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RESEARCH ARTICLE

Integration and appropriability: A study of process and product components within a firm's innovation portfolio

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Abstract

Research Summary: We examine how and when integration of process and product components within a firm's innovation portfolio increases firm returns. Strategy literature argues that integration enhances the firm's appropriation of returns from innovations. We evaluate this argument recognizing that integration is but one of multiple appropriation tools; firms can also use other (e.g., scale-based) mechanisms to enhance appropriation. Using new measures of integration based on textual coding of patent claims, we demonstrate that while higher process–product integration improves firm performance, this effect diminishes when the firm has greater production capacity or access to markets. Further, high integration lowers innovative productivity. Together, these demonstrations explain why firms, even with awareness of the benefits of integration between components, may not all choose high-integration strategies.

Managerial Summary: How should a manager design, structure, and organize the firm's innovation portfolio—as a collection of separate standalone process and product innovations, or a set of innovations each containing both new process and product attributes? Using data from the global chemicals industry and new textual-coding-based measures, we demonstrate that the latter helps the firm appropriate returns to its innovations by making it harder for others to understand and replicate its innovations, but that it comes with a tradeoff of lower innovative productivity. We stress that latter approach is less useful when the firm has other scale-based tools in place, that enhance appropriation as well, such as large production capacity or reach to markets.

KEYWORDS

appropriability, innovation, interdependence, process, product

1 | INTRODUCTION

When a firm innovates, it not only creates new products (Eggers, 2012; Katila & Chen, 2008) but often creates complementary new processes as well (Adner & Levinthal, 2001; Klepper, 1996). The strategy field has devoted substantial attention to questions surrounding a firm's product innovations, what it takes for the firm to effectively manage and develop them (Helfat & Raubitschek, 2000; Schoonhoven, Eisenhardt, & Lyman, 1990; Zhou & Wan, 2017), but has shed far less light on how a firm structures its new processes in relation to its new products and vice versa. Prior research acknowledging this process–product interaction typically does not go past the premise that the two components complement each other, with one reducing production cost and the other improving product functionalities (Athey & Schmutzler, 1995; Bhoovaraghavan, Vasudevan, & Chandran, 1996), and that their relative importance depends on lifecycle stages (Cohen & Klepper, 1996; Mcgahan & Silverman, 2001). This leaves open an issue that we still know little about and that the innovating firm's managers have to deal with in practice—its process and product innovations, even as they complement each other, can be developed in a variety of ways, ranging from more integrated process and product innovations to more "standalone" instead (Baldwin & Clark, 2000; Teece, 1986). Here we ask, how should the firm structure its new process and product innovation activities? How and when does integration between them matter toward performance?

The broader literature on structure and interdependence can provide some theoretical guidance on this issue (Baldwin & Clark, 2000; Ethiraj & Levinthal, 2004; Levinthal, 1997). It tells us that how integrated two components are depends in part on their inherent interdependency as dictated by their "true" nature or the environment, for example, attribute of the particular technological area, but only in part and not fully; it is also driven by the firm's decisions as well (Lenox, Rockart, & Lewin, 2010; Rivkin & Siggelkow, 2003; Yayavaram & Ahuja, 2008; Yayavaram & Chen, 2015). In fact, it is well established that the way the firm integrates its components can be a source of superior firm performance (Porter, 1985; Rivkin, 2000), to the point where developing that insight is regarded as a staple of the core strategy class in many if not most institutions. The power of integrating components in enhancing performance arises from bolstering the firm's ability to appropriate returns from the integrated components (Ethiraj, Levinthal, & Roy, 2008; Rivkin, 2000; Zhao, 2006). Since the power of integrated systems comes from how the individual components fit into the whole, the imitator in such a context has the relatively difficult task of imitating the innovator's entire system or else suffer a significant performance penalty (Milgrom & Roberts, 1995; Rivkin, 2001).

Applying this theoretical concept of "integration enhances appropriation" to our study on process–product integration within a firm, though, raises two issues that are yet unaddressed in the literature. First, as the components here refer to process and product innovations, there are other mechanisms the firm can access to help appropriate returns from these innovations, for example, economies of scale that lower the firm's costs relative to other competitors or superior access to markets that help them commercialize the innovation over a broader geographic domain (Ghemawat, 1986; Klepper, 1996). Such scale-intensive assets serve as alternate mechanisms for obtaining superior returns from innovations (Clarkson & Toh, 2010; Nerkar & Roberts, 2004; Teece, 1986). This triggers a question: do the mechanisms of scale and process–product integration act as substitutes for each other in appropriating value of innovations, or do they jointly enhance firm performance?

Second, the reasoning for the "integration enhances appropriation" effect identified above generates another refutable implication of the process underlying this effect, and leads to a related but distinct insight: the same integration of process and product innovation that enhances appropriation because the complexity of an integrated innovation process makes imitation difficult also makes the overall innovation task harder and decreases the firm's overall innovative productivity. When the firm's process innovation is highly integrated with its product innovation, further improving on one component or using it to generate further innovations requires more simultaneous consideration and management of how the other would be affected, and the firm is more likely to face difficulty or innovation failure in doing so (Baldwin & Clark, 2000; Ethiraj et al., 2008). Further, the set of activities that constitute the integrated innovation efforts themselves need more coordination, thereby increasing the organizational resources required for innovation (Kretschmer & Puranam, 2008; Puranam, Goetting, & Knudsen, 2010). Exploring this implication of integration is helpful because it (a) provides further empirical evidence consistent with the integration-complexity mechanism underlying the protection from imitation argument we highlight, and (b) helps us to understand a related question: if integrating process and product innovation enhances the firm's performance, then why would all firms not do so?

As befits any important question, the broader literature has at least in part addressed this question and suggested one reason. Highly integrated components limit adaptation in the event of a major environmental change: the deeply interconnected components are more difficult to change as a change in any component leads to a ripple effect across components (Khanna, Guler, & Nerkar, 2018; Levinthal, 1997; Yayavaram & Ahuja, 2008), making modification of the whole system difficult (Anders, Ethiraj, & Zhou, 2017; Stan & Puranam, 2017). In our context of process–product components: the firm struggles with adapting to a major shift in the type of product features the market demands, if its existing process and product components are highly integrated.

In this article, we suggest a second reason for why firms may not all highly integrate their process and product innovation activity: even without having to adapt to a major environmental change, process–product integration decreases a firm's overall innovative productivity by raising the cost of innovating the integrated portfolio and decreasing the frequency of generating further innovations off it. With process components highly integrated with product ones, improving on one component or using it to generate further innovations would require more simultaneous consideration and management of how the other would be affected, and the firm is more likely to face difficulty or failure in doing so (Baldwin & Clark, 2000; Ethiraj et al., 2008). Even the creation of the current set of integrated components needs more coordination and experimentation, thereby raising the cost (Kretschmer & Puranam, 2008; Puranam et al., 2010). Further, connecting this argument with the first issue identified above, we note that where alternative mechanisms to appropriate returns to the innovations are available to the firm, this argument provides further explanation for why the returns to high integration may be muted.

To examine these issues, we direct the paper's focus onto the firm's integration per se of its process and product components within its innovation portfolio. We propose that over and above having both types of components in its portfolio and enjoying the well-known benefits of process–product complementarities that ensue, the firm, by tightly integrating these two types of components, can additionally enhance its profit margin. This is consistent with the concept that component integration improves the firm's appropriation of returns from the innovations. We then address the two issues raised above. First, we theorize and propose that when firms have control over scale-intensive assets in the form of production capacity and access to markets, the marginal return to higher integration between process and product components diminishes. Simply put, these scale-intensive assets act as substitute mechanisms for appropriating returns to innovations, and their presence reduces the firm's benefits of process–product integration. Second, we propose that higher integration of the firm's process and product components in the innovation process is associated with lower rates of innovative productivity. In other words, when the firm integrates these components, it is less likely to succeed in any innovation attempt, but when it does succeed, such innovation offers better returns.

We empirically test our propositions in the context of the global chemicals industry. In conducting these tests, we develop a new approach to measuring process and product components in the firm's innovation portfolio, based on coding of claims in the firm's patents. This approach allows us to capture process and product components residing not only separately across innovations but together within each innovation as well, thus acknowledging that each innovation can consist of both process and product features. In fact, we find that a large portion (29%) of patents in our sample each individually contains both process and product components. This approach also enables us to differentiate the way a firm structures its innovation portfolio, in terms of whether its process and product components are more integrated within innovations or more separate across innovations, and accordingly allows us to isolate the performance effect of within-innovation integration apart from merely having both types of components in the firm's portfolio. We elaborate on these features in a later section. This empirical approach could be broadly applicable to many contexts beyond and distinct from our current focus on integration of process and product components. This represents an empirical contribution of the paper.

2 | THEORY AND HYPOTHESES

2.1 | Complementarities between process and product components

The traditional view of new process and product components within a firm's innovations is that they complement each other, with the former driving cost reductions and the latter constituting functional improvements (Athey & Schmutzler, 1995; Klepper, 1996; Scherer, 1982). The fundamental complementarities are typically depicted as follows: new product designs help the firm improve products' functionality, which increases customers' willingness to pay. This leads to an outward shift of the demand curve and hence raises volume demanded. Higher demand volumes in turn expand cost-reduction potential and increase marginal returns to new process engineering advances, as these new processes can now be applied to the larger production volume (Athey & Schmutzler, 1995; Cohen & Klepper, 1996). Stemming from this depiction, the literature then describes when process innovations may take on more important roles than product innovations, or the reverse, depending on the stages of the industry lifecycle (Adner & Levinthal, 2001; Mcgahan & Silverman, 2001).

Further, process and product complementarities can arise through economies of scope (Panzar & Willig, 1981). When the firm engages in both new product design and process engineering, it often ends up building resources that can be shared, such as plants, equipment, laboratories, and administrative support (Henderson & Cockburn, 1996). Even if each new component—product design and process engineering—functions independently, information generated from one may still benefit the other. For instance, knowing about costly production constraints in advance could reshape the product team's assessment of projects' payoffs (Brown & Eisenhardt, 1995). Early information about products in design phase could allow the process teams to have head starts on complementary projects and cut down on cycle time (Eisenhardt & Tabrizi, 1995; Terwiesch & Loch, 1999). Note that the complementarities described thus far can arguably be actuated even with a structural approach that minimizes interactions between process and product innovations and innovators.

The way these process and product complementarities arises has its theoretical basis rooted in the familiar notion of superadditive value in the presence of complements, that is, the presence of one component raises the value of the other (Milgrom & Roberts, 1995). Indeed, scholars have widely documented similar complementarities across a variety of settings, between knowhow and physical assets, technological and market resources, and so forth (Henderson & Cockburn, 1996; Mitchell, 1992), and showed that they lead to superior firm performance. Helfat (1997) examines a pattern of research investments suggesting that a firm's entry into specific research areas was explained by its related complementary assets or knowhow. Ichniowski, Shaw, and Prennushi (1997) study the simultaneous adoption of different HR practices. Tanriverdi (2006) studies complementarities in IT investments and processes. Vickery, Droge, Setia, and Sambamurthy (2010) examine joint occurrence of IT investments and organizational initiatives. Grimpe and Sofka (2016) find that search strategies in innovation domains are complementary and conditional—using both relational (alliance) and transactional (market-based) search for technologies is more productive, especially when markets for technology are underdeveloped. Nerkar and Roberts (2004) show that technology and product market capabilities mutually enhance the effectiveness of each other and are thus complementary in fostering new product sales.

Notice these studies and similar others (e.g., Brusoni, 2005; Caroli & Van Reenan, 2003; Laursen & Foss, 2003; Lee & Kapoor, 2017; Leiponen, 2005), while establishing how the presence of complementary components add to firm value, tend not to directly consider how the complementary components in question are being innovated jointly or separately. Most of the time, it is not clear whether the superadditive value they describe would be absent if the components are contemporaneously created but with little integration across the underlying innovation processes, or would vary when they are jointly created and extensively integrated. A noteworthy extension along this vein is Zhao (2006), who demonstrates that when firms conduct R&D in weak IP regimes where imitation is easy, they tend to locate those technologies in weak IP nations that have strong complementarity with other internal resources of the firm, such as other technologies or complementary assets. In other words, firms use complementarity between technologies to protect the technologies that are housed in weaker IP regimes so as to better appropriate returns from them. This starts to point to a different mechanism that creates superadditive value, one that is less about increasing market's willing-to-pay but instead more about enhancing the firm's appropriation of returns to its innovations. Importantly, this shift steers us to see that perhaps the level of integration between the components matters, given the widely accepted wisdom that the firm's appropriation of returns from its components intricately depends on how these integrated these components are to each other. We expand on this in the section below.

2.2 | Integration of process and product components

When the firm creates new process engineering advancements and new product designs, it can do so with processes that have varying degrees of integration between them. Here, integration refers to how closely coordinated and jointly conducted the process innovation and product innovation processes are. The level of integration is in part determined by the interdependencies in the "natural world" (Yayavaram & Chen, 2015), that is, interdependencies as dictated by the technological environment, knowledge domain, or industry in which the firm operate (Kauffman, 1993; Lenox et al., 2010; Levinthal, 1997; Yayavaram & Ahuja, 2008). Within these confines, there remains variance in the level of integration, and where the firm lies in this distribution depends on factors such as the firm's strategy, existing routines, its knowledge-based resources, or other sociopolitical factors (Galunic & Rodan, 1998; Yayavaram & Ahuja, 2008).

The realized level of integration between the firm's process and product components themselves tends to reflect the innovation approach that the firm has adopted when designing these components. Innovation activities leading to the creation of process and product components can be split up, where the product component is designed independently, and thereafter the process component is designed with the product as a given. Such approach would result in relatively low integration between process and product. This aligns with the traditional depiction of new products as discrete functional improvements and, separately, new processes as components that reduce production cost (Athey & Schmutzler, 1995; Klepper, 1996; Scherer, 1982). In this innovation approach, process and product components tend to be designed separately and independently, with built-in standardized interfaces in the components which allow the components to be subsequently connected (Sanchez & Mahoney, 1996; Ulrich & Eppinger, 1995). Product attributes and corresponding production requirements are prespecified and often generic to the extent possible, so as to reduce complications in the subsequent production with the new processes. As the process–product interfaces are standardized, the new processes are likely nonspecific and can be used to produce other products with similar standardized attributes. Likewise, the new products tend to be producible by alternative production methods that can even be purchased "off-the-shelf" or from other firms (Ulrich & Ellison, 1999). Organization of the process-engineering and product-design teams tends to be more loosely coupled (Ethiraj & Levinthal, 2004; Orton & Weick, 1990), with "throw-over-the-wall" relationships between teams where designs are passed on sequentially (Ha & Porteus, 1995; Nadler & Tushman, 1997). Overall, such a modular innovation approach would result in relatively limited integration between the process and product.

In contrast, in high integration, the process and product components are designed with far closer coordination with the key parameters of both process and product being developed together. Highly integrated process and product innovation activities are likely to create dependencies and co-specialization between the innovated process and product components. There is significantly greater functional interdependence between the process and product components when they are tightly integrated. This usually necessitates joint development, also known as parallel or concurrent development, between the process engineering and product design teams (Daniels, Hoopes, & Mazzola, 1996; Ha & Porteus, 1995). The two teams coordinate and communicate frequently and intensely (Ettlie, 1995; Terwiesch & Loch, 1999), engaging in cross-team feasibility checks (Dougherty, 1992; Loch, Terwiesch, & Thomke, 2001) and intermediate progress reviews (Ha & Porteus, 1995). Problem solving within each team is more disciplined, in that each is more bound by the feasibility and constraints of its counterpart (Brown & Eisenhardt, 1995).

We argue that integration of the firm's process and product components enhances the firm's performance. The broader literature on structure and interdependence abounds with illustrations of integration's merits using case studies, simulation-based modeling papers, and other empirical methods under a variety of closely related headings. Harvard Business School has published a number of case studies of individual firms highlighting the creation of highly integrated strategies by successful firms such as Southwest Airlines, Progressive, and Wal-Mart. In a case study for a scholarly audience, Siggelkow (2002) highlighted the underlying processes that led to the emergence of "fit" between activities at Vanguard.

In this broader literature portraying integration's merits, one mechanism stands out most clearly apart from the merits of complementarities earlier—integration enhances the firm's ability to appropriate returns from its components (Rivkin, 2000; Rivkin & Siggelkow, 2003). Formal models have been developed leading to insightful characterizations of this mechanism. For instance, Rivkin (2000) formally demonstrates that imitating complex strategies is difficult as algorithmic, heuristic and learning strategies to mimic innovators are all challenged in the face of complexity. In a subsequent paper, Rivkin (2001) highlights that both imitation and replication become difficult at high levels of complexity but that the informational edge of the innovator can provide an advantage in replication while limiting imitation at moderate levels of complexity.

We import these theoretical insights to establish the merits of integration in our context. When the firm's process and product components are highly integrated, the firm is better able to appropriate returns to these components. With concurrent design of the two components, both tend to be customized and this tighter matching leads to higher causal ambiguity. It is difficult for external parties, such as rivals, to identify and completely comprehend the drivers of functions or of performances of particular components (Lippman & Rumelt, 1982; Sorenson, Fleming, & Rivkin, 2006; Thomke & Kuemmerlie, 2002). To begin with, both process and product components need to be studied before a given causal effect can be understood. There is also magnified uncertainty as to where an observed effect on a component arises from, given the web of causal directions and magnitudes (Ethiraj et al., 2008; Simon, 1962). A tweak in one component creates a ripple effect reverberating across the system of integrated components (Rivkin, 2000), obscuring the origin of an observed effect at any given point. Accordingly, causal ambiguity acts as an isolating mechanism that prevents firms from homogenizing their product–process components (Lippman & Rumelt, 1982; Porter, 1991). Clusters of integrated choices in designs of process–product components thus create persistent heterogeneity across firms (Lenox, Rockart, & Lewin, 2007; Levinthal, 1997).

Such process–product integration also enhances the firm's appropriation of its components in ways other than accentuating causal ambiguity. For rivals to experiment with the firm's product components via reverse engineering (Lieberman & Montgomery, 1988), they would have to concurrently put in place the integrated process components, and vice versa. This not only raises the financial and implementation hurdles, but also increases the likelihood of mistakes across either the product components or supporting processes. To reduce such mistakes, rivals may try to access technical information on these components via patents (Clarkson & Toh, 2010). However, not all aspects of the firm's process and product technologies are explicitly spelled out in patents, especially the more tacit components in process technologies (Cohen, Nelson, & Walsh, 2000), and even more so, the nature of integration across these components. Even if rivals try to expropriate these technologies via hiring the firm's inventors, integration obstructs interfirm knowledge transfers (Ganco, 2013). To decipher the technicalities of the firm's products, rivals must hire not just the firm's product-design team members but also its process engineers with the necessary knowledge to support the functioning of the products. Such enlarged hiring can be prohibitive.

Thus, we note that even with relatively limited integration, having both process and product components in the firm's innovation portfolio, all else equal, enhances the firm's performance through the complementarities between them as laid out earlier. However, higher levels of integration between the firm's process and product components could provide the additional benefits of enhanced ability to appropriate returns to these components.[1,2] This suggests:

Hypothesis (H1). *Having both process and product components within a firm's innovation portfolio will enhance the firm's financial performance.*

Hypothesis (H1a). *Higher levels of integration between process and product components in the firm's innovation portfolio (relative to lower levels of integration) will enhance the firm's financial performance.*

2.3 | Alternatives to integrating process and product components

In this section, we examine the role of the firm's alternative scale-based mechanisms as substitutes to its integration of process and product components. Per above, process–product integration demands significant effort in terms of organizational coordination. The benefits of engaging in this additional coordination and the attendant working complexity depend on whether the firm has access to alternative appropriation mechanisms. Past research has proposed scale-based mechanisms as alternatives that help the firm appropriate returns to its innovations (Cohen & Klepper, 1996; Kapoor & Furr, 2015; Teece, 1986). They mostly come in the form of downstream assets with convex adjustment costs (Lenox et al., 2007), that accord advantages of scale in exploiting the process and product components in the firm's innovation portfolio. Such scale advantages provide the firm with a superior cost structure relative to competitors and hence expands its margins as the prevailing market price creates a larger profit for the larger scale firm. Further, these scale-based mechanisms also strengthen the firm's appropriation of its innovations' value by signaling to others that even if imitation is technically possible it would be less profitable, disincentivizing entry (Clarkson & Toh, 2010).

One such scale-based appropriation mechanism is the firm's production capacity (Teece, 1986). With extensive production capacity in place, the firm is incentivized to produce in large volumes in order to ride down the cost curve. Such large-scale production allows the

[1]Note that we are suggesting process–product integration to have a systematically positive performance effect separate from the known effect of complementarities, that is, simply having both process and product components, not that such integration uniformly improves performance under all circumstances. In fact, in the following sections, we go on to explicitly acknowledge and examine instances where the positive performance effect of integration is attenuated ((H2) and (H3)), and also to lay out that process-product integration does come with cost (H4) and hence involves a tradeoff.

[2]Broadly speaking, this performance effect can potentially be generalized to other forms of integration in the firm's innovation portfolio, such as between multiple process components (process–process) or between multiple product components (product–product). However, we caution that the underlying mechanisms for such related integrations—what and how innovative activities are integrated, and whether they are integrated contemporaneously or sequentially—may not always be the same as laid out above. We focus on process–product integration here and encourage future research to "replicate" the broad argument here and explore nuanced details of other related forms of integration.

firm to appropriate returns to its investments in creating the product–process components (Cohen & Klepper, 1996). Holding constant market demand at a given point, this leaves low remaining market share to rivals, which provides two benefits. First, the lower cost of the larger scale player provides an additional margin at any price relative to that obtained by the higher cost, smaller player. Second, the higher scale of the innovator discourages entrants especially when the remaining low volume does not justify rivals' fixed cost investments (Dixit, 1980). Moreover, having production capacity in place indicates to rivals the speed at which the firm could flood the market with products and engage in price wars upon rivals' entry (Clarkson & Toh, 2010; Lieberman & Montgomery, 1988). The firm's large production volume further provides a cost advantage during these price wars.

Production capacity, however, attenuates the performance effect of higher process–product integration as represented in (H1a). Scale and process–product integration being alternative mechanisms for enhancing appropriability would intuitively suggest that greater commitments to scale should reduce the marginal appropriation benefit of integration. Closer examination of the relationship between production capacity and process–product integration supports this intuition. Large investments in production capacity make close integration between process and product components both difficult and more expensive. If process components are closely customized to and jointly developed with new products, commercializing such products will require tailoring of existing capacity. Larger existing capacity would make such tailoring more expensive. Further, mistakes in the functioning of integrated process–product systems are more likely than in modular systems as we discuss below, and are also costlier to diagnose and correct, as they permeate throughout a larger production system. Consequently, the problem of strategic inflexibility due to integration is magnified with larger production capacity. Thus, a firm's production capacity exhibits a tension with increased integration between the firm's process and product components.

Another scale-based mechanism that enhances the firm's appropriation of innovations is its access to markets. Having commercialization capabilities in multiple geographic markets allows the firm to sell its products at greater volume and spread out the fixed costs of innovation (Cohen & Klepper, 1996). It carries a similar deterrence effect per earlier for production capacity, based on indicating commitment to high volume production and also speed of capturing market demand. A firm's access to multiple markets requires investments over time especially when these markets are geographically distant or span national boundaries, and hence new entrants cannot quickly imitate this advantage of head start. Moreover, experience in markets helps the firm develop in-depth knowledge about these particular markets, which gives the firm a competitive edge over rivals (Mitchell, 1992; Nerkar & Roberts, 2004). For innovations with more uncertainty regarding marketing and marketability, access to multiple markets also provides the firm with a greater set of possible test sites for initial launches.

Like production capacity, access to markets creates a tension with process–product integration in contributing to the firm's performance. Extended market presence can help to commercialize innovations faster and at greater scale, thus serving as an alternative to higher process–product integration as a mechanism to enhance appropriation. Moreover, like production capacity, commitment to multiple geographic markets also accentuates the costs of having highly integrated process–product components, and limits the joint value of these two appropriation mechanisms. As products extend across geographic boundaries, they have to be adapted to local markets. If they are extensively tailored to processes and the processes have to be closely adapted in multiple different markets, the complexity and cost of close tailoring increases. Further, in the event of products not succeeding in a given geographic market, diagnosing the source of problems is required. With variations in product, process and geography as possible sources of problems, both identifying the problem source and creating a solution become more difficult. This suggests that higher levels of market presence, while providing appropriation benefits of their own, may limit the appropriation benefits from increased process–product integration.

Hypothesis (H2). *The greater the firm's downstream production capacity, the less that integration between process and product components in the firm's innovation portfolio will enhance the firm's financial performance.*

Hypothesis (H3). *The greater the firm's access to multiple geographic markets, the less that integration between process and product components in the firm's innovation portfolio will enhance the firm's financial performance.*

2.4 | Integrating process and product innovations and innovative productivity

Per our arguments above, higher integration between process and product innovation provides appropriation benefits as the attendant causal ambiguity and related enhanced coordination commitments limit imitability. However, the greater coordination demanded by an integrated process–product innovation approach also necessitates higher complexity. We explore the implications of this higher coordination and attendant organizational complexity next. This exploration is useful because (a) it provides an opportunity to identify an additional refutable implication of the "higher integration enhances appropriability" argument. Testing this implication may help to flesh out and better understand the mechanisms implicit in (H2) and (H3). Also, (b) explicit acknowledgment of integration-induced complexity is itself useful in understanding the core issue studied in this article as it helps address the question of why some firms may not integrate their process and product innovation if doing so provides appropriability benefits.

We argue that higher integration of these components is problematic for the firm in two related ways. First, increased integration is likely to increase the failure rate of research efforts. Given an integrated set of process–product components, the firm would need more simultaneous understanding and consideration of how one component affects another, in order for the firm to further use one or more of these components to generate further innovations (Khanna et al., 2018; Yayavaram & Chen, 2015). In other words, the firm is in essence taking on a bigger problem to be solved, and accordingly, is more likely to fail (Baldwin & Clark, 2000). A lower-integration approach, on the other hand, limits the connections considered to only those that fall within the focal component (Ethiraj et al., 2008), and reduces the problem being attempted to be solved.

For instance, let us assume that 10 components constitute a process and product in the firm's innovation portfolio. For simplicity, assume further that the components are evenly split between process and product. In the case of high integration, all the mutual connections between these 10 components have to be understood and managed in order for the firm to create another successful innovation using one or more of the integrated components. Even considering just two-way connections between the components, this leads to ${}^{10}C_2 = 45$ connections to be understood. In the corresponding low-integration case, further innovations based on existing product designs would mean that the product designers only have to focus on five product components. Again, considering only two-way connections, they will have to understand and manage $^5C_2 = 10$ connections. Similarly, to build further innovation based on existing process components, the process design team will only need to manage 10 connections. Thus, the task of innovating in the high-integration approach is much harder—the firm needs to manage 45 problems to create a successful innovation; whereas the firm in the low-integration approach needs to manage only 20. Other things being equal, using the same R&D budget, we would expect the firm using the high-integration approach to succeed less often in generating innovations subsequently (than the firm using low-integration approach) and hence have lower innovative productivity.

Second, the integrated approach is higher in its initial organizational and coordination demands also. Because of the greater number of components and connections between components built into the design, the R&D process for integrated process–product innovation requires more coordination and experimentation (Kretschmer & Puranam, 2008; Puranam et al., 2010; Stan & Puranam, 2017). To coordinate joint development between process engineering and product design, the firm often needs to set up integrating mechanisms, structures, and policies (Ettlie, 1995). Project objectives and sequencing of activities have to be prespecified and synchronized between teams (Sanchez & Mahoney, 1996; Toh & Polidoro, 2013). Coordination between teams is also susceptible to many well-documented problems, such as opportunism, free-riding, suboptimal investments, and interpersonal conflicts (Dougherty, 1992; Eisenberg, 2001; Williamson, 1975). Further, process–product integration, by requiring more connections to be considered, raises the possibility of errors or breakdowns, which not only reduces chances of successful innovations but also increases the cost of fixing these errors (Rivkin, 2001). Causal ambiguity, coupled with the many possible sources of a given effect within the web of integrated components, makes it difficult for the firm to identify where the mistakes originate, lengthening the time needed. Based on the above arguments, we argue that the integrated process–product innovation approach requires higher organizational inputs and accordingly cost, relative to a given innovation outcome.[3]

> **Hypothesis (H4).** *Higher levels of integration between process and product components in the firm's innovation portfolio (relative to lower levels of integration) will lower innovative productivity, that is, increase R&D expense per unit of innovation.*

[3]Lenox et al. (2010) similarly argued that interdependency between process components and other mechanisms (such as secrecy, patent protection, etc.), and likewise between product and these other mechanisms, imposes cost to the firm. They represent these costs through a curvilinear performance effect of interdependency, assuming that at high levels of interdependency, cost would start outweighing benefits. Note that our focus here is different—on integration between process and product components rather than their individual interdependencies with other IP-related mechanisms. We also represent cost differently: we do not assume that benefit of integration outweighs cost at a lower level of integration and vice versa at a higher integration level. Such assumption would have been needed to justify an overall curvilinear performance effect of integration. Rather, we directly and separately hypothesize and measure cost of process–product integration. Going further, we also checked for possible curvilinear performance effect of process–product integration in our sample. We use the main tests for (H1a) which we report later in Table 3. Instead of splitting into two subsamples (high and low integration), we split the sample into three subsamples instead (high, medium, and low integration), to see if the medium subsample exhibits the most positive performance effect of integration and hence a curvilinear relationship could exist. We find that the results for process-product integration in the high and low subsamples remain the same, while the medium subsample with medium level of integration appears to have no effect on performance (no significant coefficient). Hence, there is no sign of curvilinear performance in our sample.

3 | METHODS

We examine our propositions with data on the global chemicals industry 1982–1988. This is appropriate for several reasons. This period saw vibrant industry growth, with over 80% of production occurring in OECD countries, preceding the economic recession (early nineties) that slowed down chemical production. R&D was a major contributor to firm growth, and decisions on structuring process and product components were likely consequential. This setting is also apt for studying process–product integration, as new industrial chemical products often come with accompanying new process designs.[4]

Focusing on a single industrial setting reduces the problem that unobserved heterogeneity across industries could be determining both the firms' structure of process–product components and performance. It also helps reduce systematic errors in patent-based measures (described later) that may arise because not all innovations are patented and patenting propensity varies across industries (Cohen et al., 2000), since this propensity is likely stable within industry (Griliches, 1990). Moreover, the chemical industry is one where patents are effective and patenting propensity is among the highest across industries (Cohen et al., 2000).

We identify global chemical firms from trade journals such as *Chemical Week* and *C&E News*. To avoid survivor bias, we select firms that exist in the beginning of the sample period. We combine subsidiaries listed separately in the trade journals with their respective parent firms. We then link these firms to the NBER patent databases and patent claims data from USPTO. Consistent with prior research (Patel & Pavitt, 1997; Stuart & Podolny, 1996), we focus on U.S. patents for all firms, including non-U.S. firms, in order to maintain consistency, reliability and comparability of information. The U.S. market represents one of the largest for chemicals, and non-U.S. firms tend to file for U.S. patents as well for their inventions (Basberg, 1983). Next, we append data on other firm attributes, obtained from WorldScope Global, Compustat, and *Who Owns Whom* (annual edition) and supplemented with information from *Japan Company Handbooks*. We cross check the consistency of databases by tallying financial figures or referencing trade publications, and remove observations with missing or unreliable data. This procedure results in 101 firms across the United States, Europe, and Japan over the sample period. These are mostly large leading firms with nontrivial downstream production capacity and access to geographic markets.

3.1 | Variables

3.1.1 | Process–product components variables

For our purpose of examining how integration of a firm's process and product components affects performance, we need to capture not only instances where both process and product components reside modularly within a firm's portfolio, but also instances where process and product components are integrated within one innovation. Often, a single innovation that

[4]A chemical compound (product) is usually created by a specific chemical reaction (process) involving mechanical steps such as pumping and conveying, size reduction of particles, classification of particles, and their separation from fluid streams, evaporation, and distillation with attendant boiling and condensation, absorption, extraction, membrane separations, and mixing. In fact, the field of chemical engineering focuses on developing processes and production designs for changing materials' physical or chemical states, which are essential for creating new products.

seems like a standalone product design does in fact embody new production methods, and likewise, a new process design would inherently require or result in new product components (Bhoovaraghavan et al., 1996).

Existing measures typically do not capture process–product nature of innovations at such a fine-grained level. Past research has used surveys or external-party classification to identify an innovation discretely as either a process or a product (Bertschek, 1995; Kotabe & Murray, 1990; Mcgahan & Silverman, 2001).[5] These discrete measures could over-aggregate the process–product nature by assigning innovations to one category or another and miss the integration between components within one innovation. Even a single patent, commonly deemed as the narrowest unit of an innovation, can contain both process and product components (e.g., see Patent # 4454077—Patent A in Table 1). Other studies have inferred the process–product nature from innovations' applications, for example, by classifying an innovation applied in the firm's own line of business as "process" and one applied to other lines of businesses as "product" (Cohen & Klepper, 1996; Levin & Reiss, 1988; Lunn, 1986; Scherer, 1982). This approach is not suitable for our purpose either: besides missing within-innovation integration of process and product components, relying on application breadth could pick up other confounding performance effects.

To bypass these problems, we construct a new measure that is continuous and based on the process–product nature of an innovation. This measure starts with the coding of each individual claim within a patent as a process or a product claim. Claims lay out in detail the novelties described in a patent. They allow the patent assignee to "lay claims" legally to these novelties, that is, to exclude others from using or building on these novel ideas without consent (Lanjouw & Schankerman, 2004; Toh, 2014). A patent usually has multiple claims corresponding to various components within the innovation. Together, the claims represent the boundaries of intellectual property accorded by that patent. By coding individual claims, we are able to separate a patent that consists of both process and product components from another patent that has purely process, or purely product, components. Since all components integral to the functioning of the core idea in a patent are usually listed as claims within the same patent (rather than across patents), the former patent likely contains greater process–product integration than the latter.

We illustrate this claims coding with two patents listed in Table 1, both filed in the same year (1982) and have two claims each. In Patent A ("Process and apparatus for mixing a gas and a liquid," patent number 4454077), the first claim spells out novelty in the form of a process for mixing gas and liquid in an apparatus with details on this process, and hence is coded as a process claim. The second claim spells out details about the apparatus, and hence is coded as a product claim. Patent A thus integrates both process and product components. In Patent B ("Thermoplastic molding material," patent number 4367311), the first claim is about a thermoplastic molding material and the second claim elaborates on features of this molding material, and hence both claims are coded as product claims. Patent B thus consists purely of product components.

We consulted extensively with a senior IP lawyer (who preferred to be anonymous) with deep expertise and experience in patent litigation and drafting to verify our understanding of patent drafting and claims and to validate our measures. We learned that whether a set of process and product claims are listed within or across patents is primarily determined by the nature

[5]Using classifications provided by the Canadian Intellectual Property Office (CIPO) to measure process-product inventions is problematic for this study. CIPO defines each patent discretely as either a process or product, based on the "description" section of the patent. We contacted a patent examiner in CIPO by phone to inquire about this process of classification. The patent examiner expressed that discrete classification is often difficult and imperfect, as process-product ambiguities exist even in the "description" section of the patent.

TABLE 1 Examples of claims coding

	Patent A	Patent B
Patent number	4454077	4367311
Patent title	Process and apparatus for mixing a gas and a liquid	Thermoplastic molding material
Assignee	Union Carbide Corporation (Danbury, CT)	BASF Aktiengesellschaft (Ludwigshafen, DE)
Claims	1 In a process for mixing a gas and a liquid in an apparatus comprising, in combination:	A thermoplastic molding material based on a mixture of
	(a) a vessel;	(a) a styrene polymer, of intrinsic viscosity from 40 to 140 ml/g, as the hard component,
	(b) a cylindrical hollow draft member open at both ends and having a theoretical axis running from end to end, said axis being in a vertical position and the upper end of the draft member being conically flared;	(b) a cross-linked rubber grafted to the extent of 10–60% by weight with styrene, the rubber, in turn, comprising, as polymerized units, from 30 to 80% by weight of an alkyl acrylate, alkyl being of two to eight carbon atoms, and from 20 to 70% by weight of butadiene, and
	(c) an axial flow downpumping first impeller fixedly connected to a rotatable shaft, (i) the first impeller being positioned within the draft tube; (ii) the shaft corresponding in position to the axis; and (iii) the diameter of the first impeller being less than, but proximate to, the diameter of the draft tube;	(c) a polyphenylene ether having on average not less than 50 benzene units in the chain, wherein the weight ratio of a:b is (95–40):(5–60) and the weight ratio of (a + b):c is (5–90):(95–10).
	(d) first vertical baffling means disposed above the impeller;	
	(e) means for rotating the shaft; and	
	(f) means for introducing the gas and the liquid into the vessel and for removing gas and liquid from the vessel,	
	The process comprising:	
	(A) energizing the shaft to provide the first impeller with a rotational speed sufficient to cause (i) vortex formation downward from the surface of the liquid in the vicinity of the first vertical baffling means and	

TABLE 1 (Continued)

	Patent A	Patent B
	the flare of the draft member such that the gas is drawn into and down the draft tube and (ii) turbulence in the draft tube;	
	(B) introducing a sufficient amount of liquid into the vessel to provide, during operation, a liquid level above the upper end of the draft tube; and	
	(C) recovering liquid from the vessel,	
	The improvement comprising	
	(1) providing a rotational speed to the first impeller sufficient to impart a liquid velocity down the interior of the draft tube of at least one foot per second;	
	(2) increasing the turbulence of the liquid at the shaft proximate to the first impeller;	
	(3) in the area in the draft tube below the first impeller or in the area below, and immediately exterior to, the lower end of the draft tube, providing second vertical baffling means; and	
	(4) in the area in the draft tube between the first impeller and the second vertical baffling means providing a radial flow impeller fixedly connected to the shaft whereby a high shear zone is created in the area heretofore mentioned in this paragraph (4).	
2	In an apparatus for mixing a gas and a liquid comprising, in combination:	The molding material of claim 1 wherein the cross-linked rubber contains, as polymerized units, from 3 to 10% by weight of a vinyl alkyl ether, alkyl being of one to eight carbon atoms.
	(a) a vessel;	
	(b) a cylindrical hollow draft member open at both ends and having a theoretical axis running from end to end, said axis being in a vertical position and the upper end of the draft member being conically flared;	
	(c) an axial flow downpumping first impeller fixedly connected to a	

TABLE 1 (Continued)

	Patent A	Patent B
	rotatable shaft, (i) the first impeller being positioned within the draft tube; (ii) the shaft corresponding in position to the axis; and (iii) the diameter of the first impeller being less than, but proximate to, the diameter of the draft tube; (d) first vertical baffling means disposed above the impeller; (e) means for rotating the shaft; and (f) means for introducing the gas and the liquid into the vessel and for removing liquid from the vessel, The improvement comprising: (1) protuberances or indentations located on the shaft or first impeller of sufficient size, and positioned, to increase the turbulence at the shaft proximate to the first impeller; (2) second vertical baffling means located in the area in the draft tube below the first impeller or in the area below, and immediately exterior to, the lower end of the draft tube; and (3) a radial flow impeller fixedly connected to the shaft located in the area in the draft tube between the first impeller and the second vertical baffling means whereby a high shear zone is created in said area.	
Both process and product claims?	Yes	No

of the innovation. The U.S. patent law requires "sufficiency of disclosure/enablement,"[6] such that a new process component integral to a new product component (i.e., the product cannot be made without this process) would both have to be listed in the same patent by law. The lawyer or applicant cannot arbitrarily split the process and product components and list them as separate patents. Moreover, the principle of "double patenting"[7] precludes the applicant from including within one patent claims over components that are less integral to the patent and that are already listed separately in other patents. Patent examiners scrutinize and approve claims eventually listed in granted patents; the applicant or lawyer does not get to solely dictate how

[6]"Sufficiency of disclosure/enablement" requires that a single patent application must disclose a claimed invention in sufficient detail for the notional person skilled in the art to carry out that claimed invention.
[7]The principle of "double patenting" dictates that "if two or more independent and distinct inventions are claimed in one application, the Director may require the application to be restricted to one of the inventions."

claims are written. This lends additional assurance that our claims-based measures are not distorted by preferences of applicants or lawyers, but rather do reflect the underlying invention attributes as we intended. Toward the end of the paper, we elaborate on more tests that we conducted to bolster the validity of our measures.

To code the claims, we access the claims text of all patents that the 101 sample firms filed over the sampling range from the USPTO website. This amounts to 44,440 patents, with an average of over 12 claims per patent, totaling 534,520 claims that we manually code. We use the following coding key: a process claim is one where the novelty takes the form of a new way or method of production, and contains descriptions of sequence of implementations, components used, or its purposes. A product claim is one where the novelty takes the form of an object/device/service, and contains descriptions of its structure, composition, set-ups, or uses. We also include "both" or "not sure" options, where "both" allows for ambiguity of process–product nature even within one claim, and "not sure" provides the option of not coding a claim where its nature is unclear.

We employed six coders, and trained each one individually on the structure of patent texts and the coding key. We then conducted a practice session using 100 patents for each coder, and provided feedback on the coding. Next, we selected another 100 patents randomly from our sample, and had each coder individually code them. The six sets of coding were compared to ensure common understanding across coders. Pair-wise correlations were 90% and above for all pairs of coding, indicating reliability of the key and consistencies across coders. Following that, we assigned the coders to different parts of the 534,520 claims. We conducted extensive and frequent checks to ensure accuracy of coding. Across all 534,520 claims, only six were coded as "Both" and 275 "Not sure." Given these small numbers relative to total claims coded, we are reasonably confident that our coding provides precise measures of inventions' process–product nature. We dropped the claims with "Both" and "Not sure" from subsequent analyses.

To construct the variables, we first calculate, for each patent, a ratio of the number of product claims over total claims, ranging in value from 0 to 1. A value of 0 (1) represents a pure process (product) patent, and values between 0 and 1 reflect a mix of process and product components *within* the patent. Referring back to the examples in Table 1, Patent A would have a value of 0.5 since it consists of 1 process and 1 product claim, and Patent B would have a value of 1 since it consists of 2 product claims. We then calculate the mean of this ratio across all patents filed by a firm in a year (***Process–Product***). Suppose all patents filed by the firm which Patent A (B) is assigned to have the same composition of process–product claims, then *Process–Product* for this firm would be 0.5 (1).

As we need the variable to indicate the extent to which the firm has a mix of process–product components, rather than whether the firm is a process- or product-specialist, we transform *Process–Product* with the formula "1—absolute[0.5—*Process–Product*]" to create the variable ***Process–Product Mix***. This variable reflects how close *Process–Product* is to an even mix of product and process components. The lowest value (0.5) indicates all patents in the firm-year are either of pure process claims (*Process–Product* = 0) or of pure product claims (*Process–Product* = 1). The greater the value of *Process–Product Mix*, the closer the firm-year is to an even mix of process and product components. Referring back to the patent examples in Table 1, if all patents filed by the firm look like Patent A (B), then *Process–Product Mix* for this firm would be 1 (0.5). Note that this variable, *Process–Product Mix*, captures the extent to which the firm has a mixture of both process and product components in its portfolio, but does not indicate the level of process–product integration within the portfolio. We describe how we measure such integration in a later section on "Empirical Model Design."

3.1.2 | Other variables

We use ***Firm Profit*** as the first dependent variable to capture a firm's financial performance, measured as the firm's net profits over total revenue. Scaling by total revenue also helps account for the influence of firm size.[8] The second dependent variable, ***R&D Per Patent***, is measured as the natural log of the firm's R&D expenses (scaled in millions) divided by the number of patents the firm files for in the year. For the contingency variables, we use the firm's property, plant and equipment as a proxy for its ***Production Capacity***. We use the number of countries that the firm has operations in as a proxy for its ***Access to Markets***.

We control for factors that could drive both a firm's profits and the process–product nature of its portfolio. The more innovative firm may be more profitable and also more likely to create both process and product components. As we are capturing these components by patent claims, we use a more direct control of innovative activities with the firm's total number of claims in patents filed in the year (***Total Patent Claims***).[9] A firm with greater sales/marketing orientation may have a stronger product focus (lower process–product mix) and lack abilities to appropriate returns via production. We control for this with the firm's selling and general expense (***SG&A***). Product line diversification may result in greater process–product mix and concurrently improve financial performance. We add ***Diversification*** based on the standard entropy measure (Palepu, 1985). The firm's capital structure could affect both its profits and ability to invest in both process and product improvements. We include the firm's ***Debt/Equity*** ratio and its fixed-charge coverage ratio (***Financial Slack***). We add dummies for Japanese (***JAP***) and European (***EUR***) firms to capture possible region-specific effects, technology category dummies to control for other unobserved nature of technologies, and year dummies to capture possible intertemporal heterogeneity.

3.2 | Empirical model design

Examination of our propositions presents two related hurdles. First, the empirical design needs to separate an instance where there is greater integration of process and product components within each innovation in a firm portfolio, from another where the firm has a portfolio of innovations each containing pure process or pure product components. Second, the empirical design needs to isolate the performance effect arising from the former instance of greater process–product integration within each innovation, apart from any performance effect of the firm having both process and product components but residing separately within different innovations as in the latter instance. The mechanisms related to integration, as theorized in earlier sections, pertain more to the former than the latter instance. Isolating these mechanisms, however, is complicated by the fact that whenever the firm has greater integration between its process and product components as in the former, it also has, by construction, both process and product components residing within its portfolio that could affect performance via other confounding mechanisms.

[8]We alternatively scale net profits by total assets and use this return on total assets as a dependent variable instead. All subsequent findings remain robust, except that the main effect of *Process–Product Mix* in Models 1 and 2 of Table 2 becomes significantly positive only at 10% level, which is still meaningful given the one-tail nature of the tests.

[9]Alternatively, we use the more aggregated measure of total number of patents the firm files in a year, in place of total number of claims. Findings remain fully robust.

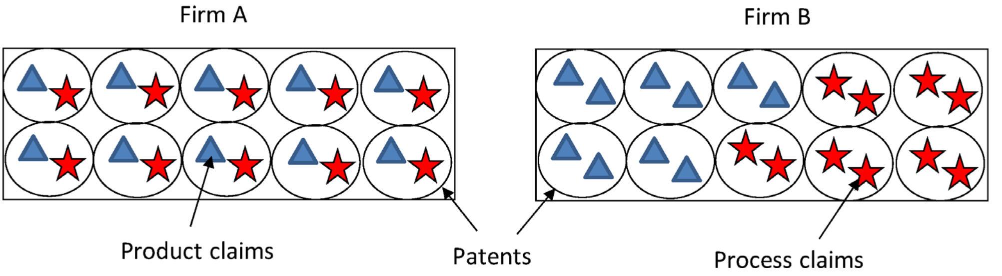

FIGURE 1 High-integration versus low-integration of process–product components

The main variable described in the earlier section, *Process–Product Mix*, by itself does not overcome these hurdles. First, while it captures a firm having patents that individually integrate both process and product components (call this Firm A), it does not differentiate this firm from another that possesses process and product components separately located across different patents (call this Firm B). Figure 1 illustrates this difference: Firms A and B each has 10 patents with two claims per patent. Each of the 10 of Firm A's patents has one process claim and one product claim. Firm B has five patents with two process claims each (pure process patents) and five patents with two product claims each (pure product patents). Since both firms have the same overall composition of process–product claims, that is, each firm has a total of 10 process claims and 10 product claims, both firms have *Process–Product* = 0.5 and hence *Process–Product Mix* = 1. However, within-patent process–product integration exists in Firm A, but not in Firm B.

Second, even within Firm A, high levels of *Process–Product Mix*, by construction, always correspond with having both process and product components. The variable does not ensure that any observed performance effect arises solely from the two types of components being *integrated*, and not from the two being *present* in the firm. For example, if Firm A is observed to have strong financial performance, relative to another firm that has only pure process (or pure product) patents and thus have low *Process–Product Mix*, this variable alone does not allow us to determine if this strong performance is arising from Firm A integrating process–product components within each of its innovations or from Firm A having both types of components in its portfolio.

To overcome the first hurdle, we split the sample. We calculate the *SD* around the firm-year level *Process–Product*. Recall that *Process–Product* is the firm-year mean of patents' ratio of product claims over total claims. The *SD* indicates how dispersed the individual patent's ratio is around the firm-year mean. While both firms have high *Process–Product Mix*, Firm A has a low *SD* for *Product–process* since the process–product ratio of its patents are closely clustered around the even mix, and Firm B has a high *SD* since its patents' ratios are widely dispersed around the mean *Process–Product*. We then split the sample, by the median, into two subsamples with low and high *SD*s. The subsample with low *SD*, which we term "treatment group," contains observations more similar to Firm A, with greater within-patent integration of process and product components. The high *SD* subsample, which we term "control group," has observations similar to Firm B, where process and product components reside more separately across different patents.

To overcome the second hurdle, we compare the effects of *Process–Product Mix* across the treatment and control groups, much like in a difference-in-difference (DID) approach

(Card & Krueger, 1994). We test if observed findings in the treatment group exist over and above those in the control group. The main idea is that the confounding effect, of the firm having both product and process components, exists in both treatment and control groups. By differencing the observed effect across the two groups, we "dummy" out these confounding effects and isolate the effect arising from within-patent integration of process–product components.[10]

We use generalized least square regressions for the main analyses, given that both graphical method and Park's test indicate heteroscedastic variance with ordinary least square. All independent variables have a 2-year lag to allow time for them to affect financial performance. We check the robustness of our findings using different lags in a later section.

4 | FINDINGS

Table 2 reports descriptive statistics. The mean of *Process–Product Mix* is 0.85, indicating that firms typically have some mix of process and product components in their portfolios. The minimum value of 0.5 suggests that there are firms in the sample (3.4% of observations, not reported in table) generating purely process or purely product components in a given year. To determine the extent that the mix of components is occurring within- versus across-patents, we further examine the data at the patent level. We find that out of 44,440 patents in the sample, 12,980 (29%) individually contain both process and product components. This confirms our earlier suspicion that process–product integration exists even within a unit of innovation, as represented in one patent, and justifies the need to trace within-patent process–product nature.

The central tenet in (H1a) is that integration of process and product components additionally improves firm performance, over and above the presence of both process and product components. As an initial check, we plot in Figure 2 *Firm Profit* against the firm-year level *Process–Product*, where 0 (1) represents pure-process (pure-product) firms, allowing for 2-year lags. We use best-fit quadratic lines, since we suspect performance to peak when firms have a mix of process and product components, for the full sample, and separately, the treatment and control groups. The full-sample graph shows only a slight hint of stronger performance associated with a mix of components. However, the graph for the treatment group (with greater process–product integration) clearly demonstrates that firms with an even mix of process–product components (around 0.5) exhibit the highest performance. In contrast, the graph for the control group (with less process–product integration) exhibits an almost opposite pattern. These graphs are consistent with (H1a). While inconclusive on causality, these graphs provide an assuring start to our analyses.

[10]Referring back to examples in Table 1: Patent A was assigned to Union Carbide. In that year (1982), Union Carbide has *Process–Product Mix* = 0.95 and falls into the subsample with lower *SD* of *Process–Product* (treatment group), suggesting respectively that its portfolio of patents contain both process and product components, and most of these patents individually contain a mixture of both process and product components (claims). Patent B was assigned to BASF. In that year (1982), turns out BASF has also has *Process–Product Mix* = 0.95 but falls into the subsample with higher *SD* of *Process–Product* (control group), suggesting that BASF also has a portfolio that contains both process and product components, but that most of its patents individually contains either only process components or only product components. When testing performance effects, the DID models shows how much larger the performance gap is between Union Carbide (high *Process–Product Mix* but low *SD*) and another firm with low *Process–Product Mix*, as compared to the performance gap between BASF (also high *Process–Product Mix* but high *SD*) and another firm with low *Process–Product Mix*.

TABLE 2 Descriptive statistics

	Variable	Obs	Mean	*SD*	Min	Max	Pairwise correlation											
							i	ii	iii	iv	v	vi	vii	viii	ix	x	xi	xii
i	Firm Profit$_t$	397	3.97	3.27	−2.63	30.48	1.00											
ii	R&D Per Patent$_t$	261	155.23	236.06	0.21	1,431.84	−0.37	1.00										
iii	Process–Product Mix$_{t-2}$	397	0.85	0.11	0.50	1.00	0.09	−0.20	1.00									
iv	Production Capacities$_{t-2}$	397	1.35	2.35	0.01	16.61	0.08	−0.26	0.25	1.00								
v	Access to Markets$_{t-2}$	397	14.45	15.60	1.00	77.00	0.27	−0.54	0.29	0.50	1.00							
vi	Total Patents Claims$_{t-2}$	397	838.72	1,359.18	10.00	8,806.00	0.19	−0.34	0.32	0.81	0.61	1.00						
vii	SG&A$_{t-2}$	397	0.63	1.01	0.02	7.08	0.04	−0.27	0.24	0.73	0.66	0.73	1.00					
viii	Diversification$_{t-2}$	397	1.28	0.34	0.20	2.15	−0.19	−0.07	0.20	0.44	0.41	0.38	0.57	1.00				
ix	Debt/Equity$_{t-2}$	397	119.18	147.10	4.05	1,094.39	−0.32	0.23	−0.06	−0.12	−0.29	−0.15	−0.14	0.11	1.00			
x	Financial Slack$_{t-2}$	397	4.50	5.69	0.37	55.73	0.35	−0.25	−0.06	−0.06	0.04	−0.01	−0.02	−0.27	−0.30	1.00		
xi	Japan$_t$	397	0.60	0.49	0.00	1.00	−0.46	0.77	−0.19	−0.33	−0.73	−0.40	−0.36	−0.12	0.40	−0.31	1.00	
xii	Europe$_t$	397	0.14	0.34	0.00	1.00	0.07	−0.30	0.23	0.19	0.62	0.20	0.53	0.39	−0.16	0.00	−0.3917	1.00

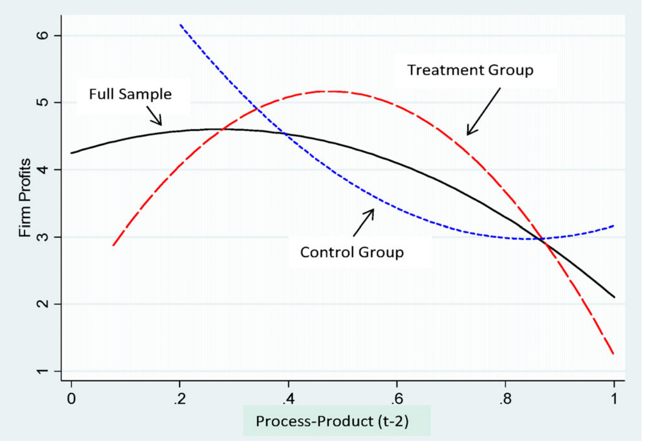

FIGURE 2 Relationship between firm profits and process–product

We test these patterns in Table 3. Model 1 contains the full sample. Models 2 and 3 split the sample into treatment and control groups respectively. *Process–Product Mix* positively affects financial performance (*p*-value .006) in Model 1. This supports (H1). This positive effect exists in the treatment group (Model 2, *p*-value .007), but not in the control group (Model 3, *p*-value .167). *t*-Test of difference in coefficients shows that *Process–Product Mix* is significantly more positive (*t*-statistic 2.77) in the treatment group (Model 2) than in the control group (Model 3). This supports (H1a), suggesting that greater integration between process and product components, relative to having them separately across different innovation within firm, enhances the firm's financial returns. Going from having purely process or product patents to having an even mix of product–process components (increasing *Process–Product Mix* from 0.5 to 1) increases profit margin by 0.82 percentage points in the full sample, and by 1.31 percentage points in treatment group, or 2.12 percentage points increase relative to the same change over the control group.

We address the possibility that, even with firm- and technology-controls, findings may be confounded by other unobserved firm heterogeneity. The empirical design raises the hurdle for these confounding effects: the unobserved factor would have to affect the treatment group systematically more than the control group to produce earlier findings, and it is not immediately apparent why they would do so. Nonetheless, in Models 4–6, we try to suppress them by adding the firm's presample profit margin. We measure presample profit margin as the average of *Firm Profits* over 2 years prior to the sampling range. This assumes, as in fixed-effect models, that unobserved firm abilities are time-invariant, such that they equivalently affect presample profits. Findings remain fully robust: *Process–Product Mix* remains positive in the full-sample Model 4 (*p*-value .012), and greater in the treatment group (Model 5, *p*-value .008) than in the control group (Model 6, *p*-value .235), with significant difference between them (*t*-statistic 2.59). In Models 7–9, we further use random-effects estimation. The effect of *Process–Product Mix* in the full sample weakens slightly though remains positive (*p*-value .092), providing weak support for (H1). This is likely due to reduced variance, given the relatively short panel in our sample. Findings for (H1a) in the split-sample tests in Models 8–9, however, remain robust. *Process–Product Mix* is positive in the treatment group

TABLE 3 Main treatment effects of process–product integration

Dependent variable	Firm profit								
Model	Generalized lease square			Generalized lease square			Random effects		
	Full sample	Split-sample		Full sample	Split-sample		Full sample	Split-sample	
		Treatment group	Control group		Treatment group	Control group		Treatment group	Control group
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Process–Product Mix$_{t-2}$	1.642 (.006)	2.613 (.007)	−1.622 (.167)	1.854 (.012)	2.579 (.008)	−1.448 (.235)	2.729 (.092)	7.276 (.025)	−3.178 (.262)
T-statistics of difference between coefficients		2.77			2.59			2.41	
Production Capacities$_{t-2}$	−0.002 (.954)	0.111 (.071)	−0.017 (.806)	−0.019 (.658)	0.165 (.001)	−0.064 (.334)	0.214 (.481)	0.794 (.295)	−0.582 (.186)
Access to Markets $_{t-2}$	0.019 (.041)	0.005 (.740)	−0.003 (.833)	−0.013 (.231)	−0.015 (.181)	−0.022 (.159)	0.024 (.483)	−0.001 (.994)	−0.083 (.059)
Total Patents Claims$_{t-2}$	0.000 (.020)	0.000 (.948)	0.001 (.000)	0.000 (.276)	−0.000 (.000)	0.001 (.000)	−0.001 (.370)	−0.004 (.081)	0.000 (.665)
SG&A$_{t-2}$	−0.635 (.000)	−0.439 (.014)	−1.394 (.000)	−0.191 (.149)	−0.093 (.437)	−1.000 (.000)	−0.388 (.544)	−0.927 (.596)	1.237 (.250)
Diversification$_{t-2}$	−0.831 (.000)	−1.851 (.000)	−0.477 (.079)	−0.504 (.059)	−0.729 (.029)	−1.074 (.001)	−0.783 (.233)	−0.908 (.554)	−0.465 (.542)
Debt/Equity$_{t-2}$	−0.003 (.000)	−0.005 (.000)	−0.001 (.000)	−0.002 (.000)	−0.004 (.000)	−0.002 (.011)	−0.003 (.042)	−0.005 (.119)	−0.001 (.560)
Financial Slack$_{t-2}$	0.193 (.000)	0.020 (.111)	0.328 (.000)	0.068 (.058)	−0.056 (.215)	0.234 (.000)	−0.034 (.544)	−0.133 (.217)	0.185 (.014)
Japan$_t$	−2.299 (.000)	−2.739 (.000)	−2.394 (.000)	−1.624 (.000)	−1.631 (.000)	−1.524 (.000)	−0.830 (.251)	−1.458 (.298)	−1.335 (.111)
Europe$_t$	−0.218 (.493)	0.599 (.181)	−0.587 (.100)	0.919 (.012)	2.502 (.000)	−0.053 (.922)	1.772 (.063)	0.965 (.706)	−0.610 (.609)
Presample Profits				0.423 (.000)	0.615 (.000)	0.162 (.045)	0.592 (.000)	0.803 (.007)	0.289 (.096)
Year dummies	Included	Included	Included	Included	Included	Included	Included	Included	Included
Technology category dummies	Included	Included	Included	Included	Included	Included	Included	Included	Included
Constant	3.807 (.004)	5.879 (.000)	5.536 (.000)	2.037 (.262)	3.298 (.001)	6.001 (.000)	1.640 (.357)	−1.023 (.784)	7.267 (.013)
Observations	397	199	198	322	161	161	322	161	161

Note: *p* values in parentheses.

(Model 8, p-value .025) but not in the control group (Model 9, p-value .262), with significant difference between them (t-statistic 2.41).[11]

Table 4 reports tests of the contingency predictions. The first (Models 1–4) and second (5–8) panels test contingencies related to production capacity (H2) and access to markets (H3), respectively. In Models 1–4, we classify each observation as being "low" or "high" on production capacity, relative to its median. We then divide the sample into four subsamples: low production capacity and treatment group (Model 1), low production capacity and control group (Model 2), high production capacity and treatment group (Model 3), and high production capacity and control group (Model 4).[12] The objective is to show that the treatment effect (i.e., *Process–Product Mix* having a stronger performance effect in the treatment relative to the control group) is more pronounced when the firm has less production capacity (Models 1 and 2), and less so when the firm has greater production capacity (Models 3 and 4). We use the same approach in the second panel for access to markets (Models 5–8).

Process–Product Mix is positive in Model 1 for treated observations with low production capacity (p-value .006), while negative in Model 2 for control observations that also have low production capacity (p-value .42). t-Test comparison of coefficients across the two models confirms this difference (t-statistic 2.54), suggesting that the treatment effect as in (H1a) exists when the firm has low production capacity. In contrast, when production capacity is high, there is no evidence that *Process–Product Mix* has any effect in either treatment or control group (Models 3 and 4, p-values .714 and .372, respectively). t-Test does not show difference in coefficients across Models 3 and 4. Together, these findings support (H2), suggesting that the less production capacity the firm has, the more that process–product integration will enhance firm performance. The magnitude of effect is pronounced here: where production capacity is low (Models 1–2), changing *Process–Product Mix* from 0.5 (pure product or pure process) to 1 (even mix) increases profit margin by 1.77 percentage points in the treatment group, or 2.26 percentage points increase relative to the same change over the control group.

[11]We further examine the conjecture that the firm's level of process–product integration and its performance effect is only driven by the "true technological interdependence nature" as determined by the technological environment, such that idiosyncratic firm choice in integration level is inconsequential, or that deviation from the "true nature" results in poorer performance. We do not believe this conjecture is accurate, based on the following. First, if the conjecture is accurate, then there should not be much variance in integration within industry. Our within-industry study exhibits substantial variance across firms (see Table 2), with some firms being purely process or purely product specialists (*Process–Product Mix* = 0.5) and others having even mix of process and product components within their portfolios (*Process–Product Mix* = 1). Second, if the conjecture is accurate, then the firm's choice of process–product integration should have no performance impact. The robust results of estimations with technological category dummies reported here and in Table 3 show otherwise. Third, we went further to test if a firm's deviation from the "optimum true interdependency" level as defined by the environment hurts its performance. We assume that the industry's average level of process-product integration reflects the "true interdependency" level. Within each year, we calculate the firm's deviation as the absolute of (the firm's *SD* of *Process–Product*) minus the (average *SD* of *Process–Product* across all firms in the year). We then reran Models 1–3 of Table 3, this time with the treatment group being defined as the firms with higher deviation from the industry average. We find no significant difference between the treatment group (those that deviated more from the industry average) and the control group (those that deviated less from the industry average). Based on the above, we do not believe that the firm's choice of process–product integration or its performance impact is solely determined by the technological interdependency nature as determined by the environment.

[12]Note that sample sizes are not even across the four subsamples because each observation is classified separately on two dimensions (treatment/control and production capacities) and its assignment into the subsample depends on its classification on both dimensions. For example, among observations in the "low production capacity" classification, there may not be the same number assigned to the treatment group as that assigned to the control group.

TABLE 4 Contingency effects of process–product integration

Dependent variable	Firm profit							
	Split-sample		Split-sample		Split-sample		Split-sample	
	Low production capacities and treatment group (1)	Low production capacities and control group (2)	High production capacities and treatment group (3)	High production capacities and control group (4)	Low access to markets and treatment group (5)	Low access to markets and control group (6)	High access to markets and treatment group (7)	High access to markets and control group (8)
Process–Product Mix$_{t-2}$	3.530 (.006)	−0.990 (.420)	0.967 (.714)	−1.780 (.372)	4.407 (.000)	−0.438 (.691)	1.697 (.264)	0.837 (.739)
T-statistics of difference between coefficients	2.54		0.83		3.26		0.29	
Production Capacities$_{t-2}$	−1.845 (.084)	0.628 (.336)	0.105 (.254)	0.009 (.912)	0.037 (.931)	0.716 (.030)	0.075 (.371)	0.037 (.625)
Access to Markets$_{t-2}$	−0.045 (.169)	−0.083 (.000)	−0.025 (.226)	−0.008 (.684)	−0.036 (.614)	−0.097 (.046)	−0.016 (.470)	−0.030 (.146)
Total Patents Claims$_{t-2}$	0.005 (.000)	0.000 (.289)	−0.000 (.082)	0.001 (.000)	0.000 (.798)	0.002 (.000)	−0.000 (.725)	0.001 (.001)
SG&A$_{t-2}$	4.297 (.006)	1.981 (.050)	0.137 (.582)	−1.659 (.000)	0.097 (.912)	−0.543 (.513)	−0.240 (.325)	−1.107 (.001)
Diversification$_{t-2}$	−0.771 (.084)	0.536 (.094)	−1.886 (.003)	−2.128 (.000)	−0.891 (.017)	−0.329 (.199)	−2.015 (.000)	−2.024 (.001)
Debt/Equity$_{t-2}$	−0.003 (.000)	−0.003 (.000)	−0.005 (.002)	0.001 (.109)	−0.002 (.000)	−0.001 (.103)	−0.007 (.000)	−0.004 (.025)
Financial Slack$_{t-2}$	0.004 (.794)	0.276 (.000)	0.065 (.528)	0.602 (.000)	0.310 (.000)	0.587 (.000)	0.026 (.336)	0.217 (.000)
Japan$_t$	−2.682 (.000)	−2.910 (.000)	−3.519 (.000)	−2.344 (.000)			−2.820 (.000)	−2.371 (.000)
Europe$_t$	0.689 (.424)	0.621 (.544)	−0.382 (.459)	−0.300 (.574)			0.730 (.161)	−0.576 (.244)
Year dummies	Included	Included	Included	Included	Included	Included	Included	Included
Technology category dummies	Included	Included	Included	Included	Included	Included	Included	Included
Constant	4.990 (.000)	3.540 (.007)	6.886 (.006)	5.397 (.008)	0.404 (.662)	1.225 (.308)	6.502 (.000)	5.257 (.050)
Observations	93	106	106	92	79	125	120	73

Note: *p* values in parentheses.

We similarly test (H3) in Models 5–8. Where access to markets is low (Models 5–6), *Process–Product Mix* has a positive effect in the treatment group (Model 5, *p*-value .000) but not in the control group (Model 6, *p*-value .691). *t*-Test confirms this difference in coefficients (*t*-statistic 3.26). This indicates that the treatment effect in (H1a) exists when the firm has low access to markets. Where access is high (Models 7–8), there is no apparent effect in the treatment or control groups, nor difference between them. These findings support (H3), showing that the less access to markets the firm has, the more that process–product integration enhances its performance. The magnitude of the effect is also pronounced here: where access to markets is low (Models 5–6), changing *Process–Product Mix* from 0.5 (pure product or pure process) to 1 (even mix) increases profit margin by 2.2 percentage points in the treatment group, or 2.42 percentage points increase relative to the same change over the control group.[13]

To test (H4) (Table 5), we replace the dependent variable with the firm's logged *R&D Per Patent*. Per earlier, we included a 2-year lag. The full sample Model 1 offers no clear evidence of *Process–Product Mix*'s effect—overall, the coefficient estimate, while negative, does not convincingly indicate that having both product and process components decreases cost per patent (*p*-value .79). However, this effect is positive and pronounced in the treatment group where process–product components are more integrated (Model 2, *p*-value .024), and importantly, is greater (*t*-statistic 2.69) than in the control group (Model 3) where process–product components reside more separately across patents. This supports (H4), suggesting that the more integrated the process–product components, the higher R&D expense per unit of innovation. We repeat these tests using random effects estimation (Models 4–6) to try to mitigate potential unobserved firm heterogeneity, and find fully robust results. In Models 7–9, we use the measure of *R&D Per Patent* without log as an alternative dependent variable, to see if findings were specific to the log version of the measure. Findings remain fully robust.[14]

4.1 | Additional analyses

4.1.1 | Matching

We further address potential selection issues in the main effect of product–process integration (Table 3) with a matching method. While we tried earlier to address these issues with presample profit margin and random effect models, it is still possible that unobserved time-varying heterogeneity, not captured in the prior models, could systematically select observations into

[13]In additional analyses (not reported in Table 4), we attempt to account for unobserved firm heterogeneity in the contingency tests with the firm's presample profit margin and random effects estimations. We note that the empirical design raises the hurdle for selection issues to be confounding results. Unobserved heterogeneity, if it was to drive results, would not only have had to systematically affect the treatment group more than the control group, but also differentially affect performance as such more so when the firm's production capacity or access to markets are lower than when they are higher. This hurdle notwithstanding, we start by including presample profit margin as a control. Findings for (H2) remain fully robust per Table 4 Models 1–4. The main finding for (H3) remains robust: *Process–Product Mix* is more positive in Model 5 than in Model 6 (*t*-statistic for difference 2.33). But *Process–Product Mix* is also significantly more positive in Model 7 than in Model 8 (*t*-statistic of difference 3.2), which is not predicted by (H3). When we use random effects estimation, though, all findings for both (H2) and (H3) remain fully robust per Table 4.
[14]Additionally, we check for robustness of our main findings (Models 1–3) and found stable results using three alternative dependent variables—(a) log of R&D expense while controlling for the denominator (log count of patents), (b) the average of 1-year ($t + 1$), 2-year ($t + 2$), and 3-year ($t + 3$) time lags from the independent variables (t), and (c) a contemporaneous version of *R&D Per Patent*, that is, year t. Results are reported in the online appendix.

TABLE 5 Cost of process–product integration

Dependent variable	R&D Per Patent$_t$ (Log)						R&D Per Patent$_t$ (without log)		
Estimation model	Generalized least square			Random effects			Generalized least square		
	Full sample	Split-sample		Full sample	Split-sample		Full sample	Split-sample	
		Treatment group	Control group		Treatment group	Control group		Treatment group	Control group
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Process–Product Mix$_{t-2}$	−0.097 (.790)	1.671 (.013)	−1.422 (.126)	0.489 (.276)	2.695 (.006)	0.053 (.939)	−41.852 (.501)	233.109 (.023)	−323.222 (.063)
T-statistics of difference between coefficients		2.69			2.19			2.76	
Production Capacities$_{t-2}$	−0.056 (.014)	0.013 (.797)	−0.105 (.033)	−0.067 (.299)	0.004 (.967)	−0.071 (.375)	0.897 (.791)	4.791 (.468)	−11.861 (.143)
Access to Markets $_{t-2}$	−0.016 (.000)	−0.022 (.005)	−0.007 (.247)	−0.012 (.294)	−0.024 (.166)	−0.014 (.284)	0.955 (.146)	1.109 (.476)	1.141 (.192)
Total Patents Claims$_{t-2}$	−0.000 (.987)	−0.000 (.002)	−0.000 (.482)	−0.000 (.725)	−0.000 (.116)	0.000 (.474)	−0.001 (.910)	−0.024 (.146)	0.001 (.885)
SG&A$_{t-2}$	0.716 (.000)	0.862 (.000)	0.839 (.001)	0.421 (.062)	0.665 (.042)	0.263 (.381)	0.593 (.964)	8.226 (.688)	50.317 (.233)
Diversification$_{t-2}$	−0.422 (.000)	−0.959 (.000)	0.065 (.738)	−0.012 (.962)	−0.222 (.595)	0.022 (.936)	3.805 (.850)	−11.046 (.767)	64.188 (.133)
Debt/Equity$_{t-2}$	−0.001 (.000)	−0.002 (.042)	−0.000 (.137)	0.000 (.955)	−0.000 (.991)	−0.000 (.816)	−0.206 (.003)	0.144 (.532)	−0.286 (.004)
Financial Slack$_{t-2}$	−0.040 (.000)	−0.061 (.000)	−0.037 (.000)	−0.020 (.158)	−0.028 (.242)	−0.020 (.355)	−0.947 (.314)	0.445 (.846)	−1.652 (.196)
Japan	5.093 (.000)	4.941 (.000)	5.165 (.000)	4.963 (.000)	4.958 (.000)	4.903 (.000)	376.418 (.000)	400.938 (.000)	361.477 (.000)
Europe	0.003 (.980)	0.001 (.996)	−0.353 (.219)	−0.051 (.891)	0.101 (.819)	0.048 (.920)	−8.539 (.595)	−19.401 (.504)	−63.090 (.146)
Year dummies	Included	Included	Included	Included	Included	Included	Included	Included	Included
Technology category dummies	Included	Included	Included	Included	Included	Included	Included	Included	Included
Constant	2.752 (.000)	1.797 (.003)	3.016 (.006)	0.602 (.413)		1.092 (.249)	92.615 (.244)	−142.511 (.121)	296.801 (.104)
Observations	190	95	95	190	95	95	190	95	95

Note: *p* values in parentheses.

being treated or not in ways that biased findings. Thus, earlier regressions run on a whole sample could have ended up comparing observations with fundamentally different attributes. The matching method reduces this problem by comparing each treated observation (more integrated process–product components) with only one (or a set of) control observation(s) (less integrated process–product components) that are otherwise similar based on certain matching criteria.

We separate observations into treatment and control groups per Table 3 (treatment being high process–product integration). We focus on the subsample of observations where the firm has greater mix of process–product components (above mean[15] of *Process–Product Mix*) to narrow down the observed effect to that arising from how these components are organized (more integrated vs. less). The method matches each treated observation to one similar control observation, based on the criteria specified (see below).[16] It then calculates the average treatment effect on the treated (ATET) by differencing (treatment minus control) the outcomes (*Firm Profits*) of this pair (or set), and taking the average across all pairs (or sets). ATET represents the treatment effect of process–product integration on firm performance. We report the ATETs in Table 6. As a baseline comparison, we also report equivalent ATETS for the subsample with low *Process–Product Mix* at the bottom of the table.

Model 1 matches treatment and control based on nearest Mahalanobis distances in terms of year and technological categories. The ATET is 1.179 percentage points, significantly larger than zero (p-value .022), suggesting that process–product integration increases firm performance, relative to a similar firm with less integrated process and product component. In Model 2, we impose a stricter criterion that the matched treatment and control must be from the same year, and have the nearest Mahalanobis distance on the technological categories. Findings remain robust (ATET 1.388 percentage point, p-value .005). In Model 3, we fine-tune the analysis by constraining the matched pair (or set) to be from the same year, and matching based on nearest distances in technological categories and other control variables.[17] Findings remain robust (ATET 1.556 percentage point, p-value .009). Across all three models, the subsample of observations with less mixture of process and product components (bottom panel of Table 6) yields no clear finding of any treatment effect, which is as expected. This aligns with our main assertion: as the firm increases its mix of process and product components (from low to high), the incremental performance effect is arising from the integrated approach to organizing the process and product components. Thus, we are reasonably confident that our earlier findings on the main treatment effect are not biased due to selection issues.

4.1.2 | Validation of process–product measures and tests of key mechanism

A key mechanism in our hypotheses is that process–product integration within each innovation improves the firm's financial returns (relative to having both types of components separately across innovations within the firm's portfolio) by enabling greater appropriation of its innovations' value. The corresponding measures for the integration of process–product components are meant to reflect this mechanism. In this section, we further examine this key mechanism

[15]Splitting the sample at the median of *Process–Product Mix* yields robust findings.

[16]If there are more than one control observation with the same score, the average across this set of controls is used.

[17]Other control variables used in matching includes *Production Capabilities*, *Commercialization Capabilities*, *Total Patent Claims*, and *SG&A*. Due to sample size constraint, we are unable to add other variables in the matching criteria.

TABLE 6 Average treatment effect on treated from matching analysis

	Average treatment effect on treated[a]		
Treatment (control): High (low) levels of integration	**Matching: Nearest Mahalanobis distance based on year, technology categories (1)**	**Matching: Within-year, nearest Mahalanobis distance based on technology categories (2)**	**Matching: Within-year, nearest Mahalanobis distance based on technology categories and other control variables**[b] **(3)**
Subsample: High Process–Product Mix_{t-2}	1.179	1.388	1.556
	(0.516)	(0.492)	(0.599)
	[.022]	[.005]	[.009]
Subsample: Low Process–Product Mix_{t-2}	0.897	0.786	0.290
	(0.504)	(0.581)	(0.531)
	[.075]	[.176]	[.585]

[a]*SE* in parentheses (); *p*-value in brackets [].
[b]Control variables include Production Capacities, Access to Markets, Total Patent Claims, and SG&A.

and validity of the corresponding measures at both firm-level (persistence of returns) and patent-level (citations received).

4.1.3 | Persistence of returns

Stronger financial returns to a firm could indicate the firm's superior ability to appropriate returns to its innovations due to inimitability of these innovations as we theorized, but it could be also driven in part by the market's greater willingness to pay for the firm's products, for example, due to the superiority of product features. If the former "appropriation" mechanism underlying process–product integration is at work, we should observe the firm's stronger returns persisting over time, since it is more difficult for imitators to erode this returns; whereas it is less apparent why the latter "willingness to pay" mechanism would lead to persistently strong financial returns for the firm over time, barring unobserved attributes that enable this firm to consistently generate innovations over time for which the market would pay up.[18]

Here, we further examine persistence of returns for firms with greater process–product integration and exhibit stronger financial returns. First, we compile a list of top-performing firms in terms of financial returns (*Firm Profits*). For each year in our sample, we identify the top 10 firms with the highest returns. We find that 21 firms occupy the "top 10" spots across the 7 years in our sample. Next, for each of these 21 firms, we trace the number of years (out of 7) that the firm was in the top 10. We find that three firms were in the "top 10" for all 7 years, and the other 18 firms range from being in "top 10" for 1–6 years. Then, for each firm, we calculate the mean of the firm's *SD* around *Process–Product* across years. Recall that this *SD* captures whether the firm has integrated process–product components within each patent or if the firm

[18]Along this vein, the additional robustness checks for different time lags have contributed to demonstrating this persistence—our findings for the performance effect of process–product integration appear to persist over time, even after 3 years, lending confidence that our theorized "appropriation" could be at work.

has these components separate across patents in its portfolio, with higher values indicating the latter. We find that the three persistently top-performing firms (i.e., in "top 10" for all 7 years) has an *SD* of 39% on average, whereas the other 18 also top-performing but not as persistent firms have an *SD* of 43% on average. This is in line with our theorizing—among the firms that exhibit strong financial returns (all 21 firms), persistence of such returns (the 3 persistently top-performing firms) appears to correspond with greater process–product integration within patents (lower *SD*).

We also demonstrate this persistence of returns more systematically in our sample. First, we obtain the returns unexplained by other observed influences, by using the main Model 1 in Table 3, regressing *Firm Profits* on all the control and dummy variables and obtaining the residual. We categorize the sample firms into "high" and "low" subsamples (at the median) along three dimensions: (a) *Process–Product Mix* (i.e., firms with more vs. less mixture of process and products within their portfolios), (b) treatment-versus-control (*SD* of *Process–Product*, i.e., whether there is more or less integration of process–product components within patents), and (c) residual returns. As a baseline check, we find that the average residual returns for firms are higher when *Process–Product Mix* is high than when it is low (0.35 vs. −0.6, respectively), as consistent with results in Table 3 for (H1).

Next, we demonstrate persistence of strong performance, by examining (lack of) fluctuations of residual returns for the high-return firms.[19] We restrict our analysis to the "high" residual returns subsample, since we mean to examine firms with strong performance. For each firm, we measure the fluctuation of its residual returns over the sampling range (7 years), by calculating the *SD* of such residual returns. Focusing on the subsample of firms with high *Process–Product Mix*, we find that firms in the treatment group (more integration of process–product components in patents) have lower fluctuations of residual returns (1.17) over the years than firms in the control group (2.56). This suggests that firms with greater process–product integration within patents experience more persistence of strong financial returns, as in line with our expectation. As a further check: we would expect to find less of such difference in persistence among firms with low *Process–Product Mix*, since there are less of a mixture of process and product components within a firm's portfolio for integration to occur. Indeed, when we perform the same comparison in the subsample with low *Process–Product Mix*, we find a substantially smaller difference in fluctuations of residual returns between the treatment group (fluctuation of 1.96) and control group (fluctuation of 1.37). Overall, the above evidence on persistence of strong financial returns appears to suggest that our theorized "appropriation" mechanism is likely at work.

We further validate the measures by examining citations at the patent-level, the key logic being that if process–product integration within patents enhance appropriation of returns, we should see the firm's patents with greater within-patent process–product integration experiencing less building-on by other firms, as they are more difficult to disentangle and learn from. See online appendix for details. The appendix also contains other additional analyses and discussions. (a) We use conventional interaction terms to test the contingency hypotheses (H2) and (H3) to show that results are not specific to our earlier split-sample specifications. (b) We check for robustness of findings to different time lags. (c) We further discuss the issue of process–process or product–production integration within the firm's innovation portfolio. Please refer to online appendix for details.

[19]Persistence of strong performance would imply low fluctuation of residual returns.

5 | DISCUSSION AND CONCLUSIONS

This article examines how different levels of integration between a firm's process and product components in its innovation portfolio influence the firm's subsequent financial performance. Using new measures of process–product integration based on textual coding of patent claims within the global chemicals industry, we first show that high integration in the firm's process–product components, over and above having both types of components in the firm's innovation portfolio, enhances the firm's profitability. We then demonstrate a tension between such integration and other alternative mechanisms for enhancing appropriation, namely, the firm's production capacity and access to markets, by showing that integration contributes more to performance when the firm is low on these other mechanisms. Finally, we demonstrate that high integration between the firm's process and product components lowers its innovative productivity.

In demonstrating these effects of integration and complementarity on firm performance, we hope to add to the literature that is examining the implications of intraorganizational integration. As we argue and demonstrate here, the benefits of higher levels of integration, celebrated in the strategy literature as a mechanism to enhance and maintain rents, are also subject to bounds. Specifically, higher integration may also imply tackling higher complexity and entail much higher coordinative effort. These consequences may lower productivity and may also make it profitable to use other, simpler mechanisms such as ownership of critical complementary assets as a path to monetizing innovation.

Drawing attention to coordination costs even between potentially complementary activities highlights an implication of complementarity that has perhaps been underemphasized in the literature. Realizing complementarity benefits may entail significant coordination costs. Thus one possible explanation of why all firms do not adopt complementary activities and we observe variation in the joint adoption of what appear to be complementary activities is simply that the coordination and costs required to realize complementarity benefits may not be worthwhile for many firms, especially when they have other sources of competitive advantage.

A related implication that these results suggest is that having multiple means of appropriability does not necessarily imply increased appropriability or competitive advantage. More is not necessarily better as we note that both, conceptually and empirically, higher activity integration and scale-based appropriability strategies appear to diminish the marginal value of the other. Further, in illustrating the tension between integration and other scale-based mechanisms, the broader message that we aim to convey is the need at times to consider alternatives in tandem when examining particular tools in strategy. Often, for parsimony and depth, research focuses on one tool at a time. In the context of our study, appropriation mechanisms such as integration or downstream assets have been studied in isolation (Klepper, 1996). While the existence of alternatives may not negate, or even affect, the study of *how a single mechanism works*, nonconsideration of these alternatives stifles our ability to understand *when the mechanism in question works best*, especially when it exhibits a tension with these other alternatives as we propose. The essence of strategy lies less in the knowing of mechanics of a strategic tool and more in the identifying of when this tool is to be used in contrast to others. In the natural progression of our knowledge on integration, it is time to shift our inquiry from the mechanics of "*how*" to the strategy of "*when*" integration contributes to firm value.

In terms of methodological contributions, the new process–product measures in this article hold promise in helping us measure something that has so far been elusive—process and product innovation in large samples. This article suggests that the claims in a patent may be a useful mechanism to characterize the process versus product focus of R&D activity in a firm. It enables both a measurement of the propensity to innovate in terms of process and product but may also potentially provide additional information about the actual interactions between these activities. The claims-based measures may thus capture the process–product nature of the underlying innovations more comprehensively than other measures. There has been no standard approach available to measure process and product innovation. Focusing on claims to create such a measure is a novel approach and we believe it holds great promise for accomplishing this vital research measurement. We hope to extend toward this direction in future research.

DATA AVAILABILITY STATEMENT

Research data are not shared.

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