ABSTRACT

Title of Dissertation: DEMAND-SIDE ACCOUNT ON FIRM STRATEGIES IN RESPONSE TO TECHNOLOGICAL AND REGULATORY CHANGES

Najoung Lim, Doctor of Philosophy, 2022

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The focus of my dissertation is to understand how firms adapt to a new demand environment by leveraging their vertical and horizontal scope, the change triggered by an arrival of either new technological or regulatory regime. I follow an abductive approach to understand mechanisms using both quantitative and qualitative data in the context of the medical diagnostic imaging industry.

In the first chapter, I document the process of an important technological regime change occurred in the early 1990s—standardization in medical image communication. Identifying users as an important actor, the chapter describes how the emergence of a medical image sharing platform and its underlying standard was triggered and influenced by user group's (i.e., radiologists) request for interoperability across various imaging equipment. The chapter reveals that users can actively shapes both standard-setting process and a resulting competitive landscape for firms. The second chapter examines how the emergence of the standardized open platform affects firms' product diversification, which connects pre-existing standalone products that were technologically

independent but complementary for users. Compatibility and modularization reduced the benefit of internal coordination, but also lead to an increase in end-users' heterogenous needs thanks to their ability to mix and match products, which in turn increased the benefit of internal coordination. I find the pattern of increasing product diversity in the post-standard period, which was particularly driven by the firms that became integrators to create customized systems around their platform software. The third chapter studies how and why prior differences in vertical structure affects firms' ability to adapt to sudden and exogenous decreases in demand. Exploiting a major Medicare reform that created an unexpected negative derived demand shock for imaging device manufacturers, the analysis suggests that integrated firms were more likely to exit treated markets than nonintegrated firms. Drawing on literature conceptualizing firms' vertical boundaries as a representation of existing resources and governance choices, the study explains that integrated firms with dedicated sales force were not able to shed costs associated with downstream sales functions effectively, while non-integrated firms were poised for timely reconfiguration by working closely with distributors in the locations unaffected by the shock.

Together, the three chapters acknowledge the demand-side factors as an important source of change in firms' external environment that firms (should) actively incorporate when deciding their scope of activities, which has been overlooked in the standard-setting, ecosystem, and diversification literature.

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by

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List of Abbreviations

ACR	The American College of Radiology
ACR-NEMA	The American College of Radiology—National Electrical Manufacturers Association
CT	Computed Tomography
DICOM	The Digital Imaging and Communications in Medicine
DRA	The Deficit Reduction Act of 2005
EHR	Electronic Health Records
FDA	The U.S. Food and Drug Administration
HIPAA	The Health Insurance Portability and Accountability Act of 1996
HITECH	The Health Information Technology for Economic and Clinical Health Act
ISO	The International Organization for Standardization
IT	Information Technology
MRI	Magnetic Resonance Imaging
NEMA	The National Electrical Manufacturers Association
NGO	Non-governmental Organization
PACS	Picture Archiving and Communication Systems
RBV	Resourced-based View
RSNA	The Radiological Society of North America
SPIE	The Society of Photo-Optical Instrumentation Engineers
SSO	Standard Setting Organization
TCE	Transaction Costs Economics

Introduction

Central to the inquiry of strategic management is to understand firms' constant interactions with changing external environment as an important way of gaining and sustaining their competitive advantage (Agarwal & Helfat, 2009; Porter, 1991). Firm scope—either vertical in value chain activities or horizontal in a set of products offered—is an important dimension of firm strategy that often results from firms' deliberate choice to align their activities efficiently and effectively with their external environment (Williamson, 1985). Much of the scholarly research in strategy thus has examined the relationship between firm scope and external environment, and its implication to firm performance (Chatain & Zemsky, 2007; Qian, Agarwal, & Hoetker, 2012).

Most of the previous theoretical discussion on firm scope has adopted transaction cost economics (TCE) lens and examined how transaction costs can be economized by shifting firm boundaries (Williamson, 1985). While these works assume that transaction cost is a primary deciding factor of firm scope, not all changes in external environment can be reduced to the dimension of costs associated with transactions. Changes in a technological or regulatory regime often shake up firms' competing landscape, forcing them to reconsider what activities (or transactions as in a TCE perspective) should be kept within the boundary. Firms should calibrate whether the current position represented by the scope of activities enables or limits them to cope with a new environment. Acknowledging the importance of the factors beyond transaction costs, my dissertation joins a recent conversation in the literature bridging TCE and resource-based view (RBV), and builds on the premise that firm scope is a representation of its resources and capabilities, poised for adaptation to a new environment by adjusting its boundary (Argyres, Mahoney, & Nickerson, 2019; Williamson, 1999).

While a myriad of factors comprises firms' external environment, my dissertation makes a special focus on external changes associated with the demand side. I acknowledge the demand-side factors as an important source of change in firms' external environment that firms (should) actively incorporate into their strategies. The three chapters of my dissertation highlight new theoretical and empirical insights on how firms adapt to a new demand environment by leveraging their vertical and horizontal scope, the change triggered by an arrival of either new technological or regulatory regime. Specifically, I address the following questions: What is the role of users in shaping a new technological regime? What is a firm's product breadth under a new technological regime driven by users? What implication does a firm's vertical scope have for its ability to adapt and for the ultimate market outcome when faced with an abrupt decrease in users' demand?

The empirical context of my dissertation is the medical diagnostic imaging industry. The industry includes various markets reflecting unique production technologies and user applications: X-ray, computed tomography (CT), magnetic resonance imaging (MRI), ultrasonography (Ultrasound), and nuclear medicine. On the supply side, while all medical imaging equipment serve the common purpose of internal body visualization, these technologies vary in their ability to process different properties of human tissues, resulting in images that are markedly different and often complementary to each other. On the demand side, the major buyers of imaging equipment are hospitals and independent imaging facilities. Physicians, the ultimate users of the equipment, carry unique characteristics as a professional group both with expertise in technology and power to influence purchasing decisions of hospitals. Most importantly, the industry has undergone a significant change in product architecture through the introduction of an IT platform technology which allows interoperability among different imaging equipment produced by different manufacturers. These unique characteristics of the industry enable a systematic investigation of the interplay between the changes in competitive landscape and firms' scope of activities, and thus make it an ideal context for my dissertation.

In the first chapter of my dissertation, I begin with documenting the process of an important technological regime change occurred in this industry in the early 1990s—standardization in medical image communication. The chapter identifies users as an important actor that actively shapes a technology standard-setting process and a resulting competitive landscape for equipment manufacturers. The paper describes how the emergence of a medical image sharing platform and its underlying technology standard was triggered and influenced by user group's (i.e., radiologists) request for interoperability across various imaging equipment. By theoretically adopting a demand-side perspective on standard-setting and focusing on the context where end-users are organized as a collective force, the paper examines how bargaining power of the demand side can shape firms' incentives to join a standard-setting organization and the competitive dynamics within and beyond the organization. Using qualitative evidence from online documentations, interviews, and industry journal proceedings (1981-2013), the chapter documents stylized findings that users' unmet needs can be a strong driver of technology standards setting when they become a collective institution, and firms' competition can be shaped by the users' influence. By recognizing the demand-side (i.e., users) as one of the important factors affecting a standard-setting process, this chapter complements the perspective of prior research neglecting other stakeholders beyond firms as a driving force behind the standard setting and the ultimate ecosystem design around it.

The second chapter shifts the level of analysis to firms and examines how the emergence of a standardized open platform connecting previously independent products affects firms' horizontal scope—product diversification. The context is novel in a sense that a platform software and an interface standard shifted the 'system of use' by enabling connectivity among the products that were technologically independent but complementary for users. I theoretically focus on the idea that compatibility and modularization reduced the benefit of internal coordination, but also lead to an increase in end-users' heterogenous needs thanks to their ability to mix and match products, which in turn increased the benefit of internal coordination. Following an abductive approach with quantitative and qualitative data in the U.S. medical imaging device industry (1985-2008), I find that imaging equipment firms expanded their product diversity in the post-standardized platform period. The pattern is driven by the firms that also offered a platform software, which became integrators to create customized systems with their knowledge on user preference leading to both product and product interface innovations for diversification. These findings suggest that demand heterogeneity influences firms' horizontal scope decision within an open ecosystem, which has been overlooked in the prior literature.

Lastly, the third chapter investigates the implication of vertical scope in firms' ability to adapt and eventually in the market outcome when users' demand decreases unexpectedly. Drawing on the literature conceptualizing firms' vertical boundaries as a representation of existing resources and governance choices, the paper explores theoretical reasons for potential responses by integrated and nonintegrated firms. Exploiting a major Medicare reform that created an unexpected negative derived demand shock for imaging device manufacturers, the difference-in-difference-in-difference analysis suggests that integrated firms were more likely to exit treated markets than nonintegrated firms. Using qualitative evidence, the paper finds that integrated firms with dedicated sales force were not able to shed costs associated with downstream sales functions effectively, while non-integrated firms were poised for timely reconfiguration by working closely with distributors in the locations unaffected by the shock.

Together, the three chapters shed light on how the demand-side factors can interact with firms' scope of activities configured either vertically or horizontally. Contrary to the prior literature that has focused on the supply-side and technology-push changes, my dissertation shows that users' demand heterogeneity is an important element that should be factored in the structure of firms' vertical and horizontal activities.

Chapter 1. The Role of Users in Technology Standard-setting and Ecosystem Emergence

A technology standard is adopted when economic agents benefit from harmonizing activities (Arthur, 1988; David & Greenstein, 1990). Ensuring product compatibility and interoperability, technology standards increase users' utility by creating network effects for those complying with the standards (Katz & Shapiro, 1985). Unlike markets or governmental forces driving a standardization process (e.g., Cottrell, 1994; Funk & Methe, 2001; Schilling, 2000), a standard setting organization (hereafter SSO) is a voluntary organization where stakeholders coordinate among themselves to ensure interoperability by setting agreements around technological specifications to develop open standards (Anton & Yao, 1995; Leiponen, 2008). Recognizing firms as an important stakeholder, prior research in strategic management conceptualizes SSOs as interorganizational relationships and examines firms' incentives to participate in standardization (Simcoe, 2012), firms' strategic behaviors to influence standards' contents (Jones, Leiponen, & Vasudeva, 2021; Leiponen, 2008; Ranganathan, Ghosh, & Rosenkopf, 2018; Ranganathan & Rosenkopf, 2014; Toh & Miller, 2017), and the factors explaining firms' returns from standard setting (Miller & Toh, 2020).

While firms serve important roles in SSOs as a decision-making stakeholder and a technology/complement provider (Toh & Miller, 2017; West, 2006), this paper shifts focus to another important stakeholder group that largely left unexplored in the literature—*users*. Despite the fact that standards often grow out of users' latent needs and their intended role as the eventual consumer of the standards (West, 2006), the literature has been silent about when and how users can influence the process and outcome of standard setting in SSOs. Individual users have been considered assuming a passive role as a value receiver, however, we increasingly see the rise of user groups impelling standardization, actively communicating with SSOs, or even exercising voting rights in SSOs to manifest their interests. For example, a group of American cable operators, who are the user-buyers of cable modems in their hub sites, were unsatisfied with the proprietary standards provided by cable modem manufacturers and developed an open and interoperable cable modem standard themselves which eventually became an industry-wide standard (Eisenmann, 2004). Also, communities of knowledgeable software engineers have a significant influence on standardization policies, particularly regarding open source software (Franke & Shah, 2003; Shah & Nagle, 2020). Thus, the paper particularly focuses on end-users who both purchase (or strongly influence purchasing decisions on) the implementations of standards and receive values from their use. Specifically, I examine users' roles as a trigger and a driving force behind standardization and how the outcome shaped by the users eventually affects the dimension of firms' competition.

This paper shows a particular process through which professional users have created a pervasive influence throughout the industry-wide standardization process. I describe a historical event where a special group of users were able to use their bargaining power to exert significant influence throughout the standard setting process. In this process, users' bargaining power was what triggered technology emergence/takeoff, paved the way to consensus-based standard setting in avoidance of regulatory mandate, and enabled pervasive influence of users on standardization. By drawing out emergent themes from the historical account, the paper acknowledges that users' bargaining power and thereby a strong presence along the standardization process can shape the outcome of standard setting and the subsequent firm competition within an ecosystem in important ways (Adner & Snow, 2010; Rietveld & Eggers, 2018). Since users bear the cost of inefficiency arising from the coexistence of multiple standards and incompatibility between different systems, they have strong incentives to undertake action aimed at "forcing" the market to move towards greater compatibility between products and integrated systems (Foray, 1994). Communicating their needs collectively can create bargaining power over manufacturers to initiate and push the standard setting process forward. Their knowledge on how a standard should also be applied to actual implementations can provide necessary feedback for writing specification of the standard (von Hippel, 1986). Furthermore, their preference towards compatibility can expedite adoption of an open standard by the industry participants, which further put firms on the verge of reevaluating the dimensions of product competition.

The context is the medical diagnostic imaging industry, where the emergence of a platform and its underlying standard setting process were triggered and influenced by user community's request for interoperability across products. The medical diagnostic imaging industry is composed of five different imaging technological subfields (X-ray, computed tomography (CT), magnetic resonance imaging (MRI), ultrasonography, and nuclear medicine), and a platform technology called Picture Archiving and Communication System (PACS) on which the electronic medical images taken from different imaging equipment are stored, transmitted, and displayed to end users (radiologists and physicians) for patient diagnosis. The PACS and its underlying communication standard, the Digital Imaging and Communications in Medicine (DICOM), have both risen to address users' needs for interoperability among various imaging equipment. The standard setting organization comprises both the members of user and manufacturer associations having an equal footing on the decision-making process. The demand side of the industry is characterized by a number of large research hospitals having bargaining power over the purchase of medical equipment and the professional end-users organized as a collective force. In addition, on the supply-side, technological knowledge are evenly dispersed among participating firms without a clear platform leader. The absence of a strong platform leader that has control over other participating firms provides the case where the effect of users' heterogeneous demand can be amplified (Gulati, Puranam, & Tushman, 2012; Miller & Toh, 2020; Ranganathan et al., 2018). Therefore, the context is ideal to unpack the resolution of demand-side problems as a driving force behind the standard setting and how users can shape the competitive dynamics of platform ecosystem.

The paper draws on a single case study (Siggelkow, 2007). I rely on archival documents, trade journal articles, and interviews with key individuals served on the standard setting committee. After laying out theoretical background on standard-setting organizations, I document a historical account on how PACS emerged and the DICOM was set via a SSO called the DICOM committee. Building on the unique characteristics of the medical diagnostic imaging industry, I provide descriptions on how users imposed a significant influence on standard setting and how their presence further affected participating firms' strategies to achieve competitive advantage in an ecosystem. The paper then presents a revised framework for the standard setting process.

Embracing the peculiarities of the setting, the descriptive case study discusses several interesting findings emerged from the narrative. First, the paper documents how the end-users who were otherwise dispersed were able to create a collective force by leveraging their professional association and highly regulated nature of the industry.

When users are organized as a collective force, leveraging their bargaining power can spark and drive a standard setting process to address users' unmet needs. Communicating their needs as a collective force can invoke firms' coordination for a greater value proposition to customers. Second, standard-setting led by both users and firms resulted in industry-wide participation in expanding an open platform ecosystem. While manufacturing firms were reluctant toward standardization of technical architecture as their potential for proprietary benefits significantly decreases by an open standard, the user community strongly expressed its preference towards the interoperable products by leveraging their bargaining power. Third, after joining the open standard, firms eventually competed by actively incorporating heterogenous user demand into their product and service offerings. Firms competed on non-standardized factors on top of the open standard such as customer service and upgrade, integration with greater hospital IT system, functionalities such as image quality, speed, user interface, as well as different combinations of them. Overall, the paper describes the process through which the users were able to gain their bargaining power and exert influence on the industry-wide standardization process.

The paper contributes to several literature streams. First, it recognizes the demand side (i.e., users) as one of the important factors defining standards and resulting ecosystem architecture. While the previous work has not paid attention to demand characteristics except that users prefer ecosystems with greater compatibility and more complements (Katz & Shapiro, 1985), I relax the assumption of users' passive role in standardization and the homogeneity in demand and theoretically adopt a demand-side perspective on the standard setting process. Second, the paper contributes to the recent calling in ecosystem literature to further our understanding of how a set of common "rules" of interoperability emerges in the absence of hierarchical force and how it is shaped by divergent factors. Third, while user unmet need have been introduced as one of the important triggers of industry incubation and evolution (Agarwal, Moeen, & Shah, 2017), less understood is the process initiated by a systematic effort of an institutional user group beyond a single or a few knowledgeable users. Acknowledging that user communities have not attracted much attention from management literature (Shah & Nagle, 2020), the paper reveals their key strategic implications to the industry and firms' competitive landscape.

Theoretical Background

Technology Standard and Standard-setting Organization (SSO)

A standard can be defined broadly as a consensus of different agents to do certain key activities according to agreed-upon rules (Farrell & Saloner, 1992). While there are several kinds of standards—reference, minimum quality, and compatibility standards (David, 1987), here I focus on an interface or compatibility standard which is a set of technical specifications adhered to by a producer so that users are assured of compatibility across products provided by different suppliers (David & Greenstein, 1990; Farrell & Saloner, 1992). A product that conforms to an interface standard can serve as a component or subsystem for a larger system, which is built from numerous components that are provided by different firms conforming to the same standard (David & Greenstein, 1990). Standards ensuring product compatibility and interoperability become common rules for interdependent technologies and a prerequisite for generating network effects.

Several important benefits of standardization feed back into the industry participants' incentive to develop standards. Customers benefit from a direct network externalities in that one consumer's value for a good increases when another consumer has a compatible good, as in the case of telephones or computer software (Katz & Shapiro, 1985). Benefits also arise from complementary goods becoming cheaper and more readily available as the size of the compatible market expands (Katz & Shapiro, 1985). Producers can also benefit from making their products compatible since standardization allows them to get inputs with lower costs by exploiting economies of scale in production of the inputs. Standards increase market efficiency by lowering transaction costs (Kindleberger, 1982) and expedites technology adoption (Baron & Schmidt, 2019). Since technological innovation requires to achieve interoperability between different technological components (Arthur, 1988), a need for coordination for technology development also triggers standards development (Leiponen, 2008; Toh & Miller, 2017). Standards ensuring product compatibility and interoperability become common rules for interdependent technologies and a prerequisite for generating network effects.

Standards may arise in several ways. Standardization is a process aimed to resolve situations where involved actors prefer a common solution to a problem but have not yet agreed which option to choose (Farrell & Saloner, 1988). To establish a common solution, standardization requires coordination among actors by developing solutions which are later implemented by all of them (Farrell & Saloner, 1988; Narayanan & Chen, 2012; Wiegmann, de Vries, & Blind, 2017). Literature has documented how standards are set by three different modes—markets, governments, and voluntary arrangements called standard setting organizations (SSOs) (Narayanan & Chen, 2012; Wiegmann et al., 2017).

Market-based standardization entails competition between solutions developed by anyone in the market, and individual market actors pursuing a private benefit can engage in the market to influence the standard battle (Schilling, 2002). Firms can orchestrate a new platform and gain power in it by collecting complementary firms around its own standard (Gawer & Cusumano, 2002). Government-based standardization is driven by governmental bodies using their hierarchical position to develop standards and/or impose their use on others (Borraz, 2007; Pelkmans, 2001). Unlike these two modes, standardization via SSOs pursues coordination through cooperation between stakeholders during standard development (Farrell & Saloner, 1988).

The focus of this paper is particularly on the standard setting via SSOs. Since different options are proposed and evaluated before a standard is approved and diffused, engaging in explicit coordination activity within SSOs becomes an important avenue to influence the contents and diffusion of standards (Jain, 2012; Wiegmann et al., 2017). Membership is clearly defined, and the members' roles and responsibilities are well documented for the communication purpose. It is therefore a suitable setting to understand the influence of different participating stakeholders on the standard setting process.

Standard-setting Process Orchestrated by Firms in SSOs

A voluntary arrangement for standard setting is often created by the industry participants who intend to develop and disseminate technology standards. While any interested stakeholder can join these committees making the process 'inclusive' (Botzem and Dobusch, 2012), the actors in the private sector often dominate committees, leading the literature to focus particularly on the role of firms in SSOs.

Prior work has examined firms' private incentives to participate in SSOs (Büthe & Mattli, 2010; Jakobs, Procter, & Williams, 2001; Kang & Bekkers, 2015; West, 2006). Since producers can provide technical expertise necessary to write standards, standards are often vulnerable to be captured by large producer interests. Thus, major vendors rather than users or minor suppliers are likely to dominate voluntary standard setting bodies, as they see an advantage in securing their market position or in undertaking the background R&D. Also, coalitions of existing producers can use voluntary standard setting processes to issue product specifications that impose cost burdens upon current or potential rivals. In fact, many standards are often created by groups of firms united in competing against a proprietary standard to avoid being shut out of the market (Grindley, 1995).

Studies has also documented how the emergence of standards is orchestrated by the private actors (Botzem & Dobusch, 2012). SSOs can serve as tools for firms to engage in strategic behaviors, where firms make efforts to shape the standard setting process in a way that favors their own position and thus increases their power in the resulting ecosystem (Gawer & Cusumano, 2002; Jones et al., 2021; Ranganathan et al., 2018). Firms often attempt to win acceptance of their technologies to be on standards to control direction of the standard implementation and earn a stream of proprietary rents (Gawer & Cusumano, 2002; West & Dedrick, 2000). Firms can also forge interorganizational relationships within SSOs and gain technological knowledge from other participating firms (Fleming & Waguespack, 2007; Vasudeva, Alexander, & Jones, 2015).

How standards are being set has significant implications for firms' competition and power in resulting ecosystems (Anton & Yao, 1995). Issues of interoperability are crucial elements of soft regulation with significant implications for power and equity in the ecosystem. Since the alignment structure dictates technological and strategic interdependence among firms, it further affects the potential for future innovations and competitive advantages of firms (Marion, Meyer, & Barczak, 2015; Vakili, 2016; Wakke, Blind, & Ramel, 2016). It further affects firms' competition including licensing of technologies (Chiao, Lerner, & Tirole, 2007), alliances beyond SSOs. In complementary product space, the standard setting process can have a lingering effects on returns to other complementary innovations (Miller & Toh, 2020) or complementary product competition.

The typical standard-setting process is displayed in Figure 1-1. When a technology rises and needs a compatible standard as it develops, the standard setting process begins. Usually, an SSO defines its scope by translating the technology into a complete specification. Specification for the standardized technology does not provide interoperability until an implementation is made available to end users. Vendors offer their own individual implementations as well as complementary products. The products are eventually adopted and used by the end-users.

[Insert Figure 1-1 here]

Role of Users in Standard Setting

Both theoretically and empirically, major producers in the industry are often considered as dominating and controlling standard setting processes, in the absence of users during the process. However, standardization hardly happens in isolation from the ultimate end-users of the standards. The actual end-users bear the costs of inefficiency resulting from the coexistence of multiple standards and incompatibility between different systems.

Users therefore have incentives to undertake action aimed at "forcing" the market to move towards greater compatibility between products and integrated systems (Foray, 1994). Users also possess specific knowledge required for local application of a standard, providing necessary feedback for writing specification of the standard (von Hippel, 1986).

In fact, users' unmet needs often become foundation for standard setting. In 1904, when there was a big fire in Baltimore which burnt more than 1,500 buildings, fire fighters rushed down from New York and Philadelphia to assist had to stand idly by and watch the fire ravaging more than 70 blocks of the city are. It was due to incompatibility of fire-hosing couplings—their hoses did not fit Baltimore hydrants due to the difference in diameters and hose connections (Seck & Evans, 2004). Soon after, efforts immediately began for selecting a national standard for the shape of and size of the fire hydrants connections, resulting in the one that we see now on the street (Seck & Evans, 2004). This exemplifies users' needs as an important trigger for the development of interoperability standards.

In addition, while individual users are often considered assuming a passive role as a value receiver, we increasingly see user groups also present in SSOs and participate as voting members to manifest their interests. For example, the International Organization for Standardization (ISO), which is a global federation of national standards bodies, explicitly described its key principles in ISO standard development as "the technical committees are made up of experts from the relevant industry, but also from consumer associations, academia, NGOs and government" ("ISO," n.d.). Especially, the U.S. cable operators, a consumer group unsatisfied with the proprietary standards offered by cable modem suppliers developed a standard by themselves which eventually gained its position as a global standard (Eisenmann, 2004). Also, communities of knowledgeable software engineers have a significant influence on standardization policies, particularly regarding open source software (Franke & Shah, 2003; Shah & Nagle, 2020).

Despite the importance of users in a standardization process, there is scarce research on the role of users in technology standard setting. While prior studies on SSOs have yielded many useful insights from producers' perspective, it remains largely unexplored where and how the users affect standard setting and how their influence further reach the competitive landscape within the resulting ecosystem. Since different stakeholders assign different priorities, it is important to understand how a process of coordination and resulting outcomes are shaped by different members in SSOs. Notable exceptions are the work in accounting literature on financial analysts and institutional investors' participation in accounting standard setting (e.g., Durocher, Fortin, & Côté, 2007; Tandy & Wilburn, 1996)—however, these studies focus on the development of a quality standard, not a technological interoperability standard.

To address this gap, the paper examines the emergence of a platform and its underlying standard setting process which was triggered and influenced by user community's request for interoperability across products. By focusing on the context where the end-users are organized as a collective force, the paper examines how the bargaining power of the demand side can shape the competitive dynamics of platform ecosystem. The paper takes a research question-based approach and ask: *How may users influence the standard setting process and outcomes?* Within this broad research question, I specifically seek to answer three inter-related questions: *How can users trigger a standard setting process? What influence do they exert on firms' incentives to participate in an open standard?* And *what effect may they have on post-standard firm competition?*

Research Context and Method

The nature of the research question suggests the use of case study methodology and the qualitative evidence to examine the phenomenon of interest (Eisenhardt, 1989; Siggelkow, 2007). In particular, my research strategy is focused on detailing the sequence of events and participating actors that contributed to the standard development. The intent is to cut deeply into the specifics of a time and place and trace the underlying factors that affect both the process of outcome of standard setting.

The phenomenon of interest is the standardization in medical image communication in the medical diagnostic imaging industry. Particularly, I look at the emergence of a medical IT platform and its underlying standard which are used for the transfer, storage, and display of patients' image scans taken from various imaging equipment. This setting is suitable to examine for several reasons. First, unlike other IT standardization which is mostly dominated by IT vendors and where users are largely under-represented (Jakobs et al., 2001), the user group (radiologists' association) in this setting played a critical role throughout the standardization process. Second, the actions of important actors, such as platform/complement providers and more importantly users, are easily identifiable and observable in this industry. Third, the standard was set in 1993 and it was apparent early on that the standard would be adopted industry-wide and be a critical element to the functioning of this industry.

I collected data for the period of 25+ years beginning with the invention of large scale PACS in 1982. The data collection involves integrating information from different sources using multiple methods to ensure the reliability and validity of findings (See Table 1-1). The primary source is archival data including trade journal articles (1,625 articles), meeting minutes of the standard-setting committee (50 documents), books written by industry experts, business publications, websites, and other corporate materials. I also conducted in-depth semi-structured interviews with 7 individuals who were involved in establishing the standard, and additionally collected a second-hand interview transcript of two individuals who were also the members of the standard committee. I used the list of conference participants and standard-setting committee members as my initial contact for interviews. Between March 2021 to May 2021, I conducted virtual interviews with 4 informants who were current/former executives of imaging equipment manufacturers and 3 informants who worked at academic hospitals either as a radiologist or a nuclear medicine physicist. Five of them actively participated in the standard-setting committee. The semi-structured interviews ranged from 40 to 60 minutes in length and were recorded separately.

[Insert Table 1-1 here]

I begin by documenting a case history using the collected data and develop a narrative account that traced the flow of events key to the emergence and evolution of the medical image communication standard. In developing the narrative, I remained cognizant of the theoretical issues and constructs emerged from the data. The themes in turn guided further data collection and the process of iteration between theory and data continued until the emerging theoretical account adequately captures the narrative and latent generative mechanisms were identified and specified. In the Discussion and Conclusion section, the emerging theoretical insights are compared with existing literature to identify similarities and differences.

Overview of the Medical Diagnostic Imaging Industry

The medical diagnostic imaging industry is composed of the five different imaging technologies—X-ray, computed tomography (CT), magnetic resonance imaging (MRI), ultrasonography, and nuclear medicine—and a platform technology called Picture Archiving and Communication System (PACS) on which the images taken from different imaging equipment are stored, transmitted, and displayed to end users, physicians. While all imaging equipment serve the same general purpose of internal body visualization, equipment built on different underlying technologies are significantly differ in their ability to process different parts of human body. Thus, each type of image equipment provides complementary information to one another that ultimately help physicians make a timely and right diagnosis for patients.

On the demand side, hospitals and imaging centers are the key buyers of imaging equipment. Hospitals often engage in capital investment plans deciding a combination of various imaging equipment to be purchased and installed in hospital sites. Since all imaging equipment markets cater to the same customer base, several major vendors in the market are often diversified across several imaging product markets to offer one-stop shopping to these end customers. However, because imaging equipment are expensive in price ranging from USD 10,000 to over 1 million, and device manufacturers sell only a few to tens of thousands a year, users often exert greater bargaining power over device manufacturers.

The ultimate users are physicians working at hospitals, who decide and make orders for which equipment to be used for a patient's diagnosis. While patients also benefit from the use of imaging equipment, they do not have discretionary control over the use of machine which leaves them to assume a passive role as beneficiaries.

Therefore, I confine the definition of users only to physicians and radiologists for the purpose of this paper. Physicians and radiologists in large academic hospitals are often affiliated with research universities and have strong influence on the purchasing decisions of hospitals' capital investment in imaging equipment, of which the costs range from USD 10,000 to over 1 million. While users are often fragmented and dispersed, radiologists who themselves are professional users with technological and market-related expertise have formed an industry association to promote academic interactions and to protect their interests against other stakeholders.

The Digital Imaging and Communications in Medicine (DICOM) is a world-wide standard for medical image file format, which establishes a network communications protocol and a definition for a rich set of metadata on patients and images taken. The standard enables electronic images taken from one medical imaging equipment to be transmitted to another, or to a PACS workstation where physicians can pull out several images of a patient taken from different imaging devices. For example, CT scanners, MRI machines, film digitizers, shared archives, laser printers, and host computers made by multiple vendors and located at one or many sites can "talk to one another" by means of DICOM across an open-system network (Tong, 2008:7). As a result, medical images are communicated more quickly, and physicians can make diagnoses faster and better using complementary medical information provided by the various equipment.

The U.S. medical device industry is highly regulated by the federal government. To promote patient safety, the U.S. Food and Drug Administration (FDA) imposes significant control over the design, specification, and quality of medical products being marketed by device manufacturers. While the FDA often forces market participants to conform to its regulations such as premarket approval for new product commercialization, the agency also supports development and use of voluntary consensus standards for emerging products and technologies to promote efficiencies and lessen regulatory burdens.[1] Consensus standards contribute to regulatory quality because consensus-based SDOs must demonstrate adherence to the tenets of transparency, openness to participation by interested stakeholders, balance of representation, and due process, among other principles.

The timeline of the events in the PACS emergence and the DICOM standard setting is illustrated in Figure 1-2. The DICOM standard setting committee was launched in 1983 quickly after the first large-scale installation of PACS in 1982. The first two resulting standards that came out in 1985 and 1988 respectively were still at alpha version since they were not yet communication network standards enabling large-scale multiuser transmissions but only worked for point-to-point transmission between two devices. The third and final standard was released in 1993, which eventually given its name the DICOM, finally enables open system interconnection of imaging equipment over networks while maintaining compatibility with earlier standards.

[Insert Figure 1-2 here]

Findings

User Group's Bargaining Power as a Driver for Standard-setting

PACS was born out of users' innovation. The concept of digital image communication and digital radiology was first introduced in a 1979 report by Dr. Heinz U. Lemke, a professor of computer graphics and computer-assisted medicine (Lemke, 1979). The

[1] https://www.fda.gov/medical-devices/premarket-submissions-selecting-and-preparing-correct-submission/standards-and-conformity-assessment-program

latent needs for interoperability across medical equipment rise to the surface in a form of the idea of using computer networks to move digital images around instead of printing them on film. Sparked by the rise of the Internet and the newly developed imaging technologies that generate digitally formatted images (i.e., CT and MRI), there were several PACS precursors in the 1970s and 1980s at universities, hospitals, and research facilities around the world. Throughout the mid-1980s, pioneering radiologists began building homegrown prototype PACS systems in their affiliated academic hospitals (Matthews, 2005). For example, in the early 1980s at the University of Pennsylvania, the radiology department had done developmental work in digital angiography that captured images with digitizers, sent the images over a self-built network to a computer, and sent them back to the angiography suite (Matthews, 2005). At UCLA, a newly formed medical imaging division under the radiology department worked on building a homegrown PACS in 1989 to 1991 which made use of early color monitors and digitized X-ray scanners to display images on the PACS monitors (Matthews, 2005). Such experience "gave [users] a lot of experience in capture, archiving and transmission," letting users accumulate technical knowledge around equipment connections and interfaces (Matthews, 2005).

Such effort, however, was limited to simple point-to-point wiring between the same type of equipment and with monitors. Abound with technical knowledge and experience around building prototype PACS, physicians knew exactly what they needed: *interoperability* across equipment. Since each equipment was purchased separately from a different vendor each year, various types of equipment were used in the institutions. While medical physicists had to be able to exchange data because they needed to compare different radiation treatment plans, they seriously lacked ability in transmitting and sharing images from different imaging equipment without a standardized protocol. Given the complementary role each imaging technology serves to end users, it significantly harmed doctors' ability to make timely diagnoses for patients because of the extended amount time and effort it took to share images.

The most significant problem hampering the free communication was that image information obtained from equipment could be modified or handled only by the manufacturer of the equipment. Magnetic tape, which was a typical way of imaging acquisition at that time, was problematic because recording on them required an understanding of the tape format and pixel packing technique which was proprietary to manufacturers that they were often not willing to reveal. A radiologist gave a testimony on such difficulties that the medical community was facing:

> [Equipment manufacturers] did not want the competitors being able to read the [digital] tapes. Even the reconstructions were proprietary…I had been in the trenches trying to read tapes, and I thought if we were ever going to make PACS possible, we had to get away from the proprietary stuff (Matthews, 2005).

Acknowledging the obstacle that physicians faced, Andre Duerinckx and Samuel J. Dwyer III, who were then electrical engineers working on digital imaging, organized the first international PACS conference in 1982 to spark discussion around PACS development, as part of the Society of Photo-Optical Instrumentation Engineers (SPIE) Conference (Matthews, 2005). The term "PACS" did not exist until then, but the concept began to be widely used and recognized by radiologists, academic researchers, and vendor representatives who were present at this PACS conference.

The foremost emphasis made at the first SPIE PACS meeting was on the need for standard (Honeyman-Buck, 2008). The transcript of the panel discussion at the conference documents the medical community's identification of the problem that "PACS means communication," but "the standardization of the information itself, the procedures between different departments, [was] a tremendous problem," which "require[d] protocol standardization to send those images" (Glenn et al., 1982). Doctors began to write in trade magazines that the community as a whole needed a common standard to facilitate communication between different devices, as "standardization of image formats would help radiologist compare a patient's ultrasound, nuclear medicine or CT images before deciding to acquire additional examinations" (Dwyer et al., 1982, p. 317), and "an integrated image, multiuser system could reduce the time patients spend waiting for examinations and would reduce the physician's time in acquiring the most thorough patient consultation" (Dwyer et al., 1982, p. 318). The radiologist community's call for standardization brought the American College of Radiology (ACR), the industry association of the user group, to actively seek for a solution to this problem.

In the beginning, equipment manufacturers were highly reluctant towards an open standard despite the clear request made by the radiologist community for the interface standardization. Firms were concerned about losing potential for a proprietary lock-in benefit which was possible by making their equipment compatible only with their own products. For example, "there was no way that Siemens would ever make [an open] standard format to output from their equipment because they would lose lock-in," as evidenced by one of the interviewees. The divergent views between manufacturers and radiologists were also evident from the discussions made at the first SPIE PACS conference (Wake et al., 1982). The equipment manufacturers strongly voiced that:

[Standardization] will hurt us.

How can I have a competitive advantage?

It is going to be a deterrent to innovation.

The ACR, however, constantly compelled the manufacturers to join forces in creating an open technology standard. The user group had both incentives and ability to persuade the manufacturers, since the open standard to be set by the users was guaranteed from the onset its legitimacy, wide adoption, and therefore a large market for complementary products around the standard. Having a close relationship with manufacturers, the user group made strong appeals to the manufacturers about their immediate needs for interoperability. The Food and Drug Administration moderated the conversation and paved a way to a standard setting by leaving a choice for the manufacturers' association, the National Electrical Manufacturers Association (NEMA), between making the standard an FDA-enforced mandatory versus a voluntary one. A committee member from explained:

> The FDA said, 'The radiology community is yelling and screaming about not being able to get images out in a standard format. You need to do something about this.' What was said by the FDA was we can do [standardization] in two ways: we can make this a voluntary standard, or you have to do this to be FDA compliant. The vendors know what that's like—if you have to do something for the FDA, there is an awful lot of red tape you have to deal with. They said, 'If it's a voluntary standard, we adhere to it.'

With the help of the FDA, radiologists finally had the NEMA to agree to codevelop an interoperability standard (Matthews, 2005). The joint standard committee called the ACR-NEMA DICOM Committee kicked off in 1982 to develop an open industry standard on the communication of digital image information. The minute of the first committee meeting explicitly documents the purpose of this joint committee:

> The purpose of this committee shall be to establish a stable, effective and mutually beneficial working relationship between NEMA and the ACR with respect to the development of certain digital communication standards. The Committee shall establish standards which will (1) promote ease of communication of digital radiologic image information regardless of source or time of manufacture; (2) facilitate the development of PACS objectives in radiology departments; and (3) allow constitution of information networks in Radiology.

All of the accounts above explicate the importance of users' unmet needs and their collective efforts in the spark of standard setting. In this particular case, the otherwise diffused radiologists were able to create bargaining power by leveraging their industry association. As opposed to in other industries, the highly regulated nature of the medical device industry also allowed customers to exert influence in bringing manufacturers to the table. It can be an important impetus and a strong driver for a standard setting process, when users can form a collective force as an institution.

Standard-setting Process Led by Both Users and Firms

Unlike other IT standardization committees dominated by vendors and service providers, the DICOM Committee was represented by both manufacturer and user groups. The members were assigned to one of the three interest groups—(i) producers, (ii) users, and (iii) general interest. The resulting structure of the DICOM standard-setting committee included two co-chairs each representing producer and user groups, and working groups each focusing on the subspecialties of the standard. Figure 1-3 is excerpted from the meeting minute of the first ACR-NEMA meeting on standard setting, which displays the example of members participated in the committee. This structure enabled the committee to solicit and incorporate inputs from both manufacturers and users. NEMA, representing the diagnostic imaging equipment manufacturers, served similar roles that typical vendor participants in SSOs would take, such as development of proposed image data format, proposed electrical/protocol standard connection, and proposal to define and analyze gateways between other medical information systems (Horii, 2005). The ACR, on the other hand, "focused its efforts on defining the needs and rationale, i.e., 'what do radiologists want?'" (Horii, 2005). One of the interviewees emphasized the value of having users with knowledge about where a technology is applied and how it is used:

> We have the working groups with people who are domain experts. They are definitely not standard writing experts. What they are expert in is how we generate these images, how we use them, and what is important to the clinicians. The dermatology people say, 'Color is important. We really need something to standardize at least how you

> represent color.' So, we can do that. Pathology has the same way. You stain things, and stains and colors of the cells are important. So, we had some color performance [feature] in [the standard].

[Insert Figure 1-3 here]

While the openness of standards is often an important dimension to be determined through a lengthy process of negotiation and voting among the SSO members, the openness of the DICOM was a premise on which the committee embarked on from the very beginning. Commitment to the openness was shared by both users and manufacturers, as explained by the committee members from each side:

> The goal [for the standard] since day one was to be very open. The DICOM standard has always been free. Yes, there is a copyright from NEMA, but it has always been freely available to all the people—all the vendors and the users that want to understand or implement DICOM. That was an early goal right away. The reason for that was we wanted DICOM to be international worldwide, and we did not want it to be secular and limited to just certain situations. That was always the goal (User-side member of the committee).

> The DICOM Committee was meeting on the basis of that they were not going to use any patented technology. The DICOM standard should be free, there should not be any royalties to any company… Compression was an important technology especially for large images, and [our company] had a lot of compression patents. It was when there was a little bit of discussion about whether [the company] would

> grant permission to the DICOM Committee to use free of charge [which it eventually granted]. It was a very unusual group of people who were not pushing their own company (Producer-side member of the committee).

The standard development followed the iterative processes of proposal, evaluation, and voting. The openness on which everyone agreed early on was not just about the access to the standard but also about the process in which the standard should be developed. Once working groups prepared a draft, it went through a public comment period. Anyone even not on the committee could provide feedback on whether it fits with the way they work in the real world. After it went through the public comment, the working group members examined the feedback and made suggestions for corrections. Finally, the draft was voted on, and when approved, it became part of the official standard. Competition was limited, but rather the developmental process was highly cooperative. One committee member explained that "there were disagreements, but that was the whole idea behind having the working groups and [disagreements] were relatively small. You could generally resolve these things pretty quickly." A member of the committee described this inclusiveness of the process:

> A key to the adoption of DICOM is that it is completely open. Not just the major multinational corporations but even a single academic or a single small company engineer could participate in the standardization process. Their opinion was listened to just as much as... it was a merit-based organization, if you like, rather than a political organization. There were small companies that specialized in

> this interoperability field, and those little companies provided a lot of the expertise. Because DICOM was open to participate in, open to get hold of, anybody who wanted it could get a copy of it. Initially there was a small charge just to cover publication, but now, of course, it is completely free and open.

Although the standard committee was influential in the medical imaging community, many of the imaging equipment manufacturers were slow to respond and comply with the DICOM standard in the early period (Tong, 2008). However, since the markets for advanced imaging equipment were small and highly conservative, users could leverage their tight relationships with manufacturers and the bargaining power over expensive equipment to strongly express their preference towards the products enabling interoperability. Three producer-side members each provided testimonies on how user groups had threatened the vendors to adopt the DICOM standard:

> The market forced us to make it compatible.

> We're going to write a requirement for DICOM into all of our purchase agreements. The vendors will have a choice: either they have DICOM and bid on the sale, or sorry, we are not going to buy from them. That was very powerful.

> It was not the vendors agreeing to do this, it was the customers saying, 'No, I demand that this have the standard interface on it, or I'm not going to buy it.' They had a lot of bargaining power and because hospitals in the U.S. by and large do what each one wants to

> do independently. Except for a few big chains in those days, every hospital was doing its own thing.

After the first live demonstration of the DICOM interface at the industry conference called the Radiological Society of North America (RSNA) in 1993, five out of six major vendors elected to participate in it and demonstrate their early implementations. The sixth one, who was a major medical device vendor, chose not to participate because they had developed their own standard that they wanted people to use. But soon after when the hold-out vendor had joined the mainstream and agreed to implement the DICOM, the standard had its take-off with all the major vendors on board.

In summary, the users in this setting were able to gather their voice on the preference for adopting the open standard either at the standard setting committee through the radiologists' association (ACR) or at the professional conference (RSNA). Such collective opinion was able to lead the manufacturers to finally adopt the open standard and eventually participate in an expanding open platform ecosystem.

Firms' Competition in Post-Standard Period

As the standard became widely accepted, the manufacturers took a cooperative manner and began to develop new versions of software and equipment based on the DICOM standard (Tong, 2008). The PACS industry slowly started to witness implementations of large-scale PACS with the DICOM standard, most of them initiated by university hospitals and by research laboratories of major imaging manufacturers (Huang, 2004). The implementation model in the early period involved a multidisciplinary team assembled by the radiology department in the hospital which became a system integrator and selected components from various manufacturers. The team developed interfaces and wrote the PACS software tailored to the clinical environment of the hospital. The system developed became one of a kind, consisting of components from different manufacturers. This model later transitioned into a partnership wherein a hospital forms a partnership with a selected manufacturer, which is responsible for its PACS implementation, maintenance, service, training, and upgrading (Huang, 2004). Manufacturers had to learn about the heterogenous demand at different institutions, since they each had different flows of work. Both of the two former executives who each worked at the major imaging equipment manufacturers explained:

> My duty at that time was to talk especially to radiologist… in Canada, US, and Europe, ask them what they would like to have, what they need, what they would be able to compromise because the technique as not sufficient enough. That was existing in much different because people are different. … it was just about the technique, but even it was hard to understand radiologist and his special needs… It was very helpful to have many small projects because the requirements we have are much different.

> PACS is not just this configuration of hard and software, it includes the science or the knowledge of the behavior how a radiologist and assistants, how they work. It all has to come together, become routine.

Firms eventually began to compete by actively incorporating heterogenous user demand for implementations of their products. They competed on non-standardized factors on top of the open standard, for example, on the functionalities such as image quality, speed, user interface, and integration with greater hospital IT system. Since PACS is a system that involves both the platform software and various services associated with it, the PACS companies differentiated in the clinical applications on their PACS workstations, such as memory repository of the system or user interfaces for displaying and manipulating images. Customers required superior and easy-to-use functionalities catering to the requirements and tastes of radiologists, healthcare provider, and technologists who generate the images. Workflow management was crucial, such as how many times a user should click on to get to the display of an image or dictate report, how a user goes from scheduling to interpretation when a scan is ordered. Applications could also come with different combinations, such as integrating reporting with viewing, or adding a certain compression method versus not. The possibility of different configurations allowed negotiation between the hospitals and the manufacturers. For example, one vendor could approach to say it could support certain features with better performance or the ones that competitors did not support. The chosen combination of applications was implemented as a project in which the PACS company connected applications to and integrated with the existing hospital IT system as well as across different imaging equipment. A radiologist described how the manufacturers added such proprietary features to both the PACS system and their imaging equipment, for which the radiologists sometimes had to devise a way to circumvent the restricted access:

> Definitely there was some advantage to having all your equipment from a single vendor, because there was proprietary stuff in there and because the vendors were doing things that had not yet been

> standardized in DICOM. Primarily, [vendors say] 'We have some new imaging sequences in MRI, and they are not yet supported in DICOM. If you buy our equipment, our PACS will support that method.' That is decreasing steadily but we still have it…We have had situations where the vendors put stuff in proprietary elements that are supposed to be in part of the standard… We had a problem for a while with radiation dose. For CT machines, you have to report the rate. For a while, the vendors put that [information] from proprietary fields so you could not get [access] to it. What we wound up doing is one of my colleagues, she and a couple of medical students, basically did a screen capture.

Differentiating factors also included customer service and upgrades *after* implementation. Customer service post-installation was one of the most important factors that users cared about since large-scale information systems often required constant technical maintenance and upgrades. For example, one executive from a PACS company explained that "for an IT system, [they had] to work with the customer all the time even after the sale," and that "every employee at [his firm had] to make five or more customer visits per year." Some of the large companies failed to understand the importance of post-sale upgrades and simply assumed that they would sell a new system after several years. Not being able to keep up with development, they had to withdraw their PACS buisness. The interviewee added, "they learned it a hard way that customers would not buy from them just because they are big."

In summary, equipment manufacturers in post-standardization period had to participate in an open ecosystem where their products could now be interoperable with other firms' equipment. With the new competitive landscape they faced, firms competed by adding features on top of the standards and sought ways to differentiate against other firms. Successful firms were those that were better able to implement catering to the needs of the end-users. Thus, firms participating in an open ecosystem compete by adding features on top of standardized specifications by leveraging their access to users' heterogeneous demand.

Discussion and Conclusion

The descriptive case study reveals several interesting emergent themes. First, when users are organized as a collective force, leveraging their bargaining power can result in firms' coordination for a greater value proposition to customers. Second, while manufacturing firms may be reluctant toward standardization of technical architecture as their potential for proprietary value appropriation significantly decreases, the institutional user group can compel them to join forces in creating an open technology standard as well as expanding the open platform ecosystem. Leveraging its bargaining power, the user community can strongly express its preference towards the products enabling interoperability. Third, firms collaborating and joining the open standard can compete by actively incorporating heterogenous user demand. Firms can add non-standardized features and applications on top of the open standard such as workflow management, customer service and upgrade, integration with greater hospital IT system, image quality and speed, user interface, as well as different combinations of them.

Such findings supplement prior research on the triggers, the process, and the outcome of standard-setting organizations. Prior work has emphasized that the need for coordination for technology development, innovation, and adoption (Baron & Schmidt, 2019; Leiponen, 2008; Toh & Miller, 2017), the government push for public benefit (Pelkmans, 2001), and firms' competitive motive for ruling out a dominant player can be important triggers behind technology standardization. The assumption was that firms dominate the standard setting process from writing a technology into specification and implementing the standard. However, findings of this paper suggests that users can contribute and actively engage in throughout the entire standard setting process—from the invention of a technology, the specification of technological standards and the implementations of them, to the adoption and use of the implementations, as described in Figure 1-4.

[Insert Figure 1-4 here]

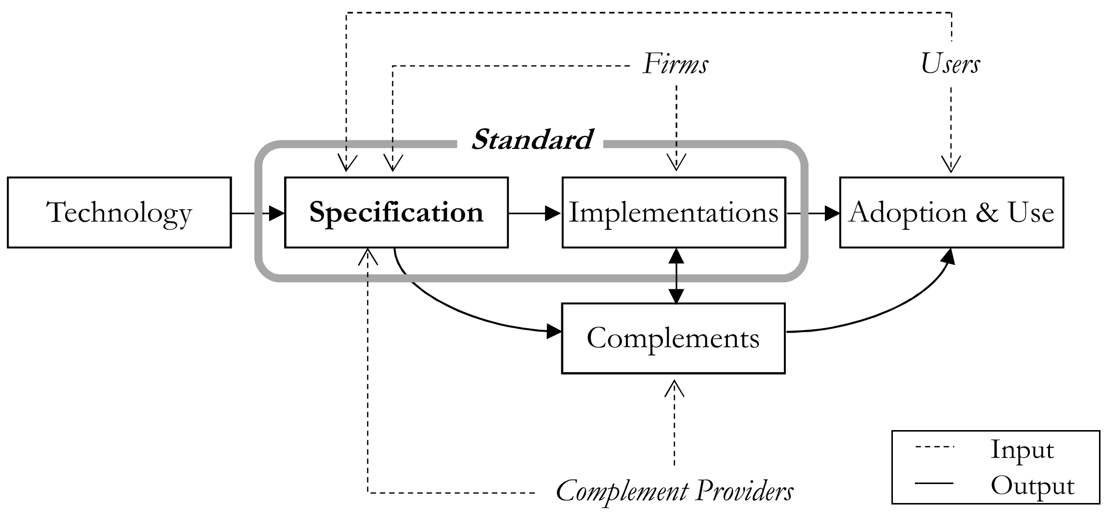
The users' involvement was possible in this context because the radiologists were able to create a collective force and unite their voices on the unmet needs and preferences during the technological development. They were also able to threaten the vendors when needed, using their ability to influence purchasing decisions made at the hospitals and imaging centers which were the key customers investing large capital in the standardized technology (i.e., PACS) and its complementary products (i.e., medical imaging equipment). As a result, the bargaining power of users could affect the firm actions and the mold of a nascent ecosystem architecture by restraining firms' ability to extract private benefits out of the standardization process.

Several limitations worth noting. First, I remain cognizant of verifiability of the data sources, since interviewees had to rely on their personal memories and recall the events happened several decades ago. Also, the meeting minutes were only available for the periods after 1998, which limits my ability to observe the early discussions among stakeholders since the inception of the standard setting committee. Second, because the paper only describes a single case, potential idiosyncrasies of the context may limit generalizability of the findings to other contexts. Future work will have to be centered around triangulation of findings with extended data sets and validations of results by examining standard settings in other industries.

The paper contributes to several literature streams. First, it recognizes the demand side (i.e., users) as one of the important factors defining ecosystem architecture. While prior work disproportionately discusses the comparative market power between platform providers and the complementors in platform ecosystem, I examine the case where consumers are aggregated to act collectively and impose threats on firms not joining the standard setting process. The paper further highlights the importance of demand heterogeneity in formation and execution of firms' ecosystem strategies (Rietveld & Eggers, 2018). Second, the paper contributes to the recent calling in ecosystem literature that we lack understanding of how a set of common "rules" of interoperability emerges in the absence of hierarchical force and how it is shaped by divergent factors. As the foundation of rules, roles, and relationships of ecosystems, standard is fundamental to the interdependency among ecosystem firms. Understanding through which process an interoperability standard is formed is of strategic importance because market power in an ecosystem often arises from gaining acceptance as a standard or a core element of technological architecture of the system (Miller & Toh, 2020; Ranganathan et al., 2018). Third, while user's unmet needs have been introduced as one of the important triggers of industry incubation and evolution (Agarwal et al., 2017), less understood is the process initiated by a systematic effort of an institutional user group beyond a single or a few knowledgeable users. Prior work on unmet user needs as an industry incubation trigger only focuses on the role of individuals pursuing user entrepreneurship. Despite their relevance to key strategic concepts, user communities have not attracted much attention from management literature (Shah & Nagle, 2020).

Tables and Figures

Figure 1-1. Process model for stakeholders in creation and adoption of standards



Note: Recreated from Figure 3.2. in West (2006)

Figure 1-2. Timeline of the DICOM standard setting

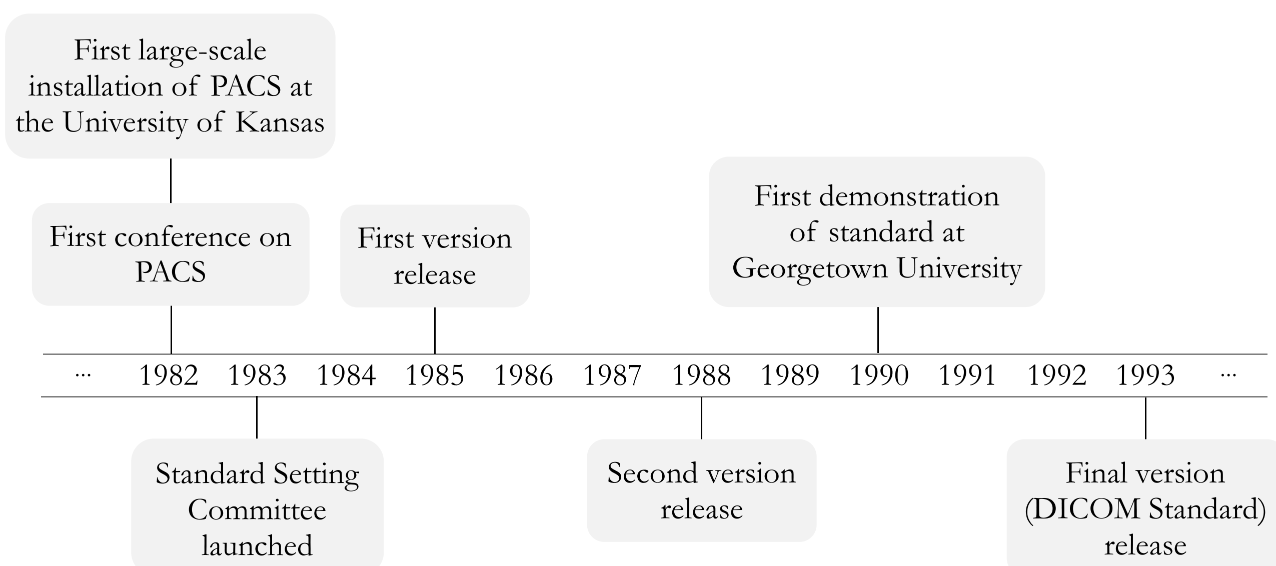


Figure 1-3. Example of the Members Participated in the DICOM Committee

MINUTES:	AD HOC TECHNICAL COMMITTEE (EMERGING TECHNOLOGY COMMITTEE) AND AMERICAN COLLEGE OF RADIOLOGY'S SUBCOMMITTEE ON COMPUTER STANDARDS
PLACE OF MEETING:	PALMER HOUSE CHICAGO, ILLINOIS
DATE AND TIME:	SATURDAY, NOVEMBER 12, 1983 12:00 NOON - 3:00 P.M.

<u>MEMBERS PRESENT</u>

Howard Berke (part-time)	ADAC Laboratories
Hartwig Blume, Ph.D.	Philips Medical Systems, Inc.
Al Dunn, M.D.	American College of Radiology
Allan Edwin	General Electric Company
Mel Hellstrom	CGR Medical Corporation
Richard Lackmond	Siemens Medical Systems
James Lehr, M.D.	American College of Radiology
Gwilym S. Lodwick, M.D.	American College of Radiology
John Moore, Ph.D.	American College of Radiology
Al Rothlauf	Picker International, Inc.
J.P. Steele, M.D.	American College of Radiology
Martin Sonntag	Medical Data Systems

<u>MEMBERS ABSENT</u>

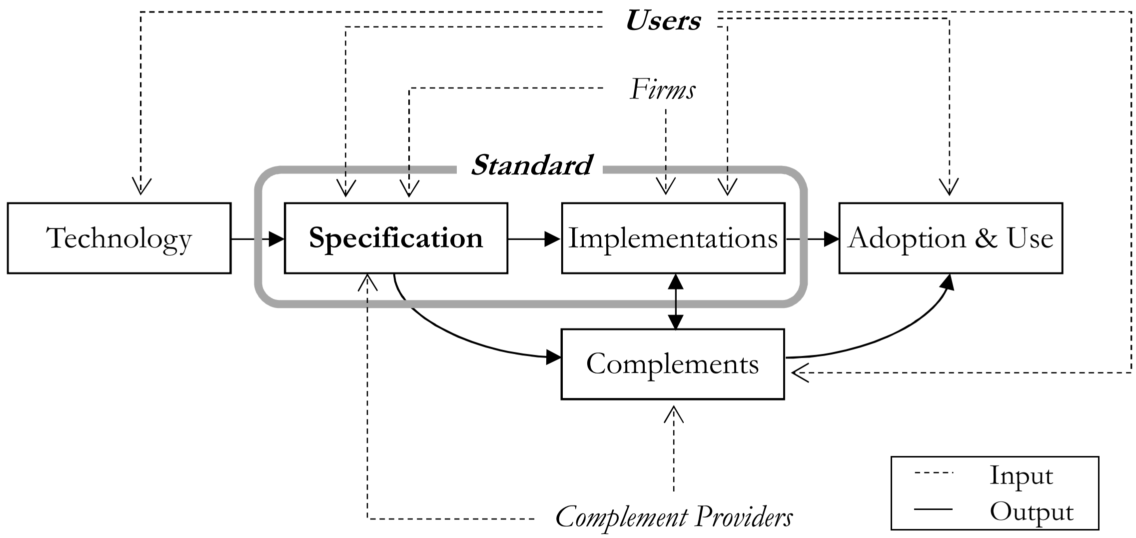
David Stepner	Diasonics, Inc.

<u>OTHERS PRESENT</u>

Dan Gahlon	3M
Richard Hardy	ACR Staff
Robert G. McCune	NEMA Staff
Laura Lee Murphy	NEMA Staff

Source: The meeting minute of the first ACR-NEMA meeting on standard setting (Horii, 2005)

Figure 1-4. Revised process model for stakeholders in creation and adoption of standards in the medical imaging industry



Note: Recreated from Figure 3.2. in West (2006)

Table 1-1. Overview of data collection

Source	Description
Interviews	7 formal interviews with the members of the standard setting committee, 4 of whom were the former executives of the major imaging equipment manufacturers and 3 were radiologists and medical physicists.
	A second-hand interview transcript of 2 individuals who were the members of the standard setting committee, featured on a podcast
Archival data	1,625 articles of industry trade journal articles (SPIE Proceedings)
	50 documents of DICOM Committee meeting minutes
	Webpages archiving the history of the DICOM (dicomstandard.org) and PACS (pacshistory.org)
	White papers

Chapter 2. Creating Seamless Experiences: Firms' Product Scope Expansion in Response to Platform-enabled Modularity-in-use

Introduction

The benefits of related product diversification arise from the utilization of resources within the firm to obtain economies of scope (Markides & Williamson, 1994; Montgomery, 1994; Palich, Cardinal, & Miller, 2000). Such economies of scope derive from the contemporaneous sharing of assets in firms' activities, resulting in lower joint costs of combining two or more product lines in one firm than to deliver them separately (Panzar & Willig, 1981). While the bulk of the literature has focused on the cost economies in production, more often than not the economies of scope can arise when customers perceive increased utilities when consuming two or more complementary products offered together (Adner & Snow, 2010; Priem, 2007; Ye, Priem, & Alshwer, 2012). When demand-side complementarity exists, firms can exploit economies of scope by offering one-stop shopping to the customers, as exemplified by a gas station that sells gasoline also has a convenience store at the same location. Accordingly, firms' product scope choice is often a function of scope economies arising from demand-side complementarities among different products and services[2] (Siggelkow, 2003; Tanriverdi & Lee, 2008; Ye et al., 2012).

Firms, however, constantly face changes in their demand environment where potential for demand-side scope economies shift by the changes in product architecture and how it is used by the customers (i.e., "system of use") (Dattée, Alexy, & Autio, 2018;

[2] Hereafter I use the term "product" interchangeably with "products and services."

von Hippel, 2021; Kapoor, 2013). A group of components or modules often interact during use to accomplish a system-level goal (von Hippel, 2021), and thus demand-side complementarity is determined by the degree to which each component, a standalone final product itself, is required to constitute a system of use.[3] For example, a bed frame, a pillow, and a mattress are product components coming out in standard sizes which may all be needed to make a product system, a bed. While consumers can derive utility by combining these elements (i.e., a bed frame, a pillow, and a mattress) into a system of use (i.e., sleeping in bed), the modular nature of these complements means that producers do not need to coordinate product offerings internally to enable such value. On the other hand, a firm can also strategize to deliver the entire product system by developing systemic innovations to create greater value. For example, Shimano, a bicycle company, persisted with integration strategy despite the initial modularity in product architecture in the bicycle drivetrain industry and deliberately introduced systemic innovations that offered mountain bike riders superior performance (Fixson & Park, 2008). Therefore, the nature of interdependencies among product elements would dictate how much value a firm can generate by delivering a system of products or specializing in one of the product elements.

However, there is a dearth of both theoretical and empirical understanding in how a shift in a product system design at the industry level and the resultant change in potential for demand-side complementarities affects a firm' product scope decision. While changes in a product system design is at the center of ecosystem and industry evolution research, prior work has focused on how technological interdependency of a

[3] Complementarity between A and B means the value of A is maximized with B (as opposed to B'). The complementarity can be strong if A requires B, specific if A requires B to be customized to it to be productive, or generic if no need for specific coordination between A and B.

product system can be efficiently managed by firms from innovation and production perspectives (Baldwin, 2012; Baldwin & Clark, 2000; Helfat, 2015; Helfat & Campo-Rembado, 2016). Diversification literature has often taken a static view and been silent about how firms adjust their product scope to the industry-level change in product architecture. In addition, disproportionate amount of attention has been paid to the supply-side economies of scope as a key determinant of firms' product diversification.

The paper fills this gap by examining firms' product scope decisions after the arrival of an industry-wide standardized platform, which significantly reduces potential for firms' demand-side economies of scope. The standardized open platform enables interoperability across pre-existing standalone products[4] and provides customers 'modularity-in-use,' which allow them to mix and match products purchased separately from different manufacturers to come up with a final product system that best suits their taste and need (Baldwin & Clark, 2000, 2003; Matutes & Regibeau, 1988). The compatibility thus significantly eases coordination across products by users (Baldwin & Clark, 2000; von Hippel, 2021), reducing the benefits for a firm to offer a diverse portfolio of products. However, the integrated product system can still allow system-level innovation and customization catering to demand heterogeneity induced by the ability to mix and match. The introduction of an interoperability standard therefore inherently poses a strategic tension in deciding the range of products a firm offers (Gandal, Markovich, & Riordan, 2018; Schilling, 2000; Schmidt, Makadok, & Keil, 2016; Staudenmayer, Tripsas, & Tucci, 2005). Accordingly, I investigate *whether the modularity-in-use decrease or increase within-industry product diversification.*

[4] Interoperability across pre-existing standalone products is enabled when an interface standard is introduced to assure that "a product that conforms to the interface standard can serve as a subsystem within a larger system" (David & Greenstein, 1990, p. 4).

The research context is the medical diagnostic imaging industry, where compatibility in use among major imaging equipment was achieved by the introduction of a platform software and an interface standard.[5] The industry is characterized by various imaging equipment which had been *technologically independent* but provided complementary benefits to physicians who use the equipment.[6] Prior to early 1990s, while physicians required joint usage of images taken from various devices for patient diagnosis, they had to read scans separately on each imaging equipment due to the lack of interoperability between equipment. The introduction of the medical image communication platform enabled connection of the technologically independent set of products to form a loosely coupled product system, and allowed physicians to enjoy the 'system of use' in patient diagnosis. Thus, the context allows me to examine imaging equipment manufacturers' product scope decision before and after the shift in the system of use.

Using a question-driven abductive approach (Graebner, Knott, Lieberman, & Mitchell, 2022; King, Goldfarb, & Simcoe, 2020), the paper seeks to identify a systematic pattern and to provide theoretical explanation on the mechanisms behind it. I first use quantitative data on the U.S. medical imaging equipment manufacturers (1985~2013) to understand the evolution of imaging device firms' product diversification over time. Next, I rely on supplementary analyses on both quantitative and qualitative evidence to infer the best explanation for the observed patterns. I find that in face of the standardized open platform, platform providing firms took advantage of their existing

[5] The industry-wide standard, called the DICOM, was set forth by the agreement of all firms in the industry without favoring any manufacturers. Detailed description on the standard setting process is provided in the research context section.
[6] Namely, X-ray, computed tomography (CT), magnetic resonance imaging (MRI), ultrasonography, and nuclear medicine.

positioning and differentiated product offerings by providing better customized solutions which simple plug and play would not be able to accomplish. Controlling for other sources of supply- and demand-side scope economies, imaging equipment firms that also offered an open platform software expanded their imaging product diversity and became integrators to create customized systems. Leveraging deep knowledge in customers' heterogeneous needs, these firms were able to engage in product and product interface innovations. On the other hand, firms without having a platform software in their product portfolio did not show this pattern.

The paper has contributions to the literatures it draws on. By investigating how incumbent firms adapted to increased dependencies between their and competitors' products, the paper contributes to the research on incumbent response in the strategy literature (Ethiraj & Zhou, 2019). The paper also adds to the work on within-industry diversification by suggesting that firms can further expand their product scope based on demand-side relatedness even when supply-side synergy is limited (Schmidt et al., 2016; Siggelkow, 2003; Tanriverdi & Lee, 2008; Ye et al., 2012). To the research on interfirm dependencies, the paper describes a strategic implication of demand-side interdependency arising at the point of users' consumption, which has been less highlighted in the literature. While the previous discussion on modularity has been reduced to the implication on manufacturing and innovation efficiencies, the paper suggests that when customers have modularity-in-use as a result of modular design, diverse product portfolio can serve as integrated knowledge for managing demand-side interdependencies. Lastly, while platform literature assumes that the introduction of a platform precedes the arrival of complementary products, the paper recognizes how the relationship among pre-existing standalone products can evolve to form a product system around a platform.

The sections below are structured as the following. I first situate my broad research question under the theoretical concepts of demand-side economies of scope and modularity-in-use. After describing my research context, I present the statistical analysis on firms' product scope post-standardization, along with the supplementary analyses to explore mechanisms. Weaving and tying all the empirical evidence back to the theoretical framework, I elaborate on my inference to the best explanation. The paper concludes by elucidating the contributions of this paper to the relevant literature.

Theoretical Backdrop

Demand-side Economies of Scope and Firms' Product Scope

Demand-side complementarity arises when the utilities of consuming two or more products and/or service by users are complementary to one another within a larger value delivering system (Jacobides, Cennamo, & Gawer, 2018).[7] Demand-side research has focused on a typical form of demand-side interdependency as customer-specific economies of scope, which arises a) when offering combinations of product and/or service incurs lower cost to the firms than delivering them separately to customers, or b) when the combinations create larger value for customers by expanding their utilities more than the sum of utilities derived from separate offerings, and thus increase

[7] Demand-side interdependency may also be materialized in a negative relationship between products (i.e., generating negative utility to customers when consumed together). For the purpose of this paper, I confine the discussion to the complementary relationship.

customers' willingness to pay for the product combination (Chatain, 2011; Chatain & Zemsky, 2007; Schmidt et al., 2016; Ye et al., 2012).[8]

I define firms' horizontal scope as the set of products and services offered— ranging from specializing in a limited product or service to expanding activities across a broad set of products— and the expansion of horizontal scope (i.e., product diversification) as entry into new markets with new products based in a different area of technology beyond firms' existing area of specialization (Penrose, 1959). Traditionally, technical dependency implies economic complementarity (e.g., Hart & Moore, 1990), and thus when the joint production of related (sub-)products costs less than producing each (sub-)product separately, scope economies arise and coproduction occurs within a single firm (Panzar & Willig, 1981; Teece, 1982). Likewise, when scope economies occur from interactions with specific buyers, such demand-side interdependence results in "one-stop shop" strategy with a greater range of product offering (Chatain & Zemsky, 2007). Customer-based synergies can create value independently from producer-side synergies (Ye et al., 2012), and relational capital with customers can provide windows for new market opportunities in customers' markets, often resulting in customer-led diversification (Mawdsley & Somaya, 2018, 2021).

Rise of Modularity-in-use and Reduction in Potential for Demand-side Economies of Scope

When customers enjoy greater benefits from the combination of two or more products, this in turn indicates that the products are interdependent in creating value, or part of a

[8] Supply-side economies of scope are typically understood to lower production costs, irrespective of who the customer is (Panzar & Willig, 1981). Demand-side economies of scope, in contrast, refer to increases in added value due to higher willingness to pay or lower costs, or both, by jointly offering different products or services (Chatain, 2011).

'system of use' (von Hippel, 2021). A system of use is a group of components or modules interacting during use to accomplish a system-level goal (Garud & Kumaraswamy, 1995; von Hippel, 2021). Demand-side complementarity can thus be determined by the degree to which each component is required to constitute a greater system of product use. For example, a teacup, boiling water, and a tea bag are product components which may all be needed to enable a system of use, a cup of tea.

A product system requires coordination of interdependent activities for successful value creation and delivery to customers (Adner & Kapoor, 2010; Baldwin & Clark, 2000; Brusoni, Prencipe, & Pavitt, 2001). While a product system is often complex in nature in that it is "made up of a number of parts that interact in a nonsimple way" (Simon, 1962, p. 468), its underlying architecture undergoes simplification of interactions when a design rule is introduced for each component to adhere to (Baldwin & Clark, 2000). An interface standard is what assures "a product that conforms to the interface standard can serve as a subsystem within a larger system" (David & Greenstein, 1990, p. 4). Prior work in ecosystem and industry evolution literature have focused on how technological interdependency of a product system can be efficiently managed by modularity from innovation and production perspectives (Baldwin, 2012; Baldwin & Clark, 2000; Helfat, 2015; Helfat & Campo-Rembado, 2016). Likewise, consumers' usage of a product system can also be modular in nature (i.e., "modular-in-use") if component products conform to the predetermined set of design rules so that consumers can easily engage in the joint consumption of complementary products offered by different suppliers.[9]

[9] Baldwin and Clark (2000) make important distinction among the types of modularity based on how humans interact with artifacts: modularity-in-design, modularity-in-production, and modularity-in-use. While all based on a predetermined set of design rules, modularity-in-design arises from establishing

The modularity in consumption enabled by an interface standard eases coordination across subproducts by users (Baldwin & Clark, 2000; von Hippel, 2021). It provides customers the benefits of mix and match by purchasing product elements separately from different firms to create a final product system that fits their needs (Baldwin & Clark, 2000, 2003; Matutes & Regibeau, 1988). Traditionally, consumers can buy bed frames, mattresses, pillows, linens, and covers from different manufacturers but they all fit together because every firm offers their products according to the standard sizes (Baldwin & Clark, 2003). Early bicycle was also modular-in-use, as customers could purchase any components that were interchangeable both within and across firms (Fixson & Park, 2008). The modularity-in-use has also become a prevalent phenomenon with the advent of digital platform and connecting technologies that allow compatibility across different products.[10] [11] For example, we see the rise of Internet-of-Things or 'smart home system' which is based on a platform that connect and control various smart devices and home appliances.

Such compatibility across products inherently poses strategic tensions in deciding the scope of products offered by a firm (Gandal et al., 2018; Schilling, 2000; Schmidt et al., 2016; Staudenmayer et al., 2005). The nature of interdependencies among product

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partitions of knowledge and effort in a design process, modularity-in-production emerges from the partitioning of production tasks, and modularity-in-use provides customers the benefits of mix and match to create a final product system that fits their needs. While a certain product system can be characterized by different types of modularity, I make a conceptual distinction among them for the purpose of this paper and focus on the role of modularity-in-use enjoyed by consumers.

[10] A platform can be defined as "any combination of hardware and software that provides standards, interfaces, and rules that enable and allow providers of complements to add value and interact with each other and/or users" (Teece, 2018, p. 1375). This definition is different from the engineering design literature that conceptualizes a platform based on product architectures and components (Gawer, 2014).

[11] Modularity-in-use does not necessarily imply modularity-in-design, as it means that modules can be produced and consumed as final end-products by themselves but can also be connected and configured via a standardized interface to compose a larger product system (Baldwin & Clark, 2000). For example, a sectional sofa is modular in use, but not modular in design or production.

elements would dictate how much value a firm can generate by delivering a system of products or specializing in one of the product elements. The compatibility may significantly reduce the benefit of coordinating and integrating various products within a firm. The modular nature of product complements (e.g., a bed frame, a pillow, and a mattress) means that producers are not able to create greater value from internalizing production and providing a holistic combination of different product elements (e.g., a bed). Compatibility across products from different manufacturers may erode lock-in effect that previous product system providers may have enjoyed. Therefore, when firms face a shift in technology that creates modularity-in-use, firms may not see the value in diversifying because of the reduced potential for demand-side economies of scope.

Research Question Approach

Despite the importance and prevalence of the industry-level shift in a product system design, there is both theoretical and empirical lack of understanding the implication to firms' product strategy. While changes in a product architecture is at the center of ecosystem and industry evolution research, prior work has focused on how technological interdependency of a product system can be efficiently managed by modularity from innovation and production perspectives (Baldwin, 2012; Baldwin & Clark, 2000; Helfat, 2015; Helfat & Campo-Rembado, 2016). Platform literature assumes that the introduction of a platform precedes the arrival of complementary products whereas it has not recognized how the relationship among pre-existing standalone products can evolve to form a product system around a platform. Diversification literature has also been silent about the role of platforms and disproportionate amount of attention has been paid to the supply-side economies of scope as a determinant of firms' product diversification.

Accordingly, the paper examines the shift in firms' product scope as a product system arises at the industry level after the arrival of a standardized platform enabling interoperability among standalone products. It is theoretically unclear *a priori* whether the patterns will be similar under modularization in technology and under modularization in the way of customers' use. To understand how firms' product strategies will pan out differently given the divergent incentives in configuring product portfolios, I use an abductive approach for the inference to the best explanation (King et al., 2020). Specifically, I ask: *Does modularity-in-use decrease within-industry product diversification?* In the following sections, I probe deeply into my empirical context and allow empirics to adjudicate the relationship.

Research Context: Medical Diagnostic Imaging Industry

In this section, I describe my context in detail and how it can help understand the effect of modularity-in-use on firms' product diversification. The summary of key characteristics across the evolution of the industry is summarized in Table 2-1.

[Insert Table 2-1 here]

The medical diagnostic imaging industry includes various markets reflecting unique production technologies and user applications: X-ray, computed tomography (CT), magnetic resonance imaging (MRI), ultrasonography, and nuclear medicine. On the supply side, while all medical imaging equipment serve the same purpose of internal body visualization, these sets of equipment are based on fundamentally different technologies. Thus, these technologies have little in common and vary in their ability to process different properties of human tissues, resulting in images that are markedly different and often complementary to each other. On the demand side, these products are purchased by the same customer base, which are hospitals and imaging facilities.

Accordingly, the industry is characterized by little technological interdependencies but high demand-side interdependencies. The five major imaging equipment types—X-ray, CT, MRI, ultrasound, and nuclear medicine equipment—each use highly distinctive technologies with different underlying principles. Since technologies do not build on one another or share common components, there is less potential for the economies of scope in production, as cost-sharing opportunities are unlikely. On the other hand, since all equipment is purchased and used by the same set of customers (e.g., hospitals and imaging centers), demand-side economies of scope coming from distribution and sales as well as customer synergy arising from the complementarity of functions loom particularly large (Mitchell, 1989a, 1991).

Medical Image Communication Platform and Compatibility Across Imaging Equipment

An electronic communication software for medical image sharing called Picture Archiving and Communication System (PACS) is installed in hospitals and imaging centers to be used by radiologists to store, access, and integrate image scans from various machines for patient diagnosis. Through the early 1980s, physicians had to read images separately on each device due to the lack of interoperability between the source machine types. Thanks to the PACS software that can be combined with a hardware monitor and linked to the imaging devices, radiologists could retrieve and overlay, say, scans from X-ray machines onto the scans from MRI scanners on the same screen (see Figure 2-1).[12] Prior to the advent of a standardized interface, early software and imaging equipment were proprietary to the manufacturers. Because there was no industry-wide standard that could promote compatibility, manufacturers especially having a diversified product portfolio had incentives to create their own platforms and benefit from lock-ins.

[Insert Figure 2-1 here]

While typical modularization begins with a complex integrated system becoming decentralized with modular subsystems as a standard interface is developed, modularization process in the medical imaging industry happened in the *opposite* way: it arose when the previously independent imaging equipment (but only related on the customer side) each became modules of a broader system via a common standardized interface. In 1993, the industry-wide interface standard for the encoding, storage, and transmitting of medical image information, called the DICOM,[13] was established by the agreements arrived at within and published by a voluntary standard-setting organization.[14] The standard setting was strongly driven by the user community's (i.e., radiologists) requirement for open compatibility across equipment from different manufacturers. After the interface standard was set, physicians could now simultaneously retrieve and use scans from any machines regardless of which manufacturer supplied the equipment. Hospitals and imaging centers could now choose a PACS software from one

[12] The best analogous example to describe the PACS and its related imaging equipment can be the Enterprise Resource Planning (ERP) system and a set of its complementary software. MRI, CT or ultrasound scanners are complementary products for the PACS platform just as accounting, inventory, and customer relationship management software are to the ERP system of Oracle or SAP.

[13] Digital Imaging and Communications in Medicine. https://www.dicomstandard.org/

[14] To preclude the possibility of monopolies, the Federal Trade Commission required that the standard should not favor any firms contributing to its setting and required all firms to make their technologies applied to the standard public.

vendor, imaging scanners from others, and plug-and-play various equipment for their own needs.[15]

Firms that had been providing own proprietary software were forced to relinquish control and open up their software, because consumers strongly required nonproprietary software and devices that were fully compatible. The introduction of a compatibility standard and the standardization of how devices are connected to one another transformed the basis of competition from manufacturer-specific closed systems of product offerings to an open architecture where various firms compete on modular imaging products. Since the introduction of an interface standard allowed specialized software providers to enter, firms had to face increased competition from independent PACS vendors that also provided open software.

Data and Empirical Strategy

The primary source of data for the imaging firms and their product portfolio is the Medical Device Register (MDR) directories (1981-2013), a comprehensive compilation of medical products and manufacturers in the U.S. The MDR contains data on product categories (e.g., 'Processor, Radiographic Film, Automatic') and the FDA medical specialty areas to which each product is assigned (e.g., 'Neurology', 'Orthopedics', 'Radiology'), manufacturers who offer them, and firm-division level information such as distribution methods (e.g., direct sales, indirect sales, OEM, importer, exporter) and number of employees. To construct the estimation sample, I first compile division- and product-level information to firm-level observations and restrict the sample to the firms

[15] PACS platform providers can either be imaging equipment manufacturers or specialized software firms without a clear leader within the industry. For the purpose of this paper, I focus only on the imaging equipment manufacturers that also provide a PACS software and exclude software firms from the analysis.

active in 'Radiology' specialty area. I then keep the firms that have products assigned to the five imaging product markets—X-ray, ultrasound, nuclear medicine, magnetic resonance imaging, computed tomography—and PACS market. Using the Dorenfest Complete IHDS+ Database and the Dorenfest 3000+ Database, I supplement identification of imaging equipment manufacturers that also provided PACS software. The final sample consists of 4,024 firm-year observations from 1985 to 2008 with 450 unique firms.

Variables

The operationalization of the variables is described in Table 2-2 and summary statistics are shown in Table 2-3.

[Insert Table 2-2 and 2-3 here]

Dependent Variable The key dependent variables of interest is $Product\ Diversity_{it+1-t+5}$, which indicates 5-year average of Herfindahl indices calcaulated based on the count of product categories within each of five imaging markets. To test potential mechanisms, I additionally examine firms' product innovation using $Patent\ Application_{it+1}$ and $510(k)\ Application_{it+1}$, and test firms' selection into software business using an indicator variable $Platform\ Offering_{it+1}$.

Independent Variable $Post\text{–}standardization_t$ takes a value of 1 for the years that belongs to the period after the industry-wide image sharing standard was set (1993-2009). I use an indicator variable $Platform\ Offering_{it}$ to test the effect of having PACS in the firm's product scope. Also, $Product\ Diversity_{it}$ is used to test whether firms already having a diverse product portfolio are more likely to select into platform offering. $Pre\text{–}standard\ Platform\ Offering_i$ and $Pre\text{–}standard\ Product\ Diversity_i$

each represent the firm's state in the pre-standard period (i.e., prior to 1993), constructed as time invariant variables. These variables are used for sensitivity analysis exploiting time differences before and after standard was set, which will be described in detail in the later section.

Control Variables I use several firm-level control variables to account for potential confounding factors. $Cross\text{–}industry\ Diversification_{it}$ is an indicator variable capturing whether the firm operated in nonmedical device industries or not in year *t*. $Number\ of\ Medical\ Device\ Segments_{it}$ is used to control for the firms' presence in other medical device segments outside diagnostic imaging, and $Patent\ Stock_{it}$ to account for the firms' accumulated technological capabiliites. I also control for firms' possession or access to distribution/sales related assets using $Direct\ Sales_{it}$ and $Indirect\ Sales_{it}$.

Model Specification

To achieve greater interpretability, I use linear regression (OLS) models. Standard errors are clustered at the firm level to account for dependence across observations within the same firm. The regression model takes the following form:

$$\text{(i) } DepVar_{it+1} = \gamma_i + \beta \cdot X_{it} + \lambda \cdot Post\text{–}standard_t + \theta \cdot IndVar_{it} + \delta \cdot IndVar_{it} \cdot Post\text{–}standard_t + \varepsilon_{it}$$

$DepVar_{it+1}$ indicates the key dependent variables defined above. γ_i is firm-fixed effects and X_{it} indicates the firm-year level controls. The coefficients of interest are λ, which captures the difference between the effects in pre- and post-standard periods (alternatively, λ_t is included for year-fixed effects), θ capturing the effect of the independent varaible, and δ, which captures the impact of the key independent variable on the within-firm variation pre-and post-standard.

To minimize the potential endogeneity in firms' software offering and imaging product diversification, I estimate additional specifications for sensitivity analysis by grouping the sample by the firms that began offering software in the pre-standard period (prior to 1993), in the post-standard period (post 1993), and never offered software throughout their lifetime. Using both subsamples and full sample, I test the model of the following form:

$$\text{(ii) } DepVar_{it+1} = \gamma_i + \beta \cdot X_{it} + \lambda \cdot Post\text{–}standard_t + \theta_1 \cdot Offered\ Platform\ Early_i \cdot Post\text{–}standard_t + \theta_2 \cdot Offered\ Platform\ Late_i \cdot Post\text{–}standard_t + \varepsilon_{it}$$

Results

Selection into Offering PACS Platform Software

Firms' decision to offer PACS platform software is not an exogenous choice. I examine what type of imaging manufacturers offered platform software in the first place. Firms with diverse product portfolio might be in a better position to reap the benefits from providing image sharing software than firms specialized in a single product market, as demand-side synergy increases with the number of complementary products connected to one another. Firms who already have greater number of complementary product businesses can use bundling strategies by entering a software business to reduce firms' costs of serving a customer and allow customers to experience larger benefits (Schmidt et al., 2016).

Using an indicator variable $Platform\ Offering_{it+1}$ as the dependent variable and $Product\ Diversity_{it}$ as the key independent variable, I estimate the likelihood of offering PACS software. The results are presented in Table 2-4. Columns 1 and 2 report the uncontrolled results comparing pre- and post-standard periods, Column 3 includes control variables and firm-fixed effects except the interaction term. Column 4 adds the interaction term between *Product Diversity* and *Post-standard.* Finally, Column 5 further includes year-fixed effects. Based on the full model in Column 5, the term *Product Diversity* × *Post-standard* (δ=0.190, *s.e.*=0.087) indicates that within years in the post-standardization period, a 0.1 incease in a firm's product diversity was likely to increase the likelihood of software offering by 1.9%. The results are consistent with the idea that diversified firms were likely to bundle software with their imaging products.

[Insert Table 2-4 here]

Statistical Analysis on Product Diversification

The main regression results are presented in Table 2-5. Columns 1 and 2 report the uncontrolled results comparing pre- and post-standard periods, Column 3 includes controls and firm-fixed effects except the interaction term. Column 4 is the full model adding the interaction term between *Platform Offering* and *Post-standard.* Finally, Column 5 further includes year-fixed effects. The cross-variation results in Columns 1 and 2 indicate that on average, firms were likely to have lower product diversity in the post-standard period, but firms offering software were likely to have greater product diversity (δ=0.0.037, *s.e.*=0.063). For within-firm variations in Columns 3 to 5, firms were likely to increase product diversity in the post-standard period. The coefficient estimate for *Post-standard* in Column 3 (δ=0.0.037, *s.e.*=0.063) suggests that firms on average were likely to have greater product diversity in the post-standard period, controlling for supply- and demand-side economies of scope. Based on Column 5, the term *Platform Offering* × *Post-standard* (δ=0.042, *s.e.*=0.018) further indicates that in the post-standard period, a firm offering platform software was likely to have 0.042 greater product diversity in the post 5 years than without platform. The different results for between (Columns 1 and 2) and within regressions (Columns 3 to 5) are indicative of (a) the first order selection effect that while vast majority of firms in the industry were specialized, a few that offered platform software were likely to be diversified ones, and (b) the second order treatment effect that firms owning platform software were likely to increase their product diversity over time.

[Insert Table 2-5 here]

Supplementary Analyses and Robustness Checks

Product Innovation by Platform Ownership To explore potential mechanisms, I test the idea whether firms offering software were able to engage in more product innovations, which can potentially lead to product diversification. Using $Patent\ Application_{it+1}$ and $510(k)\ Application_{it+1}$ as key dependent variables, I test the effect of $Platform\ Offering_{it}$. Columns 1 and 3 report the results using the full sample (equation(i)) and Column 2, display results for the three groups of firms by their PACS software ownership: (a) firms that began offering platform software in pre-standard period (prior to 1993), (b) began offering in the post-standard period, and (c) never offered software throughout lifetime. The base line category is the third category (c) (equation (ii)).

The results for $Patent\ Application_{it+1}$ in Column 1 suggest that in the post-standard period, a firm offering software are likely to have greater patent applications (δ=0.756, *s.e.*=0.309). The result was especially true for the firms that entered PACS software business prior to the standard: in Column 2 (θ_1=0.732, *s.e.*=0.323). Turning on to $510(k)\ Application_{it+1}$, the results in Column 3 (δ=-0.202, *s.e.*=0.129) and Column 4 (θ_1=-0.168, *s.e.*=0.128; θ_2=-0.105, *s.e.*=0.102) do not provide any meaningful evidence to conclude any pattern.

[Insert Table 2-6 here]***Pre-standard Software Offering and Diversification in the Post-standard Period*** Firms' decisions to offer software and expand product scope are inherently endogenous in that unobservable factors can concurrently drive such decisions and reverse causality is highly likely as seen in the results for the selection into offering PACS platform software. To partly solve this empirical challenge, I exploit the difference in timing between software offering and product diversification. I grouped the sample to three categories: the firms that (a) began offering platform software before the standard was set (prior to 1993), (b) began offering after the standard was set, and (c) never offered software throughout lifetime.

The binned scatterplot in Figure 2-2 shows the trends in firms' product diversity, categorized by their pre-standard software ownership. In the pre-standard period, imaging firms that had software in their portfolio were the firms diversified already. Conditioning on software offering, tracking their product diversity in the post-standard period, the plot also suggests that firms with software tended to increase their product diversity over time. Overall, the plot suggests the product diversification pattern found in the main regression was strongly driven by the firms that were already diversified prior to the standard setting.

[Insert Figure 2-2 here]

The results for the effect of pre-standard software offering on post-standard diversification are displayed in Table 2-7. Note that since the regression is estimating the difference in pattern between two periods, year-fixed effects are not included. Column 1, 2 and 3 report the subsample results for analyses corresponding to each group of sample, with controls and firm-fixed effects. The results for $Post-standard_t$ in Column 1 indicate that firms that had offered PACS are likely to have greater product diversity in the post-standard period compared to the pre-standard period (δ=0.036, *s.e.*=0.02), but other groups do not suggest this pattern. The models using full sample are presented in Columns 4 and 5, which include interaction terms with the firm group and the period dummy. Based on the results in Column 5 with year-fixed effects, the coefficient estimate for *Offered PACS Early* × *Post-standard* (θ_1=0.123, *s.e.*=0.070) suggests that on average, the software providers were likely to have 0.123 greater product diversity compared to the firms specialized in imaging devices in the post-standard period. indicates that on average, the software providers were likely to have 0.261 greater product diversity compared to the firms specialized in imaging devices in the post-standard period.

[Insert Table 2-7 here]

<u>Alternative Measures for Product Diversification</u> As a robustness check, I estimate the main specification (equation(i)) using alternative measures for product diversification. The coefficient estimates for the variable of interest, *Platform Offering* × *Post-standard,* are plotted in Figure 2-3. Each estimate is constructed by using different operationalization for product diversification as the dependent variable. The coefficient estimates are generated by rerunning the main specification (i.e., equation(i)) with controls, firm- and year-fixed effects, and standard errors clustered by firm. I used two alternative measures: *Average # Imaging Subfields* is the count of medical imaging submarkets that a firm operates in year *t*, and *Average # Total Imaging Products* is the count of all medical imaging product categories that a firm offered in year *t*, regardless of medical subfields. *Product Diversity* used for the main results is a composite Herfindahl Index calculated based on the other two measures.

The plot indicates that the results suggested in the main regression is only applicable when considering both the number of medical imaging subfields and the number of products within each subfield at the same time. It is because when firms only expand the product lines within a single subfield but not expanding into other subfields, such expansion should be considered as specialization. While the estimates using the log count of medical imaging subfields are slightly positive but week in both economically and statistically. I suspect that it is due to the lack of variance in the measure (mean=0.793 and *s.d.*=0.231; maximum number of subfields is five).

[Insert Figure 2-3 here]

Robustness Checks I have conducted other robustness checks to address potential alternative explanations and to validate the main results (summarized in Table 2-8). First, it is possible that technological capability is the primary reason behind diversification. However, there is little overlap among imaging technologies and between hardware and software capabilities, which limits potential for supply-side resource and technology synergies. I controlled for individual firms' technological capability by including their patent stock as a control variable. Second, it is also highly likely that the having a tight relationship with customers or a downstream distribution channel might enable firms to diversify due to the one-stop shopping type of economies of scope. This can be controlled by using firm-fixed effects and having distribution method as a control variable, where the effect of a firm switching from one distribution to another could be picked up. Third, the pattern would have been driven by few large dominant firms if they were able to push their own platform to become an industry-wide standard. However, the standard setting process did not favor a certain company and was supervised by a professional user association and regulatory agencies such as the Food and Drug Administration and the Federal Trade Commission. Lastly, another potential alternative explanation that could invalidate the result is that hospitals have been consolidating throughout the study period, which would have created changes in the competitive landscape and lead firms to make expansion through diversification. However, the period is also characterized by the expansion of free-standing imaging centers and outpatient imaging centers, which makes the demand environment remain competitive. Research design-wise, I have done subsample analysis to address sample selection with the sample confining to the firms that entered pre-standard versus those that never entered, and used different operationalization for the dependent variable in terms of time span. The results stay robust to subsample analysis and using a simple t+1 measure.

[Insert Table 2-8 here]

Qualitative Evidence on Motivation to Diversify

To deeply understand the context and seek for potential mechanisms, I conducted interviews with six key individuals—current senior executives of a PACS firm, former managers at imaging equipment firms and radiologists. All informants were also actively involved in the interface standard setting process during early 1980s. I conducted semi-structured interviews lasting for on average 40-60 minutes by requesting informants to describe their background, roles within their organizations, and the evolution of their organizations' strategies within medical imaging equipment industry. The representative quotes from the interviews are summarized in Table A2-1. I also collected archival text data and industry news articles to triangulate events and findings in my study period.

The qualitative evidence suggest that the underlying customer preference has shifted by the introduction of the PACS and the standardized interface. Before the compatibility was enabled, all the users wanted was interoperability and connection between various equipment. As the standard was set and imaging products became modular-in-use, customers began to find a combination that best suits their workflows and request for seamless integration. Since each hospital has its own flow of work, the modularity-in-use created heterogeneous preferences for different product combinations and workflow customization. In fact, hospitals sought for customized integration enabled by PACS, "as PACS is not just a configuration of hardware and software, but it includes the science or the knowledge of the behavior, how radiologists work. It all has to come together, become routine." Also, "all that integration can be done in the [PACS] project," suggesting the value of integration to the customers leveraging the add-on software.

Diversified firms also attempted differentiation by providing new functionalities or aesthetics that are not standardized and therefore available by other component producers. One informant on the customer side described the advantage of "having all equipment from a single vendor, because there was more proprietary stuff in there because the vendors were doing things that had not yet been standardized in DICOM."

[Insert Table 2-9 here]

Understanding Equipment Manufacturers' Product Scope Expansion under Modularity-in-use

Managing Demand-side Interdependencies by Product Scope

Modularization of a product system provides unique opportunities for firms in shaping their product scope. A firm's product scope within a modular product system is a function of the cost and benefit associated with internally coordinating interdependencies between sub-products. If a standard interface can play a coordination role efficiently, then the coordination cost is lower for external arrangements. When internal coordination incurs less cost or greater added value to the customers than external coordination, diversification will occur. Depending on which side of interactions are being modularized, opportunities to create added value by diversification can arise from changes in either production activities or demand conditions. While research has been disproportionately examined how supply-side interdependency is managed by either specialization or integration, less attention has been paid to the firms' product scope implications of demand-side interdependency.

From production perspective, a firm's product scope under modularization can be dictated by comparative cost economies associated with coordinating technological interdependence internally versus externally. Modularization can significantly reduce the coordination benefit of integrative production (Jacobides, 2005; Langlois & Robertson, 1992; Sanchez & Mahoney, 1996). Less of an engineering effort is required to achieve seamless coordination across different subproducts, because standardized interfaces serve to structure the technical dialogue between component product design engineers, reducing the benefit for unstructured coordination through integration. Because of the enabled compatibility, once the component product has been developed for others, firms can free ride on these investments and 'plug-and-play' the product directly into their own offers (Adner & Kapoor, 2010; Garud & Kumaraswamy, 1995). Thus, the benefit of investing in other technologies is reduced and results in specialization in limited area. Firms can simply decide what subsystems are indispensable to its competitive position within the technological architecture and choose to specialize. Since the complex interdependencies between components are reduced to a simple interconnectivity rule, modularization facilitates reduction in scope of innovation and production activities assumed by a unit or an organization, and thus allows for specialization (Baldwin & Clark, 2000; Garud & Kumaraswamy, 1995; Langlois & Robertson, 1992; Schilling, 2000). Such line of reasoning has grounded the "mirroring hypothesis" in modularity research, which states that organizational design reflects product designs (Colfer & Baldwin, 2016; MacCormack, Baldwin, & Rusnak, 2012; Sanchez & Mahoney, 1996) and furthermore the vertical structure of an industry (Helfat, 2015; Helfat & Campo-Rembado, 2016; Kapoor, 2013).

Likewise, from demand-side perspective, a firm's product scope under modularization can be dictated either by potential cost economies or by added value associated with coordinating demand-side interdependence internally. The ability to mix and match products by users allows them to build a product system that is closer to their ideal (Baldwin & Clark, 2000). Since it can blanket the product space more completely with superior functionalities, a product system characterized by modularity-in-use can address a wider set of customer preferences (Matutes & Regibeau, 1988). However, modularity-in-use may decrease the benefit of coproducing products that have customer-specific economies of scope by a single firm, mirroring the "mirroring hypothesis."

When customers for a particular solution have very different needs, it is more difficult for a single integrated solution to closely match their idiosyncratic requirements (Schilling, 2000). For example, to meet the heterogenous preferences of college course instructors, publishing companies in the late 1990s began designing their own customized textbook systems using assembly of various textbook sources—ranging from book chapters, articles, cases, and other materials (Venkatraman, 1997).

However, internal coordination benefit may still exist despite the modularization, resulting in the 'exception to mirroring hypothesis' (Colfer & Baldwin, 2016). Since product architectures are never "perfectly modular" because of uncertainty and unexpected variation in technology and usage, interdependencies may continually emerge even after the standardization and modularization (Staudenmayer et al., 2005). In fact, Hoetker's (2006) study of outsourcing choices in the notebook computer market shows that organizational coordination challenges exist even when technologies are highly modular. Also, to generate component products that incorporate new functionality or aesthetics that are less well understood by other component producers, it requires efforts at systems integration to cope with unpredictable product-level interdependencies (Brusoni et al., 2001). For example, in the automobile industry, firms that positioned for differentiated products remained vertically integrated because they incorporate unique components with less-modular interfaces with other components, which requires internalization instead of market transactions (Argyres & Bigelow, 2010).

Firms can also add value by providing an integrated system of use to the users by making different components work seamlessly, when there are factors that cannot be perfectly predefined by design rules. Since interdependencies can continually emerge throughout the value delivering system of products despite the efforts to limit them

(Staudenmayer et al., 2005), coordination benefit may still be available to the customers. When additional product or service enables better integration of usage across products, more customers may be willing to pay higher price for the combination of products offered by a single supplier (Chatain, 2011; Stremersch & Tellis, 2002). Such integration through bundled products and services can further increase customer profitability, which constitutes another source of value added (Hinterhuber, 2002). For instance, faced with growing pressure to make different kinds of office software programs work together better, a product bundle that could integrate word processing, spreadsheets, databases, and presentation graphics seamlessly became much more valuable than the components individually. Consequently, the early 1990s witnessed a move from stand-alone software products (such as WordPerfect or Microsoft Excel) to suites of integrated software products (such as Microsoft Office) designed to work better in combination (Gandal et al., 2018; Schilling, 2000). A firm can also strategize to deliver the integrated product system by developing systemic innovations to create greater value. The combined product systems can allow customization addressing heterogeneity in users' demand, which is induced by their ability to mix and match. For example, in the bicycle drivetrain industry, Shimano persisted with integration strategy despite the initial modularity in product architecture and deliberately introduced systemic innovations that offered mountain bike riders superior performance (Fixson & Park, 2008).

In addition, demand for high degree of customization can be an important determinant affecting firms' product scope. In a context characterized by high degree of customization, the internal coordination of demand-side dependency will incur less cost and greater benefit than the external coordination. This will result in expansion of product scope to appropriate added value from integration across products. To be effective, they must understand all parts of a complex process in enough detail to address defects and cater to heterogeneous customer demand (Baldwin, 2020). Diversification across modular products than specialization may be more feasible for firms to differentiate (Brusoni et al., 2001). For example, construction projects, movies and TV shows that require customization and/or integration of subprojects (Brady, Davies, & Gann, 2005; Hobday, Davies, & Prencipe, 2005), the agents contributing to the final product may be brought together through the efforts of a systems integrator, who is responsible for making sure the whole system works (Brusoni et al., 2001).

Product Scope Expansion to Create Integrative Systems in Medical Imaging

The different types of medical imaging equipment prior to the emergence of PACS were hardly able to form a system of use, despite being complementary in use for radiologists. Users would often manually print out scans on films to compare, transfer them from one physical location to another, or store them in a room already packed with older films, which often resulted in loss and repetitive scans. Manufacturers were incentivized to provide the proprietary equipment, and very few with technological capabilities attempted to build a local ecosystem to create lock-ins and achieve market power early on to secure a solid customer base.

However, the arrival of a medical image communication platform and interoperability standards sparked the transformation of product architecture and therefore the system of use. Connectivity enabled by the interface standard allowed relevant functions and technologies from various vendors to be linked, increasing the potential size of users' utility arising from the joint use of complementary products

(Jacobides et al., 2018). Accordingly, users' preference has shifted from product-level demand to seamless integration among different equipment. Prior to the product compatibility, users were not able to create a combination of products and services due to the lack of standard. Post-standardized platform, however, users could find the combination that suits their workflows at the hospitals. Since the context also allowed for the high degree of customization, the integration tailored to the specific need of hospitals could significantly improve radiologists and physicians' productivity in making precise and timely diagnosis of a patient, and thus increase willingness to pay for better integration across products.

Because the standard was free to all and allowed open access, firms were now able to easily create integrated solutions around the platform. Creating own platform standards requires extensive costs and efforts especially for manufacturing firms, evidenced by one of the executives at a PACS company. Freely accessible standards meant lower cost for the manufacturing firms to incorporate in their own product and corresponding software applications. Having decomposed modules that can be easily assembled together, firms might have been able to add different functionalities or aesthetics to a certain module and fit together with other components with less cost (H. L. Lee & Tang, 1997).

However, firms varied in their capability and incentive to create such customized integrative systems. As modularity-in-use increased demand heterogeneity, especially the incumbent imaging equipment firms that had their own proprietary platform software were both able and incentivized to leverage customer relationships to garner better knowledge on their preferences. Leveraging existing relationship with their customers, platform software providers can further expand businesses in the imaging product markets by bundling its own software's functionality with that of the imaging devices. Access to the market information on users' preference through existing user base helped these firms identify that hospitals' main concern was workflow optimization and the radiologists wanted to achieve efficiency through seamless interoperability across different equipment. Firms having more insights into customers' changing demands could engage in more product innovation. Firm having better understanding of how consumers use products differently could provide better integration across products. Such envelopment could further create demand-side synergy for customers by pushing out other imaging device firms (Eisenmann, Parker, & Van Alstyne, 2011). By providing diverse products, software providers could solidify the lock-in effect with their platform software, prevent further entry (Cusumano & Gawer, 2002), and lessen dependence on other imaging device firms (Jacobides, MacDuffie, & Tae, 2016).

The results jointly suggest that incumbent firms with the platform software expanded the scope of product-focused activities towards integrated solutions around an open platform. By incorporating human factors that were not amenable to being modularized, diversified firms created integrated and customized systems designed to work better together. On the other hand, firms without such software service repositioned themselves as specialists in modular product space.

Discussion and Conclusion

The paper investigates a novel context of where the products that were technologically independent but related on the demand-side become modular-in-use through the introduction of an industry-wide interface standard. While modularity increased competitive pressures by allowing new entrants and decreasing potential for demand-side economies of scope, it also allowed mix and match by the customers and creates opportunities to address heterogeneous customer demand. The quantitative analysis on the U.S medical diagnostic imaging equipment manufacturers revealed that firms on average increased product diversity despite the modularization and the pattern was strongly driven by the firms that were able to leverage their pre-existing demand-side economies of scope. The qualitative evidence corroborated such findings.

We see in many industries the sources of competitive advantage shift from superior standalone products to integrated value propositions based on an ecosystem of interdependent products. In particular, digital connectivity creates an ecosystem around existing products and transform them into components of a larger product system (Fixson & Park, 2008; Stonig, Schmid, & Müller-Stewens, 2022). How a firm can adapt its focal product activities to support the emergence of an ecosystem has thus become a critical strategic question (Ganco, Kapoor, & Lee, 2020). Answers to the question could enhance understanding of the processes and mechanisms underlying the adaptation of established firms facing new integrated value propositions (Altman, Nagle, & Tushman, 2022).

Several limitations of this paper bear noting. First, and perhaps more importantly, the analyses are not entirely free from endogeneity issues even though I employed subsample analysis with a lagged time frame and examined within-firm variations. Inherent in firms' scope decisions, unobservable characteristics of firms or environmental factors might have confounded the results I found. Second, my analysis is based only on a single context, which presents both empirical and inferential challenges. A key empirical challenge is that the results would be confounded by any unobservable event that affected the hospitals' IT software adoption rate. The single context study compromises external validity, of which the results may be idiosyncratic to the medical diagnostic imaging industry. Given that the industry is characterized by high degree of customization, future work can examine generalizability of the findings to different contexts and investigate other boundary conditions.

The paper contributes to several streams of literature. By investigating how incumbent firms adapted to increased dependencies of their products with competitors', the paper contributes to the research on incumbent response in strategy literature (Ethiraj & Zhou, 2019; Seamans & Zhu, 2017). Especially by looking at how firms adapt to the changing environment as a traditional value chain industry shift towards increased dependencies through modularization. To the modularity literature, while the previous discussion on modularity has been so far reduced to the implication on manufacturing and innovation efficiencies, when your customers start having modularity-in-use as a result of that design, then there can be another route for a strategic implication to the firms, which is product diversification to leverage demand heterogeneity. The paper also adds to the work on within-industry diversification by providing a boundary condition for the related diversification, when there is limited room for supply-side synergy and demand-side relatedness looms large (Schmidt et al., 2016; Siggelkow, 2003; Tanriverdi & Lee, 2008; Ye et al., 2012). By accounting for the context and period where firms faced transformation from analog to digital form, the paper contributes to the work on the implications of the emerging digital age for corporate strategies (Menz et al., 2021). Lastly, to the research on ecosystem and interfirm dependencies, it describes a strategic implication of demand-side interdependency. The primary focus in the literature has been on how firms position themselves in an ecosystem based on the supply-side technological interdependencies (Adner & Kapoor, 2010). The paper further made special emphasis on the role of demand-side interdependencies, arguing that when customers have modularity-in-use as a result of modular design, diverse product portfolio can serve as integrated knowledge for managing demand-side interdependencies.

Tables and Figures

Figure 2-1. Picture Archiving and Communication System (PACS)

Source: https://www.gehealthcare.com/products/interoperability/ihe/radiology-pacs-workstations-mammo-ris-ihe-integration-statements ((accessed 10/27/2020)

Figure 2-2. Binned Scatterplot for average imaging product categories by firms

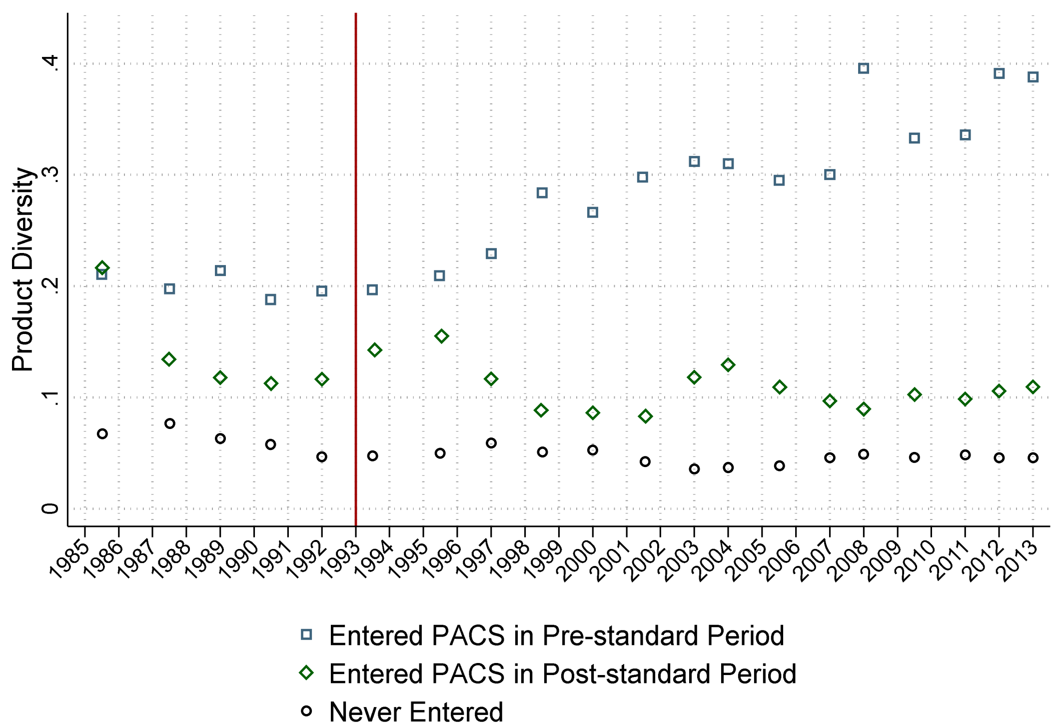
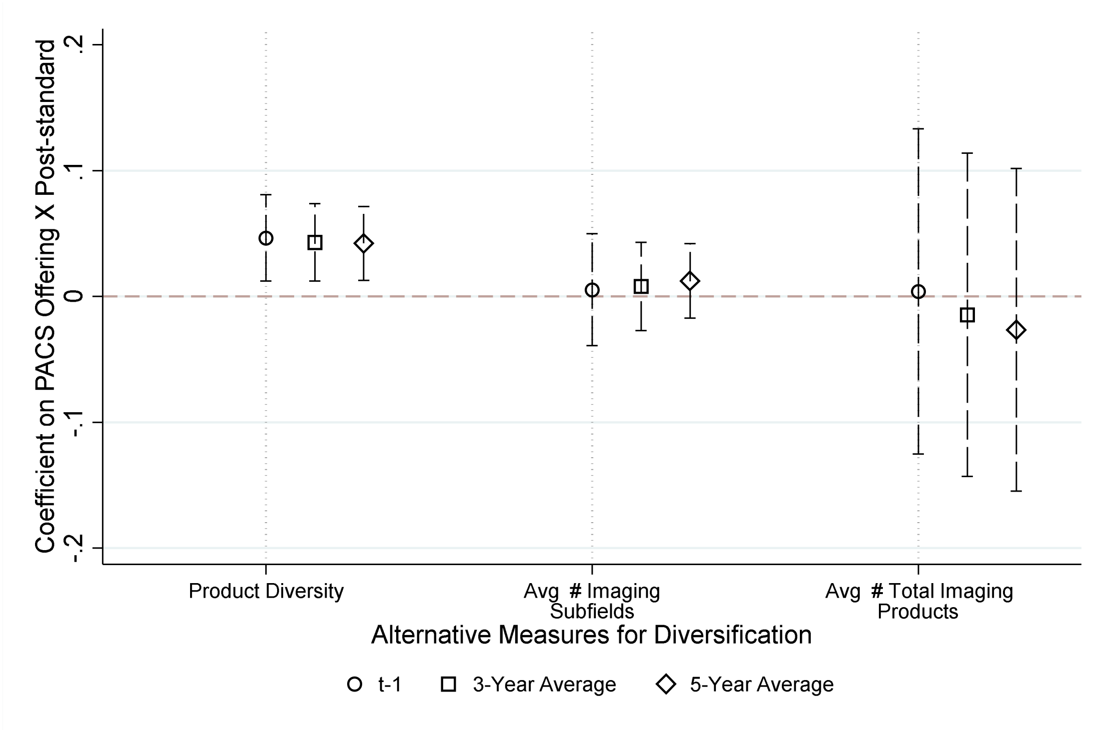


Figure 2-3. Coefficient estimates using alternative measures for product diversification



Note: Each estimate is constructed by using different operationalization for the key dependent variable, product diversification, defined by the graph. The coefficient estimates for *PACS Offering* × *Post-standard* are generated by running the main specification (equation(i)) with controls, firm- and year-fixed effects, and standard errors clustered by firm. *Average # Imaging Subfields* is the log count of medical imaging submarkets that a firm operates in year *t*, and *Average # Total Imaging Products* is the log count of all medical imaging products that a firm offered in year *t*, regardless of medical subfields. *Product Diversity* is a composite Herfindahl Index calculated based on the other two measures.

Table 2-1. Firms' product diversification pre- and post-standardization

	Study period	**Pre-standardization** 1985~1993	**Post-standardization** 1993~2013
Industry characteristics	**Interface standard** (i.e., image sharing format)	Very few firms offered proprietary compatibility standard	Common industry standard (DICOM)
	Platform software (i.e., PACS hardware and software)	Early stage Vendor-specific proprietary software (add-on features) Local connectivity	Growth and mature stage Vendor-neutral software platform Global connectivity
	Products (i.e., imaging equipment)	Connection was only possible between products from the same manufacturer	Compatible across different products from different manufacturers
	End-customers (i.e., physicians, radiologists)	Devices are independently used by end-consumers Latent need for compatibility across products from different manufacturers Lack knowledge in best product combination	Heterogeneous demand Knowledgeable regarding best product combination
Firms' product diversification	**Incentives to diversify**	Economies of scope in distribution and sales Demand-side synergy via providing one-stop shopping	Economies of scope in distribution and sales Demand-side synergy via providing one-stop shopping Demand-side synergies across integrated and customized systems Address increased demand heterogeneity induced by modularity-in-use
	Incentives to specialize	Limited scope economies in production due to heterogenous underlying technologies	Reduced demand-side economies of scope via open compatibility Increased competition

Table 2-2. Description of variables used in the main analysis

Variable	Description
Dependent variables	
Post 5-yr Product Diversity	Average of yearly Herfindahl index of a firm's product portfolio from *t+1* to *t+5,* using the number of imaging product categories within each of five markets
Patent Application	Log number of patent applications in year *t+1*
510(k) Application	Log number of FDA 510(k) applications in year *t+1,* subsequently approved
Platform Offering$_{t+1}$	1 if the firm offers PACS platform software in year *t+1*
Key explanatory variables	
Post-standard	1 if the year belongs to the post-standard period
Software Offering$_t$	1 if the firm offers PACS platform software in year *t*
Offered Platform Early	1 if the firm offered PACS platform software in pre-standard period
Offered Platform Late	1 if the firm offered PACS platform software in post-standard period
Product Diversity$_t$	Herfindahl index of a firm's product diversity using the number of imaging product categories within each of five markets in year *t*
Pre-standard Product Diversity	Average of yearly Herfindahl index of the firm's product portfolio pre-standardization period (i.e., 1985~1992), using the number of imaging product categories within each of five markets
Control variables	
Cross-industry Diversification	1 if the firm also operates in nonmedical industries in year *t*
# Medical Device Segments	Log count of medical device segments in which the firm markets products in year *t*
Patent Stock	Log cumulative count of the firm's patent applications from its establishment until year *t*
Direct Sales	1 if the firm owns direct distribution and sales function in year *t*
Indirect Sales	1 if the firm uses independent distribution and sales in year *t*
Firm Age	Log of the firm's age since its establishment in year *t*

Table 2-3. Summary statistics

Panel A. Descriptive Statistics

	N	Mean	*S.D.*	Min	Max
(1) Product Diversity $_{t+1-t+5}$	4025	0.09	0.19	0.00	0.75
(2) Platform Offering $_{t+1}$	4025	0.10	0.31	0.00	1.00
(3) Patent Application	4025	0.44	1.22	0.00	7.58
(4) 510(k) Approval	4025	0.14	0.49	0.00	3.61
(5) Post-standard	4025	0.69	0.46	0.00	1.00
(6) Platform Offering $_t$	4025	0.10	0.30	0.00	1.00
(7) Offered Platform Early	4025	0.06	0.25	0.00	1.00
(8) Offered Platform Late	4025	0.11	0.31	0.00	1.00
(9) Product Diversity $_t$	4025	0.08	0.19	0.00	0.78
(10) Cross-industry Diversification	4025	0.33	0.47	0.00	1.00
(11) # Medical Device Segments	4025	1.23	0.49	0.69	2.83
(12) Patent Stock	4025	0.77	1.90	0.00	10.34
(13) Direct Sales	4025	0.67	0.47	0.00	1.00
(14) Indirect Sales	4025	0.51	0.50	0.00	1.00

Panel B. Correlation Table

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
(1) Product Diversity $_{t+1\text{-}t+5}$	1.00													
(2) Software Offering $_{t+1}$	0.26	1.00												
(3) Patent Application	0.15	0.36	1.00											
(4) 510(k) Approval	0.37	0.39	0.38	1.00										
(5) Post-standard	-0.06	0.06	-0.03	-0.09	1.00									
(6) Platform Offering $_t$	0.26	0.94	0.36	0.38	0.07	1.00								
(7) Offered Platform Early	0.28	0.60	0.44	0.48	-0.08	0.60	1.00							
(8) Offered Platform Late	0.11	0.44	0.03	0.05	0.04	-0.09	0.41	1.00						
(9) Product Diversity $_t$	0.88	0.24	0.14	0.36	-0.07	0.27	0.09	0.24	1.00					
(10) Cross-industry Diversification	0.10	0.13	0.26	0.11	-0.09	0.24	-0.05	0.14	0.11	1.00				
(11) # Medical Device Segments	0.23	0.17	0.23	0.19	0.00	0.25	0.01	0.18	0.23	0.07	1.00			
(12) Patent Stock	0.17	0.32	0.91	0.39	-0.01	0.37	0.06	0.32	0.16	0.24	0.22	1.00		
(13) Direct Sales	0.06	0.12	0.12	0.13	-0.05	0.07	0.05	0.11	0.06	-0.00	0.00	0.12	1.00	
(14) Indirect Sales	0.01	0.20	0.09	0.11	0.20	0.13	0.15	0.20	0.02	0.02	0.10	0.09	-0.21	1.00

Table 2-4. Selection into offering PACS platform software

DV: Platform Offering	(1)	(2)	(3)	(4)	(5)
Product Diversity	0.385	0.223	0.083	-0.037	-0.036
	(0.128)	(0.117)	(0.084)	(0.083)	(0.083)
	[0.003]	[0.057]	[0.326]	[0.657]	[0.663]
Post-standard		0.028	0.036	0.018	
		(0.020)	(0.023)	(0.024)	
		[0.171]	[0.108]	[0.439]	
Product Diversity × Post-standard		0.268		0.189	0.190
		(0.127)		(0.087)	(0.087)
		[0.035]		[0.031]	[0.030]
Cross-industry Diversification			0.202	0.152	0.151
			(0.157)	(0.139)	(0.137)
			[0.197]	[0.276]	[0.272]
# Medical Device Segments			0.025	0.027	0.029
			(0.028)	(0.027)	(0.028)
			[0.370]	[0.322]	[0.309]
Patent Stock			0.002	0.002	0.001
			(0.013)	(0.013)	(0.012)
			[0.876]	[0.897]	[0.937]
Direct Sales			0.007	0.006	0.006
			(0.029)	(0.029)	(0.030)
			[0.820]	[0.847]	[0.841]
Indirect Sales			0.034	0.035	0.034
			(0.022)	(0.022)	(0.024)
			[0.129]	[0.117]	[0.153]
Constant	0.072	0.053	-0.048	-0.021	-0.009
	(0.015)	(0.017)	(0.072)	(0.067)	(0.069)
	[0.000]	[0.003]	[0.505]	[0.751]	[0.891]
N (firm-years)	4,025	4,025	4,025	4,025	4,025
n (firms)	450	450	450	450	450
R^2	0.06	0.07	0.81	0.81	0.81
Firm FE			✓	✓	✓
Year FE					✓

Note: Standard errors clustered by firm in parentheses and *p*-values in brackets. In Column 5, the term *Post-standard* is subsumed after inclusion of year-fixed effects.

Table 2-5. Product diversification in pre- and post-standard periods

DV: Product Diversity	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**
Post-standard	-0.024	-0.034	0.016	0.012	
	(0.013)	(0.013)	(0.009)	(0.010)	
	[0.066]	[0.010]	[0.076]	[0.203]	
Platform Offering		0.138	0.046	0.012	0.012
		(0.071)	(0.026)	(0.027)	(0.027)
		[0.051]	[0.076]	[0.663]	[0.645]
Platform Offering × Post-standard		0.037		0.043	0.042
		(0.063)		(0.018)	(0.018)
		[0.557]		[0.018]	[0.018]
Cross-industry Diversification			0.005	0.005	0.003
			(0.016)	(0.016)	(0.016)
			[0.760]	[0.742]	[0.857]
# Medical Device Segments			0.002	0.004	0.004
			(0.007)	(0.007)	(0.007)
			[0.734]	[0.568]	[0.577]
Patent Stock			0.008	0.007	0.006
			(0.003)	(0.003)	(0.003)
			[0.011]	[0.038]	[0.074]
Direct Sales			-0.005	-0.006	-0.006
			(0.012)	(0.012)	(0.011)
			[0.676]	[0.604]	[0.609]
Indirect Sales			-0.003	-0.002	-0.004
			(0.009)	(0.009)	(0.009)
			[0.761]	[0.839]	[0.663]
Constant	0.103	0.093	0.093	0.067	0.078
	(0.014)	(0.014)	(0.014)	(0.012)	(0.010)
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]
N (firm-years)	4,025	4,025	4,025	4,025	4,025
n (firms)	450	450	450	450	450
R^2	0.00	0.08	0.91	0.91	0.91
Firm FE			✓	✓	✓
Year FE					✓

Note: Standard errors clustered by firm in parentheses and *p*-values in brackets. In Column 5, the term *Post-standard* is subsumed after inclusion of year-fixed effects.

Table 2-6. Software offering and product innovation in the post-standard period

Dependent Variable:	Patent Application		510(k) Application	
	Full	Categorical	Full	Categorical
	(1)	(2)	(3)	(4)
Platform Offering	-0.606		0.166	
	(0.304)		(0.124)	
	[0.046]		[0.182]	
Post-standard	0.049	0.039	-0.041	-0.033
	(0.031)	(0.032)	(0.014)	(0.013)
	[0.120]	[0.216]	[0.005]	[0.010]
Platform Offering × Post-standard	0.743		-0.216	
	(0.311)		(0.129)	
	[0.017]		[0.095]	
Offered Platform Early × Post-standard		0.729		-0.169
		(0.322)		(0.128)
		[0.024]		[0.188]
Offered Platform Late × Post-standard		0.037		-0.104
		(0.141)		(0.102)
		[0.790]		[0.308]
Cross-industry Diversification	0.274	0.297	0.251	0.292
	(0.113)	(0.130)	(0.121)	(0.149)
	[0.015]	[0.023]	[0.039]	[0.051]
# Medical Device Segments	0.024	0.032	-0.021	-0.021
	(0.050)	(0.050)	(0.024)	(0.023)
	[0.626]	[0.522]	[0.390]	[0.360]
Patent Stock	0.329	0.330	0.022	0.021
	(0.054)	(0.054)	(0.012)	(0.011)
	[0.000]	[0.000]	[0.056]	[0.071]
Direct Sales	-0.026	-0.021	0.021	0.019
	(0.050)	(0.049)	(0.022)	(0.021)
	[0.605]	[0.666]	[0.328]	[0.370]
Indirect Sales	-0.031	-0.029	0.045	0.044
	(0.031)	(0.030)	(0.019)	(0.018)
	[0.319]	[0.335]	[0.016]	[0.016]
Constant	0.068	0.022	0.058	0.056
	(0.092)	(0.097)	(0.052)	(0.059)
	[0.459]	[0.820]	[0.267]	[0.337]
N (firm-years)	4,025	4,025	4,025	4,025
n (firms)	450	450	450	450
R^2	0.90	0.90	0.79	0.79
Firm FE	✓	✓	✓	✓

Note: Standard errors clustered by firm in parentheses and *p*-values in brackets. Columns 1 and 3 display results from the panel regressions. Columns 2 and 4 display results for the three groups of firms by their PACS software ownership: (a) firms that began offering platform software in pre-standard period (prior to 1993), (b) began offering in the post-standard period, and (c) never offered software throughout lifetime. The base line category is the third category (c).

Table 2-7. Pre-standard platform software offering and product diversification in post-standard period

DV: Product Diversity		**Subsample**		**Full Sample**	
	Offered Platform Pre-standard	Offered Platform Post-standard	Never Offered		
	(1)	(2)	(3)	(4)	(5)
Post-standard	0.036	0.058	0.011	-0.024	
	(0.020)	(0.039)	(0.010)	(0.014)	
	[0.091]	[0.146]	[0.288]	[0.087]	
Offered Platform Early				0.108	0.107
				(0.062)	(0.062)
				[0.081]	[0.084]
Offered Platform Late				0.066	0.066
				(0.057)	(0.057)
				[0.244]	[0.245]
Offered Platform Early × Post-standard				0.122	0.123
				(0.070)	(0.070)
				[0.081]	[0.081]
Offered Platform Late × Post-standard				0.019	0.017
				(0.049)	(0.049)
				[0.704]	[0.721]
# Medical Device Segments	0.008	-0.033	0.011	0.065	0.066
	(0.019)	(0.028)	(0.007)	(0.018)	(0.018)
	[0.680]	[0.245]	[0.119]	[0.000]	[0.000]
Patent Stock	0.004	0.032	0.003	0.002	0.002
	(0.002)	(0.014)	(0.002)	(0.007)	(0.007)
	[0.087]	[0.029]	[0.228]	[0.769]	[0.764]

Direct Sales	-0.015	-0.014	-0.005	0.009	0.009
	(0.018)	(0.015)	(0.015)	(0.016)	(0.016)
	[0.417]	[0.373]	[0.742]	[0.562]	[0.576]
Indirect Sales	-0.008	-0.024	0.003	-0.015	-0.017
	(0.019)	(0.022)	(0.012)	(0.017)	(0.017)
	[0.678]	[0.289]	[0.782]	[0.363]	[0.328]
Cross-industry Diversification		0.006	-0.005	0.014	0.014
		(0.036)	(0.005)	(0.021)	(0.021)
		[0.860]	[0.320]	[0.508]	[0.489]
Constant	0.256	0.134	0.045	-0.001	-0.018
	(0.031)	(0.040)	(0.015)	(0.027)	(0.026)
	[0.000]	[0.002]	[0.002]	[0.971]	[0.484]
N (firm-years)	260	436	3,329	4,025	4,025
n (firms)	19	41	390	450	450
R^2	0.97	0.90	0.88	0.14	0.14
Firm FE	✓	✓	✓		
Year FE					✓

Note: Standard errors clustered by firm in parentheses and *p*-values in brackets. Columns 1-3 display results from the panel regressions on the corresponding subsample of firms. Columns 4 and 5 display results for the three groups of firms by their PACS software ownership: (a) firms that began offering platform software in pre-standard period (prior to 1993), (b) began offering in the post-standard period, and (c) never offered software throughout lifetime. The base line category is the third category (c). In Column 5, the term *Post-standard* is subsumed after inclusion of year-fixed effects.

Table 2-8. Summary of Robustness checks

Concerns	Robustness checks
A. Alternative Explanations	
1. Technological capability is the primary reason behind diversification	Little overlap among imaging technologies, between hardware and software capabilities. Results robust to inclusion of firms' patent stock as a control variable.
2. Tight relationships with customers or downstream distribution channel may enable firms to diversify due to economies of scope in sales and distribution	The effect of a firm switching from one distribution to another is controlled by inclusion of firm-fixed effects and firms' distribution method as a control.
3. Dominant firms could push their own platform to become a standard, that might also affect the pattern.	The standard setting process did not favor a certain company and was supervised by the user association and regulatory agents such as FDA and Federal Trade Committee.
4. Hospitals have been consolidating throughout the study period, which may create change in the competitive landscape and lead firms make expansion through diversification.	The period is also characterized by the expansion of free-standing imaging centers, or outpatient imaging centers, which makes the demand environment remain competitive.
B. Research Design	
5. Firms may have selected into software offering.	Results remain consistent in Table 2-7 using subsamples of firms that entered pre-standard versus never entered.
6. Large diversified firms are few outliers driving results.	
6. Operationalization of dependent variable	Results stay robust to using alterative operationalization of the dependent variable (e.g., t+1, number of product categories)

Appendix

Table A2-1. Representative quotes from interviews

Theme	Representative quotes	References	Informants
Pre-standard			
Creating local interoperability	"Siemens had decided to make SPI [Siemens Internal Standard]. Siemens decided that all imaging equipment, ultrasound, MRI had to meet SPI to guarantee some compatibility. So, since 1985, 1986, all Siemens modalities became compatible to SPI." "We had an internal network standard, which was called PMSNet [Philips Medical System Network]"	2/6 (33%)	2/6 (33%)
Accumulating market and technological knowledge through prototype	"Around 1985, I told my bosses and my colleagues in the engineering development department, now … we should set up models. So, we invented the word PDM, PACS Demonstration Model, that was a very important step. The PACS Demonstration Model consisted of an imaging modality, at least one, maybe two or three cities. A workstation which means something to display the pictures, to post process the pictures. A network to transport pictures and a storage or archiving system… [We] installed such PDM in Austria, another one ... in Canada, … a third one in Belgium, in hospital and one in France. There were four PDMs where we could really prove the principles of facts. And through this process after two years or so, I wrote a second specification. It was merely a booklet, but I called it customer requirement specification. So put all together what we learned from these PDMs, what they turned out, okay, it's feasible, but the technique available at that time, that's not enough."	3/6 (50%)	2/6 (33%)
Post-standard			
Differentiating effort by adding	"There are still some proprietary stuff that the vendors put in… You can't punish people if they don't adhere to DICOM. But we have had situations where the vendors put stuff in proprietary elements that are supposed to be in part of the	3/15	1/3

proprietary element on top of standard	standard… We had a problem for a while with radiation dose. For CT machines, you have to report the rate. Well, for a while, the vendors put all that stuff from proprietary fields so you couldn't get to it. And what we wound up doing is one of my colleagues, she and a couple of medical students, I think. They got a paper out of it; it was pretty good. They figured they'd basically did a screen capture." "Definitely, there was some advantage to having all your equipment from a single vendor. Because there was more proprietary stuff in there because the vendors were doing things that had not yet been standardized in DICOM. Primarily, we have some new imaging sequences in MRI, and they're not yet coded, they're not yet supported in DICOM. So, if you buy our equipment, hey, are PACS will support that method. That's decreasing steadily. We still have it."		
Learning about heterogenous market demand	"My duty at that time was to talk especially to radiologist… in Canada, US, and Europe, ask them what they would like to have, what they need, what they would be able to compromise because the technique as not sufficient enough. That was existing in much different because people are different. … it was just about the technique, but even it was hard to understand radiologist and his special needs." "But I think for Siemens, it was very helpful to have many small projects because the requirements we have are much different. It depends how radiologist is able and how willing he is to adapt to a technique." "PACS is not just this configuration of hard and software, it includes the science or the knowledge of the behavior how a radiologist and assistants, how they work. It all has to come together, become routine." "There's the three components. There's the radiologist, the healthcare provider, and then there's the technologist. So, you got to meet those performance user interface that fits the requirements of the users. And what we do is we look at how well they do those things."	4/15	2/3
Costly integration across	"Later on, DICOM came. And now, we had to make SPI and DICOM compatible. It was developed what we later called SiNet [Siemens Networking]. Especially these are software services which allow to combine SPI with DICOM to make it compatible. We made it compatible without having to change the modalities inside, compatible by	8/15	2/3

software and hardware	these [software] services. That was in the 1990s. It was, I would say a huge redevelopment." "It seems to be extremely difficult to be a hardware company, selling IT or be an IT company selling hardware, because we tried that… We decided to invest in [mammography] a little bit. And then, one thing led to another. It ended up with us building an entire mammography device. That was a huge mistake. We couldn't do that. We don't know how to... You can't ship an X-ray tube with an attachment and in an email. And I still remember, a customer in Germany called us and said, "It's growing green algae in the cooling system." And then, "What? We didn't know how to deal with green algae." We're a software company. So, we didn't succeed that. We never got it working properly. "It was too expensive, but the salespeople and the countries, needed something digital from Philips… So, outside of Sweden and Norway, Philips sold our PACS. Especially notably, they sold it in the US. We started up a little company set on North America, but that was only there to support Philips with expertise, because we didn't trust Philips could do it well, because they didn't know enough about digital. And that was around 1997."		
Differentiating factors			
Customer service and upgrade	"[For] IT, you work with the customer all the time and they will not leave you have to eight years… [Failed companies] can't keep up with development… They think they don't have to do upgrades over the eight years and then, after years they will sell a new one. It doesn't work like that. And the fact is that, none of them have succeeded, not in the systems' area." "Customer satisfaction, of course. …some of these big companies think that customers would buy from them, just because they are big. That works for a while, but not long term. So, you need to keep customers happy for a reasonable price… Every single employee at Sectra has to do five or three customer visits per year."	3/19	1/4

	"When we got the FDA clearance finally, customers in the U.S., they require a service engineer, live flesh in a car within a four-hour drive, over the entire us. That doesn't work. We can't do that. We didn't know how to do it."		
Different combination of functionalities	"The PACS companies could actually also come with the clinical applications on PACS workstations. They say, we will sell you the PACS which is a sort of big repository, a big memory. Then we will sell you workstations. But for these images we can do a lot of applications and we can also sell you these. And then you get a kind of competition on clinical applications on workstations." "Other vendors can look at that and say, "I can support this and this and this and this." It also allows you to negotiate… GE may have a compression method that's faster, but that the PACS vendor doesn't support. And you say, "If you don't support that, I support this compression." You say, "I don't support any of those. So, we're going to do default." And default can be everybody has to do the default compression or non-compression." "Because there was more proprietary stuff in there because the vendors were doing things that had not yet been standardized in DICOM… [They say] 'we have some new imaging sequences in MRI, and they're not yet supported in DICOM. So, if you buy our equipment, hey, our PACS will support that method.'" "If we win a PACS, it's a lot of services involved. So, we both sell the system and the software, but we also sell a lot of services. We actually do the project. It's like an ERP. You have to connect the ERP to everything. The companies, other IT systems, in order to make it to work and all that integration work is done in the project."	4/19	3/4
Superior integration	"The PACS in that case has to be able to talk to your electronic healthcare record… It's nice to know that if I'm reading a radiology study, and I click on the patient, that the electronic healthcare record, when it opens up that patient's file, it puts right at the first screen that comes up all the stuff that I'm interested in. So, I'm reading a CT scan with contrast. What are the renal function parameters? What are the symptoms? What are the lab values? All those sorts of things. Obstetrical ultrasound, how many weeks of bleeding. So, that's the thing I like to know, rather than having to go and search through it. And some vendors do a better job of it than others. And partly, it's	4/19	2/4

	because of the lack of that connection between the PACS and health information system." "Stability of the system. We have very little downtime, if these systems go down. All operating rooms today have it and won't open with the patient images while operating. If the system goes down in operation time, that could stitch that patient up and restart next day. When the PACS systems are so large, it might be 30 ORs, that 30 patients have been stitched up, because the imaging system doesn't work. So, it is extremely sensitive system and we are very good at stability. "Our customers do not buy from us because it's a PACS. The computers are not their prime interest in life. They want to do their job. Then we need to provide a system that does that, with stability and performance." "We both sell the system and the software, but we also sell a lot of services. We actually do the project… The companies, other IT systems, in order to make it to work and all that integration work is done in the project."		
Superior functionalities	<u>*User interface*</u> "The other major one is the user interface part. How easy is it to use your system? …if I can get to displaying images and manipulating them without having to look at an instruction manual, or have somebody point to and say, "Oh, click this, click this, click this," that's another thing is that user interface. Does it fit a reasonable mental model? That's another way to look at it… And the interesting thing about PACS, not only easily usable by the radiologist, it also has to be easily usable by the technologists who generate the images… Their requirement's a little different. So, there's the three components. There's the radiologist, the healthcare provider, and then there's the technologist. So, you got to meet those performance user interface that fits the requirements of the users. And what we do is we look at how well they do those things." <u>*Workflow management*</u> "And to some extent, on how well they manage workflow. So, how many times do I have to click on things to get to looking at an image? And then once I do that, how much do I have to go through to dictate my report?"	8/19 3/19 2/19	1/4 1/4 1/4

	"So, vendors who can do that, who can integrate these reporting things with their viewing things, that's another feature. Some can do it better than others. The workflow management part. So, how do I get from scheduled to interpretation from when it gets ordered?" *Image quality* "So, the imaging vendors differentiate themselves typically by speed and by image quality. So, if your images look good, that's going to sell the radiologist. And it's going to sell the other referring doctor. Particularly for those of us who have to read these things, we'd like good images. So, that's key. We told the vendors, a machine can have a lot of bells and whistles but if the images aren't good, doesn't matter." *Speed* "What they generally do is performance is one. Speed. When I say I want to see this image, and I hit the button, how long does it take for it to show up? That's one differencing characteristic."	 1/19 1/19	 1/4 1/4
Price	"Generally, big health systems will get a very large purchase price advantage if they buy from a single vendor. Usually, we build in a carve out. So, you see 80% of your equipment has to come from us. Otherwise, 20% come from anybody you want. So, that allows for the individual division or whatever to use what they want. [The vendors] used to want to make it a requirement. Or they tell you that there's a huge advantage that if all your equipment comes from us. Right now, that advantage is primarily in pricing. It's not so much in performance as it is in pricing."	1/19	1/4

Chapter 3. Weathering a Demand Shock: The Impact of Prior Vertical Scope on Post-shock Firm Response

Introduction

Negative environmental shocks—such as a sudden decrease in demand—create a new "equilibrium state" in the market and require firms to appropriately adjust to new realities. These shocks pose unique and important sets of strategic problems to firms distinct from other types of environmental changes, such as those resulting from technological shocks (e.g., radical technologies, innovations introduced by rivals) or evolutionary trends (Argyres et al., 2019; Bigelow, Nickerson, & Park, 2019) Negative demand shocks may not uniformly affect all firms in the same industry, however. Heterogeneity of firms in vertical integration of value chain activities and associated differences in positioning and capabilities (Ghemawat, 1991; Helfat & Campo-Rembado, 2016; Karim, 2006) implies the same shock results in differences in firm responses and (involuntary) decisions to exit the market (Argyres et al., 2019). Though scholars have examined how organizations adjust their vertical scope when faced with environmental changes (Bigelow et al., 2019; Kapoor & Adner, 2012; Qian et al., 2012), left relatively unexamined is how *prior differences* in vertical firm scope affect firms' ability to adapt to environmental changes.

In this paper, we conceptualize firms' pre-shock vertical scope as a representation of its existing set of resources and governance choices (Argyres, Felin, Foss, & Zenger, 2012), and examine how and why pre-existing vertical scope may cause differences in organizational responses to negative demand shocks. Examining this question is important for firm level consequences in terms of ability to reposition and/or exit. Such firm level consequences additionally may alter the overall industry structure through changes in the composition of firms with different vertical scope and positioning. Answering the research question also allows for an empirical disentangling of the endogeneity arising from the interdependence between firms' adjustment and vertical scope decision. While some scholars have used an instrumental variable approach to address this issue (Argyres & Mostafa, 2016; Forbes & Lederman, 2010; Kosová, Lafontaine, & Perrigot, 2013; Novak & Stern, 2008), an inherent challenge arises because firms adjust transaction costs and capabilities in ways that also affect vertical scope (Forbes & Lederman, 2010; Richardson, 1996). The utilization of an industry-wide shock provides the empirical ability to investigate how differences in pre-shock vertical scope and organization of transactions may affect the firm's post-shock adjustments.

We use an abductive approach to examine our research question within the context of the U.S. diagnostic imaging industry in 2004-2009. Within medical devices, a setting extensively used to examine firm structure of value chain activities and capability (re-)configuration (Chatterji, Cunningham, & Joseph, 2019; Karim, 2006; Mitchell, 1989b, 1991), the medical diagnostic imaging industry is particularly suitable for our difference-in-difference-in-difference research design. The industry consists of multiple markets; some but not all experienced an adverse derived demand shock due to the Deficit Reduction Act. Also, firms in the industry can be distinguished based on their pre-existing vertical scope. Moreover, rich quantitative and qualitative data from diverse sources enable us to probe into different mechanisms at play in firm adaptation.

The empirical analysis reveals that integrated firms were more likely to exit markets affected by the adverse demand shock compared to nonintegrated firms. We explain this pattern by showing that integrated and nonintegrated firms responded differently by leveraging their own distinctive capabilities (specialized sales force, distribution networks, types of relational capital). We infer that the higher market exit of integrated firms is consistent with both voluntary decisions (resource redeployment) and higher adjustment costs (competitive pressures).

The paper contributes to existing literature by unpacking how prior vertical scope affects firm responses post-shock. While theoretical priors preclude an unequivocal prediction (Argyres & Bigelow, 2010; Chatterji et al., 2019; Folta, Helfat, & Karim, 2016; Wang, Aggarwal, & Wu, 2020), the empirical analysis reveals that integrated firms were more likely to exit markets affected by the adverse demand shock compared to nonintegrated firms. Our study also extends work at the integration of transaction cost economics, capabilities and positioning perspectives (Argyres et al., 2019; Zenger, Felin, & Bigelow, 2011) through additional analysis and qualitative insights. We show that integrated and nonintegrated firms each responded by attempting to leverage their own distinctive capabilities (specialized sales force, distribution networks, types of relational capital), and that higher market exit of integrated firms is consistent with both voluntary decisions (resource redeployment) and higher adjustment costs (competitive pressures). Finally, prior work has shown that industries reflect more disintegrated vertical structures as they evolve (Bigelow et al., 2019; Kapoor, 2013; Qian et al., 2012), and our study provides evidence that negative environmental shocks may also contribute to changing compositions of firms.

Can Vertical Scope Explain Market Exit under Negative Demand Shock?

Firms' Pre-existing Vertical Scope as Representation of Capabilities

We focus on firms' pre-existing downstream vertical scope as a key source of firm heterogeneity, building on prior studies that have integrated transaction cost economics (TCE) and resource-based view (RBV) lenses (Argyres & Bigelow, 2010; Brahm & Tarziján, 2014; Jacobides & Winter, 2005; Qian et al., 2012; Zenger et al., 2011). This literature highlights that "*integration of a given activity varies from firm to firm and depends on its history and the idiosyncratic activities in which it is already engaged in and the extant resources it possesses*" (Zenger et al., 2011, p. 120). Moreover, the choice of vertical scope also reflects firms' efforts at optimizing the fit of their resources and capabilities with desired strategic positioning in the industry (Argyres & Bigelow, 2010; Brahm & Tarziján, 2014). Thus, a firm's vertical scope represents path-dependent decisions regarding governance and capability development within and across firm boundaries to establish a position.

Integration of manufacturing and downstream capabilities is associated with several firm properties. Firm-specific investments in sales and distribution implies more control and decision rights over the distribution and sales process, thus reducing frictions and misalignment of interests (Brahm & Tarziján, 2014; Zenger et al., 2011). The common codes and routines developed within integrated firms also enable efficient communication and coordination. These streamlined routines reduce information asymmetry by facilitating real-time incorporation of information across manufacturing and downstream operations (Forbes & Lederman, 2010). Moreover, integration enables direct relational capital with buyers for learning and knowledge, which mitigates coordination and trust-based challenges and increases buyer switching costs (Wang et al., 2020). Such direct relational capital permits firms to acquire fast and accurate information about buyer needs and associated tradeoffs between price and quality so as to incorporate them in their products and services (Argyres & Bigelow, 2010). Vertical integration of downstream capabilities also complements a diversification strategy, inasmuch as the associated brand and reputation provide synergies for other businesses targeting the same customer segment (Harrigan, 1985). Taken together, integrated manufacturing and downstream capabilities allow firms to create customized products to accommodate heterogeneous buyer preferences (Argyres & Bigelow, 2010) by offering various product models representing different "mix and match" of features (e.g., product attributes, price, sales, marketing, maintenance, and service).

Meanwhile, nonintegration of manufacturing and downstream capabilities reflects a host of other properties. Both manufacturers and distributors can develop specialized capabilities for their own value chain activities to create product or service improvements and generate internal efficiencies (Jacobides & Winter, 2005; Kogut & Zander, 1992; Langlois & Robertson, 1995). Manufacturers can rely on distributors with preexisting logistics network and relationship with end-customers to obtain access, with speed and efficiency, to diverse geographic locations (Johanson & Vahlne, 2009). To do so, they may opt towards developing standardized knowledge for reduced asset-specificity and leakage hazards (Argyres & Bigelow, 2010). Moreover, nonintegrated manufacturers may develop relational capital with distributors for knowledge sharing and creation of complementarities (Dyer & Singh, 1998). Such relational capital also embeds effective governance to mitigate transaction hazards and sustain long term commitments (Kale, Singh, & Perlmutter, 2000). Nonintegration may not preclude diversification, as nonintegrated firms may develop relational capital with distributors within the focal market, and with the same or other distributors across a diversified business portfolio (Hoetker, 2005). Taken together, these properties associated with nonintegration allow firms to lower resource commitments by reducing scope of value chain activities and leveraging standardized products in distributor networks for economies of scale.[16]

Negative Demand Shock and Pressures for Market Exit

Consistent with prior literature, we define negative demand shock as an important and sudden industry level change that decreases aggregate demand and creates unexpected changes in customer preferences (Argyres et al., 2019; Priem, 2007; Wang et al., 2020). Negative demand shocks may originate from various events independent of firms' control and hard to anticipate, including natural disasters, technological advances, economic recession or government policy.

While the decrease in aggregate demand may be directly observable at the industry level in terms of both reduced price and quantity, such reductions in price and quantity are not uniformly distributed across firms, resulting in differences in individual demand that each firm faces. Instead, these reductions depend on individual demand elasticities, and importantly, on firm responses to the adverse shock. Firm response begins with the need to assess the negative impact on its expected profitability. Each firm has to sense-make the effects on its individual demand and identify how to adjust its

[16] Capability alignment for customization/standardization may correlate with positioning in terms of differentiation/low price respectively, but this is not necessary. Customization through mix and match of modular components can cater to both lower price/lower quality and higher price/higher quality preferences, while standardization may focus on fewer product offerings, but at the higher end of quality and price distribution. Thus, standardized products offered by nonintegrated firms may have higher, similar or lower price (and quality) features than the "average" price and quality features offered across customized options offered by integrated firms. Indeed, this is borne out in our context: integrated imaging firms offered greater variety of product models, but there is no evidence of their products being higher priced on average than nonintegrated firms. Moreover, advertisements by both types of firms across multiple issues of *Diagnostic Imaging* during our sample period revealed that neither firm pursued a cost-leadership positioning (i.e., we found no ads touting lower prices of diagnostic imaging equipment).

existing activities so as to bring its capabilities into closer alignment with new market conditions (Argyres et al., 2019). Engaging in such strategic renewal requires firms to incur adjustment costs, including costs associated with sense-making about the problem-solution scope (Nickerson & Zenger, 2004), workforce adjustment (Davis & Haltiwanger, 1992), modification of transactions with other value chain participants (Susarla, 2012), or reconfiguration of capabilities (Folta et al., 2016).

In the extreme case, if the disruptive effect on a firm's individual demand is deemed to be too high for a firm, it may choose to exit the market (quantity reduces to zero) without attempting any adjustment. Such a choice is more likely if the firm believes that the net benefit of redeploying its capabilities in other businesses (Anand & Singh, 1997; Lieberman, Lee, & Folta, 2017) or selling its assets (Fortune & Mitchell, 2012) is greater than the net benefit of adjustment. If a firm chooses to stay, adjustment pressures manifest in two ways—managing demand and reducing costs. Managing demand requires each firm to devise and enact strategies to retain the existing customer base or generate new demand to minimize a shift in its individual demand curve. Reducing cost requires the firm to create efficiencies in operations both within and across value chain activities. Here, differences across firms will likely result in differences in the strategies they undertake to manage demand and reduce cost. Should firms fail to match their product offerings with post-shock demand conditions or incur higher adjustment costs relative to their competitors, they are likely to succumb to competitive pressures and exit the product market in spite of their adaptation efforts.

Research Question Approach

In summary, post-aggregate-demand shock, differences in pre-existing vertical scope manifest not only in a differential impact on integrated and nonintegrated firms' individual demand curves, but each type of firm is also likely to enact different strategies to weather the demand shock in a manner that matches with their capabilities, relationships, and positioning. Thus, differences in strategies and positioning resulting from pre-existing vertical scope will lead to differences in the rates of firm market exit. These firm level consequences also imply important changes in firm composition and associated structural changes in the industry regarding value chain configuration.

However, it is *a priori* unclear from the theoretical rationale above whether a particular vertical firm scope is dominated by the other in terms of market exit under the negative demand shock. Prior literature on firms' vertical scope was unable to set apart the concurrence of firms' boundary choices and their actions driving market exit, resulting in empirical challenges to uncover the true underlying effect of having vertical scope integrated or not. Accordingly, we adopt a research question-based approach to ask: *how does a firm's pre-existing vertical scope affect its likelihood of market exit post a negative demand shock?* We first allow the empirics to adjudicate the relationship (or reveal existence of the relationship). Conditional on the statistical finding, we shed light on potential differences in the adaptation strategies enacted by integrated and nonintegrated firms, building on a set of quantitative and qualitative analyses (King et al., 2020).

Research Context: Demand Shock in Medical Diagnostic Imaging

The medical diagnostic imaging industry includes various markets reflecting unique production technologies and user applications: X-ray, computed tomography (CT), magnetic resonance imaging (MRI), ultrasonography (Ultrasound), and nuclear medicine. On the supply side, while all medical imaging equipment serve the common purpose of internal body visualization, these technologies vary in their ability to process different properties of human tissues, resulting in images that are markedly different and often complementary to each other. On the demand side, the major buyers of imaging equipment are hospitals and independent imaging facilities (Figure 3-1a). These facilities serve physicians who order body scans, and the choice (or combination) of diagnostic imaging is determined by medical needs and treatment plan. Hospitals and imaging centers generate most revenues for diagnostic imaging from public and private insurance reimbursements.

The differences across imaging markets in both technology and end-use imply that the device manufacturers vary in not only their degree of diversification (i.e., number of markets served in diagnostic imaging) but also how the firms organize their value chain activities. Figure 3-1b depicts differences in imaging firms' integration of value chain activities, including manufacturing and distribution/sales. Vertically integrated imaging manufacturers distribute and sell their products directly to customers (i.e., hospitals and imaging facilities). Nonintegrated manufacturers sell their products through third-party distributors.

[Insert Figures 3-1a-3-1b Here]

Demand Shock: The Deficit Reduction Act

The federal Medicare program is the largest insurance payor for healthcare in the U.S. since its inception. In 2006, Medicare covered roughly 43 million people, 36 million of whom were over 65 years of age (*2007 CMS Statistics*, 2007).[17] Medicare reimbursement rates are directly critical to hospitals and diagnostic imaging facilities, and moreover, many private insurers base their own reimbursement rates on Medicare rates.

The Deficit Reduction Act (DRA)—an effort to balance the national budget and reduce the deficit—was a major legislative change for Medicare payment policy. The legislation was signed into law on February 8, 2006 and took effect on January 1, 2007.[18] Particularly for our context, the *Diagnostic Imaging* trade magazine noted: "*After a late-night congressional session in December, Congress passed the Deficit Reduction Act, sending a shock wave that's still reverberating through the radiology community. Referred to by many in this community as "reduction without proper representation," this draconian act … has left many in a quandary, stipulating substantial cuts in services including MRI, CT, PET, ultrasound, nuclear medicine, vascular imaging, and bone densitometry. The only exception is mammography*" (Renard, 2006).[19]

The DRA imposed caps on payment rates for medical imaging services covered by Medicare.[20] For affected imaging services, a majority of scans performed were paid an amount less than the estimated cost of performing the procedure in an office setting (Dallessio, 2007). Moreover, reduced Medicare revenue was not offset by other private

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17 People under age 65 and covered under Medicare include those with disabilities and end-stage renal disease.

18 See the text of original provisions in Appendix A1. Importantly, until the law was signed, deficit reduction (across all industries) was a subject of significant congressional debate. Within the broad healthcare sector, there was significant uncertainty regarding the timing, types and severity of the DRA effect on healthcare providers (e.g., ambulatory services, hospital outpatient, independent clinics) and medical services (e.g., heart surgery, medical imaging, physical therapy).

19 Unsuccessful lobbying efforts to reduce the adverse impact on imaging services occurred *after* the passing of DRA. Goldstein (2007) noted *"two imaging trade groups hired 23 lobbyists last year to work on Medicare issues…But, this may not be enough to turn the tide—Congress has not scheduled any hearings on the imaging reimbursement issue this year, and members of both political parties have promised to make more cuts to Medicare spending."*

20 The DRA affected most imaging services covered by Medicare (i.e., X-ray, ultrasound, nuclear medicine, MRI, CT, excluding mammography). However, the imaging services that were not covered by Medicare remained unaffected from the policy change. These services include dental and ophthalmic imaging scans performed at dental and eye care clinics. As discussed later, the untreated imaging markets serve as our control group.

payors, inasmuch as many private payors adopted Medicare's cuts in creating their own new payment standards. Collectively, this resulted in dampening of growth in the use of imaging services and declining revenues (Levin, Rao, & Parker, 2012). For example, the Government Accountability Office Report (GAO) (2008, p. 7) noted that: *"From 2000 to 2006, both expenditures for and utilization of imaging services in Medicare Part B increased, but in 2007, expenditures decreased while utilization continued to rise."* Levin et al. (2012) provide evidence that hospital outpatient departments and independent imaging centers had very similar trends in utilization rates, though there were some differences across types of imaging (post DRA, CT and nuclear medicine volumes growth were higher in independent centers than hospitals, while MRIs were slightly better in hospitals than in independent centers). In terms of revenue impact, the GAO (2008) estimated that the DRA created a 12.9% decline ($1.7 billion) between 2006 and 2007 alone. Moreover, payment for the three advanced imaging services (MRI, CT, and nuclear medicine) dropped by 14.8% in 2007. Thus, changes in Medicare reimbursement rate policies had a significant and sudden effect on revenue streams of all customers of medical equipment manufacturers.

The DRA's imaging reimbursements cut became an adverse derived demand shock on imaging device manufacturers (Figure 3-1a). It significantly shifted purchasing decisions of customers, primarily manifesting in a need to contain overall operating costs and becoming more efficient in utilization of medical diagnostic equipment. Also, imaging facilities substantially reduced their routinized, large-scale commitments to upgrade and replace major equipment after the DRA. For example, hospitals and medical clinics reduced capital investment in new facilities, expansions, or upgrades, and began to cancel, postpone or scale down plans for purchase or lease of imaging equipment (Moser & Hastreiter, 2009). Radiologists expressed concern about reduced patient access to state-of-the-art equipment, noting that when *"government and other payors take money out of radiology, …we end up with are fewer dollars to upgrade or replace our major equipment."* ("Radiology Today Interview," 2018). Major imaging device manufacturers voiced similar concerns in their annual reports as they were experiencing the chain reaction of the DRA. The negative impact lasted for several years. For example, Philips (2008) acknowledged their *"sales growth was hampered by a declining US imaging market, triggered by the Deficit Reduction Act"*, and Analogic Corp (2009) noted their medical imaging products revenue was adversely impacted by the DRA. Similarly, GE reported *"not so healthy"* operating profits due to *"the 2006 law that reduced Medicare reimbursements by 20% for scans at physician offices, which made doctors and hospitals less likely to order their new machines"* (Glader, 2008).

Statistical Analysis on Market Exit

As noted in the research context section, we use the DRA as a negative derived demand shock on diagnostic imaging equipment manufacturers in the markets affected by the Medicare reform to examine our research question. We use quantitative data to conduct a difference-in-difference-in-differences (DDD) estimation, and qualitative data to explore the best explanation of our empirical observation (King et al., 2020).

Data and Sample

Our primary source of quantitative data is the Medical Device Register (MDR) directories (2004-2010), a comprehensive compilation of medical products and manufacturers in the U.S. We describe our process for identifying sample firms, their product markets, and device segments below.

The MDR contains information regarding a firm's FDA medical specialty areas, which is the highest-level categorization of medical device markets and defined as the firm's *medical device segments* in our analysis. This includes our diagnostic imaging related segments (i.e., 'Radiology', 'Ophthalmic', and 'Dental') and all the other medical device segments outside imaging. We identify the *imaging markets* based on the FDA product categories (assigned a unique code) within each device segment. Specifically, we identify all the product codes for imaging device equipment (e.g., '90QJT' for 'Chest Diagnostic Radiographic Unit' in Radiology). Because both treated and control markets are within medical imaging, they have many similar characteristics including key stakeholders (e.g., end-customers), regulation (e.g., FDA approvals), industry value chain (e.g., distribution), and payment systems (Figures 1a and 1b). The five treated markets affected by the demand shock (i.e., imaging services that experienced dramatic revenue declines due to the DRA) are X-ray, ultrasound, nuclear medicine, magnetic resonance imaging, and computed tomography. The three control markets include mammography (covered by Medicare but exempt from the DRA), dental, and ophthalmic imaging (not covered by Medicare and thus untreated by the demand shock). [21]

For each firm, we identify various FDA *product categories* offered within each market and year (e.g., Ultrasound product categories include Ultrasonic Imaging System, Ultrasonic Probe, Ultrasound Computers, Ultrasound Scanners, etc.). Firms may also offer *product lines* representing variations within each product code. Each variation may require a firm to obtain FDA's 510(k) approval (e.g., within Ultrasonic Imaging System,

[21] Medicare does not cover routine dental care or most dental procedures or annual eye exams to check vision. Dental imaging equipment include intraoral, extraoral X-ray equipment, etc., and ophthalmic imaging equipment include retinal ultrasound imaging systems, ophthalmoscopes, corneal topography systems, etc.

the firm Aloka may offer "Aloka Prosound 2 Diagnostic Ultrasound System," Aloka Prosound 6 Diagnostic Ultrasound System" or "Aloka SD-3500 Ultrasound System, " etc.).[22] We extract information from the MDR on revenues and diversification at the firm-year level, and firm's product categories and distribution types (e.g., direct sales, indirect sales, OEM, importer, exporter) amongst other firm-market level information.

Our final sample (imaging equipment manufacturers offering at least one product in treated or control group during 2004-2009 period) comprises a total of 1,043 firm-market-year observations based on 199 unique firms, with 124 treated firms and 95 firms in the control group. The sample period of 2004-2009 spans three years before and after the policy change took effect (the year 2007) to capture near-term effects of the reimbursement cut. As discussed later, we validate various assumptions: qualitative data confirm control group was unaffected by the DRA, robustness checks ensure that our results are not sensitive to the choice of the control group or time window.

Variables

Table 1-2 provides operationalization of the key variables.

[Insert Table 3-2 here]

Dependent Variables Our key dependent variable of interest $Market\ Exit_{i,m,t+1}$ indicates a firm's exit from a product market in the following year. Additionally, for each firm-year, we examine alternative firm responses, including $Patent\ Applications_{i,t+1}$ and $510(k)\ Applications_{i,t+1}$. We measure the latter based on year of submission, noting that

[22] Premarket Approval (PMA) is another pathway of the FDA's medical device approval, which we do not examine. Most imaging devices are exempt from PMA. Moreover, PMAs reflects a longer term and highly stringent process (with clinical trials prior to application) used for radical rather than incremental changes. Thus, PMA submissions observed in our post-treatment period would not be reflective of the firm's adaptation effort in response to the shock.

these applications are all subsequently approved. We also examine two other responses. $Changes\ in\ Product\ Categories_{i,m,t+1}$ takes the value of 1 if the number of imaging products offered by the focal firm increases from year t to year t+1, 0 if unchanged, and -1 if decreases. $Entry\ into\ Other\ Segments_{i,t+1}$ takes the value of 1 if the focal firm entered a medical device segment outside of diagnostic imaging in year t+1 and 0 otherwise.

Independent Variables We employ three key variables in our DDD design. $Demand\ shock_t$ equals 1 for the years 2007-2009 post the Medicare reimbursement cut and 0 for the years 2004-2006. $Treated_m$ is an indicator that takes the value of 1 for the five imaging markets affected by the DRA (treated group as noted above), and 0 for the control markets. $Integrated_{i,m}$ takes the value of 1 if the firm has the internalized distribution and sales function in the focal market, and 0 otherwise.[23] Other than in two cases, firms are either integrated or nonintegrated across all markets and the $Integrated_{i,m}$ variable is also time invariant within the firm's focal market (results are robust to the exclusion of the two firms). Moreover, the vertical scope decision preceded the entire study period (i.e. occurred prior to 2004), which allows us to rule out confounding factors, including the firm's simultaneous decisions to change the vertical scope.

Control Variables We use several control variables in the regressions to account for other firm-level factors that may impact the likelihood of an exit event or other firm responses. $Firm\ Revenue_{i,t}$ is a categorical variable that takes values from 1(<$1M)

[23] To ensure a clean separation of firms, our main analysis excludes firms using dual distribution within the focal market, though robustness tests (described below and in Table A3 of Appendix) ascertain consistent results upon inclusion.

through 9 (>$1B) based on annual revenues of the focal firm, to account for the firm's ability to respond differing by size. We use $Number\ of\ Product\ Categories\ within\ Imaging_{i,t}$, $Number\ of\ Medical\ Device\ Segments_{i,t}$ to control for presence in multiple diagnostic imaging markets and in other medical device segments (outside medical imaging). Finally, the $Diversified_{i,t}$ dummy captures whether or not the firm operated in non-medical imaging device industries in year t. Finally, we also control for the patent stock in year t using a logged cumulative count of all its applications from establishment year through time t.

Table 3-3 provides summary statistics and correlation matrices. Panel A reveals mean values of the variables are similar across treated and control groups, except for higher patent applications and patent stocks for the treated group. We do not see notable differences across integrated and nonintegrated firms. Figure 3-2 depicts raw trends in average exit rates. In Panel A, Figure 3-2, the average exit rates for both treated and control groups were decreasing in the pre-treatment period, but the treated group shows an upward trend post 2007. Panel B of Figure 3-2 reveals differences in trends by vertical scope. Notable is the sharper divergence between integrated and nonintegrated firms in the post-shock period within the treated group relative to the control group.

[Insert Table 3-3 and Figure 3-2 here]

Model Specification

We use linear probability (OLS) models for great interpretability of coefficients, especially interaction terms, and ensured robustness to alternative specifications (e.g., logit). Also, we cluster standard errors by firm to account for dependence across observations within the same firm. For all our dependent variables, we start with a difference-in-differences (DD) model to first understand the impact of the DRA on market exit of treated and control groups (See (i)). We then add the firm's pre-existing vertical scope for conducting additional subsample analyses and our DDD estimation (See (ii)). Thus, the two models take the following forms, respectively:

(i) $Y_{i,m,t+1} = \gamma_m + \lambda_t + \beta \cdot X_{i,t} + \delta \cdot Demand\ shock_t \cdot Treated_m + \varepsilon_{i,m,t}$

(ii) $Y_{i,m,t+1} = \gamma_m + \lambda_t + \beta \cdot X_{i,t} + \delta_1 \cdot Integrated_{i,m} \cdot Demand\ shock_t$

$$+\delta_2 \cdot Integrated_{i,m} \cdot Treated_m + \delta_3 \cdot Demand\ shock_t \cdot Treated_m$$

$$+ \theta \cdot Demand\ shock_t \cdot Treated_m \cdot Integrated_{i,m} + \varepsilon_{i,m,t}$$

$Y_{i,m,t+1}$ indicates the firm's response to a demand shock in year t+1. γ_m is market fixed effects for each of the eight markets, λ_t represents year fixed effects and $X_{i,t}$ indicates the firm-year level controls noted above. δ is our coefficient of interest in the DD models, which captures the impact of the DRA by comparing the change in the dependent variable pre-and post-2007 for the "treated" group compared with the "control" group. θ is our coefficient of interest in the DDD models, which compares the change in the dependent variable pre-and post- 2007 for the treated integrated group to the control nonintegrated group.

Results

Market Exit Our main regression results are presented in Table 3-4. In Columns 1 to 3, we provide the results for the DD models. Column 1 reports the uncontrolled difference-in-differences without year or market fixed effects. Column 2 includes year-fixed effects, and Column 3 adds firm-level controls and market fixed effects. Based on Column 3 (full set of controls), the term *Demand Shock* × *Treated* (δ =0.054, s.e.=0.029) indicates that a firm in a treated market was 5.4%p more likely to exit the market after the demand shock than a firm in a control market.

Columns 4 and 5 present subsample analyses for integrated and nonintegrated firms. For the integrated subsample, the *Demand Shock* × *Treated* (δ =0.107, s.e.=0.046) indicates that integrated firms in a treated market were 10.7% more likely to exit the market after the demand shock than firms in a control market. However, for the nonintegrated subsample, there is no such effect (δ =0.002, s.e.=0.035). Columns 6 and 7 provide results for treated and control group subsamples. Here, for the treated group, the term *Integrated* × *Demand Shock* (δ =0.072, s.e.=0.042) indicates the demand shock increased the likelihood of market exit for the integrated firms by 7.2%p relative to the nonintegrated firms pre-shock. However, there is no such increase in market exit for integrated firms for the control group (δ =-0.052, s.e.=0.042). Finally, in Columns 8 and 9, we estimate triple differences models. Focusing on Column 9 with the full set of controls, the triple interaction term *Demand Shock* × *Treated* × *Integrated* (θ =0.114, s.e.=0.058) reveals an 11.4%p greater rate of exit post-demand shock for integrated firms from the treated markets compared to the baseline of pre-shock period exit rates of nonintegrated firms from the control markets.

[Insert Table 3-4 and 3-5 here]

Market Exit for Subsamples based on Firm Characteristics Our sub-sample analysis explore underlying mechanisms that may correlate with firm characteristics (diversification, ownership structure and revenue size) and condition market exit.

In Table 3-5, we present results with market-, year-fixed effects and controls. To explore whether firms with a diversified product portfolio are more likely to strategically retreat from an adversely affected market and redeploy resources (Folta et al., 2016;

Lieberman et al., 2017), we group sample firms based on whether they a) were specialists in the medical imaging segment, b) operated in other medical device segments, and c) were conglomerates that also had any businesses outside of the medical device industry before the demand shock. In Panel A of Table 3-5, we observe a robust effect on increased exit (*Demand Shock* × *Treated* (δ =0.199, s.e.=0.078)) for firms that are vertically integrated *and* diversified within medical devices (Column 3), in terms of both statistical and economic magnitudes. In contrast, the estimates are not precise enough to draw any conclusions for specialized imaging firms (Columns 1 and 2) and for conglomerates (Columns 5 and 6) regardless of their vertical scope.[24] The analysis is consistent with the conjecture that integrated firms diversified within medical devices are able to redeploy their direct salesforce for other medical device segments by backing out from the less profitable treated product markets.

To explore whether firm size may buffer firms from the effects of the negative demand shock, we examine two proxies: ownership structure (public versus private) and revenue size (large versus small) in Panel B of Table 3-5. Post shock, public and private integrated firms had 16.1%p and 9.7%p higher likelihood of market exit in treated markets relative to control markets respectively (Columns 1 and 3). Also, small integrated firms in a treated market were 12.8%p more likely to exit the market respectively in the presence of a negative demand shock (Columns 7). Conversely, we do not find such support for nonintegrated firms that are public, private, or small (Columns 2, 4 and 8), or for any large firms (Columns 5 and 6). The result is consistent with the

[24] Subgroup coefficient estimates are consistent with main analysis (Table 4), but reduced n implies less precision/power.

conjecture that size may buffer demand adversity but the estimates are less precise due to smaller samples.

Sensitivity Analysis

We conducted several robustness tests to ascertain assumptions made in our research design and address potential concerns regarding our identification strategy (See Table 3-7, Figures 3-3, 3-4 and 3-5).

[Insert Table 3-7, Figures 3-3, 3-4 and 3-5 here]

Pre-trend Analysis If the industry participants anticipated the regulatory measure to address growth in federal healthcare imaging costs, our assumption of an exogenous and sudden demand shock is suspect. We bolster the qualitative evidence provided above in the research context by conducting several analyses. First, the trend in the total number of U.S. diagnostic imaging facilities (Figure A3-1 in Appendix) confirms the number continuously increased from 5,163 in 2003 to 6,514 in 2012, with a brief period of stagnation in 2010. Second, we conduct an event study analysis with control variables to examine time trends (Figure 1-2 already shows similarity in pre-demand shock raw trends of exit rates in treated and control markets). We estimate the same model we use for the main regression but allow different coefficients each year for being in a treated product market.

$$Exit_{i,m,t+1} = \gamma_m + \lambda_t + \beta \cdot X_{i,t} + \sum_{\tau=2004}^{2009} \delta_\tau \cdot \lambda_t \cdot Treated_m + \varepsilon_{i,m,t}$$

Following standard practice, the reference year is 2006, one year before the DRA took effect. λ_t represents year dummies that equal to 1 if t = τ, 0 otherwise (τ = 2004, 2005, 2007, 2008, 2009). δ_τ represents the event study coefficient at time τ, capturing the effect of being in a treated product market in each year *t*, relative to the omitted year.

Event study coefficients displayed in Figure 1-3, Panel A indiciates insufficient evidence of a pre-trend. The results support our observation that an increase in market exit was *not* because of an already accelerating trend in the treated markets due to market anticipation. Panel B displays the results of subsample event study corresponding to the specifications in Column 4 and 5 of Table 3-4. The solid line plots estimates for difference between the treated and control groups confined to integrated firms, and the dotted line corresponds to nonintegrated firms, mirroring the results in Panel A. Lastly, in unreported results available upon request, we reran our main specification using an advanced cutoff year (2006) to test the idea that the DRA effect kicked in during pre-treatment period because it was announced in 2006. The estimate on *Demand Shock* × *Treated* (δ =-0.015, s.e.=0.027) was negative, small in magnitude and its wide confidence interval includes 0, collectively not supporting a pre-treatment period effect.

Study Period Window Our analysis used a three-year window before and after the demand shock. In this section, we ensure our estimates are robust to the different lengths of pre- and post-treatment periods. Figure 3-4 presents the estimated coefficients using 3 different pre-periods (from 3 to 5 years) × 6 different post-periods (from 1 to 6 years) from separate regressions (corresponding to Column 3 in Table 3-4). The results confirm that the observed effects are not driven by our choice of pre-period length. The estimates become larger after two years post-policy change, suggesting that the derived demand shock had a lagged effect on device manufacturers.

Control and Treated Group Validity To ensure our results are not driven by a particular mix of control markets, we reran our main specification using different combinations of control markets (mammography, dental and ophthalmic imaging). Figure 3-5 displays largely similar patterns across different sets of control group (although precision of some estimates is low due to small sample sizes), suggesting our results are unlikely to be driven by the choice of any particular market as our control group. Similarly, to ensure the results hold for each of the five treated markets, we examined each treated market separately, using the same control group as in the main analysis (Figure A3 of Appendix). Overall, the results remain robust, but with less precise estimates due to the loss of sample size. It is worth noting that the estimates using only CT as a treated market are lower than the others, suggesting that firms were less likely to exit CT market regardless of vertical scope.

Another possible concern is that the treated and control groups may present different distributions of vertically integrated firms. In results using coarsened exact matching (Table A3-2 in Appendix), the effects are largely unchanged in terms of magnitude and directionality, but the loss of degrees of freedom results in imprecise estimates with wider confidence intervals, as expected.

Sample Selection Our main analysis restricted the sample to firms that were either integrated or nonintegrated and excluded firms that used a hybrid structure by utilizing both internalized direct sales force and independent distributors. Inclusion of hybrid firms provides consistent results with our main findings (Table A3-3 in Appendix).

Evidence on Firms' Responses to Demand Shock

The statistical analysis on market exit implies that post-demand shock, integrated firms were more likely to exit their product market. The differential rates of firm market exit, however, are likely induced by each type of firm enacting different strategies to weather the demand shock in a manner that matches with their capabilities, relationships, and positioning. In this section, we explore how the differences in strategies and positioning resulting from pre-existing vertical scope might have led to such differences in the rates of firm market exit.

Statistical Analysis on Other Firm Responses

We now turn to the analysis of other firm responses to the shock, namely *Patent Applications, 510(k) Applications, Changes in Product Categories,* and *Entry into Other Segments*. The four panels of Table 3-6 run the DD and DDD analyses for each dependent variable. In Columns 1 to 3 for each panel, we provide estimates for full sample, integrated and nonintegrated subsamples respectively using firm-, year-fixed effects and controls. The within-firm analysis controls for unobserved heterogeneity of firm characteristics that might affect firms' choice of market responses. In Column 4, the DDD model examines across-firm differences based on vertical scope through main and interaction terms *Integrated,* so firm-fixed effects are not included (recall that *Integrated* is a time invariant variable).

[Insert Table 3-6 here]

Firms may adapt to decreasing demand by adjusting their R&D investment or commercialization of new product varieties (Higgins, Yan & Chatterjee, 2021; Krieger, Li & Thakor, 2020). Estimates in Column 1, Panels A and B suggest firms in the treated markets reduced the number of both *Patent Applications* (*Demand Shock* × *Treated* (δ =-0.161, s.e.=0.053)) and for *510(k) Applications* (*Demand Shock* × *Treated* (δ =-0.056, s.e.=0.018)) after the demand shock. Subsample analyses further suggest both integrated and nonintegrated firms in treated markets reduced their patent applications after the demand shock by almost the same magnitude (Column 2 and 3, Panel A). In terms of *510(k) Applications*, integrated firms in treated markets reduced applications by 6.7% (s.e.

=0.022) post demand shock (Column 2, Panel B), while the comparable statistic for nonintegrated firms is -3.5% (s.e. = 0.026; Column 3, Panel B). The DDD estimation does not enable conclusions regarding differences among integrated and nonintegrated firms (Column 4, Panels A, B).

Firms may also respond by making changes in their product portfolio or entering unaffected medical device segments. The estimates for both variables—*Changes in Product Categories* (Panel C), and *Entry into Other Segments* (Panel D) are not precise across specifications. We have little evidence that treated firms responded to the demand shock by consistently adjusting their product lines in a single market or expanding into other related product markets as a response to minimize the negative shock on the focal product markets.

Qualitative Evidence on Firms' Responses

To examine whether the theoretical drivers listed in Figure 3-6 are reflected in firms' strategic responses to the demand shock, we turn to an examination of qualitative evidence, as reflected in company annual reports, earnings call transcripts from LexisNexis, press releases, and articles in trade magazines (e.g., Diagnostic Imaging, Imaging Technology News). Given the difficulty in accessing information about private firms, we focused on all 18 public imaging firms (12 integrated; six nonintegrated) in the treated group, in addition to 7 public firms in the control group. Altogether, we reviewed more than 200 documents to cull insights. Table 3-8 summarizes the qualitative findings and Table A3-4 in Appendix lists quotes in addition to those included below.

Discussion of DRA by Treated and Control Firms: The qualitative data validate the assumption that control group manufacturers were untreated by the shock—none of the control group firms' annual reports and earnings calls released during our study period mentioned the DRA and reimbursement reductions. Among the treated group, 10 of the 18 firms explicitly discussed the potential adverse market effects caused by the federal reimbursement reductions.[25] Five firms reported that they experienced a material negative impact on their operations after implementation of the DRA. The other five firms reported concerns that legislative reforms resulting in restrictive reimbursement practices of insurance payors could decrease demand for their products and customers' willingness to pay. Several firms also indicated that their customers had delayed plans to purchase imaging equipment because they were assessing the impact of the DRA on their businesses.

Integrated Firms' Response for Demand Management: Nine of 12 public integrated manufacturers (75%) engaged in demand management. Six of them (50%) focused on customized product/service offerings to close deals and maintain customer relationships. Such actions included increased advertising and highlighting of affordability of their products to financially constrained customers, and willingness to make concessions on pricing and service agreements. For example, Fonar (2008, p.35) stated intentions to leverage their highly experienced sales support, launch advertising campaigns directed at physicians and noted "*our business plan includes an aggressive program for manufacturing and selling our Upright® MRI scanners…most significantly by the replacement of existing MRI scanners…and delivering state-of-the-art, innovative and high quality equipment upgrades at competitive prices.*" Some even increased investments in sales personnel. Imaging Dynamics Corp

[25] The eight firms that did not specifically discuss the reimbursement cut in Medicare were either foreign firms or operated in multiple industry sectors. It is thus unlikely that the DRA's effect on their medical imaging division was considerably large enough to affect overall profitability, leading them to not mention the DRA as a critical market risk factor in 10-K reports and other documents.

(2008) noted that they were "*recruiting an experienced and high-profile sales leader with the intent and expectation to improve results in North America…[to] have an increasingly effective and committed sales channel.*" IRIS International Inc (2009) pursued a similar measure by increasing customer contacts in the U.S. by increasing marketing headcount in 2009. However, integrated manufacturers experienced difficulties in realizing the intended benefits of this strategy, leading several of them to subsequently downsize their sales force. For instance, Imaging Dynamics backtracked on their sales force expansion and instead switched to cost reduction (Fosse, 2009), as did Siemens (Siemens, 2009).

Consistent with their diverse and customized product offering strategy (see Table A3-1 in Appendix), 50% of the integrated firms responded by changing features to cater to changing customer preferences. For instance, Siemens' offered SPECT imaging system was "*modified to lower the overall price, yet still off er high-image quality*" as a part of the firm's "*three-pronged approach to the current cost pressures in the medical imaging market.*" Siemens also enabled upgrades to its Symbia E *"to accommodate a larger workload…allows checking the system status through remote access and diagnostics to enable system corrections to reduce downtime and therefore cost*" (Lee, 2008). Positron Corp refocused on cardiac PET imaging to target a less competitive, niche market by combining "*low cost technology and disease specific software solutions*" ("Positron Introduces New Attrius," 2007). The company's president stated *"[t]he Attrius is the only dedicated cardiac PET scanner on the market…Market dynamics combined with our cost-effective scanner offering will allow the Company to seize a leading market position as a unique niche player in the nuclear cardiology market segment*" ("Positron Introduces New Attrius," 2007).

Notably, 42% of integrated firms generated demand through entry into foreign markets by engaging into a dual distribution mode (staying integrated for the U.S. but using distributors for foreign markets). Fonar (2009), for example noted, "*During the fiscal year ended June 30, 2009, 13.2% of the Company's revenues were generated by foreign sales, as compared to 2.4% for fiscal 2008*." Imaging Dynamic Corp (2009) also selectively diversified and enhanced their global distribution. The company's top management stated that "*the company plans to further expand IDC's global position…[a]s the industry continues to respond to the effects of the Deficit Reduction Act*" ("Spotlight: IDC CEO says," 2008), and noted the motivation to capture the markets "*because [the firm] can have "the right price point*" (Fosse, 2009).

Integrated Firms' Response for Cost Reduction: Cost reduction efforts were noted by 67% of integrated firms. Boston Scientific Corp (2009, p.19) announced a plan "*aimed at simplifying plant network, reducing manufacturing costs and improving gross margins*." Also, Fonar Corp (2008, pp. 35–36) stated it "*instituted an aggressive program of cost cutting during and following the end of fiscal 2008*" including "*consolidating … office spaces, reductions in the size of workforce, compensation and benefits, as well as across the board reduction of expenses. The cost reductions were intended to enable us to withstand periods of low volumes of MRI scanner sales, such as we have experienced in fiscal 2007 and 2008*." Other integrated firms such as CR Bard (2010), Alcon (a subsidiary of Nestle) (2009), and Volcano (2009) announced similar cost reduction programs to eliminate SG&A expenses, personnel costs, and manufacturing costs.

Integrated Firms' Product Portfolio Reconfiguration for Resource Redeployment: Consistent with the quantitative evidence in Panel B, Table 5, some public integrated firms responded by exiting the treated markets. Two public integrated firms, Eastman Kodak (Austen, 2007) and MDS Inc (2006) divested their imaging business, and IRIS International Inc (2008) divested imaging research subsidiary. Notably, two of the public firms, Boston Scientific (2007) and MDS (2007), restructured or divested their non-core businesses outside imaging. The intent was largely for discontinuation of unprofitable businesses—these firms reported their struggles with high operational costs and slower growth of product lines with relatively low margins.

In addition to varying product lines in treated markets as noted above, Siemens increased presence in untreated markets by introducing a new mammography digital system (Analogic Corp, 2008a) and acquiring two diagnostic firms to enter the in vitro diagnostics segment (Siemens, 2008a). Siemens explicitly noted these measures were in response to the DRA and added: "[*W]e are addressing new markets and new customers… if you see the customer base of our IVD business, of our IT business, of our imaging business, there is not 100% overlap. So, we can benefit from the cross-selling to the customers. We do have access, we do have excellent relationships in the different business areas we are in*" (Siemens, 2008b).

Nonintegrated Firms' Response for Demand Management: Four of six nonintegrated firms (67%) reported efforts at generating demand. Four nonintegrated firms (67%) increased their presence in foreign markets by leveraging and expanding distributor networks. For example, Del Global Technologies Corp (2008, p. 4) described that its *"[distributor] network has expanded during fiscal year 2008 when [the company] has partnered with one of the largest dealer buying groups to distribute digital and general radiographic imaging equipment.*" In pursuing this strategy, Del Global (2009) noted that in "*international markets…despite the fact they too are in economic slumps, the demand for medical products remains high as these emerging economies present new opportunities.*" Similarly, Afp Imaging Corp (2009a) attempted to diversify its revenue streams in foreign markets through a "*worldwide introduction of the company's new vertical three-dimensional CT scanner,*" and Analogic Corp

(2007) made efforts to offset substantial losses in the digital X-ray business by expanding digital X-ray related business in Canada.

Most nonintegrated firms relied on increased standardization (as in Table A3-1 in Appendix) and two of our public firms noted doing so with a special focus on cost-effective products. Del Global (2007, p. 6, 2008, p. 5) touted their "*low-cost offerings for customers [so they could] obtain better patient images within a fraction of the time and with lower overall costs.*" Similarly, Analogic Corp (2008a) highlighted that "*some of the benefits that have driven customer interest … [is] a lower end-to-end cost of the system.*"

Nonintegrated Firms' Response for Cost Reduction: All but one (83%) nonintegrated firms reported efforts to economize costs, including personnel costs. Nonintegrated firms streamlined operations by implementing cost control programs, including extensive cost-reduction efforts in terms of shedding selling, general, and administrative costs and fixed costs associated with personnel and facilities. For example, X-Rite Inc (2007) was able to achieve cost savings by "*reduced duplicative management level headcount, consolidate territories, etc.*" In 2009, Analogic Corp (2009, p. 21) "*in response to a lower demand, implemented cost control programs*," including reduction of workforce by 145 employees worldwide (9% of total workforce). Del Global (2009) also embarked on "*major cost reduction programs and lean initiatives*," one of which was to move headquarter facilities and reduce floor space.

Nonintegrated Firms' Product Portfolio Reconfiguration for Resource Redeployment None of the nonintegrated firms reported exiting the treated markets. However, 50% of them they entered unaffected markets, and also reported leveraging their distributor networks when doing so. X-Rite (2009) introduced a new dental spot measurement device in 2007, and The Cooper Companies (2007, p. 10) expanded its business by acquiring a medical device firm that specialized in "*diagnostic and therapeutic medical instruments… in women's healthcare and other specialty instruments relating to dermatology, ophthalmology, anesthesiology, dentistry, and veterinary medicine.*" Primarily focusing on unaffected imaging markets, Afp Imaging Corp (2007, p. 4, 2009a) "*made aggressive [product] launch into the dental market*," which was accompanied by the acquisition of "*a global supplier of state-of-the-art, in-office three-dimensional dental computed tomography (CT),*" and the expansion of its "*Dent-X division's Canadian dealer sales network in dental market through a cooperative agreement*" with a new distributor. The company further pursued "*various sales opportunities in both the domestic and international markets with specific emphasis in the growing veterinary markets*" (Afp Imaging Corp, 2007, p. 36).

Nonintegrated Firms' Use of Distributors as a Buffer Nonintegrated firms (33%) were able to diversify risks by leveraging relational capital with their distributors to leverage their efficiencies in demand forecasting and superior inventory management (Jacobs, 2010). However, such value chain rationalization required close coordination with distributors given conflicting goals because "*many distributors continue to reduce their on-hand inventory based on their own economic circumstances*" (Afp Imaging Corp, 2009b). Esco Technologies (2009) noted "*our distributors were kind of managing their inventories down to maybe not the bare minimum but to an absolute minimum. So…they needed to have a reasonably significant restocking order to be able to get their inventory back on track so that they could meet the demand that was forthcoming here in the short-term.*". Analogic Corp (2008b) noted working with distributors to rationalize inventory in light of declined overall demand after the DRA resulted in an inventory adjustment and continued improvement in 2009.

Role of Pre-existing Vertical Scope in Post-shock Firm Adjustment and Product Market Exit

We now turn to how differences in firms' pre-existing vertical scope (and associated differences in capabilities and positioning) create differences in their post-shock adjustment strategies and in their rates of product market exit (Figure 3-6).

[Insert Figure 3-6 here]

Pre-Shock Resources and Capabilities Represented by Vertical Scope

Within our empirical context, integrated manufacturers leveraged specialized sales force and direct relational capital to provide a range of products catering to both high- and low-end segments. On the high end, state-of-the-art technology and focus on reliability, versatility, image quality, and other product features were sustained by continuous innovation (Mitchell, 1988; Steinberg & Cohen, 1984; Tilly & Handel, 2002) Additionally, Tilly and Handel (2002, p. 160) note that by the late 1990s, these manufacturers also served lower-end segments by a) removing "*less needed or non-reimbursed functions from the equipment*," b) offering mid- to low-end systems to "*first time buyers and imaging facilities that needed backup systems*," c) equipment that "*scan specific sites and deliver lower quality whole-body images*" or d) systems that "*require less space and installation costs*." Importantly, these manufacturers also engaged in design-based cost reduction strategies to reduce "overall costs" to buyers. This included a) designs that "*increase throughput of patients*," such as by introducing machines that "*can pivot between two rooms, reducing idle time*," b) providing high-end machines to enable "*less invasive form of surgery [to] save money by minimizing risk of complications and long hospital stays*", and c) "*promoting picture archiving communications systems (PACS) as a way to cut down on diagnostic imaging costs themselves*."

Within our context and consistent with industry life cycles (Helfat, 2015; Kapoor, 2013; Qian et al., 2012), 50% of the firms were nonintegrated by the mid-1970s (McKay, 1983) and through the dates within our sample period. Nonintegrated firms achieved operational efficiency by contracting with distributors who managed large-scale warehousing, delivery, and customer services. Since distributors took legal ownership of manufacturers' products upon purchase, they bore the risk of holding, transporting and selling inventory, providing manufacturers the added benefit of financial risk management (Jacobs, 2010). Nonintegrated firms also engaged in both non-exclusive and exclusive distribution agreements for geographical scope within the U.S. and internationally to achieve economies of scale (McKay, 1983; Mitchell, Shaver, & Yeung, 1994; Mitchell & Singh, 1992). Exclusive agreements aligned incentives and enabled investment of resources by both parties. For example, signing exclusive distribution agreements with distributors who already had knowledge regarding local regulations and established accesses to local customers enabled nonintegrated firms to enter new geographic markets (Kurihara, Sakayori, & Takagi, 2020; McKay, 1983; Mitchell & Singh, 1992). Moreover, in terms of standardization, while both firms are similar in how many product categories they operate within a focal market, nonintegrated firms offer fewer variations relative to integrated firms in each product category: our analysis of FDA 510(k) applications within each imaging market reveals nonintegrated firms had a lower mean *and* variance than integrated firms during our sample period (both pre- and post-shock) (Table A3-1 in Appendix).[26] Nonintegrated firms also had less control over final

[26] 510(k) approvals require "demonstration of substantial equivalence to another legally US marketed device" to establish that "the new device is as safe and effective as the predicate." (https://www.fda.gov/medical-devices/premarket-submissions/premarket-notification-510k).

product prices due to the presence of distributors (Kurihara et al., 2020), potentially limiting their ability to compete on price for the end-customers.

Post-shock Adjustment by Integrated Firms

As noted above, vertically integrated firms prior to the shock have cospecialized capabilities reflected in an internalized sales force and relational capital with existing customers, which translates into heightened trust, shared routines, and mutual understanding developed through repeated transactions (Chatterji et al., 2019; Hoetker, 2005; Kale et al., 2000). They are likely to leverage these capabilities to mitigate the effects of the adverse aggregate demand shock on their individual demand curve. In-depth relationships with customers can facilitate collection of information a firm needs on how change in preferences will impact expected sales volume, price, and quality (Rangan, Corey, & Cespedes, 1993). In the context of imaging device sales, decision-makers within buyer organizations often highly value maintaining their relationships with particular manufacturers for similar reasons (Chatterji et al., 2019). Moreover, such change in preferences can be smoothly communicated for coordinated adaption through streamlined operational routines within firm boundaries (Aggarwal & Wu, 2015; Nickerson & Zenger, 2004). In the period when customers cancel, postpone, or scale down plans for equipment purchases, an integrated firm can capitalize on its capabilities and direct relational capital to negotiate prices and other sales terms, and provide technology-related support services (Forbes & Lederman, 2010). They can tailor features and services to accommodate a shift in customer preferences towards enhanced cost effectiveness (Wang et al., 2020). Such tailoring may include both removal of more expensive modular features and services and addition of new modular features and services that help their customers achieve *overall* cost savings because these new features help reduce their operational costs in other dimensions (e.g., human capital costs in using equipment).

Beyond the above demand management strategies, integrated firms may also undertake cost reduction efforts. These include scaling down investment in direct sales force through downsizing or streamlining personnel costs. While the decision may depend on value creation potential that firm-specific assets can create, cost savings through downsizing may be a reasonable option if demand-side changes significantly reduce the potential gains realized by specialized assets (Harrigan, 1985; Jacobides, 2008). Alternatively, firm-specific investments in sales force and direct relational capital with buyers may be redeployed to other businesses both within current boundaries and for the future (Anand & Singh, 1997; Helfat & Eisenhardt, 2004; Karim & Capron, 2016; Lieberman et al., 2017). This implies that integrated firms may also strategically reconfigure product portfolio by reducing emphasis on or shutting down underperforming product lines hurt by adverse demand conditions. Thus, to the extent that integration is also positively correlated with diversification, firms may temporarily or permanently redeploy their direct sales force within the product markets affected by a negative demand shock to other unaffected businesses (Folta et al., 2016).

Post-shock Adjustment by Nonintegrated Firms

To manage the adverse effects of the demand shock, nonintegrated firms can leverage their existing distributors and develop new distributor relationships to access unaffected markets. Relational capital with existing distributors may help mitigate the effect of the aggregate demand shock on a nonintegrated firm's individual demand because distributors may be better able to rationalize across large inventories through bulk sales (Holcomb & Hitt, 2007). By increasing the aggregation of orders from multiple buyers for standardized products, distributors can help manufacturers secure purchasing orders even when demand is decreasing, as well as provide more precise forecasting of future orders (Vats, Soni, Rathore, & Yadav, 2019). In the imaging equipment context, distributors' support for demand management can help nonintegrated firms better serve budget constrained end-customers whose preferences may shift toward standardization and associated economies of scale (Schneller, 2009). Moreover, nonintegrated firms may also leverage their alliance management capabilities developed in existing relationships to forge new distributor relationships (Ireland, Hitt, & Vaidyanath, 2002; Kale & Singh, 2007) and expand their network to wider geographic markets (Swaminathan & Moorman, 2009). Taken together, existing and new distributor relationships can help nonintegrated firms reach new markets with low search costs, particularly unaffected product or geographic segments.

For cost reduction, nonintegrated firms may focus on leveraging efficiencies for cost savings, given both a decline in demand and a preference shift towards lower prices. Here, distributors can help nonintegrated firms by alleviating the burdens of contracting and pricing adjustment with their specialized routines and extensive experience about contract renegotiation (Jacobides, 2005; Jacobides & Winter, 2005). Notably, external arrangements are easier to downsize by severing or reoptimizing them, which also gives nonintegrated firms greater flexibility in reducing costs when faced with an adverse demand shock (Milgrom & Roberts, 1990; Susarla, 2012). Relatedly, distributors can also play a buffering role for nonintegrated firms as they intermediate the firms and end-customers. To the extent that outsourcing and vertical disintegration are intended to achieve specialization in each value chain activity (Jacobides, 2005), nonintegrated manufacturing firms need to make fewer internal adjustments across the value chain. While outsourcing downstream activities requires partners to share rents during periods of high demand, it also enables to share risks associated with the environmental change and lower demand.

Discussion and Conclusion

Scholars have integrated transaction costs and capabilities view to examine firms' choices of vertical scope and associated capability configuration and positioning (Argyres et al., 2012; Chatterji et al., 2019; Karim & Capron, 2016), particularly in light of environmental changes or shocks (Bigelow et al., 2019; Wang et al., 2020). Less understood is how (preexisting) vertical scope impacts a firm's ability to cope with an adverse environmental shock, to enable a causal disentanglement of otherwise endogenous and interdependent decisions of adjustment and vertical scope choices. Theoretically, it is unclear whether integrated or nonintegrated firms may be better able to overcome an adverse shock, given that preexisting differences in capabilities and positioning associated with vertical scope may also manifest in differences in responses to the adverse shock.

Accordingly, we used a research-question based approach to examine the effects of a negative derived demand shock due to the Deficit Reduction Act on medical diagnostic imaging firms. Our quantitative DDD analysis revealed integrated imaging manufacturers were more likely to exit treated markets than nonintegrated imaging manufacturers, and this finding is robust to several alternative specifications and tests. Moreover, the adverse demand shock resulted in higher market exit for treated integrated firms relative to control integrated firms particularly for subsamples of private or small firms (consistent with resource constraint mechanism), and firms diversified in other medical devices (consistent with resource redeployment mechanism). There seems to be no systematic difference, however, between integrated and nonintegrated firms in terms of other responses such as reductions in patent and 510(k) applications, changes in product categories within imaging and entry into unaffected markets. Additional quantitative analysis of all firms in the sample, bolstered with in-depth qualitative examination of the subset of public firms, showcase that both types of firms engaged in demand management and cost reduction in a manner consistent with their pre-exiting capabilities and positioning. Integrated firms tried to leverage their specialized sales force and stayed the course with customization to offer either niche or overall cost-reducing products that catered to shifting customer preferences. Nonintegrated firms utilized and expanded their distributor networks while also emphasizing cost-effectiveness of their more standardized offerings. The evidence is also suggestive of higher market exit rates of integrated firms resulting from both a deliberate redeployment of resources and competitive pressures because their adaptation strategies were not as effective as intended. Moreover, among the public firms, both types of firms entered unaffected markets and foreign markets and interestingly, some integrated firms switched to a hybrid strategy by using distributors to expand into foreign markets.

We note several limitations of our analysis. Our single industry study provides insights for an important economic sector of medical devices, but the idiosyncrasies of this industry also limit the generalizability of our findings. Moreover, we focused on a specific environmental shock—a legislative change that created derived demand pricing pressures—and our results may not be generalizable to other environmental shocks. We hope that future studies can examine other industries and other environmental shocks, in so doing, help build a corpus of knowledge that allows a deeper understanding of contingency factors that may impact how environmental shocks may change the prior vertical firm scope—outcomes relationship in an industry.

Second, in examining the firm's choice to exit product markets, we do not distinguish between different types of exit modes (e.g., divestitures, bankruptcies, redeployment to alternative businesses) utilized by a firm (Folta et al., 2016; Fortune & Mitchell, 2012; Karim & Capron, 2016). Although our theoretical discussion and qualitative evidence suggest that firms may exit for different reasons, sample size and lack of variation across exit modes constrained our ability to do so. We hope future studies can dwell into this issue further.

When employing a DDD design, our research addressed endogeneity concerns regarding firm's prior vertical scope (with no switching observed in our sample period) and the adverse derived demand shock (which occurred independent of the firm's original strategic intent for downstream (non)integration). Moreover, the additional quantitative and qualitative analysis tried to shed light on underlying mechanisms and identify how capabilities and positioning associated with prior vertical scope impacted the firm's ability to adjust to the adverse demand shock. Nonetheless, data limitations precluded us from observing and quantifying firms' internal decision and cost structure, heterogeneity in specialized sales force or use of intermediaries, and pricing strategies among other factors that may be at play in product market exit. Similarly, lack of qualitative data limited our ability to assess responses by private and small firms, where we observed that integrated firms in treated markets were more likely to exit relative to control markets. We hope future studies address these issues building on our paper.

This paper makes several contributions to the literature it draws upon. We contribute to the strategy research on firms' responses to environmental shocks (Ahuja, Lampert, & Tandon, 2014) by answering the call on empirical studies to evaluate the importance of adjustment costs (Argyres et al., 2019). By disentangling decisions to adjust to an environmental shock from decisions of firm boundary choices, we isolate the effect of vertical scope on response to environmental changes. Here, although our theories are equivocal about the ultimate effects of vertical scope on firm exit, the empirical evidence in our context was nonetheless consistent with how associated capabilities and positioning affected responses to external shocks. Moreover, we add to existing literature that has noted integrated firms may be more responsive to changes in demand (Richardson, 1996), face fixed cost barriers to exit (Harrigan, 1985; Nickerson & Silverman, 2003), strategically choose to bear fixed costs even when conditions favor lower cost specialized firms (Helfat & Campo-Rembado, 2016), or expedite market exit due to relatedness among firms' businesses (Lieberman et al., 2017). Our finding adds to this conversation by documenting that firms with internalized downstream activities may be more likely to respond by exiting markets when faced with a demand shock due to either active resource redeployment or greater competitive pressures.

Second, our paper contributes to the literature that integrates organizational economics and capabilities approach to understand firm boundaries and heterogeneity (Argyres, 2011; Argyres et al., 2012; Williamson, 1999). Building on the insight that firms' vertical scope arises from the heterogeneity in managerial choices concerning combination and governance of activities and assets, we documented potential directions of adjustment pursued by firms with different vertical scopes. We offer both quantitative and qualitative empirical evidence that sheds light on what choices have been actually made and how it affected firm outcomes.

Third, we contribute to literature on what drives the vertical disintegration of an industry, including firms' focus on systematic innovation (Kapoor, 2013), leverage of intermediary markets and specialized firms (Jacobides, 2005; Kapoor, 2013) and interactions of capability differences and transaction costs over time (Jacobides & Winter, 2005). Our results suggest aggregate adverse demand shocks may result in changes in the composition of existing integrated and nonintegrated firms in an industry, through shifted alignment between success factors and vertical scope.

Finally, our study provides an empirical resolution of a theoretical puzzle in an important economic sector, through the use of a research design that plausibly establishes a causal relationship. Moreover, the qualitative insights shed light on potential underlying mechanisms at play. While both integrated and nonintegrated firms enacted strategies that were consistent with their internal capabilities and external relationships, the environmental imperative on cost-reduction to address downstream customers financial constraints may have ultimately advantaged nonintegrated firms who had previously relied on market mechanisms to "price" the specialized capabilities for sales and distribution more efficiently than integrated firms.

Tables and Figures

Figure 3-1a. Transaction flow in medical imaging industry

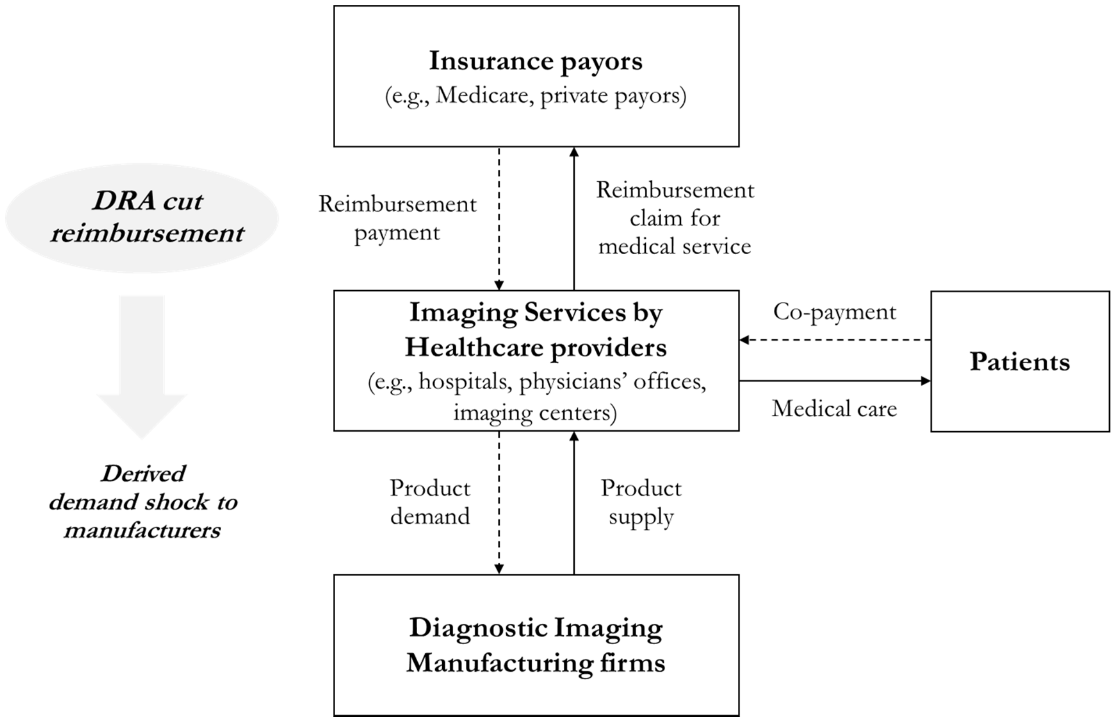


Figure 3-1b. Downstream value chain activities of medical imaging device manufacturers, by integration type

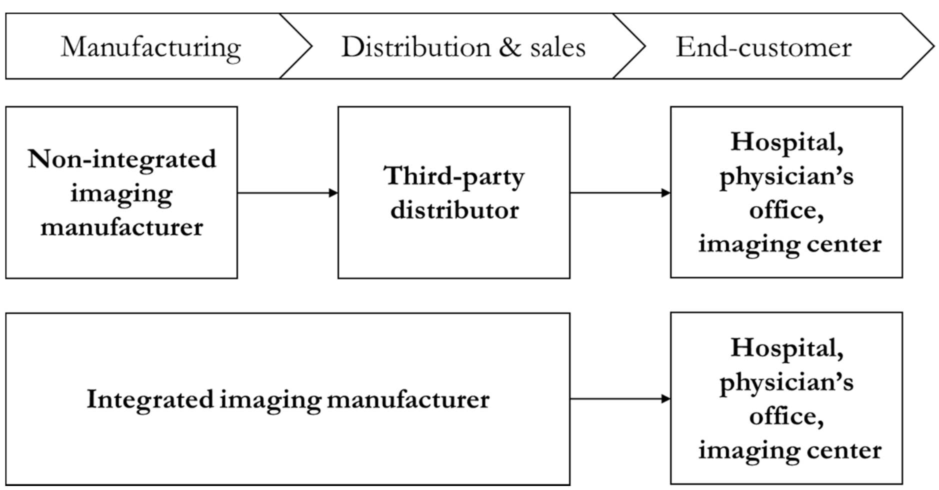
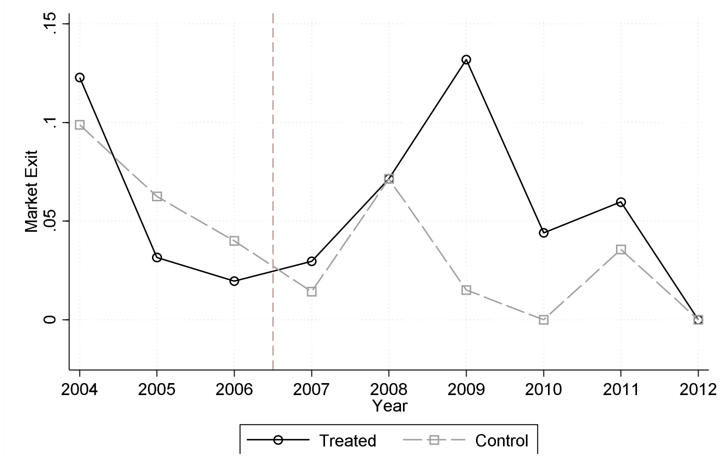
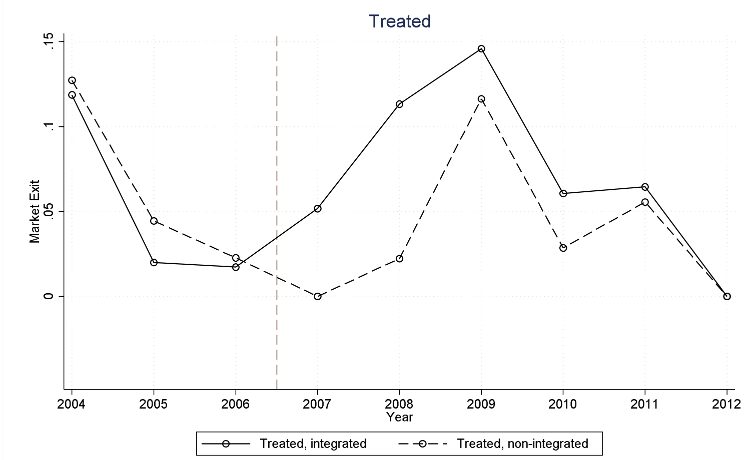


Figure 3-2. Raw trends in average market exit rates from 2004 to 2012

Panel A. Average market exit rates by treated and control groups



Panel B. Average market exit rates by treated and control groups and downstream integration



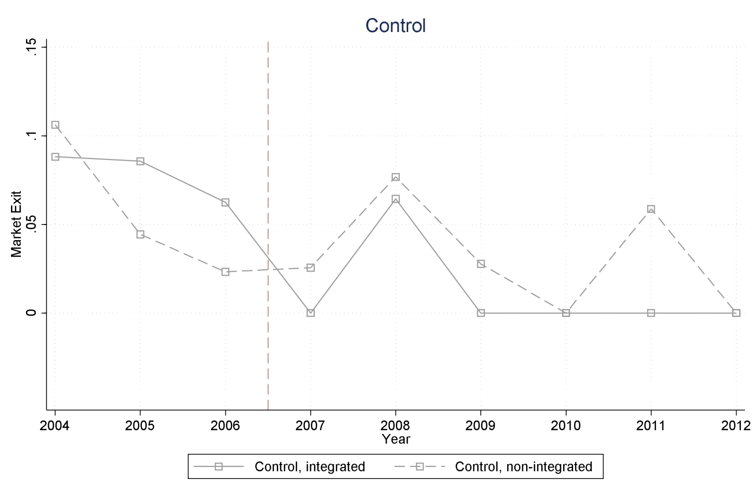
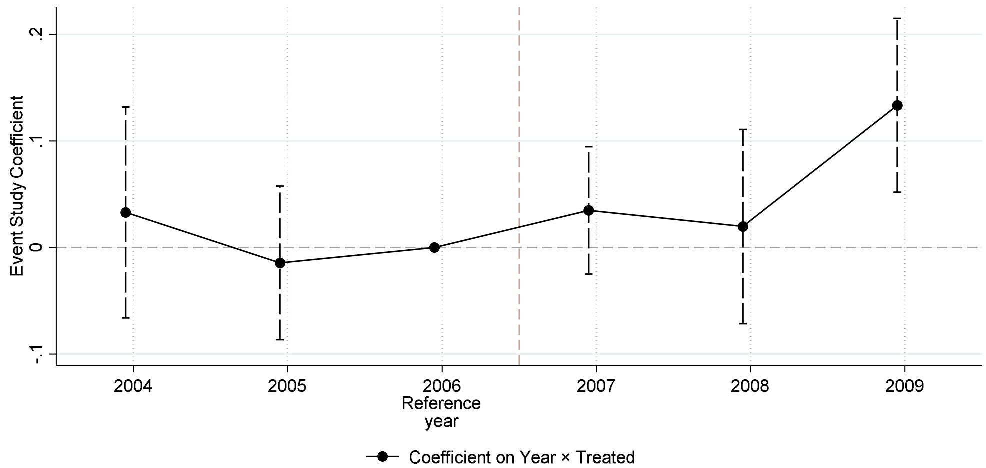
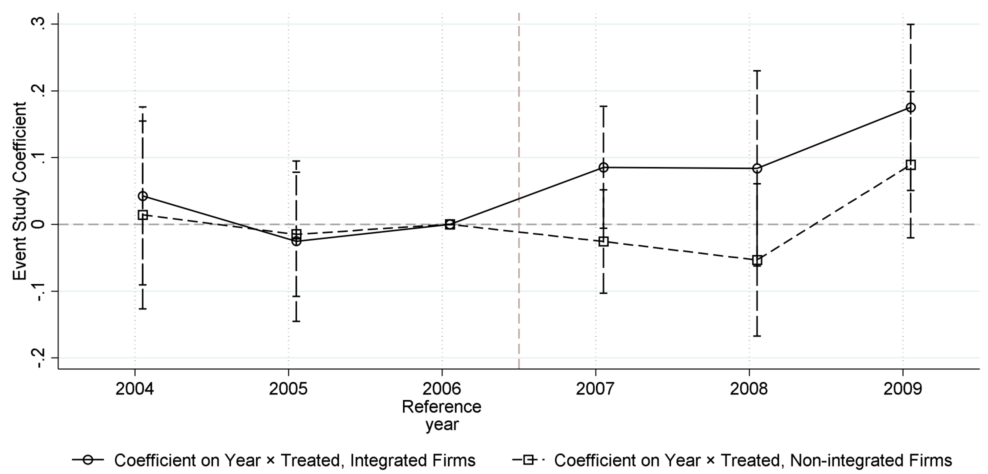


Figure 3-3. Event study plots for market exit

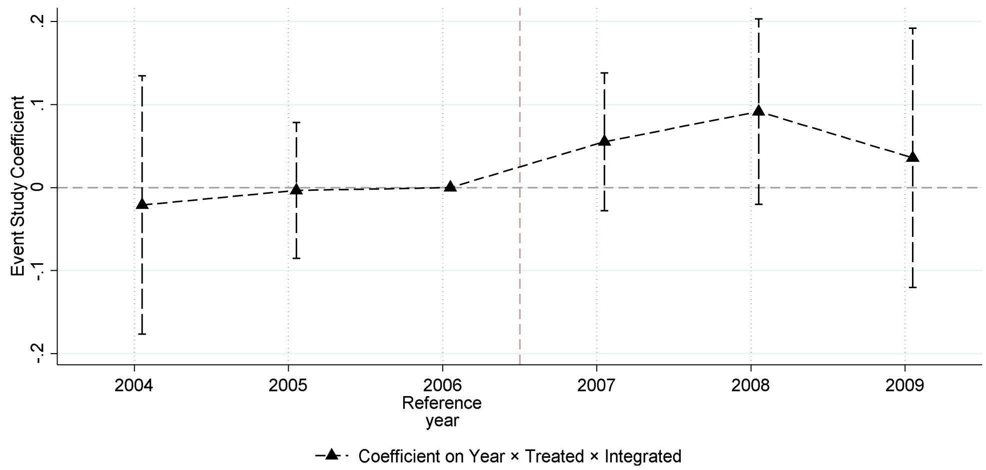
Panel A. Difference-in-difference estimation, full sample



Panel B. Difference-in-difference estimation, integrated and nonintegrated firm subsamples

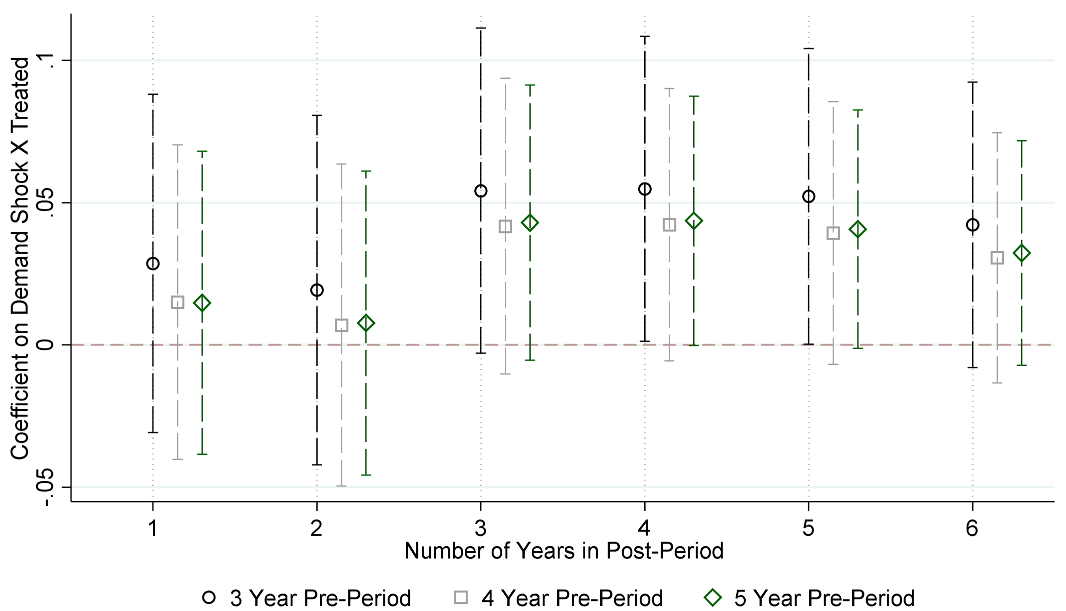


Panel C. Triple differences estimation, full sample



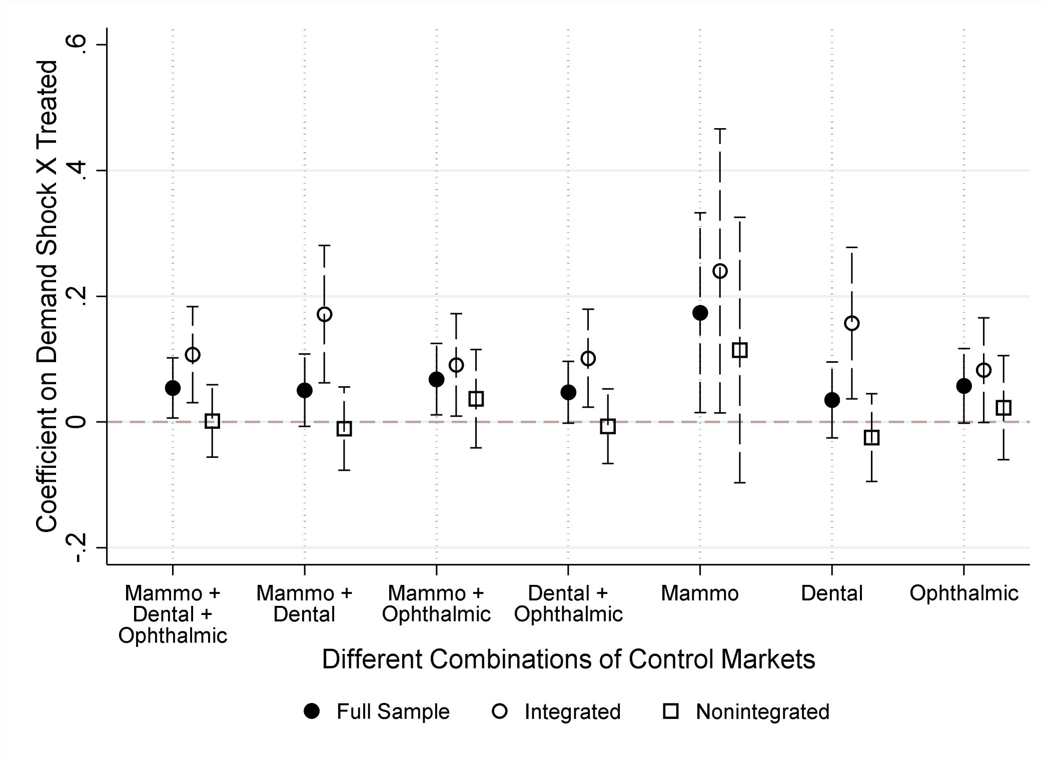
Note: The specification includes controls and market-fixed effects, with standard errors clustered by firm.

Figure 3-4. Treatment Window Robustness for Market Exit Results



Note: Each estimate is generated by restricting the sample to the corresponding window defined by the graph and then running our main difference-in-difference model with controls, market-, year-fixed effects with standard errors clustered by firm.

Figure 3-5. Robustness of Market Exit Results to Different Control Groups



Note: Each estimate is constructed by confining the sample to the appropriate group defined by the graph. "Full Sample" is based on estimates generated by restricting the sample to the treated group and each corresponding combination of control markets, and then rerunning the difference-in-difference model with controls, market-, year-fixed effects, and standard errors clustered by firm. For the series labeled "Integrated" and "Nonintegrated", we further limit our sample to the firms with each vertical scope.

Figure 3-6. Firms' vertical scope, post-shock responses, and market outcome

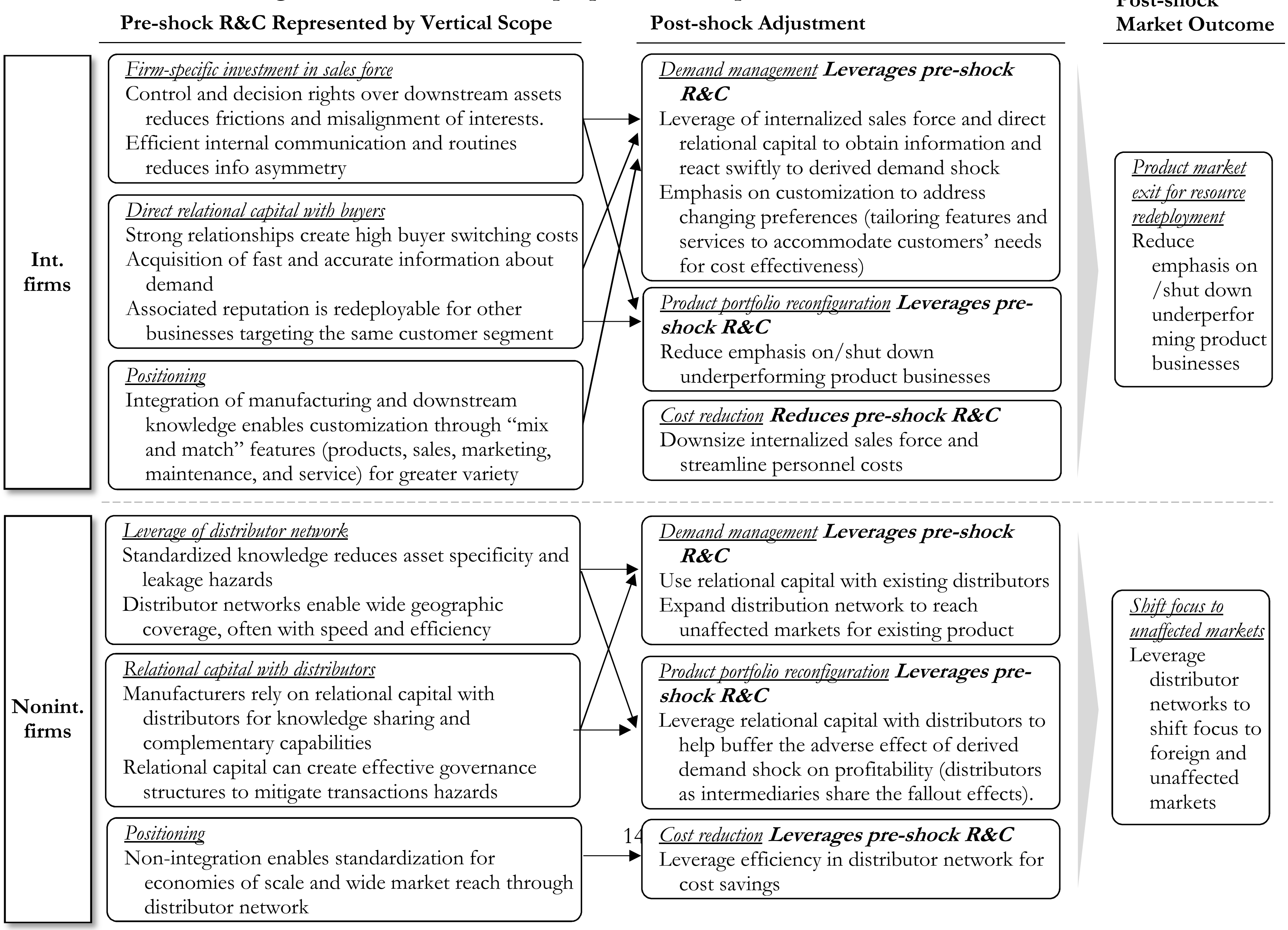


Table 3-1. Description of variables and measures used in the main analysis

Variable	Description
Dependent variables	
Market Exit	1 if a firm exits the focal product market in *t+1*
Patent Applications	Log number of patent applications in year *t+1*
510(k) Applications	Log number of FDA 510(k) applications in year *t+1,* subsequently approved
Change in Product Categories	1 if the number of product offerings increases in *t+1*, 0 if unchanged, -1 if degreases
Entry into Other Segments	1 if the firm entered any medical device segments outside diagnostic imaging in *t+1*
Key explanatory variables	
Treated	1 if the firm was an imaging device manufacturer in the pre-treatment period and affected by the DRA in the post-treatment period
Demand Shock	1 if the year belongs to the post-treatment period
Integrated	1 if the firm owned internalized sales force in the pre-treatment period
Control variables	
Firm Revenue	Categorical variable for firm revenue in year t
Number of Product Categories within Imaging	Log count of the firm's product offering within imaging in year *t*
Number of Medical Device Segments	Log count of medical device segments in year *t*
Patent Stock	Log cumulative count of the firm's patent applications from its establishment until year *t*
Diversified	1 if the firm also operates in non-medical imaging device industries in year *t*

Note: Revenue equals 9 if revenue is greater than $1B, 8 if 500M~1B, 7 if 100~500M, 6 if 50~100M, 5 if 25~50M, 4 if 10~25M, 3 if 5~10M, 2 if 1~5M, and 1 if below 1M. Categorization follows the information given in the MDR.

Table 3-2. Descriptive statistics

Panel A. Summary Statistics

	Treated			Control			Difference	
	N	Mean	*S.D.*	N	Mean	*S.D.*	Mean	*S.E.*
Market Exit	601	0.07	0.25	442	0.05	0.22	0.016	0.015
Patent Applications[a]	490	0.20	0.73	389	0.08	0.40	0.123	0.055
510(k) Applications[b]	490	0.08	0.38	389	0.05	0.47	0.028	0.043
Change in Product Categories	560	-0.01	0.27	419	-0.01	0.21	0.007	0.011
Entry into Other Segments[c]	490	0.06	0.26	389	0.03	0.28	0.026	0.018
Demand Shock	601	0.48	0.50	442	0.47	0.50	0.016	0.016
Integrated	601	0.54	0.50	442	0.44	0.50	0.106	0.068
Firm Revenue	601	3.35	2.15	442	3.01	1.78	0.345	0.282
# Product Categories within Imaging	601	0.95	0.42	442	0.89	0.38	0.063	0.053
# Medical Device Segments	601	1.24	0.52	442	1.30	0.58	-0.055	0.070
Patent Stock	601	0.72	1.82	442	0.27	1.11	0.448	0.163
Diversified	601	0.57	0.50	442	0.59	0.49	-0.018	0.067

	Treated						Control					
	Integrated			Nonintegrated			Integrated			Nonintegrated		
	N	Mean	*S.D.*	N	Mean	*S.D.*	N	Mean	*S.D.*	N	Mean	*S.D.*
Market Exit	326	0.08	0.27	275	0.06	0.23	193	0.05	0.22	249	0.05	0.22
Patent Applications[a]	274	0.20	0.82	216	0.20	0.60	177	0.08	0.47	212	0.07	0.34
510(k) Applications[b]	274	0.09	0.44	216	0.07	0.28	177	0.10	0.69	212	0.01	0.07
Change in Product Categories	301	-0.01	0.28	259	-0.00	0.26	183	-0.03	0.18	236	0.00	0.23
Entry into Other Segments[c]	274	0.07	0.29	216	0.05	0.21	177	0.05	0.38	212	0.02	0.15
Demand Shock	326	0.49	0.50	275	0.48	0.50	193	0.48	0.50	249	0.46	0.50
Firm Revenue	326	3.29	2.33	275	3.43	1.91	193	2.78	1.80	249	3.18	1.74
# Product Categories within Imaging	326	0.88	0.41	275	1.02	0.41	193	0.84	0.32	249	0.92	0.41
# Medical Device Segments	326	1.22	0.53	275	1.27	0.50	193	1.30	0.60	249	1.29	0.56
Patent Stock	326	0.80	2.04	275	0.63	1.51	193	0.37	1.39	249	0.20	0.83
Diversified	326	0.59	0.49	275	0.55	0.50	193	0.65	0.48	249	0.54	0.50

[a b c] The marked variables are at firm level to reflect our analyses in Table 6, and all other variables are at firm-market level which is our main unit of analysis as in Table 4.

Panel B. Correlation Table

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
(1) Market Exit	1.00									
(2) Change in Product Categories	N/A[a]	1.00								
(3) Demand Shock	-0.01	-0.07	1.00							
(4) Treated	0.03	0.01	0.02	1.00						
(5) Integrated	0.03	-0.03	0.02	0.10	1.00					
(6) Firm Revenue	0.04	0.01	0.02	0.09	-0.05	1.00				
(7) # Product Categories within Imaging	-0.07	-0.21	0.00	0.08	-0.14	0.20	1.00			
(8) # Medical Device Segments	0.02	-0.03	-0.01	-0.05	-0.03	0.18	0.20	1.00		
(9) Patent Stock	-0.02	-0.02	-0.05	0.14	0.07	0.22	0.21	0.09	1.00	
(10) Diversified	0.06	-0.05	0.01	-0.02	0.07	0.23	-0.07	0.25	0.13	1.00

[a] If a firm exited a product market in year t, product count changes in year t+1 are not tracible.

Note: Firm-market-year level.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
(1) Market Exit	1.00												
(2) Patent Applications	-0.04	1.00											
(3) 510(k) Applications	-0.04	0.51	1.00										
(4) Change in Product Categories	-0.05	-0.09	-0.18	1.00									
(5) Entry into Other Segments	-0.04	0.25	0.52	-0.02	1.00								
(6) Demand Shock	-0.01	-0.14	-0.03	-0.07	-0.01	1.00							
(7) Treated	0.05	0.10	0.05	-0.00	0.03	0.02	1.00						
(8) Integrated	0.02	0.01	0.07	-0.03	0.05	0.01	0.11	1.00					
(9) Firm Revenue	0.04	0.15	0.09	0.01	0.01	0.01	0.10	-0.01	1.00				
(10) # Product Categories within Imaging	-0.06	0.17	0.25	-0.20	0.16	-0.00	0.05	-0.18	0.25	1.00			
(11) # Medical Device Segments	0.05	0.03	0.10	-0.04	0.11	-0.03	-0.08	-0.04	0.18	0.15	1.00		
(12) Patent Stock	-0.00	0.70	0.41	-0.03	0.21	-0.06	0.14	-0.01	0.25	0.20	0.04	1.00	
(13) Diversified	0.06	0.07	0.04	-0.05	0.01	0.00	-0.04	0.05	0.22	-0.15	0.22	0.10	1.00

Note: Firm-year level.

Table 3-3. Downstream integration and market exit after the DRA

DV: Market Exit	Full Sample			Subsample				Triple Diff	
				Int.	Nonint.	Treated	Control		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Integrated	0.011		0.002			-0.018	0.011	0.020	0.005
	(0.017)		(0.022)			(0.041)	(0.037)	(0.034)	(0.036)
	[0.536]		[0.931]			[0.659]	[0.778]	[0.563]	[0.881]
Demand Shock	-0.034								
	(0.021)								
	[0.105]								
Treated	-0.008								
	(0.022)								
	[0.725]								
Integrated × Demand Shock						0.072	-0.052	-0.008	-0.045
						(0.042)	(0.042)	(0.039)	(0.041)
						[0.090]	[0.217]	[0.832]	[0.276]
Integrated × Treated								-0.042	-0.022
								(0.042)	(0.050)
								[0.320]	[0.658]
Demand Shock × Treated	0.049	0.049	0.054	0.107	0.002			-0.036	-0.003
	(0.030)	(0.029)	(0.029)	(0.046)	(0.035)			(0.045)	(0.037)
	[0.101]	[0.090]	[0.063]	[0.022]	[0.961]			[0.436]	[0.930]
Demand Shock × Treated × Integrated								0.112	0.114
								(0.059)	(0.058)
								[0.058]	[0.050]
N (firm-market years)	1,043	1,043	1,043	519	524	601	442	1,043	1,043
n (firms)	199	199	199	105	96	124	95	199	199
R^2	0.00	0.02	0.06	0.08	0.10	0.09	0.05	0.03	0.06
Market FE	No	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes
Year FE	No	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes
Controls	No	No	Yes	Yes	Yes	Yes	Yes	No	Yes

Note: Standard errors clustered by firm in parentheses and *p*-values in square brackets. Control variables are firm revenue (categorical), product categories, medical device segments, patent stock and diversification indicator variable. The terms *Demand Shock* and *Treated* in Columns 2, 4-5, and 8-9 are subsumed after the inclusion of fixed effects.

Table 3-4. Market Exit After DRA for Subsamples Based on Firm Characteristics

Panel A. Degree of diversification[a]

Dependent Variable: Market Exit	Imaging		Other Medical devices		Conglomerate	
	Int.	Nonint.	Int.	Nonint.	Int.	Nonint.
	(1)	(2)	(3)	(4)	(5)	(6)
Demand Shock × Treated	0.052	0.042	0.199	-0.045	0.087	0.044
	(0.033)	(0.060)	(0.078)	(0.029)	(0.095)	(0.105)
	[0.131]	[0.493]	[0.015]	[0.126]	[0.363]	[0.678]
N (firm-market years)	143	113	171	276	204	133
n (firms)	26	25	34	43	45	29
R^2	0.14	0.15	0.20	0.17	0.15	0.18

Note: We estimated specifications at the firm-year level. Standard errors clustered by firm in parentheses and *p*-values in square brackets. All models include firm-, year-fixed effects and controls. Control variables are firm revenue (categorical), product categories, medical device segments, patent stock and diversification indicator variable.

[a] These three firm categories are mutually exclusive—imaging specialists were operating only within medical imaging segment, medical device firms operated in other medical device segments, and conglomerates had businesses outside of medical device sector before the demand shock.

Panel B. Firm ownership and size

Dependent Variable: Market Exit	Public		Private		Large		Small	
	Int.	Nonint.	Int.	Nonint.	Int.	Nonint.	Int.	Nonint.
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Demand Shock × Treated	0.161	-0.045	0.097	0.014	0.078	0.109	0.128	-0.004
	(0.088)	(0.258)	(0.045)	(0.034)	(0.099)	(0.072)	(0.048)	(0.039)
	[0.087]	[0.867]	[0.034]	[0.689]	[0.436]	[0.145]	[0.009]	[0.929]
N (firm-years)	72	41	363	369	100	88	334	321
n (firms)	15	9	73	69	22	20	67	61
R^2	0.69	0.62	0.37	0.30	0.57	0.51	0.34	0.30

Note: We estimated specifications at firm-year level. Standard errors clustered by firm in parentheses and *p*-values in square brackets. Large firms are defined as firms with revenue greater than $25M. All models include firm-, year-fixed effects and controls. Control variables are firm revenue (categorical), product categories, medical device segments, patent stock and diversification indicator variable.

Table 3-5. Other firm responses to the demand shock

Dependent Variable:	Panel A: Patent Applications				Panel B: 510(k) Applications			
	Full	Int.	Nonint.	DDD	Full	Int.	Nonint.	DDD
	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
Demand Shock × Treated	-0.161	-0.134	-0.174	-0.128	-0.056	-0.067	-0.035	-0.005
	(0.053)	(0.061)	(0.089)	(0.078)	(0.018)	(0.022)	(0.026)	(0.036)
	[0.003]	[0.030]	[0.054]	[0.104]	[0.002]	[0.003]	[0.187]	[0.885]
Demand Shock × Treated × Integrated				-0.008				-0.044
				(0.096)				(0.044)
				[0.933]				[0.313]
N (firm-year)	802	409	392	802	802	409	392	802
n (firms)	157	83	74	157	157	83	74	157
R^2	0.70	0.80	0.58	0.54	0.85	0.89	0.76	0.30
Firm FE	Yes	Yes	Yes	No	Yes	Yes	Yes	No
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Dependent Variable:	Panel C: Changes in Product Categories				Panel D: Entry into Other Segments			
	Full	Int.	Nonint.	DDD	Full	Int.	Nonint.	DDD
	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
Demand Shock × Treated	-0.025	0.009	-0.038	-0.031	0.007	-0.012	0.033	0.038
	(0.031)	(0.048)	(0.038)	(0.041)	(0.021)	(0.033)	(0.024)	(0.030)
	[0.412]	[0.850]	[0.319]	[0.459]	[0.744]	[0.725]	[0.177]	[0.213]
Demand Shock × Treated × Integrated				-0.023				-0.035
				(0.059)				(0.042)
				[0.694]				[0.396]
N (C: firm-market-year; D: firm-year)	945	465	480	945	846	435	410	846
n (firms)	157	83	75	157	166	88	78	166
R^2	0.38	0.47	0.34	0.06	0.38	0.41	0.38	0.08
Firm-Market FE	Yes	Yes	Yes	No	No	No	No	No
Firm FE	No	No	No	No	Yes	Yes	Yes	No
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Note: Standard errors in parentheses and *p*-values in square brackets. All two-way interactions are included in the models. Control variables are firm revenue (categorical), product categories, medical device segments, patent stock and diversified.

Table 3-6. Summary of Robustness checks

Concerns	Robustness checks
A. Exogeneity of the DRA shock on imaging device manufacturers	
1. The common trends assumption between the treated and control groups may not hold, resulting in biased estimates.	Figure 3-2 (Panel A, B) depict no differences in the time trends between treated and control groups during the pre-treatment period. Event study analysis (Figure 3-3) provides support for the parallel trend assumption.
2. Manufacturers might have expected a negative impact of the DRA in the pre-treatment period and made strategic moves early on, rendering the year 2007 cutoff and our study period window arbitrary.	Event study analysis (Figure 3-3) provides no evidence for the pre-shock expectation. Figure 3-4 suggests that the length of pre-period does not determine the size of the DRA effect. Figure A3-1 of Appendix shows that the total number of outstanding imaging centers continued to grow during our pre-treatment period, providing evidence that the market did not expect the policy change. None of 199 firms in our sample shifted its vertical scope during the study period.
3. The DRA might not have a significant impact on manufacturers, but other events may have driven the exit.	Scholarly research in medical imaging and our qualitative data suggest that the DRA was a watershed demand shock on the treated firms.
B. Control group validity	
5. The control group may not be comparable to the DRA-affected imaging (treated) group.	Figure 5 suggests that our results are not driven by the choice of any control market or by an artifact of control group selection.
6. Treated and control groups may each represent unbalanced distribution of integrated firms.	Results remain consistent using coarsened exact matching (Table A3-2 in Appendix).
C. Sample selection and other concerns	
7. Manufacturers may have changed their vertical scope over time.	None of 199 firms in our sample shifted vertical scope during the study period.
8. Sample selection problem may arise from not including manufacturers that concurrently use internalized and external distributors.	Results are robust to the extended sample of manufacturers (Table A3-3 in Appendix), which includes integrated, nonintegrated and hybrid manufacturers using dual distribution modes.

Table 3-7. Summary of qualitative evidence on post-shock adjustment

	Post-shock adjustment	Count of firms engaging in action	
		Unique firm count	Actions mentioned
Integrated firms	*Demand management*	9/12 (75%)	
	Emphasis on customized offerings		6/12 (50%)
	- Customer relationship		3/12 (25%)
	- Increased direct sales force		3/12 (25%)
	- Emphasis on service and maintenance		3/12 (25%)
	- Increased marketing and advertisement		3/12 (25%)
	Changed product features		6/12 (50%)
	Entered or increased presence in foreign markets		5/12 (42%)
	Cost reduction	8/12 (67%)	
	Reduced operating costs		8/12 (67%)
	- SG&A expenses		7/12 (58%)
	- Manufacturing costs		3/12 (25%)
	- Personnel costs (e.g., reduced headcount)		3/12 (25%)
	Product portfolio reconfiguration	5/12 (42%)	
	Product market exit by divestiture		4/12 (33%)
	- Imaging businesses		2/12 (17%)
	- Imaging research subsidiaries		1/12 (8%)
	- Non-imaging businesses		2/12 (17%)
	New product line launch in unaffected imaging and other medical segments		2/12 (17%)
Nonintegrated firms	*Demand management*	4/6 (67%)	
	Entered or increased presence in foreign markets		4/6 (67%)
	Expanded low-cost offerings		2/6 (33%)
	Cost reduction	5/6 (83%)	
	Reduced operating costs		3/6 (50%)
	- SG&A expenses		3/6 (50%)
	- Personnel costs (e.g., reduced headcount)		3/6 (50%)
	- Sale of PPE		1/6 (17%)
	Reduced R&D expenses		1/6 (17%)
	Product portfolio reconfiguration	3/6 (50%)	
	New product line launch in unaffected imaging and other medical segments		3/6 (50%)
	- Expanding distribution network		1/6 (17%)
	Distributors serve as a buffer	2/6 (33%)	
	Inventory management by distributors		2/6 (33%)

Appendix

A3-1. Text of Senate Bill 1932 (as of Feb 9, 2006, passed Congress)

One Hundred Ninth Congress
of the
United States of America
AT THE SECOND SESSION
Begun and held at the City of Washington on Tuesday,
the third day of January, two thousand and six

An Act

To provide for reconciliation pursuant to section 202(a) of the concurrent resolution on the budget for fiscal year 2006 (H. Con. Res. 95).

Be it enacted by the Senate and House of Representatives of the United States of America in Congress assembled,

SECTION 1. SHORT TITLE.

This Act may be cited as the ''Deficit Reduction Act of 2005''.

SEC. 2. TABLE OF TITLES.

The table of titles is as follows:

TITLE V—MEDICARE

Subtitle B—Provisions Relating to Part B

CHAPTER 1—PAYMENT PROVISIONS

SEC. 5102. ADJUSTMENTS IN PAYMENT FOR IMAGING SERVICES.

(a) MULTIPLE PROCEDURE PAYMENT REDUCTION FOR IMAGING EXEMPTED FROM BUDGET NEUTRALITY.—Section 1848(c)(2)(B) of the Social Security Act (42 U.S.C. 1395w–4(c)(2)(B)) is amended—

(1) in clause (ii)(II), by striking ''clause (iv)'' and inserting ''clauses (iv) and (v)'';

(2) in clause (iv) in the heading, by inserting ''OF CERTAIN ADDITIONAL EXPENDITURES'' after ''EXEMPTION''; and

(3) by adding at the end the following new clause:

''(v) EXEMPTION OF CERTAIN REDUCED EXPENDITURES FROM BUDGET-NEUTRALITY CALCULATION.—The following reduced expenditures, as estimated by the Secretary, shall not be taken into account in applying clause (ii)(II):

''(I) REDUCED PAYMENT FOR MULTIPLE IMAGING PROCEDURES.—Effective for fee schedules established beginning with 2007, reduced expenditures attributable to the multiple procedure payment reduction for imaging under the final rule published by the Secretary in the Federal Register on November 21, 2005 (42 CFR 405, et al.) insofar as it relates to the physician fee schedules for 2006 and 2007.''.

(b) **REDUCTION IN PHYSICIAN FEE SCHEDULE TO OPD PAYMENT AMOUNT FOR IMAGING SERVICES.**—Section 1848 of such Act (42 U.S.C. 1395w–4) is amended—

(1) in subsection (b), by adding at the end the following new paragraph:

''(4) SPECIAL RULE FOR IMAGING SERVICES.—

''(A) IN GENERAL.—**In the case of imaging services described in subparagraph (B) furnished on or after January 1, 2007**, if—

"(i) the technical component (including the technical component portion of a global fee) of the service established for a year under the fee schedule described in paragraph (1) without application of the geographic adjustment factor described in paragraph (1)(C), exceeds

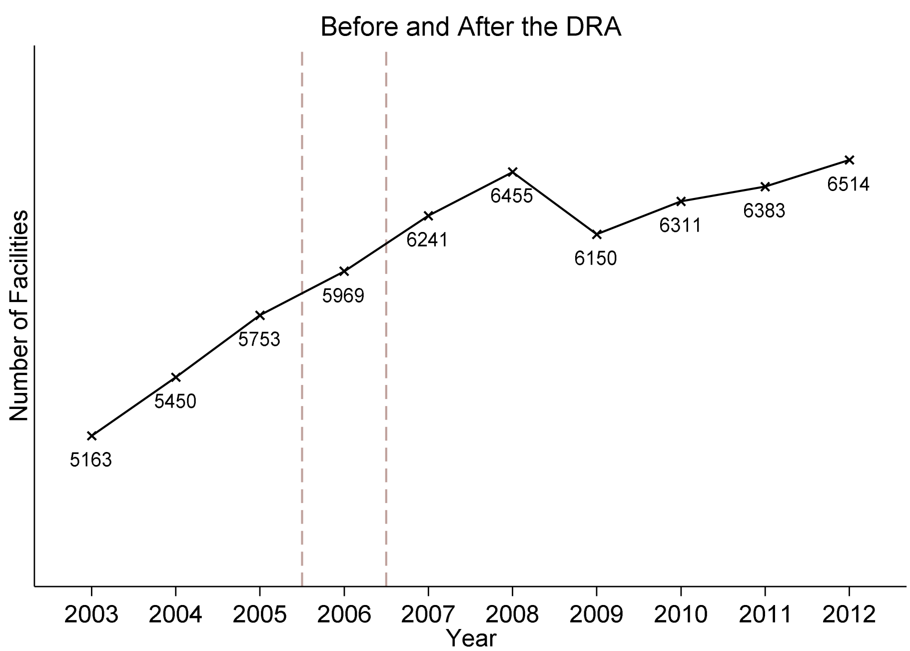
"(ii) the Medicare OPD fee schedule amount established under the prospective payment system for hospital outpatient department services under paragraph (3)(D) of section 1833(t) for such service for such year, determined without regard to geographic adjustment under paragraph (2)(D) of such section, the Secretary shall substitute the amount described in clause (ii), adjusted by the geographic adjustment factor described in paragraph (1)(C), for the fee schedule amount for such technical component for such year.

"(B) **IMAGING SERVICES DESCRIBED.**—For purposes of subparagraph **(A), imaging services described in this subparagraph are imaging and computer-assisted imaging services, including X-ray, ultrasound (including echocardiography), nuclear medicine (including positron emission tomography), magnetic resonance imaging, computed tomography, and fluoroscopy, but excluding diagnostic and screening mammography.**"; and

(2) in subsection (c)(2)(B)(v), as added by subsection (a)(3), by adding at the end the following new subclause:

"(II) OPD PAYMENT CAP FOR IMAGING SERVICES.—Effective for fee schedules established beginning with 2007, reduced expenditures attributable to subsection (b)(4).".

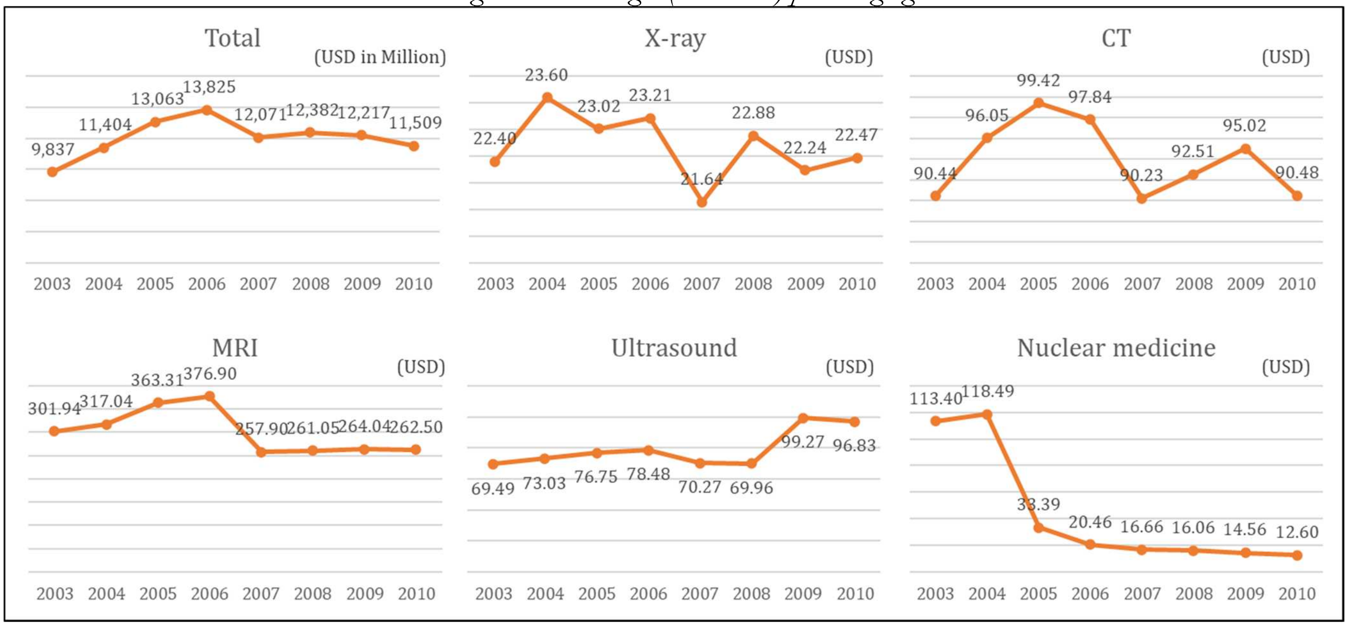
Figure A3-1. Total number of freestanding imaging centers



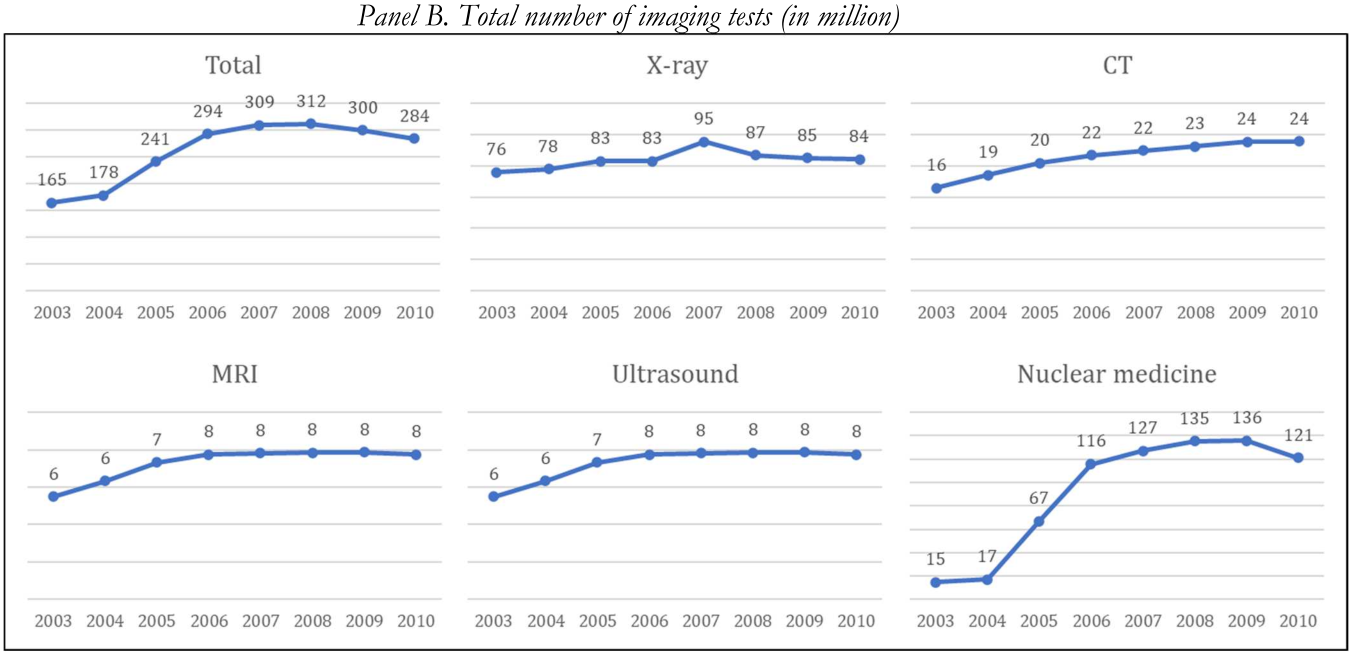
Source: Reproduced using the information provided in Proval (2012). The first vertical line indicates the timing when the DRA was signed into a law, and the second vertical line indicates the timing when the act took effect.

Figure A3-2. Allowed numbers and charges of imaging tests by Medicare B (2003-2010)

Panel A. Average allowed charges (in dollars) per imaging test

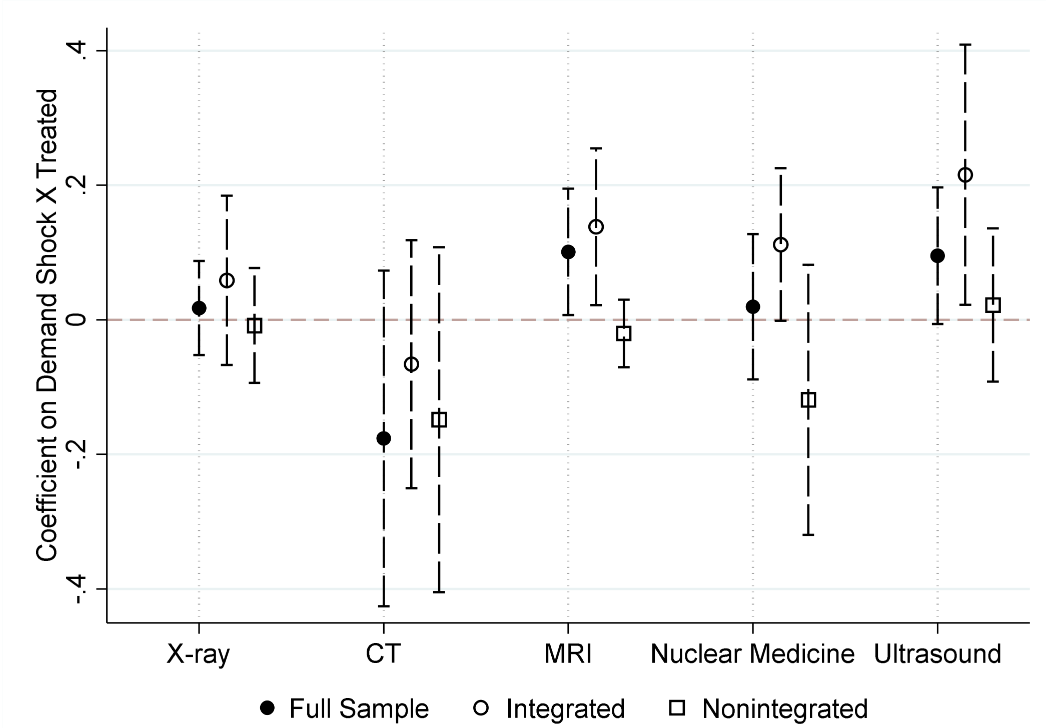


Panel B. Total number of imaging tests (in million)



Source: Authors' calculations based on data from Center for Medicare & Medicaid Services (CMS)
Note: Mammography services are excluded in calculation for X-ray volume and allowed charges, to match our empirical setting as close as possible. The number of allowed services for nuclear medicine sharply increased since 2005, because CMS expanded the reimbursement coverage of PET imaging (part of nuclear medicine) from the limited use to all cancers, effective January 2005.

Figure A3-3. Heterogeneity among treated markets compared with the same control group



Note: Each estimate is constructed by confining the sample to the appropriate group defined by the graph. The series labeled "Full Sample" comes from the estimates generated by restricting the sample to each treated market with the same control group we used in our main regressions, and then rerunning difference-in-differences model with controls, market-, year-fixed effects with standard errors clustered by firm. For the series labeled "Integrated" and "Nonintegrated", we further limit our sample to the firms with each vertical structure.

Table A3-1. Average FDA 510(k) applications by firm type and treatment period

	Pre-shock				Post-shock			
	Int.		Nonint.		Int.		Nonint.	
Market	Mean	*S.D.*	Mean	*S.D.*	Mean	*S.D.*	Mean	*S.D.*
Treated group								
X-ray	0.16	0.60	0.06	0.28	0.05	0.30	0.03	0.18
CT	16.40	14.98	0.60	0.89	16.00	12.30	0.17	0.41
MRI	1.75	6.76	0.00	0.00	1.86	6.32	0.00	0.00
Nuclear Med	1.64	5.91	0.33	0.71	1.53	5.73	0.17	0.41
Ultrasonography	1.33	5.50	0.50	1.42	0.09	0.29	0.27	0.72
Control group								
Mammography	0.17	0.41	0.00	0.00	0.00	0.00	0.00	0.00
Dental imaging	2.75	8.47	0.03	0.17	3.05	8.01	0.00	0.00
Ophthalmic imaging	0.75	4.46	0.00	0.00	0.94	4.60	0.02	0.15

Table A3-2. Downstream integration and market exit after the DRA with coarsened exact matching (CEM) weights

DV: Market Exit	Full Sample			Subsample				Triple Diff	
				Int.	Non-Int.	Treated	Control		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Integrated	-0.006		-0.016			-0.038	-0.040	-0.015	-0.041
	(0.022)		(0.026)			(0.048)	(0.053)	(0.048)	(0.053)
	[0.776]		[0.534]			[0.427]	[0.458]	[0.758]	[0.439]
Demand Shock	-0.044								
	(0.027)								
	[0.107]								
Treated	0.006								
	(0.033)								
	[0.860]								
Integrated × Demand Shock						0.092	0.001	0.006	0.003
						(0.054)	(0.048)	(0.053)	(0.050)
						[0.088]	[0.985]	[0.907]	[0.951]
Integrated × Treated								-0.041	0.004
								(0.067)	(0.071)
								[0.541]	[0.956]
Demand Shock × Treated	0.047	0.048	0.062	0.094	0.026			-0.014	0.014
	(0.040)	(0.039)	(0.037)	(0.046)	(0.056)			(0.067)	(0.060)
	[0.246]	[0.213]	[0.091]	[0.046]	[0.638]			[0.835]	[0.811]
Demand Shock × Treated × Integrated								0.105	0.082
								(0.081)	(0.075)
								[0.198]	[0.277]
N (firm-market years)	974	974	974	473	501	557	417	974	974
n (firms)	191	191	191	98	94	118	89	191	191

R^2	0.01	0.04	0.11	0.12	0.19	0.16	0.08	0.01	0.12
Year FE	No	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes
Market FE	No	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes
Controls	No	No	Yes	Yes	Yes	Yes	Yes	No	Yes

Note: Standard errors clustered by firm in parentheses and *p*-values in square brackets. Control variables are firm revenue (categorical), product categories, medical device segments, patent stock and diversification indicator variable. The terms *Demand Shock* and *Treated* in Columns 2, 4-5, and 8-9 are subsumed after the inclusion of fixed effects.

Table A3-3. Market exit after the DRA with extended sample including dual distribution mode firms

DV: Market Exit	**Full Sample**			**Subsample**			**Triple Diff**	
				Int.	Non-Int.	Hybrid		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Integrated	-0.008		-0.013				0.020	0.012
	(0.015)		(0.015)				(0.031)	(0.030)
	[0.582]		[0.407]				[0.518]	[0.680]
Non-integrated	-0.021		-0.012				0.000	0.007
	(0.014)		(0.015)				(0.036)	(0.036)
	[0.148]		[0.440]				[0.994]	[0.843]
Demand Shock	-0.040							
	(0.016)							
	[0.016]							
Treated	-0.019							
	(0.017)							
	[0.242]							
Integrated × Demand Shock							-0.034	-0.036
							(0.039)	(0.038)

							[0.381]	[0.336]
Non-Integrated × Demand Shock							0.008	0.011
							(0.042)	(0.041)
							[0.851]	[0.781]
Integrated × Treated							-0.047	-0.037
							(0.040)	(0.041)
							[0.244]	[0.365]
Non-Integrated × Treated							-0.012	-0.010
							(0.042)	(0.042)
							[0.781]	[0.812]
Demand Shock × Treated	0.047	0.047	0.047	0.107	0.002	0.044	0.048	0.053
	(0.022)	(0.021)	(0.021)	(0.046)	(0.035)	(0.031)	(0.067)	(0.065)
	[0.030]	[0.028]	[0.029]	[0.022]	[0.961]	[0.152]	[0.474]	[0.417]
Demand Shock × Treated × Integrated							0.056	0.053
							(0.051)	(0.049)
							[0.267]	[0.275]
Demand Shock × Treated × Non-Integrated							-0.056	-0.060
							(0.054)	(0.054)
							[0.300]	[0.260]
N (firm-market years)	1,807	1,807	1,807	519	524	764	1,807	1,807
n (firms)	325	325	325	105	96	146	325	325
R^2	0.00	0.02	0.04	0.08	0.10	0.07	0.01	0.04
Year FE	No	Yes	Yes	Yes	Yes	Yes	No	Yes
Market FE	No	Yes	Yes	Yes	Yes	Yes	No	Yes
Controls	No	No	Yes	Yes	Yes	Yes	No	Yes

Note: Standard errors clustered by firm in parentheses and *p*-values in square brackets. The baseline category for the triple differences models in Column 8-9 is the firms using hybrid distribution mode in a control market before the shock. Control variables are firm revenue (categorical), product categories, medical device segments, patent stock and diversification indicator variable. The terms *Demand Shock* and *Treated* in Columns 2, 4-9 are subsumed after the inclusion of fixed effects.

Table A3-4. Representative quotes used for qualitative analysis

Panel A. The integrated manufacturers affected by the DRA

Action	Sub-action	Representative quotes	Actions mentioned
Demand management			
Emphasis on customized offerings	Customer relationship	"Our customer relationships are second to none. This of course is built upon clinically advantaged products, and obviously having a strong field force that makes the difference in procedural outcomes." (Boston Scientific Corp, 2008) "We plan to enter into additional agreements to market integrated systems. These agreements allow us to coordinate our marketing efforts with our strategic partners while still dealing directly with the customer." (Volcano Corp, 2008)	3/12 (25%)
	Increased direct sales force	"Recruiting an experienced and high-profile sales leader with the intent and expectation to improve results in North America…[to] have an increasingly effective and committed sales channel that will provide the necessary sales momentum for our continued growth." (Imaging Dynamics Corp, 2008) "We intend to continue to increase our direct sales personnel." (Volcano Corp, 2008)	3/12 (25%)
	Emphasis on service and maintenance	"Our business plan includes an aggressive program for manufacturing and selling our Upright® MRI scanners. In addition, we are enhancing our revenue by participating in the physician and diagnostic services management business through our subsidiary, HMCA and are upgrading the facilities which it manages, most significantly by the replacement of existing MRI scanners with new Upright® MRI scanners… Our business plan also calls for a continuing emphasis on providing our customers with enhanced equipment service and maintenance capabilities and delivering state-of-the-art, innovative and high-quality equipment upgrades at competitive prices." (Fonar Corp, 2008)	3/12 (25%)

		"…a little bit in terms of some of that [additional] headcount [in 2009] we're thinking about is maybe in the U.S.… a couple of people potentially in the support of the service side of the group." (IRIS International Inc, 2009) "Digital radiography sales will actually grow in this constrained economic environment because of the cost benefit of digital radiography compared to film or even computed radiography… Competitors are becoming increasingly aggressive with pricing, extended warranty offerings and service contracts in order to shorten the cycle and close sales. We have had to respond accordingly to preserve sales with the consequence of eroding our margins." (Imaging Dynamics Corp, 2008)	
	Increased marketing & advertisement	"Although sales levels remained weak in fiscal 2007, we are continuing to focus our efforts on increased advertising and marketing campaigns, and distribution programs to strengthen the demand for our products… We have launched an exciting new advertising campaign, directed at physicians." (Fonar Corp, 2007) "We want to continue to support our US sales and marketing efforts." (Imaging Dynamics Corp, 2009)	3/12 (25%)
Changed product features		"Positron Corporation offers a unique combination of low cost technology and disease specific software solutions differentiating themselves from all other medical device manufacturers… Positron Corporation's President, Joseph Oliverio stated, "The Attrius is the only dedicated cardiac PET scanner on the market, which positions the Company in a unique market ascendancy point. Market dynamics combined with our cost effective scanner offering will allow the Company to seize a leading market position as a unique niche player in the nuclear cardiology market segment with virtually no other company offering such a comprehensive solution."" ("Positron Introduces New Attrius", 2008) ""One imaging system that Siemens has modified to lower the overall price, yet still offer higher-image quality, is SPECT. In October 2007, Siemens introduced the new Symbia E Series SPECT Image, … [which] can be upgraded to accommodate a larger workload…Symbia E is equipped with remote servicing capabilities, a feature that allows checking the system status through remote access and diagnostics to enable system corrections to reduce downtime and therefore cost… Marcus Lusser, vice president, global sales and marketing, Molecular Imaging Division, Siemens Medical Solutions, says	6/12 (50%)

		Siemens takes a three-pronged approach to the current cost pressures in the medical imaging market. The small c-cam has been developed for use in physician offices, the Symbia E is primarily for hospital use and hybrid devices such as Biograph and Symbia T for PET/CT and SPECT/CT imaging, respectively, are used for more complex cases. "A primary goal of ours is to offer high-quality cardiac images at a range of prices and help prevent unnecessary and expensive medical interventions. Using molecular imaging techniques in cardiology, we can determine the extent of diseases earlier and prevent the costlier interventions that might not be necessary."" (Lee, 2008)	
Entered or increased presence in foreign markets		"During the fiscal year ended June 30, 2009, 13.2% of the Company's revenues were generated by foreign sales, as compared to 2.4% for fiscal 2008." (Fonar Corp, 2009) "Selectively diversifying and strengthening our global distribution channels throughout 2009 will remain a key focus… While I expect there will be softness in North America for the foreseeable future, our non-US markets are showing good potential for 2009." (Imaging Dynamics Corp, 2009); "M. Thomas Boon, CEO and president of Imaging Dynamics Corp (IDC) told Health Imaging News that the company plans to further expand IDC's global position in hospitals, clinics and outpatient centers… As the industry continues to respond to the effects of the Deficit Reduction Act of 2005, IDC has successfully leveraged the financial benefits of its DR technology. Customers are more sensitive than ever about purchase price and are more careful to evaluate the relative value of different technologies." ("Spotlight: IDC CEO says", 2008); "We see IDC still has a very good edge with its global brand name and in 40 different countries with close to 2000 units working. Therefore, we still have a very good opportunity in emerging markets because we have the right price point." (Fosse, 2009)	5/12 (42%)
Cost reduction			
Reduced operating costs	SG&A expenses	"In order to reduce our net losses and demands on our cash and other liquid reserves, we instituted an aggressive program of cost cutting during and following the end of fiscal 2008. These measures included consolidating HMCA's office space with Fonar's office space, reductions in the size of our workforce, compensation and benefits, as well as across the board reduction of expenses. The cost reductions were intended to enable us to	7/12 (58%)

		withstand periods of low volumes of MRI scanner sales, such as we have experienced in fiscal 2007 and 2008." (Fonar Corp, 2008) "Looking to 2009, as a result of the cost reduction programs we have commenced, lower shared service center implementation costs and an expected positive impact from currency, we expect to see a year-over-year decline in SG&A expense." (Alcon Inc, 2009)	
	Manufacturing costs	"In early 2009, we announced our Plant Network Optimization plan, aimed at simplifying our plant network, reducing our manufacturing costs and improving gross margins." (Boston Scientific Corp, 2009) "We continuously improve our manufacturing processes to reduce costs and improve margins. We believe that by moving to PC-based consoles and improving our manufacturing processes through increased automation and design enhancements, we will be able to continue to reduce the cost to manufacture our consoles and single-procedure disposable products." (Volcano Corp, 2009)	3/12 (25%)
	Personnel costs (e.g., reduced headcount)	"We are looking at a 2008 to 2009 headcount base that would be roughly 4,500 heads lower than what we have today." (Boston Scientific Corp, 2007) "At this point, we [Imaging Dynamics Corp] believe we have the right cost structure in terms of head count. We have close to around 50 employees, whereas at one point a year ago, we had close to 100." (Fosse, 2009) "On April 22, 2009, the company announced a plan (the "Plan") to reduce its overall cost structure and improve efficiency. The Plan included the consolidation of certain businesses in the United States and the realignment of certain sales and marketing functions outside the United States. The Plan resulted in the elimination of certain positions and other employee terminations worldwide." (CR Bard Inc, 2010)	3/12 (25%)
Product portfolio reconfiguration			
Product market exit by divestiture	Imaging businesses	"Eastman Kodak, … said Wednesday that it would sell its X-ray film and medical-imaging equipment operations to an investment company, Onex of Toronto … Kodak decided to sell largely because of the high cost of adapting them to all-digital technology as the business was going to require a lot of investment." (Austen, 2007)	2/12 (17%)

		"Canadian life sciences company MDS Inc. says it's going to sell off most of its major divisions and focus on its troubled Nordion medical isotope business." (MDS Inc, 2007)	
	Imaging research subsidiary	"During the second quarter of 2007, we closed the operations of our Advanced Digital Imaging Research subsidiary, or ADIR, whose costs had previously been substantially covered by government sponsored grants." (IRIS International Inc, 2009)	1/12 (8%)
	Non-imaging business	"We have announced the planned sale of one of our business units, the cardiac and vascular surgery business unit." (Boston Scientific Corp, 2008) "Subsequent to the quarter, MDS Nordion divested two product lines (MDS Analytical Technologies and MDS Pharma Services businesses). These assets were non-core slower growth product lines with relatively low margins. Their sale was a key step in executing MDS Nordion's growth strategy to become a leading innovator in molecular medicine." (MDS Inc, 2007)	2/12 (17%)
Focused on unaffected product markets		"Siemens introduced its new digital mammography system, the Mammomat Inspiration, which incorporates our large detector." (Analogic Corp, 2008a); "In January 2007, we [Siemens] acquired the Diagnostics division of Bayer AG, … a leading provider of in vitro immunodiagnostics solutions. We expect the Bayer transaction to significantly strengthen our position in in-vitro diagnostics, a high growth segment of the healthcare market… In July 2007, we announced an agreement to acquire U.S.-based Dade Behring Holdings, Inc., a leading clinical laboratory diagnostics company…, making Siemens the world's first fully integrated diagnostics provider with solutions for in-vitro diagnostics, in-vivo imaging, and data- and image-management software." (Siemens 2008a); "Let's shortly discuss this DRA effect and what does that mean. …First, we offer to our customers solutions which help them to improve their operational, their financial and their clinical performance. That's the reason why they are interested to buy from us, why we are the preferred supplier, the partner of choice to them…Second, we are addressing new markets and new customers. And, third, if you see the customer base of our IVD business, of our IT business, of our imaging business, there is not 100% overlap. So we can benefit from the cross-selling to the customers. We do have access, we do have excellent relationships in the different business areas we are in." (Siemens, 2008b)	2/12 (17%)

Panel B. The nonintegrated manufacturers under the DRA shock

Action	Sub-action	Representative quotes	Actions mentioned
Demand management			
Entered or increased presence in foreign markets		"Our medical imaging systems are sold in the U.S. and internationally, principally by a network of over 300 distributors worldwide. This network has expanded during fiscal year 2008 as we have partnered with one of the largest dealer buying groups to distribute our digital and general radiographic imaging equipment for the medical, chiropractic and veterinary markets." (Del Global Technologies Corp, 2008); "The majority of our sales… continue to come from international markets around the world where, despite the fact they too are in economic slumps, the demand for medical products remains high as these emerging economies present new opportunities for us." (Del Global Technologies Corp, 2009) "An increase in marketing and sales costs of approximately $1.3 million in the current fiscal year due to (a) the Company's aggressive launch … for the new three dimensional x-ray imaging equipment, including attendance at two large international tradeshows, development of new brochures and advertising materials, and the related travel and entertainment expenses, (b) pursuing various sales opportunities in both the domestic and international markets" (Afp Imaging, 2007); "An increase in marketing and sales costs of approximately $330,000, attributable to: … (b) the worldwide introduction of the Company's new vertical three-dimensional CBCT scanner" (Afp Imaging, 2008)	3/6 (50%)
Expanded low-cost offerings		"For the medical imaging market, we currently have two digital radiographic solutions and are committed to expanding our selection to include a wider range of low-cost offerings for customers." (Del Global Technologies Corp, 2007); "During fiscal 2006 and 2008, we expanded our product portfolio with the introduction of the Del Medical U-ARC DRT Digital Radiographic System and TITAN product lines, respectively. These system enables radiologists to obtain better patient images within a fraction of the time and with	2/6 (33%)

		lower overall costs than traditional film-based systems." (Del Global Technologies Corp, 2008) "Some of the benefits that have driven customer interest are, first, a roughly 20 times improvement in the response time for bringing the x-ray up to power, which leads to reduced patient dose and also opens the door for dual energy applications. Number two, a lower end-to-end cost of the system." (Analogic Corp, 2008a)	
Cost reduction			
Reduced operating costs	SG&A expenses	"The majority of the synergy savings came from the sales functions as we moved quickly to consolidate the salesforce and reduced duplicative management level headcount, consolidate territories, etc. Additionally, we were able to reduce some of our G&A expenses in finance executive management and IT areas as we implemented our integration plan and made headcount reductions." (X-Rite Inc, 2007) "We took expense reductions in Digital Radiography. ... Revenue growth is our primary profit driver, but we'll continue to focus on streamlining our operation and low-cost supply, and we'll control expenses through engineering and G&A productivity." (Analogic Corp, 2008a)	3/6 (50%)
	Personnel costs (e.g., reduce headcount)	"In response to lower demand, we implemented cost control programs throughout fiscal year 2009. In the second quarter of fiscal year 2009, we reduced our workforce by 145 employees worldwide (then 9% of our total workforce) and recorded a restructuring charge of $3,488[thousands] for severance and personnel related costs." (Analogic Corp, 2009a) "Based on the recent losses, the Company has instituted significant cost cutting measures in Fiscal 2009, which should begin to take effect in the second quarter Fiscal 2009. These measures include reductions in operating costs and worldwide marketing and distribution costs, including payroll, employee benefits, and operating overhead charges." (Afp Imaging Corp, 2008)	3/6 (50%)
	Sale of PPE	"We will be moving into a new headquarters facility beginning actually this month and will be completed by the end of May… We are going to reduce our floor space requirements because of much of the new outsourcing initiatives that we have, as well as some of our	1/6 (17%)

		major cost reduction programs and lean initiatives. We are going from 66,000 square feet to roughly 22,000 square feet, which will also contain a world-class showroom for our new digital products." (Del Global Technologies Corp, 2009)	
Reduced R&D expenses		"We intend to reduce the R&D as a percentage of sales." (Analogic Corp, 2007)	1/6 (17%)
Product portfolio reconfiguration			
New product launch in unaffected markets		"Debuting in 2007, Shade-X® is a spot measurement device that supports the most widely used shade guides available in less than one second. Shade-X® includes two databases to match the dentin and the incisal regions of a patient's tooth (more opaque and more translucent areas)." (X-Rite, 2009) "Wallach Surgical Devices, Inc. On February 22, 2007, CSI (CooperSurgical Inc) acquired all of the outstanding shares of Wallach for $20.0 million in cash. Wallach's products consist of various diagnostic and therapeutic medical instruments primarily for in-office use in women's healthcare and other specialty instruments relating to dermatology, ophthalmology, anesthesiology, dentistry and veterinary medicine." (The Cooper Companies, 2007) "An increase in marketing and sales costs of approximately $1.3 million in the current fiscal year due to (a) the Company's aggressive launch into the dental and medical marketplaces …, (b) pursuing various sales opportunities… with specific emphasis in the growing veterinary markets… On April 19, 2007, the Company completed the acquisition of Quantitative Radiology srl, an Italian corporation, by acquiring all of the outstanding share capital of QR from the shareholders. QR is a global supplier of state-of-the-art, in-office three-dimensional dental computed tomography (CT). QR uses an imaging technology that features a cone shaped beam of x-rays (a CBCT scanner)." (Afp Imaging Corp, 2007)	3/6 (50%)
	Expanding distribution network	"Afp Imaging Corporation is pleased to announce an expansion of our Dent-X division's Canadian dealer sales network through a cooperative agreement with Global Practice Solutions, LLC." (Afp Imaging Corp, 2009a)	1/6 (17%)

Distributors serve as a buffer			
Inventory management by distributors		"We work toward what we call supplier managed inventory with our major customers… Because it doesn't do us any good for them to be inefficient with their inventory…getting each of our major customers leaned from their side with us just helps us align with the underlying demand. We also saw, with a couple of our high-end CT customers, some adjustments associated with…the DRA driving, softening the overall demand, but really resulting in, again, in more of an inventory adjustment in that first quarter, because we also expected to see and do see some improvements going forward in those areas." (Analogic Corp, 2008b) "Many customers continue to reconsider their purchases for the Company's equipment and many distributors continue to reduce their on-hand inventory, based on their own economic circumstances." (Afp Imaging, 2009b)	2/6 (33%)

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