In our model, we thus have firms all respond to industry-level events rather than follow individual strategies.
The business strategy, capability landscape search target and the vertical governance are only reconsidered whenever the firm is engaged in exploration. Whenever the firm is engaged in imitation, differentiation or radical search, the firm first finishes that search operation. We now describe these three strategies in detail.

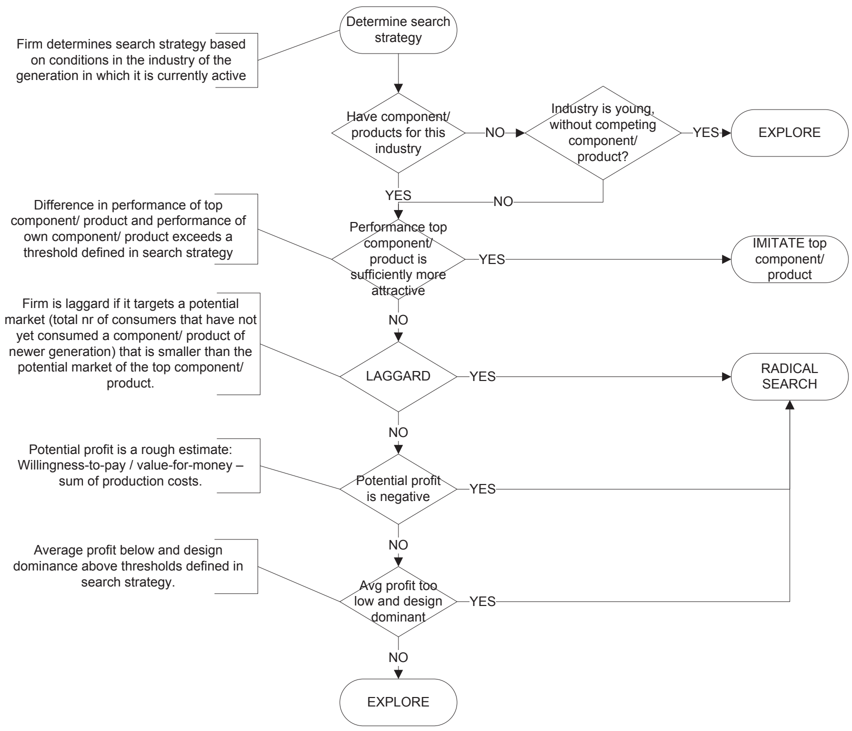


Figure 6: The search strategy determines when to explore freely, imitate the top product/ component/ assembly or to engage in radical research to unlock the next generation of capabilities.

Capability landscape search strategy

In Subsection 3.2, we described the operational search processes that yield capabilities by trial-and-error, exploratory search. Apart from *exploring* its current capability landscape for new capabilities, a focal firm may decide to *imitate* (through directed search) the capabilities used for a product currently on the market, to *differentiate*[2] away from its current capability experiment, or to engage in *radical search* to unlock a new generation capability landscape with higher performance. The landscape search strategy determines when the focal firm should engage in exploration, imitation and radical search.

The first consideration in what search heuristic to follow is that the firm (here: system assembler or integrated firm) continues exploration if the industry is premature, i.e. whenever there is no competing product or the performance of the best product is low. We assume that -in real-life- firms continue searching in a premature industry because they still try to realize a large market share in this industry by providing a top performing product in time. Otherwise, if there is a top performing competing product and the performance of that product is

[2]In the present version, we have disabled differentiation as it is not substantially different from regular exploration: random walks (our exploration) in spaces of dimension higher than two are not recurrent in expectation. So, exploration is already a move away from the current capability experiment.

sufficiently higher, the firm starts imitating that product. A supplier follows the same rationale but then for the input capability. This 'sufficiently higher' relative performance for imitation is a threshold parameter in the search strategy. In case the firm is an entrepreneur (manufacturer), and if the performance of another product is $\geq 5\%$ ($\geq 15\%$, which is higher because of higher switching costs) higher than his own product, the entrepreneur (manufacturer) will start to imitate that other product.

Imitation is operationally defined as manipulating the experimental combination of capability dimensions (abilities, skills, techniques, equipment) to decrease the distance from the experimental to the target capability. The probability of a successful step in the direction of the system/ input capability is i, where i is the imitability rate. The imitability i is, just as complexity x, an independent variable in this chapter. Consequently, given that the starting point on the landscape and the capability to be imitated are uncorrelated, the expected number of periods required to imitate the capability is $\frac{N}{4i}\left(D - 1_{D \text{ odd}}\frac{1}{D}\right)$. The higher we set imitability i, the lower is the expected number of periods needed to imitate the target capability.

If the industry is not premature but the competing product is not good enough for imitation, the firm (here: assembler, supplier or integrated firm) considers radical search. The firm will engage in radical search if one of three conditions holds. Firstly, if the firm is a 'laggard', which we operationally define as that the firm is not yet active in a new generation product technology while more than half of the consumers is already buying products of a new(er) generation. Secondly, the profitability of the current top performing product of the generation produced by the focal firm is negative. Thirdly, the smoothened profit margin is lower than a particular threshold (we picked 0.05, i.e. if the profit margin drops below 5%), while the smoothened design dominance is higher than a particular threshold (we picked 0.80, i.e. one product technology is consumed by more than 80% of the demand market already). The design considerations for this third option are that if a certain technology is already dominant and the profit is low, there are insufficient opportunities in this industry. In that case, a firm will rather try to open up a new industry with more opportunities. If these conditions do not hold (so there are enough opportunities, there still is a sufficiently high profit margin and the own performance is relatively high), then the firm continues local exploration.

The procedure that firms follow to determine their search strategy is depicted in the flowchart in Figure 6.

Business strategy

We distinguish two types of agents: entrepreneurs and mass-manufacturers. An entrepreneur is focused on technological exploration and runs a job shop with versatile production facilities. Production switching is relatively cheap, but unit fixed production costs are high. A mass-manufacturer is focused on large scale production and runs a dedicated mass-production facility. Production switching is expensive, but unit fixed production costs are low.

Firms switch between entrepreneurial flexibility and mass-production based on design dominance $\hat{H}$ (defined in Subsubsection 3.6). If $\hat{H}$ is below a threshold $H_0 - m$, firms become entrepreneurs, if $\hat{H}$ exceeds $H_0 + m$, firms become manufacturers. As $\hat{H}$ may be volatile, there may be repeated crossing of H_0 despite

a structural drift towards 1 or a steep drop due to technological turmoil. Given the high costs of changing the business form, we introduce a region of hysteresis $[H_0 - m, H_0 + m]$ to prevent repeated changes purely due to volatility rather than structural changes.
We assume that firms are entrepreneurial in the era of ferment of a new generation and (at the same time) mass-producing in the era of incremental search in the old generation. As soon as the new generation of products is phased-in in mass-production, the old generation of products -if still produced- is discontinued. As soon as a firm engages in exploration in a new generation of capabilities, the firm will pick the governance form that is beneficial for the entrepreneurial activities.

Vertical governance strategy

Whenever a firm is engaged in regular exploratory search (so, not when imitating or engaged in radical search), the firm changes its vertical governance according to the following simple heuristics. If an assembler does not find a supplier, or a supplier does not find an assembler, it will vertically integrate. In any other case, the firm picks the governance form related to the era. In the era of ferment, i.e. prior to the emergence of the dominant design, the focal firm picks the governance form for that era. Similarly, after the emergence of the dominant design, the focal firm picks the governance form for the era of incremental change, which may well be different from that for the era of ferment. These two governance form specifications are the only two variables that are endogenously trained.
Whenever an integrated firm becomes an assembler, this assembler links up with an existing supplier if this supplier provides the currently used or even a better input, but otherwise spins off its input production capabilities to a newly established supplier with whom it then links. Similarly, whenever an integrated firm becomes a supplier and does not find an assembler that switches to it, this firm spins off its system production facilities to a newly established assembler with whom it then links. From that moment onward both specialized firms follow their own (autonomous) heuristics that further improve their performance. The outsourcing agent considers switching to another supplier already the next period.
Upon integration, the firm acquires the complementary capabilities of its current value-chain partner(s) and continues to produce the products, but now fully in-house.
The costs of integration and outsourcing are discussed in Subsection 3.7.

3.4 Product launch, pricing, and withdrawal

Each assembler or vertically integrated firm has a portfolio of product propositions that it actually produces and sells on the market. If search yields a new product proposition, the firm evaluates whether it is eligible for production and, if so, adds it to the product portfolio. A product proposition is eligible for production if it outperforms one of the currently produced products or there is still room in the otherwise limited product portfolio. Moreover, the product must have positive potential profit margin. The flowchart for this procedure is found in Figure 7.

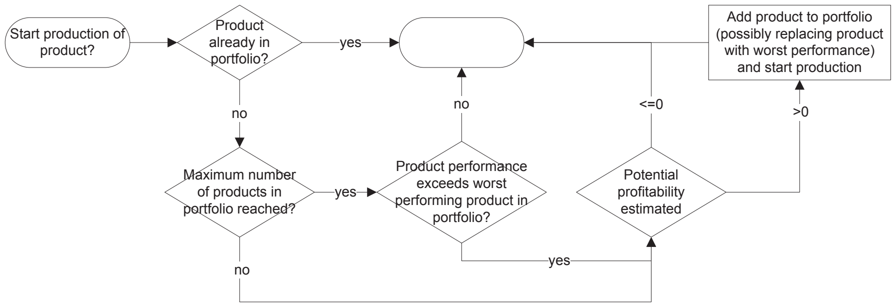


Figure 7: The flowchart for deciding on whether or not to start producing a particular product.

If a firm has not yet produced and sold a particular product before, it has to start up production (for which a fixed cost is incurred) and launch it by giving a promotional unit to a number of consumers. These consumers will thus (possibly) drive further diffusion-substitution.

A selling firm (i.e. fully integrated or assembler) withdraws a product from the market and removes it from its portfolio if there has been no sales in the current period and there are no potential future sales. Note that also sales by any of the competitors of the same product or consumers currently still consuming the product forms potential future sales.

Firms set the price upon the product launch such that the value-for-money of the product (performance divided by price) is equal to the average value-for-money of products currently on the market. The rationale is that overpricing will stifle diffusion, while dramatic underpricing would hurt revenue too much. In case it is the first product on the market, the maximum willingness-to-pay price p^* is set.

Each period, each firm conducts a poll for each of its products to determine whether to change the price or not. In this poll, the firm randomly draws a fixed number B of consumers from the population of consumers that currently consumes any product of the same product generation. The firm then asks each consumer the probability that it would buy the product in case of three scenarios: the price remains the same, is increased a little, and is decreased a little. These probabilities are in fact determined by the discrete choice model discussed later. The firm then maximizes expected sales (average probability times the (new) price) by increasing, decreasing or keeping the current price. Figure 8 contains the flowchart of this process.

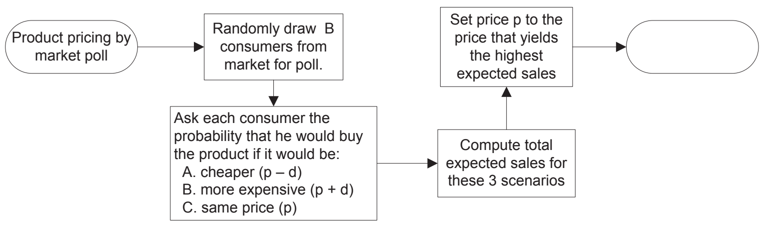


Figure 8: The flowchart for product pricing process by polling consumers.

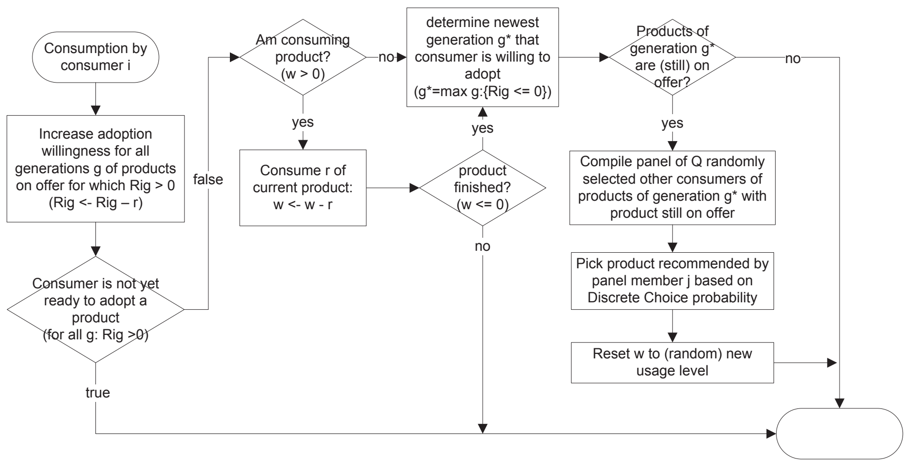


Figure 9: The flowchart for the procedure how a focal consumer decides when to purchase what product of which generation.

With multiple firms and sufficiently discriminative consumers, there is profit erosion and eventually even a (marginal) loss to be expected. Firms will end up losing money, go bankrupt and exit. As demand is inelastic, a remaining monopolist can increase its price indefinitely. As such, we assume that a monopolist will not exit the industry. As we will see in Subsection 3.6, the monopolist will eventually have a high profit margin, which in turn attracts one or multiple entrants that will restore regular price competition.

3.5 Consumption, demand, and diffusion-substitution

Generally, consumers face numerous products to choose from, often even products from multiple product technology generations. We borrow two criteria from diffusion theory (Rogers, 1995) on how a consumer selects a product: firstly, a certain reluctance to buy new products and, secondly, that peers affect a consumer in its product choice. Particularly the gradual adoption of products of a new generation makes that competing products that are introduced later still have a chance of growing a (temporary) sizable market share. As such, there is an era of ferment in which many product variants have a limited market share. However, in the end, the word-of-mouth (and imitation) causes emergence of a dominant design after which industry finds itself in the era of incremental change. Figure 9 contains the flowchart of how a focal consumer decides when to purchase what product of which generation. The mechanisms and variables in this flowchart are explained in the following subsections.

Adoption willingness

Consumers consume or wear out their products at a constant rate r. Whenever the amount w left of its currently consumed unit of product hits or drops below zero (the product is finished or worn out), the consumer seeks to buy a new unit of product. Upon purchasing a new unit of product, a consumer gets an amount w_0 of unit product left. This w_0 is drawn randomly from $\{1 - r\rho, 1 - r(\rho - 1), \ldots, 1, \ldots, 1 + r\rho\}$. This $\rho \geq 0$ defines that there are $2\rho + 1$ different usage scenarios to account for different levels of consumption, wear and tear, accidents and dissatisfaction (and to smoothen out otherwise recurring 'spikes' in demand caused by product launches). The development of the 'amount' of product left is illustrated in Figure 10.

Each consumer i has a certain 'Rogerian adoption willingness' R_i in adopting new product technology. This is a property of the consumer that does not change. Once products of a new generation are brought to the market, consumers (again) display 'first-buy' adoption willingness for this new generation. This R_i is drawn[3] from $\mathcal{N}(\mu, \sigma)$ with $\mu = 3\sigma$. For R_i close to zero, consumer i is an 'early adopter', for R_i close to $\mu + 3\sigma$, the consumer is a 'late adopter'. An illustrative histogram of the number of consumers with a certain adoption willingness R for the first-buy of a new generation of product technology is given in Figure 11.

Once a new generation g of products is launched at time T_g, each consumer's 'adoption willingness' counter *for that generation* starts to count down from $R_{ig}(T_g) = R_i$ to zero at rate r per period[4]. So, consumer i is willing to buy a product of the generation g launched at time T_g as of time $t = T_g + R_i/r$.

Once a consumer has finished its current unit of product (possibly of an old generation g'), and the consumer has to buy a new unit of product, the consumer purchases a product of the newest generation he is willing to adopt (i.e. the highest generation g with a non-positive R_{ig}). If a product of that generation is not available, the consumer will not buy an old generation, but will try to buy a product of this generation next period. Under the assumption of availability of products of yet discovered generations (which is assured due to our entry criteria), all first-buyers have purchased their first unit of product of generation g in approximately $6\sigma/r$ periods after the launch.

Word-of-mouth

Each consumer that purchases a product of generation g compiles a panel of Q randomly selected consumers that are currently consuming a product of generation g and whose product is still on offer on the market. The consumer favors the product recommended by panel member i according to the following discrete choice probability (cf. Anderson et al., 1992):

$$p_i = \frac{e^{\gamma v_i}}{\sum_{j=1}^{Q} e^{\gamma v_j}}$$

Where v_j is the value-for-money of the product of panel member j at the time of purchase and γ is the 'choosiness' of consumers for the value-for-money.

[3] In diffusion theory, the social network structure and potential adopter characteristics *cause* a Normally distributed first-buy adoption pattern. In the present work, we *impose* a Normally distributed period until the first-buy and a uniform random social neighborhood for the first-buyer at the moment of product selection (as described later). This gives rise to the Rogerian curve without having to specify the social network structure and particularities of consumers.

[4] We scale R such that we can use deterioration/ usage rate r for the rate at which a consumer is increasing its adoption willingness for this.

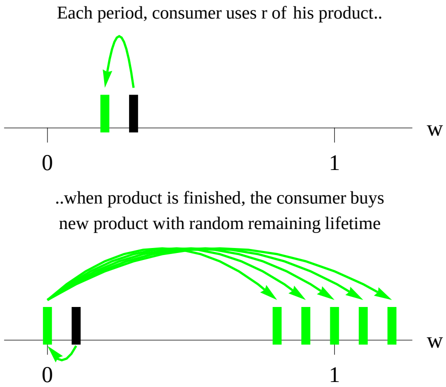


Figure 10: Graphical illustration of the development of w over time.

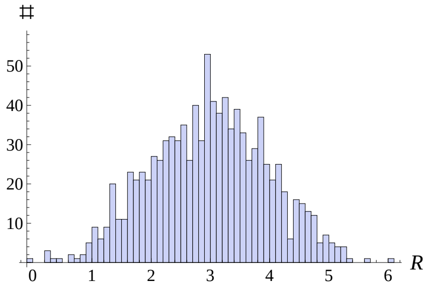


Figure 11: An illustrative histogram of the number of consumers with a certain Rogerian adoption willingness R.

The value-for-money of a product is defined as:

$$v = \frac{q}{q^* p}$$

The value-for-money is in essence how much value (performance q) the consumer gets per dollar (price p). We normalize the value to q/q^*, with q^* the highest performance yet found, to make the payoff independent of the *absolute* performances.

A firm launches a product by providing a fixed number of random consumers with a free unit and thereby resetting these consumers' product-amount-left w as if this is a regular purchase. As these consumers will thus become part of the panels consulted by buyers, new demand for the product might be generated, and the product potentially diffuses.
Our implementation assures there is regular diffusion, as well as intra- and inter-generational substitution.

3.6 Entry and exit

Upon the initialization of the first run of an industry, there is a fixed number of firms that immediately enter. To prevent favoring a particular strategy, we initialize A firms with all A combinations of integration and outsourcing before and after the emergence of the dominant design. From that moment onward, firms enter and exit the industry fully endogenously. A firm exits the industry if its capital drops below the bankruptcy level (zero). However, we assume that a monopolist succeeds in persuading creditors not to file for bankruptcy. Given the inelasticity of demand, the pricing mechanism has the monopolist raise its prices. Once a new firm enters the industry, and the industry no longer is a monopoly, the old exit conditions are restored.

Following Nelson and Winter (1982), we assume that there is always a firm on the sideline, waiting for the industry conditions to meet its entry criteria to then enter. Each period, the potential entrant (imperfectly) imitates the strategy of the firm with the highest (discounted) cumulative capital. Upon imitation, the potential entrant changes the governance strategy in 5% of the cases. This constitutes local search in the governance strategy. Following this strategy, the potential entrant determines whether it becomes entrepreneur or manufacturer and whether it would then enter or not.

We assume that an entrepreneur is eager to enter when profit margins for the latest generation of products are high while the product design dominance in that generation is low. In that case, there are considerable market and technological opportunities. The entry rate e of entrepreneurs is $e(x) = 1/x$, with x the present number of firms. We assume that a manufacturer enters when the profit margin (for the latest generation of products) is not too low while the design dominance in that generation is already relatively high. In this case, the manufacturer can cover investments while it is unlikely that a switch in production is required. The conditional entry rate e for manufacturers is $e(x) = a/(1 + x)$ with $0 < a < 1$ to reflect that manufacturers are crowd-avoiding.

The entry criteria revolve around the profit margin and design dominance. For the design dominance statistic, we use the following concentration index for generation g:

$$H_g^2 = \frac{\sum_{i \in M_g} s_i^2}{S^2} \tag{3}$$

where the s_i with $i \in M_g$ are the market shares of products of generation g on the market (possibly marketed by more than one firm), M_g is the index set of products of generation g on the market, and S is a normalization constant (over all generations).

We compute this H for each generation g of products on the market. We do not pick $S^2 = (\sum_i s_i)^2$. In our case, s_i need not sum up to 1 as there may be potential adopters that still need to do their first-buy. As we use H to reflect market *opportunities*, we rather take $S = rN$, where rN is the average demand per period (in number of consumers) with all repeat-buyers. Due to first-buys and future peaks in sales due to launches, the H may be temporarily higher than 1. Given the volatility of s_i, particularly in the onset phase, we have firms use an *exponentially smoothened* $\hat{H} \leftarrow hH + (1 - h)\hat{H}$ with smoothing rate h. For the profit margin per generation, we use the weighted average of the profit margins of all products of that generation. We again have firms use an exponentially smoothened average profit margin as there is volatility due to introduction and withdrawal of products.

3.7 Cost structure

We control the cost structure as a mediating variable. We pick a cost structure that closely meets the classical product life-cycle notions of entrepreneurial activities before and mass-manufacturing activities after the emergence of the dominant design. We assume that an entrepreneur runs a job shop, which is flexible and allows switching to producing another product at low costs. However, a job shop is less efficient than a dedicated production line, such that there are high unit production costs. In contrast, a manufacturer has high production switching costs, but is more efficient and has low unit production costs.

The actual vertical governance form affects the immediate production costs

through the transaction costs that exist to contact, contract and control the supplier as opposed to production in-house. Changing the governance form also goes at certain expenses. Integration requires investments in production facilities, while these facilities are scrapped upon outsourcing.
We assume that there are no explicit search costs (i.e. for imitation, exploration or radical search), just periodic operation costs.
The actual values used in the standard simulation runs are provided in Appendix 6.

4 Results

In this section, we present, analyze and interpret the simulation results. In Subsection 4.1, we show that our model reproduces the stylized facts of a product life-cycle. In Subsection 4.2, we present experimental results on how imitability and complexity (substitutability) affect the evolutionary emerging governance forms in the era of ferment and the era of incremental change. We statistically analyze and conceptually interpret the simulation results, and compare them with our theoretical predictions.

4.1 Analysis of the simulated industry evolution

In this subsection, we cross-validate the simulation results with common stylized facts in evolutionary economics for industry evolution under homogeneous demand. We start off with a discussion of the parameter values chosen. We then establish that our simulation model of the product life-cycle indeed produces results that features consecutive product life-cycles with eras of ferment and incremental change with the common stylized facts. We then discuss the effect of our parameter choices on the stylized life-cycles.

Parameter settings

The parameter values for the costs structure, technology landscape, demand and pricing modules, and strategy parameters have been attuned to each other to assure that the simulation results feature the stylized facts. In this parameter fine-tuning, we had to balance the ratio of feasible capabilities (tuned by the landscape parameters), the periodic operation costs, and possible revenue (as tuned by number of customers, maximum willingness-to-pay, diffusion-substitution rate, and price adjustment rate). This can be conceptually explained by the fact that if firms have to search longer, the costs are higher, such that the total revenue must be higher to assure that at least some firms succeed in recovering the search costs. In fact, during experimentation with the market and pricing modules determining the revenue, and the technology landscape module determining the average search trajectory length, we noticed that the parameter settings seem to be relative rather than requiring a particular absolute setting. Ultimately, we aimed for parameter values that have an 'economically sensible interpretation', but also targeted a reasonable computer processing time. To this end, we have limited the market size to 4000 consumer agents. More consumers would slow down simulating the industry tremendously. Using this market size, we then picked the willingness to pay, search costs, and initial capital endowments. Given the development of capital, we tuned the fraction of feasible capabilities in the landscape search module, with the scale and tail of the performance levels to agree with empirical findings.

After selecting the value for these parameters, there are only a few parameters left to specify.
The smoothing rates that we use to calculate macro-economic variables like design dominance and average profit margin make these macro-economic variables less volatile for period-to-period changes. As design dominance and average profit margin are used by firms to determine their strategies, higher volatility of these variables may cause firms to execute certain actions rather erratically, e.g. upon early incidental crossings of decision thresholds or even repeatedly. So, we used these parameters indeed to smoothen out macro-economic variables, thereby make the product life-cycle somewhat less erratic, but without changing the simulation results structurally.

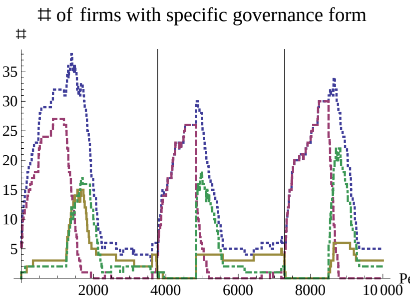
Ideally, all strategy parameters and thresholds described in Subsection 3.3 would be learned by the firms over the course of the industry evolution. However, our focus is on the governance strategy, such that we want to reduce the interference of other strategy parameters; a firm with an otherwise superior governance strategy may perform inferiorly due to unfavorable settings for other strategy parameters. After experimentation, we decided to increase the discriminative power of evolution on the governance strategy by removing such 'noise' of other strategy parameters on performance. So, in the present study, we fixed all strategy parameters but those related to vertical governance.
Clearly, when fixing the strategy parameters for the search strategy (imitation, exploration, radical search), adoption of newly found products, and entry, it is of great importance that we pick values with an 'economically sensible interpretation'. With regard to imitation, our idea is that firms will only engage in the -possibly lengthy- imitation process if the performance is more than $y\%$ better than the firms currently own top product. As imitation will inevitably mean that this product is also taken into production, and production switching is argued to be more costly for manufacturers, the improvement for manufactures must be even greater than for entrepreneurs. Something similar holds for discovered products in recombination of capabilities: if the product is not more than $z\%$ better than the top product, the firm will not take it into production because consumers have only a small probability of buying it.
In our operational definition of entry and parameter choices, we have assured that firms will not enter if the profit margin is too low or if the design dominance is too high. Even if a firm succeeds in finding a top product that consumers switch to, the expenses may not be recovered before other firms find a radical breakthrough. In our operational definition of radical search and parameter choices, we have assured that firms will start radical search if the profit margin is very low and the design dominance is very high. After all, there are then only limited opportunities to make a profit in this generation of product technology. In our operational definition of the business strategy and parameter choices, we have assured that firms will not switch to mass-manufacturing facilities whenever they are expected to have to switch production due to technological turmoil.

Stylized facts reproduced

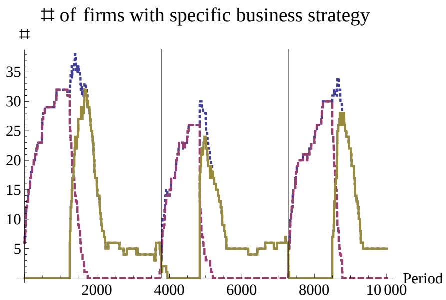
The simulation results are externally valid in that -for our choice of parameters (see Appendix 6)- our model robustly produces distinct eras of ferment and incremental change and robustly produces the stylized facts of the product life-cycle for homogeneous demand of swarm-in/ shake-out of firms, the pattern of turmoil and convergence in technology, and profit erosion.
For the illustration, we initialize our application to simulate an industry evolution for $X = 10000$ periods. We set the independent variables imitability $i = 0.025$ and complexity $x = 4.0$, and -anticipating results discussed later- preset the governance strategy to integration in the era of ferment and vertical specialization in the era of incremental change. The simulation results are plotted in Figure 12. The vertical bars (here at about periods 3750 and 7250) in all subfigures signify radical innovation punctuations at which an era of ferment starts. The era of incremental change is associated with a high level of concentration/ dominance of particular product technology. Figure 12c contains square curves (different colors only for clarity) for the life-spans and performances of the various products on the market. During the intervals of roughly $[0, 2000]$ and $[3750, 5000]$ there are many product introductions and removals, and the performance levels of these products varies much but tends to increase. During the intervals $[2000, 3750]$ and $[5000, 7250]$, there is are only very few product introductions and there is one 'top product' that persistently dominates. Figure 12e contains the curves of the smoothened design dominance (see Eq. 3 in Subsection 3.6). We have three curves (with different colors for clarity) starting at the radical innovation punctuations, each indicating the dominance of one generation of product technology. We see that the curves start low, steeply rise and then level off when the top product technology starts to dominate. On the basis of these simulation results, we argue that our simulation model reproduces the stylized fact that there is turmoil followed by convergence in product technology. As far as technology turmoil is concerned we recognize the distinct features of the era of ferment and the era of incremental change.

Figure 12a contains the curves of the number of firms. The blue dotted curve is the total number of firms. The purple dashed curve is the number of integrated firms. The khaki continuous line is the number of system assemblers, while the green dot-dashed line is the number of input component suppliers. Right after the radical innovation punctuations at period 0, 3750 and 7250, there is a steep increase of the total number of agents. With the design dominance -plotted in Figure 12e- approaching 1, and the technological turmoil almost over (see the intervals mentioned above), the (total) number of firms steeply drops. We also see that the firms switch their governance form from vertical integration to vertical specialization. On the basis of these simulation results, we argue that our simulation model reproduces the stylized fact that there is a swarm-in of firms after a radical breakthrough and a shake-out around the moment that one or a few particular product technologies start(s) to dominate.

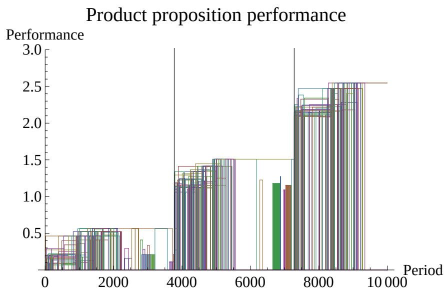
Figure 12f contains plots of the smoothened average profit margin of products on the market, per generation. We see that there is a very steep rise just after the radical breakthrough, to then decrease and approach zero. We see three consecutive curves (with different colors for clarity), one for every generation of product technology. The steep increase is caused by the fact that we use the *smoothened* average profit that starts at 0. As explained in Subsection 3.4, the



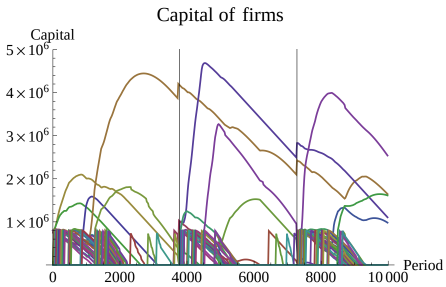
(a) Number of firms of each type



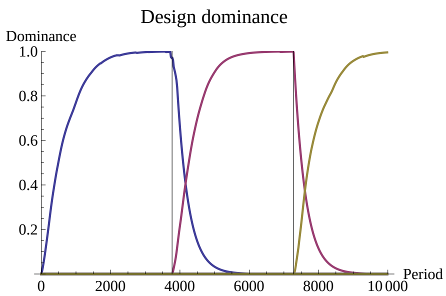
(b) Number of firms per business strategy



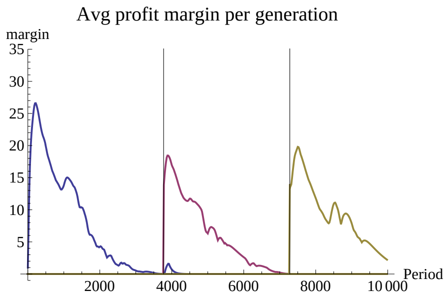
(c) Performance



(d) Capital of the firms



(e) Design dominance $\hat{H}$



(f) Average (smoothened) profit margin

Figure 12: Plots of various statistics of an industry evolution with three life-cycles. A detailed description of the figures and the curves is found in Subsection 4.1.

price of the first product of a particular generation is equal to the maximum willingness to pay p^*. Note that the average price for products of a certain generation is decreasing, while Figure 12c indicates the product performance is increasing. The temporary increase in profit margin around 4000 is due to a monopolist raising its price for (inelastic) demand from consumers that are still consuming an old generation product (see Subsection 3.4). On the basis of these simulation results, we argue that our simulation model reproduces the stylized fact that there is profit erosion due to price competition.

There are two figures that are not immediately related to the stylized facts. Figure 12b contains the curves of the number of firms per business strategy (entrepreneur, manufacturer). The blue dotted curve is the total number of firms, the purple dashed curve the number of entrepreneurs, and the khaki continuous curve the number of manufacturers. We see that endings of the eras of ferment (around periods 2000 and 5000) coincide with the switching of firms from the entrepreneurial to the mass-manufacturing business strategy.
Figure 12d contains curves of the capital for each firm. The colors of the curves differ to be able to distinguish one from the other. For some firms, the capital increases first and only after some time starts to decrease. Some firms exist over multiple product life-cycles. Other firms fail to realize a (substantial) market share and are forced to exit shortly after entry.

The product life-cycles keep on featuring the stylized facts (swarm-in/ shake-out, technology turmoil/ convergence, and profit erosion) for different, non-extreme values of imitability and complexity (substitutability). However, the higher the complexity, the more detrimental technological distance between input and system is, the lower the average product performance becomes. As the probabilities of being deselected relate to the relative product performances, the market concentration is lower in case of high than is in case of low complexity. The revenue differences between firms drops with complexity and there are fewer big players. Furthermore, the lower imitability, the longer imitation takes, the more firms with top products appropriate the value of their products. These firms with top products will thus grow a bigger market share and gain more capital, and cause a more concentrated industry.

Effects of parameter changes on the stylized product life-cycle

At present, we have tuned the parameters for the costs structure, technology landscape, demand and pricing modules, and strategy parameters to assure that the simulation results feature the stylized facts as described above. Neo-Schumpeterian models lend themselves for treating these parameters as mediating variables and to study the effect of these parameters on the industry evolution. Given the number of parameters in our model, we cannot discuss all possible variations.
As discussed in detail in Subsection 4.1, there is a relative balance between the ratio of feasible capabilities (tuned by the landscape parameters), the periodic operation costs, and possible revenue (as tuned by number of customers, maximum willingness-to-pay, diffusion-substitution rate, and price adjustment rate). If we change the relative number of peaks in the technology landscape by changing N, D, this has obvious implications. For instance, increasing N or D requires longer search, and firms thus incur higher search costs before finding feasible capabilities, and thereby more bankruptcies (and more entries, see

Subsection 3.6). Simulation studies revealed that the number of consumers and maximum willingness-to-pay p^* lengthen the product life-cycle. The underlying cause arguably is that the total market revenue increases. Lowering the price poll size increases the volatility in pricing. Lowering the profit margin at which firms start doing radical research will extend the era of incremental change of the product life-cycle. Other parameters, like the transaction and periodic operating costs, merely change the slope of the capital curves.
The product life-cycles keep on featuring the stylized facts (swarm-in/ shake-out, technology turmoil/ convergence, and profit erosion) for different, non-extreme values of imitability and complexity (substitutability). However, the higher the complexity, the more detrimental technological distance between input component and system is, the lower the average product performance becomes. As the probability of being deselected relates to the relative product performances, the market concentration is lower in case of high than is in case of low complexity. The differences in revenue between firms drop with complexity and there are fewer big players. Furthermore, the lower imitability, the longer imitation takes, the more firms with top products appropriate the value of their products. These firms with top products will thus grow a bigger market share and gain more capital, and cause a more concentrated industry.

4.2 Governance patterns

We report the findings from extensive simulation experiments for four combinations of imitability (low $i = 0.025$/ high $i = 0.125$) and complexity (low $x = 0$/ high $x = 8$) and the statistical analysis of the governance patterns emerging. For each of these four combinations, we simulate the industry evolution for 50000 periods, and for 100 different seed values. For each seed value, we take the governance strategy with the highest (discounted) capital stock at the end of these 50000 periods and register the governance form in both the eras of ferment and incremental change. We thus construct a 2×2 contingency table with the governance form in the era of incremental change on the X-axis and the governance form in the era of ferment on the Y-axis. Figure 13 contains a 2×2 table with the four scenarios for the particular settings for imitability and complexity, with the contingency table of the simulation results in each cell of this table. We first discuss the statistics used and then the simulation outcomes, their statistical analysis and the interpretation thereof.

Statistics used

To test whether firms prefer one or the other governance form in either one of the eras (ferment and incremental change), we point out that under the null hypothesis of *no* preference, the count data follows a Binomial distribution with $p = \frac{1}{2}$. Suppose the top strategy emerging from simulation prefers outsourcing n_o times and integration n_i times. The probability of this observation (n_o, n_i) under H_0 is equal to $\binom{n}{n_o} p^n$.
The so-called p-value (a different p than the probability just mentioned) of observing (n_o, n_i) or a more extreme outcome under the null-hypothesis is defined as $\mathbb{P}(B < \min\{n_o, n_i\} \,|\, H_0)$ with $B \sim \text{Bin}(n, \frac{1}{2})$. The p-values are also presented in Figure 13, where p^{row} (p^{col}) is the p-value for a preference for one or the other governance form in the era of ferment (era of incremental change).

substitutable/modular x=0.0 | complex x=8.0

i=0.025 'low imi–tability'

	outsource	integrate			outsource	integrate	
outsource	53	2	55	outsource	16	0	16
integrate	32	13	45	integrate	58	26	84
	85	15	100		74	26	100

$p^{row} \approx 0.136$ $p^{col} \approx 7.65 * 10^{-14}$ $X^2 \approx 26.5$ | $p^{row} \approx 3.42 * 10^{-13}$ $p^{col} \approx 2.82 * 10^{-7}$ $X^2 \approx 58.0$

i=0.125 'high imi–tability'

	outsource	integrate			outsource	integrate	
outsource	84	3	87	outsource	23	2	25
integrate	9	4	13	integrate	68	7	75
	93	7	100		91	9	100

$p^{row} \approx 7.12 * 10^{-14}$ $p^{col} \approx 6.35 * 10^{-14}$ $X^2 \approx 3.0$ | $p^{row} \approx 9.05 * 10^{-8}$ $p^{col} \approx 9.49 * 10^{-14}$ $X^2 \approx 62.2$

Figure 13: Governance patterns emerging in our simulation for low and high imitability and low and high complexity (high and low substitutability). Row (column): type of governance form picked in the era of ferment (incremental change).

complexity	imitability	Era		McNemar X^2
		Ferment	Incremental change	
$x = 0$	$i = 0.025$	55% outsources	85% outsources	$X^2 = 26.5$
	$i = 0.125$	87% outsources	93% outsources	$X^2 = 3.0$
$x = 8$	$i = 0.025$	84% integrates	74% outsources	$X^2 = 58.0$
	$i = 0.125$	75% integrates	91% outsources	$X^2 = 62.2$

Table 2: McNemar statistics on change in vertical governance strategy from the era of ferment to the era of incremental change for different levels of complexity and imitability. With one df, the McNemar test rejects H_0 (no change) if $X^2 > 3.84$ (5% significance level).

To test whether the emergence of the dominant design changes the choice of firms to outsource or integrate, we use McNemar's chi-square statistic $X^2 = \frac{(n_{12}-n_{21})^2}{n_{12}+n_{21}}$ for matched-pair homogeneity. McNemar's non-parametric test based on this statistic signals whether or not there are significantly many counts in the off-diagonal cells. The X^2 values in Figure 13 indicate whether or not there is a significant change in preference from outsourcing to integration or vice versa. With one degree of freedom, the McNemar chi-square statistic X^2 for matched-pair homogeneity leads to rejection of H_0 of equality if $X^2 > 3.84$ (5% significance level).
We also use McNemar's statistic to test whether -within the same era- a certain change in *parameter value* also changes the preference for a certain governance form. We do so by running the simulation with exactly the same parameter settings and seed value, changing only this one parameter (here, complexity x or imitability i). Table 3 contains these results.

Statistical findings and interpretation

In Table 2, we see that the dominant pattern is to outsource in the era of incremental change (for occassional recombination and upstream scale economics)

and to integrate under low substitutability and to outsource under high imitability in the era of ferment.
In the era of incremental change, firms are significantly often vertically specialized (low p^{col} values) regardless of imitability or complexity/ substitutability. In Table 3, we see that complexity decreases the propensity to outsource: if complexity is higher, incompatibilities with a newly discovered complement is more likely, so the benefit of being able to switch is lower. Interestingly, imitability mediates the effect of increasing complexity. If imitability is low, there is significantly less outsourcing (more integration) when complexity increases. The conceptual interpretation is that, given that it takes -in expectation- many periods to imitate a competing product, the value of an integrated product can be appropriated. For high imitability, $i = 0.125$, the integrated product is imitated near instantly, the value is not appropriated by the inventor, so developing an integrated solution is less attractive, which further discourages integration (although it is not significant). Moreover, the integrated firm does not enjoy the benefits of being able to switch to a newly discovered complement (or being switched to in case of an input supplier). Particularly under low complexity, a specialized supplier with a top input enjoys scale economies and thereby its customers. Conclusively, firms prefer outsourcing in the era of incremental change. However, there is less outsourcing whenever complexity increases, particularly when the value of synergistically attuned products can be appropriated more (i.e. under low imitability).
In the era of ferment, there is no clear preference for either outsourcing or vertical specialization. However, we see that firms vertically integrate more often with an increase in complexity (also see Table 3). The propensity to outsource more under low complexity and integrate more under high complexity further polarizes with imitability. The conceptual explanation is that with an increase in imitability, appropriability and hence the value of integration decreases. Whenever complexity is higher, there is more integration to overcome compatibility issues with arbitrary (new) complements. So, the trade-off of high performance plus exclusion/ appropriation through integration versus quick recombination and decentralized search tilts in favor of vertical integration with an increase in complexity, but this is countered by an increase in imitability as this lowers appropriability.
We find that costs mediate in the obvious direction. If transaction costs drop, there is more outsourcing, especially in the era of incremental change. Furthermore, the higher the costs of changing the governance form, the more firms stick to a single governance form over both eras.

Comparing theoretical predictions with statistical results

Next, we compare our simulation results contained in Table 4 with our hypotheses contained in Table 1.

We see that whenever the effects of imitability and substitutability both indicate to outsource or both indicate to integrate (i.e. the two on-diagonal cases), our simulation results confirm that this effect occurs during the era of ferment. However, whenever integration is predicted (the case with low substitutability and low imitability), that the tendency to integrate is dominated by outsourcing during the era of incremental change. We interpret this as that favorable cost differentials of outsourcing to a supplier with a top input dominate the -as we

value fixed parameter	change in value controlled parameter	Era for which test is conducted	
		Ferment	Incremental change
$x = 0$	$i = 0.025 \to 0.125$	more outsourcing $X^2 \approx 17.0$	no sign. diff. $X^2 \approx 0.529$
$x = 8$	$i = 0.025 \to 0.125$	no sign. diff. $X^2 \approx 3.60$	more outsourcing $X^2 \approx 7.26$
$i = 0.025$	$x = 0 \to 8$	more integration $X^2 \approx 4.57$	more integration $X^2 \approx 11.1$
$i = 0.125$	$x = 0 \to 8$	more integration $X^2 \approx 46.0$	no sign. diff. $X^2 \approx 2.91$

Table 3: McNemar statistics on change in vertical governance strategy upon a change in capability regime parameter value. With one df, the McNemar test rejects H_0 (governance forms are not affected by the change in regime property) if $X^2 > 3.84$ (5% significance level).

		Substitutability	
		Low ($x = 8$)	High ($x = 0$)
Imitability	Low ($i = 0.025$)	Integration for attuning and exclusion followed by outsourcing	Indifference in era of ferment followed by outsourcing
	High ($i = 0.125$)	Integration for attuning, followed by outsourcing	Outsourcing in both eras

Table 4: Emerging governance forms in both eras subject to imitability and substitutability.

already argued in Section 2.2- relatively weak factors in favor of integration. Whenever the effects of imitability and substitutability are opposites (i.e. the two off-diagonal cases), there is theoretical ambiguity on the governance form. We see that, in the era of incremental change, decentralized search and favorable cost differentials dominate benefits of integration. Under high imitability and low substitutability, we see that in the era of ferment, under technological turmoil, there is *no significant* preference for either integration or specialization. Under our parameter choices, decentralized search by specialization gives about as much competitive advantages as does appropriation through integration. As firms are entrepreneurs with flexible job shops, there is no cost advantage of outsourcing.

Reproducibility and robustness checks

An extensive number of runs for different seed values revealed that the results are reproduced for the parameter settings given in Appendix 6. In Subsection 4.1, we explained that the number of feasible capabilities on the landscape, the periodic operation costs, and possible revenue are fine-tuned to one another. Disruptive change to parameters in either one of these modules will generally cause more variance in the simulation outcomes and less significant results. The explanation of this increase in variance is sought in the fact that disruptive change in parameters weakens the discriminative power of the selection in the model. If costs increase or payoff decreases disruptively, firms generally live shorter, have only relatively few search steps, such that their survival highly depends on 'serendipitous' findings of capabilities. If costs decrease or payoff increases significantly, there are relatively few firms that go bankrupt, industries get a low clockspeed, and there are only few 'selective' technology punctuations (emergences of a dominant design and radical breakthroughs). In both cases, there is considerable 'uncertainty' in which strategy survives, and thereby considerable variation in the emerging governance strategy.

The values for the parameters of these modules are chosen such that the simulated economy does not suffer weak selective power due to the longevity of the industry, nor suffers weak discriminative power due to mostly accidental survival. Experimentation runs have revealed that incremental change to parameters has only moderate effects on the simulation outcomes.

However, given the parameter values for these modules, there still are parameters that mostly affect the costs and chances of finding top-fit capabilities *depending on the governance strategy.* The most obvious one is the transaction cost when buying components upstream. Simulation studies showed a dominant effect of transaction costs: if transaction costs drop, there is more outsourcing, especially in the era of incremental change. Other obvious ones are the costs of vertical integration and outsourcing. The higher these costs, the more firms stick to a single governance form over both eras.

5 Discussion and conclusions

In this study, we studied the governance form to be preferred in the different stages of the product life-cycle. In particular, we claimed that there is no *universal* governance pattern over the life-cycle, but rather that this governance pattern depends on imitability and substitutability of the capabilities in the industry. We formulated predictions on how imitability and substitutability affect the propensity to integrate or specialize during each of the eras of technological change. We provided a neo-Schumpeterian simulation model that reproduces an industry evolution consisting of consecutive product life-cycles. This model reproduces the usual evolutionary economic stylized facts robustly. We used our neo-Schumpeterian model to study the evolutionary emerging governance strategies of agents (and thereby governance patterns of the industry) under different settings for the independent variables imitability and complexity (inverse of substitutability).

The simulation results confirm our claims that there is no uniform governance pattern and that the evolutionary preferred governance forms strongly depends on imitability and substitutability *in interaction.* In the era of incremental change, firms prefer vertical specialization, particularly when substitutability is high. The higher substitutability (lower complexity), the more valuable is flexibility to recombine with new complementary capabilities and the higher (potential) upstream scale advantages. Higher imitability causes lower appropriability so further discourages integration. Transaction costs have a dominant mediating effect on the vertical governance form.

In the era of ferment, governance preferences are more ambiguous. Consequently, under high imitability, there is limited appropriability, and firms do not vertically integrate to develop products with superior performance. Nonetheless, firms do then not automatically vertically specialize. Under higher complexity, there generally is more incompatibility such that the combinatorial advantage of vertical specialization decreases, hence firms are more likely to vertically in-

tegrate.
The major implication of the findings in this chapter is that governance studies should take into account capability *properties*, notably substitutability and imitability in interaction. We recommend follow-up empirical research on the role of capability properties in governance decisions, particularly during the era of ferment.

Appendices

6 Parameter settings

Technology landscape parameter settings

We have the following parameter settings to specify the number of capabilities, the number of feasible capability distribution, and the distribution of the capability performances.

Number of abilities per capability	N	6
Number of types of abilities/ skills/ techniques	D	5
Number of feasible capabilities per landscape	C	100
Capability performance distribution (scale, tail)	α, β	$3.0, 0.5$

Strategy parameter settings

We have the following parameter settings for the decisions that firms take to either explore, imitate or conduct radical innovation

Imitation performance threshold (entr./ manuf.)	$1.05, 1.15$
Min. improvement of top product required (entr./ manuf.)	$0.8, 0.9$
Required minimum profit threshold to enter (entr./ manuf.)	$0.15, 0.05$
Maximum design dominance entry (entr./ manuf.)	$0.8, 0.8$
Radical search profit margin threshold	0.02
Radical search dominant design threshold	0.90
Business strategy threshold (margin)	$0.80(\pm 0.06)$
Strategy imitation failure rate	0.05

Demand/ diffusion-substitution parameter settings

We have the following parameter setting to specify the market demand and its development due to substitution-diffusion.

Market size in number of customers	M	4000
Number of customers upon product launch		150
Product panel size	Q	4
Discrete Choice Choosiness	γ	600
Replacement rate	r	0.05
Standard Deviation Rogerian adoption willingness	μ	30
Maximum willingness-to-pay	p^*	150

Pricing parameter settings

We have the following parameter settings to specify the polling that firms conduct to adjust their price.

Poll panel size	B	100
Investigated price change		0.00125

Capital/ costs parameter settings

We have to the following parameter settings to specify the capital the firms have when entering, and the costs that firms make periodically and for certain actions.

Unit production costs (entr./ manuf.)	$5, 2$
Transaction costs per supplier relation	300
Periodic operation costs per tier(entr./ manuf.)	$400, 850$
Capital starting level	$800k$
Cost of production change (entr./ manuf.)	$0, -50k$
Cost of radical search, imitation of next generation	$-400k, -200k$
Cost of governance change (insourcing, outsourcing)	$-50k, 0$

Parameter settings for macro-economic variables

We have the following parameter settings in the initialization of and (plotted) macro-level metrics during the simulation of an industry.

Initial population size	A	4
Discounting/ expon. smoothing rate capital		0.001
Exponential smoothing rate design dominance		0.003
Exponential smoothing rate profit margin, market concentration		0.01

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