J PROD INNOV MANAG 2021;38(1):192–215

DOI: 10.1111/jpim.12547

The Transformation of the Innovation Process: How Digital Tools are Changing Work, Collaboration, and Organizations in New Product Development*

Tucker J. Marion, and Sebastian K. Fixson

Over the past several decades, digitization has invaded all areas of human activity, including innovation. The result of digitization of existing tools for design and collaboration, and the introduction of entirely new digital tools, is a far more substantive change of innovation than previous generations of tools enabled. It affects not only the quality of the output and speed of its generation, but it affects the innovation work itself, changes work content, collaboration patterns, decision authority, organizational set-ups, governance structures, firm boundaries, and ultimately entire ecosystems.

In this paper, the digitization of New Product Development (NPD), a subset of innovation, is studied to pursue two research questions: (1) How has the digital tool landscape in NPD changed over the past 15 years, and (2) how have these changes affected how firms innovate?

This research uses a longitudinal multi-method, qualitative approach to deep dive into actual use cases of digital design tools such as computer-aided design CAD and new tools such as collaborative information technology (CIT). The changes in these tools and observations into how these tools are transforming the very nature of how things are designed is the research focus of this study.

These tools have become increasingly more sophisticated while being easier to use and are integrated earlier in the design process. As a result, digital tools have a far broader reaching impact than previous generation of tools. Not only do they affect output and process efficiency, but they also increase depth and breadth of the work of individual innovators, they lead to rearrangement of the entire innovation processes, enable new configurations of people, teams, and firms, and rewrite the rules on how knowledge management acts as a critical competitive capability. The progression of digitization is laying the groundwork for changes to what firms are and do and points to different ways of organizing, specializing, and training for NPD professionals.

Practitioner Points

- Digital design and collaboration tools are essential to all facets of the innovation process, and that importance is accelerating as tools gain in intelligence and capabilities.
- New tools are changing approaches to design tasks, organizational design, and the skills required of innovation professionals.
- Firms should consider giving teams autonomy to decide on the tools they use, but be conscious of issues such as churn due to tool switching costs, over iteration, and data management.
- Central digital groups, a migration to a more systems thinking approach to design, and roles moving from solution generators to solution selectors will become more significant as intelligent tools play a bigger role in new product development tasks.

Address correspondence to: Tucker J. Marion, Entrepreneurship & Innovation Group, Northeastern University, 360 Huntington Ave., 209 Hayden Hall, Boston, Massachusetts 02115, USA. E-mail: t.marion@neu.edu

*We thank PTC Corporation for their assistance and efforts in data collection. We also thank the Industrial Designers Society of America (IDSA) for their assistance in the Phase 1 exploratory survey. Prior versions of this work and research were presented at the International Conference on Engineering Design (ICED) 2019, the International Product Development Management Conference in 2018, The Product Development Management Association Research Forum 2019, PTC's LiveWorx 2019, and the Academy of Management 2019 annual meeting.

Introduction

Over the last 15 years, the NPD process has become increasingly digitized. Collaborative Information Technology (CIT) tools such as Basecamp, #Slack, Asana, and Teamwork.com have seen enormous growth in popularity (Marion, Reid, Hultink, and Barczak, 2016; Song, Berends, Van der Bij, and Weggemen, 2007), while digital design tools such as computer-aided design (CAD) (e.g., Solidworks, CREO, Onshape, etc.) and analysis packages (e.g., COMOS, ANSYS, etc.) have become increasingly capable and accessible. From the perspective of a knowledge-based view (KBV) of the firm, these tools can foster the creation of knowledge via faster problem-solving through the rapid dissemination of ideas, comments, and revisions to design. With the addition of new technology such as real-time, cloud-based analysis tools, some design functions are seeing the speed of solving problems increase by thousands of percent during the design and analysis revision cycle (Brown, 2018). This dramatic change in performance is creating entirely new ways to design and model systems by dramatically accelerating iteration and experimentation concomitantly with reductions in time and cost.

The digitization of communication and collaboration has augmented design tools such as CAD, analysis software, product lifecycle management (PLM) systems, project management software, and desktop software such as spreadsheets (i.e., Microsoft Excel). CIT has gained in popularity among development teams, especially those that are distributed or virtual (Duranti and de Almeida, 2012). Unfortunately, few studies have investigated the project-level influence these new tools, when combined, have on the new product development (NPD) process. Gilson, Maynard, Young, Vartiainen, and Hakonen (2014) concluded that a majority of studies of IT still focus on traditional tools such as e-mail but ignore social media and new cloud-based solutions. While some research has found no relationship between IT tools and NPD outcomes, others have shown the variety and social aspect of these news tools can have a significant impact on NPD (Durmusoglu, Calantone, and Sambamurthy, 2006; Markham and Lee, 2012; Marion, Meyer, and Barczak, 2015b; Roberts and Candi, 2012). Since nearly all facets of the NPD process are impacted by the tools used by NPD teams (Marion, Barczak, and Hultink, 2012), understanding their influence on the process and outcomes is an important area of investigation.

This research bridges the theoretical and practical by trying to understand how these tools have evolved and how this evolution affects real-life projects. This research seeks to make sense of how these design and communication tools have matured and developed over time, how they are being used by project teams today, what factors enhance or inhibit their use, and how they contribute to changes in design activities during the NPD process. To accomplish this goal, a longitudinal, qualitative study of digital design and CIT tools use among real-world designers and project teams was undertaken. Additionally, this study systematically collected data on design and CIT tool introduction and propagation over the last decade to inform the research.

Understanding how design and collaborative IT can influence the process by which new knowledge is created and communicated to inform design and NPD is relevant, as the tools have become an increasingly valuable resource affecting knowledge-based

BIOGRAPHICAL SKETCHES

Dr. Tucker J. Marion is an associate professor in Northeastern's D'Amore-McKim School of Business, Entrepreneurship & Innovation Group, Faculty Director of Innovation Masters programs, and the Samuel Altschuler Research Professor. Dr. Marion's interdisciplinary research is concentrated on product development, innovation, and entrepreneurship. Specifically, he looks at how innovation efforts can be made more efficient and effective through the use of collaborative IT, digital design, rapid prototyping, outsourcing, and product architecture. His work has appeared in books and journals including *Journal of Product Innovation Management*, *Journal of Business Venturing*, *R&D Management*, *IEEE Transactions on Engineering Management*, *MIT Sloan Management Review*, *Research-Technology Management*, *Design Studies*, *International Journal of Production Research*, and others.

Dr. Sebastian K. Fixson is Associate Dean of Graduate Programs and Innovation at the F.W. Olin Graduate School of Business, and Professor of Innovation & Design, at Babson College. He holds the degree of Diplom Ingenieur (M.Sc.) in mechanical engineering from the University of Karlsruhe, Germany, and a Ph.D. in Technology, Management, and Policy from MIT. Dr. Fixson concentrates his work on helping people and organizations build innovation capabilities. In his research, he investigates how factors such as structure and governance of innovation processes, practices like design thinking, and the use of digital design tools affect the nature and outcome of innovation work. His work has appeared in books and journals including the *Journal of Product Innovation Management, Journal of Operations Management, IEEE Transactions on Engineering Management, MIT Sloan Management Review, Research-Technology Management, Creativity and Innovation Management, International Journal of Automotive Technology and Management, Research Policy, Technological Forecasting and Social Change*, and others.

competence of the firm. In this research, several contributions to further our understanding of digital tools and NPD are made. First, this study develops and adds context to understand how these tools have changed over time and how these new capabilities in-turn affect how NPD activities, at the individual and team-level, are performed. Next, it is shown that the corresponding behavioral changes are leading to different organizational approaches and also signals the importance of different types of skills required of NPD professionals. Lastly, the managerial challenges and opportunities these new approaches to the activities of NPD will present to firms in areas ranging from training to IT implementation is explored. In the next section, relevant literature for both tools, knowledge, and skills is discussed. A section on research design follows. Then, research results and their implications are reviewed. The paper concludes with thoughts on some limitations and future research opportunities.

Theoretical Background

New product development, or innovation in general, has historically been defined as the introduction of a new product, service, or method (Nonaka and Takeuchi, 1995; Schumpeter, 1934). There are two aspects to consider, one being the outcome of the NPD effort, and the other being the process with which the innovation is developed. The process perspective allows researchers to investigate the activities and interactions that are required for the successful generation and introduction of an innovation (Greve and Taylor, 2000; Griffin, 1997; Krishnan and Ulrich, 2001). Knowledge creation is often at the center of this viewpoint, with a focus on organizational attributes that can influence this process (Nonaka and Takeuchi, 1995; Tsai, 2001). In the NPD process, knowledge is created at all phases, from ideation to commercialization (Eppinger and Ulrich, 2015; Machlup, 1980). The KBV argues that knowledge creation, exchange, and recombination are essential to innovation efforts (Galunic and Rodan, 1998; Henderson and Clark, 1990; Quintane, Mitch Casselman, Sebastian Reiche, and Nylund, 2011).

According to the KBV, knowledge is an organizational resource, and the ability of a firm to generate and deploy this knowledge in the NPD process can improve firm performance (Grant, 1996; Kogut and Zander, 1992; Nonaka, 1994; Spender, 1996). Viewed through the KBV lens, the goal of new design and CIT tools is to increase knowledge generation and sharing among team members directly. The KBV offers a useful framework to examine issues of innovation, technology, and organization in firms (Alavi and Leidner, 2001; Gopalakrishnan, Bierly, and Kessler, 1999). These tools are aimed to speed design creation and foster virtual team communication, coordination, and collaboration (Duranti and de Almeida, 2012). However, most studies of IT have focused on traditional services and product offerings such as e-mail (Gilson et al., 2014). Design, analysis, and CIT tools bridge traditional approaches to design activities with new forms of technology, such as social networking. An example is the new cloud-based CAD platform Onshape, which allows real-time distributed iteration, team communication, and new plug-in functional applications similar to the Apple App Store. A knowledge-based theory of the firm provides a fundamental theoretical basis as to why the use of various IT tools in the NPD process may increase performance, as these tools can improve the efficiency of knowledge creation and transfer among the stakeholders in the organization (Marion, Fixson, and Meyer, 2014, p. 20).

There are different outcome measures for NPD, such as the efficiency of the process and overall innovation capabilities of the firm. Innovation capabilities are a set of abilities and skills in an organization that allow firms to adopt new processes and technologies in their design efforts (Ju, Zhou, Gao, and Lu, 2013; Zahra and Nielsen, 2002). These innovation capabilities are linked to the design of superior products and services (Moorman and Slotegraaf, 1999; Song, Droge, Hanvanich, and Calantone, 2005; Zhou and Wu, 2010). To understand how innovation capabilities that can serve as a competitive advantage are formed in the first place, this research builds on the knowledge transfer framework that includes three categories of knowledge reservoirs: member, task, and tool (Argote and Ingram, 2000; Argote and Fahrenkopf, 2016). In the context of NPD, members are the individuals working on various aspects of the product or project. Research has identified people-related factors such as team communication, team composition and organization, and senior management support as important factors affecting product development performance (Brown and Eisenhardt, 1995). Fostering and integrating communication and collaboration amongst team members of different skill sets and functional areas has been shown to lead to better-performing NPD processes and resulting in new products (Cooper, 2001; Kahn, 1996; Marion et al., 2014). Critical to this human side of NPD is collaboration and sharing of design and project information among team members, what Argote and Fahrenkopf (2016) call the member-member networks.

The second knowledge reservoir, task, can be mapped on the process in NPD (Hopp, Iravani, and Liu, 2009; Roemer and Ahmadi, 2004). When two or more individuals work together on a project, develop a mutual understanding, achieve collective goals, and share resources—this collaboration and the tasks and associated efforts to manage it is the development process (Appley and Winder, 1977; Kahn, 1996; Marion et al., 2014; Schrage, 1990). The development process includes numerous tasks whose sequencing and interdependencies need to be managed. For example, the operations management literature has developed insights into how to structure the NPD process to minimize rework (Browning and Ramaseh, 2007). Typically segmented into phases, the NPD process includes the up-front discovery of user needs and market opportunity, detailed design and development, and commercialization (Cooper, 2001; Ulrich and Eppginer, 2016). Specifically, the design and development phase includes conceptual design via design sketches, design concepts, detailed engineering design, comprehensive virtual and physical prototypes, design analysis, and prototype testing (Marion et al., 2014; Perks, Cooper, and Jones, 2005). During the design and development phase, numerous decisions need to be made about issues such as the design parameters, specifications, detailed design and engineering, and the prototype plan (Krishnan and Ulrich, 2001; Marion et al., 2014). In the commercialization phase, virtual and physical prototypes are further refined and tested, tools and manufacturing processes are designed and sourced, and supply chains are finalized. These decisions require input from functional areas across the organization and often contain many interdependencies (Marion et al., 2014).

The third knowledge reservoir in Argote and Fahrenkopf's (2016) framework is the tools that are used to design and facilitate interaction and communication of those design activities. A key element for successful integration of skills, knowledge, and efforts from different people are the tools they work with. How products are conceptualized, prototyped, designed, and tested are tied to the tools used by individuals and the team (Marion et al., 2012). As with most knowledge work, the tools for NPD have become increasingly digitized (Gartner, 2019). A digitized NPD process is characterized by the increasing use of digital tools and platforms for design, analysis, 3D prototyping, and collaborative communication, all of which increasingly replace traditional forms of design and communication such as hand sketching, handmade prototypes, telephone communication, and project management tools such manual task lists. In fact, over the past decade, the digitization of R&D activities has accelerated, and specifically, the digitization of collaboration has received renewed interest (Orellana, 2017). Not only does the digitization of interaction matter, but also the intensity with which the digital tools are used (Kroh, Luetjen, Globocnik, and Schultz, 2018).

Next to offshoring and contingent work, new technology has been identified as one of the significant drivers for changes in work (Barley, Bechky, and Miliken, 2017). Nambisan, Lyytinen, Majchrzak, and Song (2017) argue that digitization of the innovation process will make the innovation less bounded, the innovation agency less pre-defined, and the distinction between the innovation process and the outcome less clear. They propose four logics to explain digital innovation: dynamic problem-solution pairing, socio-cognitive sensemaking, technology affordances and constraints, and orchestration. These logics point to profound changes in how the activities of innovation are performed and managed. Given the rapid digital transformation of NPD over the last 15 years in each of these categories or logics, one needs to understand and make sense of this evolving landscape of the tools and how they impact design activities. Sensemaking is an organizational framing tool to label, categorize, and stabilize meanings from situations (Mills and Ungson, 2003; Taylor and Van Every, 2000; Weick, Sutcliffe, and Obstfeld, 2005). As a first step in the process of understanding this changing landscape and how it affects NPD, one needs to first grasp how these tools have changed and how these tools are integrated into the NPD process. What capabilities and features have been added? What types of tools and CIT have been developed that cover different NPD activities? Are there industry trends in the types of tools and the companies that commercialize them? In other words, how has the knowledge reservoir *tool* dynamically changed over time?

Research Question 1: How have digital tools that support design activities changed over time, and can this changing landscape be synthesized to make sense of it?

It is easy to imagine that digital tools affect work. But what are the precise effects of a changing tool landscape on a firm's knowledge as a competitive advantage? Empirical research has shown that the use of IT tools tends to be associated with the degree of collaboration (Peng, Heim, and Mallick, 2014), which in itself is correlated directly with knowledge creation and dissemination. Analogous to the interdependence of work, the interdependence of technologies (in a workflow) requires some form of coordination, and digitally mediated work processes, especially structured ones, have been shown to alter the relationship between collaborators (Claggett and Karahanna, 2018). Research on work with technology shows that engineers traverse these gaps between technologies, sometimes manually (navigate) and sometimes via automating (bridging) the process (Bailey, Leonardi, and Chong, 2010). In case of a narrow gap, engineers simply use mechanisms created earlier to traverse the gap (crossing). Bailey et al. (2010) find that these gap traversing strategies can also serve other functions beyond efficiency, for example, quality inspection, occupational training, and knowledge preservation. For these reasons, these strategies can also differ between occupations. The increasingly technology-mediated work environment, both concerning work content as well as communication, is increasingly requiring what Makarius and Larson call "virtual intelligence" (Makarius and Larson, 2017).

What these works suggest is that there are several interactions between the three knowledge reservoirs member, tasks, and tools. Thus, our second step in sensemaking of the impact of digital tools on NPD is to strive for a deeper understanding of how the changes in tools have affected the way individuals and organizations use the tools—what Argote and Fahrenkopf (2016) call the knowledge networks between member, task, and tools—and how this, in turn, impacts the work itself, and ultimately the organization's knowledge base as a competitive advantage. Formally, our second research question is as follows:

Research Question 2: How have these evolving digital tools influenced changes in NPD activities for individuals, teams, and performance outcomes?

In the next section, our research methodology and sample characteristics is reviewed.

Research Methods and Data

Research Frame and Setting

To explore, understand, and make sense of the changes of the tools and how the digitization of the design process is influencing NPD, one needs to appreciate the evolution of the landscape of the digital tools themselves and the details of their use in concrete work projects. Sensemaking helps to understand, develop meaning and context for individuals and organizations in an emerging situation in a comprehensive manner through the use of observed data and helps create order and interpret what has occurred from the environment (Berger and Luckman, 1967; Maitlis, 2005; Weick, 1993, 1995; Weick et al., 2005). To accomplish this task, this project was tackled through a multi-method approach that includes detailed qualitative research that allows an in-depth understanding of behavior (Bunduchi, 2017; Woodside and Wilson, 2003) as well as longitudinal data sets.

This research is following a call from a recent review on knowledge management research (Barley, Treem, and Kuhn, 2018) for a renewed focus on knowledge creation. Since this paper is focused on knowledge creation in the NPD process, associated activities, and the tools used to execute design work, it is important to investigate the connections between technology (digital tools) and work processes (activities) (Raghuram, Hill, Gibbs, & Maruping, 2019). To accomplish this task requires studying details that only project-level analysis can provide. A project-level study is a preferred method in determining the impact of IT tools since most of this tool use occurs at the project-level by the designers, engineers, and project managers (Barczak, Hultink, and Sultan, 2008; Devaraj and Kohli, 2003; Marion et al., 2012; McGrath and Iansiti, 1998). This study focused on the design and development of multi-part physical products of varying complexity. These types of products and projects require engineering, analysis, prototyping, testing, and manufacturing development. The resources and tasks used in these phases are driven and augmented by digital design and CIT tools. As such, individuals' development work and the tools that support that work was studied.

This research also follows the call for conducting more longitudinal, multi-method investigations of the role of digital design and CIT and its impact on work (Forman, King, and Lyytinen, 2014). Consequently, our investigations occurred in multiple research phases that spanned a decade. Research has shown that protracted engagement is being used in studies where there are efforts to move beyond conventional, short-term case observation and into a more in-depth investigation into phenomena (Given, 2008).

Research Design

This research was approached from a grounded theory, constructivist perspective using a multi-method approach in multiple phases. Grounded theory has been used extensively within qualitative research focused on entrepreneurship and innovation (Grodal, 2018; Khavul, Chavez, and Bruton, 2013; Lee, 1999; Marion, Eddleston, Friar, and Deeds, 2015a). In contrast to naturalistic case methods, the constructivist approach has a robust deductive element, which allows a comparative understanding of empirical findings between cases and different aspects of research (George and Bennett, 2005; Given, 2008; Marion et al., 2015a). In each research phase, multiple cases and interviews were undertaken. A multi-method case research approach is important to exploratory research as it affords the researcher the ability to triangulate observations through multiple viewpoints and data sets (Collier and Elman, 2008; Creswell, 2003). For each of the cases, both qualitative and quantitative data were collected, combining ethnographic participant observation, semi-structured interviews, review of archival material, and investigation of measures that digital tools and CIT use itself creates. A graphic of the overall research study is shown in Table 1. Table 1 notes the research phase, data collected, and key characteristics of the data.

The first phase of the research project began with an exploratory investigation into the use of digital design (CAD) tools. The goal of this phase was to gain a baseline understanding of how pervasive the usage of digital tools was in NPD, and how influential these tools were on the project and overall process. To accomplish this, a 30-question exploratory electronic survey on NPD tool use, including digital design, was sent to design and engineering firms via the Industrial Designers Society of America contact list. Project-specific questions included when and how frequently tools such as CAD and 3D printed prototypes were used during NPD, types of tools and methods used in the process (CAD software, types of prototypes, etc.), and the total percentage of billed project hours related to CAD engineering (see Appendix A). The final survey sample consisted of 44 firms, which represented a response rate of 68%. Next, multiple interviews were conducted with engineers and engineering managers at five firms, including defense, robotic, and multiple design and engineering firms. The interviews were held face-to-face and were semi-structured. An interview guide was developed and used during the interviews. Interviews were recorded with note-taking in real-time and later revisited during analysis to identify textual and conceptual themes and narratives (e.g., qualitative memoing). This approach is in accordance with grounded theory and qualitative research method design (Given, 2008; Taylor, Bogdan, and DeVault, 2015).

Phase 2 of this research project focused on two similar projects developed in two different periods by the same firm. The company and projects were selected based on their similarity of complexity and function (multi-part consumer products/tools), their use of a broad spectrum of NPD processes including industrial design, prototyping, testing and manufacturing, and the open access to the development team and associated data. This in-depth case comparison was ethnographic and used participant observation and review of historical project data to inform the investigation. An embedded, ethnographic approach was used, given its ability to understand human behavior within a natural setting (Jackson, 2000). Lengthened research engagement is increasingly being used in studies where a deeper, richer investigation can uncover unexpected insights into individuals and organizations (Given, 2008; Marion et al., 2015a). Participant observation and interviews were used to collect qualitative, ethnographic data on the firm and development projects. Ethnography involves long-term, immersive, and experiential participation by a researcher in a specific context to describe the meanings of experiences and also uncover unexpected moments (Fernandez, 1986; Geertz, 1973; Jackson, 2000; Marion et al., 2015a; Wacquant, 2003). By comparing information from different sources, these meanings are interpreted by the research team with the intent of identifying themes in the data (Marion et al., 2015a; Ware, Tugenberg, Dickey, and McHorney, 1999). The goal of this research was to build on the first phase and develop a detailed understanding of how digital tools have changed approaches to NPD and ultimate outcomes.

Table 1. Research Study Map

Characteristics	44 firms surveyed. 10 interviews include defense, robotics, engineering firms.	Two similar engineering products at a consumer products firm.	Two similar MEMS sensor modules projects at a leading Internet-of-Things sensor company.	5 interviews include consumer products, electronics, and defense.
Data	Multiple interviews, exploratory survey of design firms of CAD and tool usage.	Observation note taking, emails, project plans, documentation.	Observation note taking, access to emails, access to project wikis, project documentation, interviews, netnography.	Notes, recorded interviews, continued netnography.
Study Phase	**Phase 1:** Initial study of CAD and communication tool usage	**Phase 2:** In-depth, project-level study of two projects.	**Phase 3:** Embedded, participant observation on two projects. Historical data collection on digital tools and CIT.	**Phase 4:** Interviews with project personnel from multiple industries.

2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018

Phase 3 of the research began in 2011 with an in-depth engagement with a growing technology company that designs and commercializes sensors and systems used in consumer, automotive, and aerospace applications. This company was selected due to the high complexity of the project and comprehensive approach to the NPD process (the product is an electronic sensor module with embedded software), and as with Phase 2, the ability to have open access to all parts of the development project due to the academic interest in the research from company executives. As a follow-on to Phase 2, this phase was also an in-depth, ethnographic case comparison. The goal of this phase was to broaden the research to understand the impact of CIT tools on the NPD process, in addition to design tools. Phase 3 of the study involved several stages. The first stage was an in-depth investigation into the firm's NPD process, including the use and type of IT tools used during development. The next stage involved participant observation on two development projects at the firm, which began in 2014 and ended in 2017.

For both Phase 2 and 3, this study followed the multi-case methodology recommendations of Yin (1994, 2003) to diminish further sources of bias within the investigation and data collection effort. These techniques included: randomization of times, places and sampling methods, attention to marginal persons and details, regular debriefing by informed colleagues, and the use of note-taking to remind the participant-observer to detail events observed or experienced during the research engagement (Arnould and Wallendorf, 1994; Lincoln and Guba, 1985; Marion et al., 2015a). Also, data were collected on e-mail and wiki communication over time for both projects (Snider, Škec, Gopsill, and Hicks, 2017). Open access to project emails and project wikis was given by company management through email and internet accounts from 2011 to 2017. Thousands of emails and communications were accessed and viewed during the participant observation period. Field notes on the project were taken throughout this period. In cases were timing and frequency of communication were of interest, email and postings were tabulated using spreadsheets. A multi-method approach of this type to synthesize quantitative data with detailed qualitative cases or examples has been advocated by Gibson and Birkinshaw (2004). This method has been found to provide a rich understanding of organizational issues in business research (Cardinal, Turner, Fern, and Burton, 2011). To compare these current projects with historical data, the Phase 3 sample together with the two projects developed in 2001 and 2009 (Phase 2) was analyzed. A summary of firm and project characteristics for Phase 2 and 3 are shown in Table 2.

During Phase 3, an in-depth investigation into the features and commercialization history of both digital design and CIT tools over time using publicly available information was begun. Two graduate research assistants collected data from the internet and electronic library systems that included press releases, company and tool history, and news articles. This information was collected, sorted, and analyzed. The authors held regular research meetings with graduate research assistants to evaluate the research and progress, which allowed a comprehensive picture of the features and capabilities of the tools to be categorized over time. This research was started in 2017 and ended in 2018. The final phase (Phase 4) of the study included a continuation of the tool history investigation (with the same research assistants) and multiple, semi-structured interviews with representatives at multiple firms. An interview guide was developed and used in face-to-face meetings. As with Phase 1, field notes were taken during the interviews and reviewed during the memoing and analysis process. These firms

Table 2. Research Firm Characteristics

	Research Phase 2		Research Phase 3	
	Project A	Project B	Project A	Project B
Start date	2001	2009	2014	2015
Commercialization date	2002	2010	2017	2018
Application	Consumer R&D	Consumer R&D	Industrial R&D	Industrial R&D
Project type	Hand tool	Hand tool	Gas flow system	Gas flow system
Project manager	Yes	Yes	Yes	Yes
# of team members	4	3	8	6
Primary locations	U.S.	U.S.	U.S., China	U.S., China
NPD management	Loosely Defined, 3 Phases	Loosely Defined, 3 Phases	Defined, 3 Gates	Defined, 3 Gates

included electronics, aerospace, consumer products, and engineering firms. Each firm was selected due to the complex nature of its products and the associated use of digital tools. This phase of the research aimed to gain a better understanding of the current "state-of-the-art" and also get expert opinions on how tools will influence NPD in the near future.

Results

Changes in the Digital Tool Landscape

Broader process integration. To gain insight into Research Question 1, the study investigated digital tools, used for both design and collaboration. In Phase 1, which dates from 2008, one can see the importance of digital tools on NPD as a baseline for the investigation. In this sample of design and engineering firms, the study found that for a majority of respondents (51%), the hours designing in CAD (both initial design and design iterations) was a significant contributor to overall project cost, accounting for between 40-80% of billed project hours. Nearly half of respondents (49%) went right to CAD after initial product sketches, and almost all firms used 3D printed prototypes to inform the development process. It was apparent from this limited exploratory study that digital design tools were becoming essential to NPD and could influence overall NPD efficiency and effectiveness.

Today, a decade later, digital tools are used for every aspect of the NPD process. Illustration packages for industrial design, CAD for engineering design, finite element analysis (FEA) simulations for strength testing, computational fluid dynamics (CFD) packages for fluid and gas flow, cloud-based solutions for project management, video communication platforms for team interaction, and file storage platforms to store phase gate documents are some of the tools and functions that comprise this ecosystem of digital design and collaboration. To frame these research results, tools were segmented into categories. Following prior research that has organized various IT tools into four categories of activities (Mauerhoefer, Strese, and Brettel, 2017; Peng et al., 2014), the study condensed and considered four categories for the remainder of the discussion: (1) communication IT tools (email group-ware, video conferencing), (2) product design IT tools (CAD, simulation modeling and analysis), (3) project management IT tools (project management software), and (4) product data and knowledge management IT tools (shared parts databases). Examples of these tools by category are shown in Table 3 (this table is current as of 2020). As shown in Table 3, tools from multiple vendors populate each category, which covers nearly all aspects of the activities of NPD, from conceptualization to project management. In each category, both established vendors and new market entrants are active.

Higher performance. On the design tool side, over time, it was found that these tools are increasingly capable and are now including innate intelligence to automate the design process further. The speed of design modifications and analysis now occurs in near real-time. Cloud-based vendors such as Onshape offer fully capable CAD on mobile devices, which allow distributed team members the ability to modify designs, collaboratively, in real-time. Future trends indicate that real-time analyses and artificial intelligence (AI) will have a substantial impact on the act of engineering design (Gordon, 2017). In looking at the major CAD platforms and their feature enhancements over time, all platforms are making efforts to improve ease-of-use while increasing the ability to perform analyses, integration of 3D printing features, and embracing emerging technologies like augmented reality and virtual reality.

Similarly, the history of analysis tools shows an increasing degree of integration of hitherto separate functionalities (e.g., starting with finite element analysis (FEA), then adding computational fluid dynamics analysis (CFD), then adding electronics analysis,

Table 3. IT Tool Categories and Software and Platform Examples

IT Tool Category			
Communication Tools	Product Design And Analysis	Project Management	Product Data And Knowledge Management
Microsoft Outlook, Google Gmail, #slack, Yammer, Zoom	Dassualt Systemes Solidworks, Onshape, PTC Creo, ANSYS, COSMOS	Microsoft Project, Teamwork.com, Basecamp	PTC ThingWorx, Daussalt Systems Solidworks PLM, Github, GrabCAD

 J PROD INNOV MANAG 2021;38(1):192–215

then simulation of composite components, etc.). Also, the increasing power of computing (Nordhaus, 2007), together with increasing sophistication and user-friendliness increasingly enables designers to run real-time analyses and simulation *within* the design process, instead of handing the design over to an analysis specialist after some design decisions had been made. Tables 4 and 5 show some historical data on how CAD and analysis tools have changed in recent decades. The progression of both of these types of tools points to increased capability and tool intelligence. This evolution of digital tools changes how knowledge is created and used in the development process. Since this knowledge is a strategic resource of the firm and can be used to competitive advantage (Eisenhardt and Santos, 2002; Wasko and Faraj, 2005), firms that are best at using these tools or creating their solutions may see improved innovation performance.

Lower barriers to entry. Barriers to access to powerful design tools and related services like 3D printing have been dramatically reduced in recent years. This includes free CAD software such as TinkerCAD and freemium CAD platforms like Onshape. Individuals with no prior skills can learn and create designs, have them 3D printed or manufactured using services such as 3D Systems additive manufacturing services, and delivered in a matter of days. 3D printers themselves have seen dramatic cost reductions, with some models selling for a few hundred dollars. This makes high-quality engineering tools available to almost anyone. This, in turn, has fostered the development of engaged communities such as GrabCAD and given employees who are not in dedicated R&D roles a way to participate in idea development. And because these tools have little or no cost, trying new tools is easy with low risk.

New types of tools for collaboration and workflow. In the late 2000s, collaborative cloud-based software in the form of project wikis began to be increasingly adopted by project teams. This cloud-based centralized form of collaboration differs fundamentally from email. These sites pull comments and interaction from members and the community, rather than selectively pushing information to others (Marion and Schumacher, 2009).

Table 4. Summary of CAD Platform Historical Feature Changes (2010 to Present, Phase 3 Research)

	CAD Platform			
Year	AutoCAD	Solidworks	CREO	CATIA
2010	3D print feature, free form drawing	Improved user experience. Motion analysis added	Still Pro-Engineer	New PLM capability
2011	No major changes	Improved design features for manufacturing	CREO 1.0 introduced	Electronic and Mechanical CAD collaboration. Improved functional modeling
2012	Search function added	Costing feature added. Beams added to Linear Dynamic Studies	Freestyle drawing added. Sheet metal features improved	No major changes
2013	Cloud connectivity (AutoDesk 360)	Tools to improve design sustainability	No major changes	Improved composites simulation. Improved rendering and sketching.
2014	Updated user interface. 3D scan capability added	Solar simulation added. Improved drawing tools	More integrated suite of features	No major changes
2015	Improvements to ease-of-use	3D printing cost estimates	No major changes	No major changes
2016	New revision and drawing tools	User interface redesigned	Improved CREO Simulation. Improved sketching. Direct connect to 3D printers	Collaborative project collaboration. Improved systems engineering capabilities
2017	Improved cloud functionality. Easier 3D print tool	No major changes	No major changes	No major changes
2018	No major changes	No major changes	Improved augmented reality features. New simulation capabilities. IoT tools	Virtual reality features added. Improved systems engineering and integration

Table 5. Summary of the History of Platform Features of ANSYS Simulation Software

Year	Software Version	ANSYS Software Features
1971	2	ANSYS' first commercial version is released (boxes of punch cards; program ran overnight), focuses on FEA
1979	3	DOS interface
1980	4	Provides graphical user interface
1993	5.0/5.1	Integration of fluid dynamics software; beginning integration with CAD systems
2001	6	Introduces large-scale modeling
2005	8	Introduces a multi-field solver, which allows users to simulate how multiple physics problems would interact with
2009	12	The second version of Workbench; ANSYS also began increasingly consolidating features into the Workbench
2014	15	New features for composites, bolted connections, and better mesh tools
2015	16	Introduces physics engine and Electronics Desktop, which is for semiconductor design
2016	17	Introduces a new user interface and performance improvement for computing fluid dynamics problems
2017	18	It allows users to collect real-world data from products and then incorporate that data into future simulations. The ANSYS Application Builder, which allows engineers to build, use, and sell custom engineering tools, was also introduced with version 18.

These types of sites have added general social networking features to new product development. Research has shown that during development, these new media tools can increase collaboration and the number of concepts generated (Marion et al., 2014). In the third phase of our research, project wikis such as Basecamp became a significant form of communication. In project A, dating to 2014, the project wiki Basecamp was the primary form of communication during design and development (see Table 6).

Project management tools followed a similar pattern, migrating from notebook-based task lists to Microsoft Excel spreadsheets to online wikis to dedicated cloud-based software (e.g., Teamwork.com and Project Libre). As shown in Figure 1, the propagation of new project management tools has seen a substantial rise over the last 10 years. This is a dynamic space, with many entrants trying different approaches. These include some that are focused on brainstorming (e.g., Whiteboard) to those dedicated to software (e.g., GitHub). In our case analysis, frustration with switching between these project management tools was seen, with teams moving from one platform to another, and in the case of the two recent projects (Phase 3, projects A and B), switching project management tools several times during the development of a single project. This can cause churn, loss of data, and general frustration with the team. In the case studies, it was noticed that each time a new tool was chosen, the team enthusiasm to move to and learn the new features and use the tool, declined. In the case of Phase 3 Project B, only the project manager and product line manager became the primary users of Project Libre (a project management tool) as project B progressed from Development toward Commercialization. Ultimately this became a record-keeping tool, rather than a dynamic source of team interaction.

Of note is the introduction of new tools via start-ups. Firms such as PBWorks, Skype, Solidworks, Basecamp, Teamwork.com, Project Libre, and Dropbox were all-new, entrepreneurial ventures when they introduced their tools. An interesting observation from this research is that many of the new CIT ventures also created specific tools for a task, rather than a multifunctional platform. However, some evolve into a platform with broader capability, as a company like Dropbox is currently (circa 2020) doing. Overall, the study witnessed a period of substantial development and resources being funneled into new software to assist NPD. Significant growth and propagation of CIT tools used for NPD and general corporate management introduced over the last 15 years was observed. Below in Figure 1, new CIT introduced by categories, from project management to knowledge management by year, are highlighted.

In addition to the new tools that are commercialized via entrepreneurial new ventures, large, established firms continue to play a dominant role. These include those firms providing digital design software (e.g., PTC and Dassault Systemes), general software, and desktop tools (e.g., Microsoft Office 365 and Google) and other multifunctional platforms. The

J PROD INNOV MANAG
2021;38(1):192–215

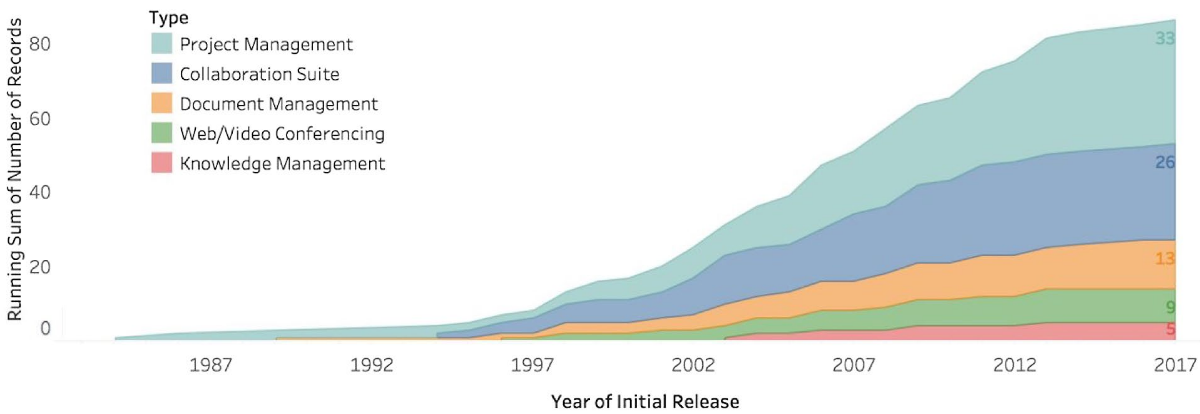

Figure 1. History of CIT Tool Introduction by Functional Type. This diagram represents a cumulative summary of tools introduced primarily in the United States in the five specific categories [Colour figure can be viewed at wileyonlinelibrary.com]

Table 6. Phase 2 and 3 Comparisons of Tools Used

	Research Phase 2		Research Phase 3	
	2001	2009	2014	2015
Primary communication tools during development	Email, Phone, Fax	Phone, email, dedicated project wiki (PBWorks)	Basecamp, email, Skype	Email, Skype, Microsoft SharePoint
Main product design tools	Paper-based sketches, 2D Drawings, SolidEdge CAD	Adobe Illustrator, Solidworks	Solidworks, Matlab, LabVIEW	Solidworks, ANSYS, Python, LabVIEW
Project management tools	Microsoft Excel	PBWorks	Basecamp, Teamwork.com, Google sites, Microsoft SharePoint	Teamwork.com, Project Libre, Microsoft SharePoint

study observed that often, the entrepreneurial ventures focus on tools with a specific scope or use. For example, initially, Yammer (now owned by Microsoft) was a focused communication application for users very similar to Twitter. Similarly, Zoom.us is a new tool focused on providing better videoconference experiences. This is opposed to Microsoft that has cloud-based platforms and applications covering a wide array of functions and activities such as document creation and sharing (SharePoint, Office 365 and Teams), video (integration of Skype technology with Teams), project management (Microsoft Project), etc. In Phase 2 and 3, the study explored the changes in tools used by the product teams.

The propagation into the process of CIT, platforms, and analysis tools is substantial by the mid-2010s. In terms of our first research question, our sensemaking of the digital tool landscape has shown that digital design tools have become increasingly capable and multifaceted in their capabilities and performance, have propagated into every aspect of the NPD process, and lowered the barriers of entry for their use. On the communication and collaboration side, there are now more tools to use that have added new ways of managing knowledge workflow to complement traditional means of communication, and the industry itself has been one of dynamic change for both new ventures and established industry vendors. Table 6 summarizes the changes in applied tool use in four projects over 15 years.

In the next section, the study is focused on the changes these tools have brought upon the individual, project teams, and the organization itself.

Effects of Changes in Digital Tools

Effect on the individual. For product design tools, it was observed that a migration from traditional engineering methods (e.g., early hand sketching, scale drawings, etc.) to proceed to design in a near-complete digital fashion has taken place. This also applies to analysis and software development. CAD is now used earlier in the process as alluded to in our Phase 1 interviews. An engineer at a design and engineering firm stated her preference for moving to digital design early in the process: "*For me, I like getting right to the CAD model. I like to fiddle around with the model right from the beginning. The applications I use most are Solidworks, email, PowerPoint, and Excel.*" This initial phase of the project highlighted the importance of digital tools in the NPD process, how these tools are being used earlier in the process, and the rise of new communication tools to augment email and telephony.

Our interviews reflected this pervasive and early use of digital design tools. "*IT is extremely important to us…more and more we go right to CAD*," expressed one engineer at a robotics company. The same engineer also expressed dissatisfaction with the complexity of some tools and the ease-of-use, which can be a benefit and liability to some surrounding the project. A design firm engineer noted: "*A few years ago, a conceptual design was done by hand. Now, we generally go right to CAD. This still takes a lot of convincing. Many older employees still like hand sketching. There is a generational difference in approaches*." But, downsides were also stated: "*CAD has been democratized. It's now a lot easier to use and share. The downside is: everyone thinks they're an engineer. CAD has a very real feel to it even if the parts are seriously flawed*."

Effect on the team. In looking across the four projects that span nearly 15 years, several trends are seen. In primary communication, one sees the continued consistency of email being used. Also, it shows that the use of traditional telephony was nearly eliminated as a primary communication method but being replaced by video calls in the recent projects.

Project A was proposed and funded in January 2014. During the prior Discovery Phase (2011 to 2014), the primary forms of communication between team members were Google Gmail for communication and posting of materials on Google Sites. At this time, a new North American President strongly advocated for all NPD activities to be managed using Google sites. This included all NPD investigations for marketing, documentation for the firm's phase-gate process, as well as video communication. The active participants in the project included an outside NPD consultant acting as a product line manager as well as a business unit Vice President. The project progressed as a market opportunity, and product specifications were defined. In January 2014, the project was officially approved to enter into development. At the firm, this is Gate 1, which is the Discovery phase, in which market investigation, business planning, project scoping, and initial conceptual design are performed. During this time, the firm began to experience issues and delays with Google sites. Hence, usage in Google Sites for NPD collaboration and information storage waned with all team members. However, another factor that contributed to usage decline in Google Sites was that after the North American President left the company in 2013, and his mandate for the use of Google Sites was no longer enforced, the development team's usage of the platform declined dramatically. It was decided by the management team to begin the migration from Google to Microsoft Office 365. This transition was completed in mid-2014.

In early 2014, the Phase 3 Project A was actively being developed. All information was migrated to Office 365, including all documentation for the phase-gate process. Project management tools such as Microsoft Excel spreadsheet action plan documents were posted, shared, and updated on SharePoint. In an interview, Project A's project manager noted that he "*didn't see any significant impact in migrating from one to the other*." During the development phase of the project, the acting product line manager mandated that all project design communication be centralized to Basecamp, a widely used product development management tool. This combined the ability to post files such as CAD, comment on design iterations, and have limited project management capabilities with the posting of tracked tasks.

The project manager noted that the use of Basecamp and other tools helped to maintain schedules and was useful during the early phases of the project. However, an engineer on the team noted that Basecamp was "*not organized, files were hard to find*." He did note its positive effects on the up-front of the process, stating, "*I find Basecamp effective during early phases where brainstorming and ideas are sharing are crucial*." Project A was 100% on-schedule during Discovery and Development. In the later stages of the project Teamwork.com, a cloud-based project management tool was used to track milestones and project progress. The project manager noted management support helped encourage tool use and support for the team. This supports the research on the importance of IT champions during NPD (Barczak, Sultan, and Hultink, 2007). An engineer on the team noted that "*managers support the use of new tools, provided it does not take a long time trying to learn or navigate them*."

Phase 3 Project B was initiated in 2015, as a new model companion to Project A. This new project did not use Basecamp, but instead relied mostly on email (Microsoft Outlook), SharePoint, Teamwork.com and Project Libre for project management. The project manager noted the benefit of SharePoint and editing files by multiple people concurrently. The project migrated from Teamwork.com to Project Libre during the development and commercialization phases. This was due to not having the capability to do resource management. This project was continually behind schedule and was noted for a large number of design changes. Primary design and CIT tools were changed mid-stream during the Development phase, which caused issues with usage among team members. The project manager stated that when dealing with design iteration and collaboration, these tools help "*only when everyone on the project uses the tool. It is not so effective when a few people are not using online tools*."

It should be noted that with ease of adoption, there is also ease of transfer to other tools. In these cases, dynamics in migrating and switching tools is observed. From Google sites to Office 365, from Teamwork.com to Project Libre. However, once a software platform is established and mature, as one sees with CAD software such as Solidworks, consistent use by NPD teams spans over time.

From an overall project perspective, the project manager noted that lack of experience on the team contributed to late design changes creating problems with the overall schedule and, in turn, more late design changes. He stated that: "*Too many iterations create frustration within the development team and management team. I believe the causes of this are inexperience and also the constant change in product requirements*." In response to a question of digital design and CIT helping meet schedules, he stated: "*Not really, as these delays are caused by product design*." This sentiment supports our findings from Phase 1 of this research stream, that process discipline stills matter in the world of digital design and CIT (Marion et al., 2012).

Data management in the projects observed, during Discovery and Development, was another challenge. Instead of one location for all filing, posting, and communication, at any one time, three platforms were used for communication and knowledge sharing. For example, one engineer relied solely on email communication, while others focused on updating and maintaining a project management site. The chances of a missed email, some team members not being copied on a reply, or not checking on updates in project management systems creates a condition of gaps in information and knowledge shared across team members. This decreases efficiency and can lead to knowledge loss and deficiencies during R&D (Meyer and Marion, 2013).

In comparing the two projects, as shown in Figure 2, some interesting differences are noted. Project A during development committed to a single platform, Basecamp, as the primary form of design iteration and project management during Discovery and Development (the project management migrated to Teamwork.com during Commercialization). Project B used Teamwork.com during Development. Basecamp use was very active, with all members contributing to design iterations, comments, etc. Project A's project manager noted this. In fact, in looking at the frequency of communication, the team working on Project A was more concentrated and intense, particularly in the design phase. The teams used the quick design iterations and communication of those changes using CIT to beneficial effect.

It should be noted that this project was 100% on-schedule during the Discovery and Development phase. The project manager and one of the engineers on Project A emphasized the benefit of a single place for communication and iteration. The communication frequency is similar to what should be expected in a well-performing project per project management literature (Meredith, Mantel, and Shafer, 2017). CIT tools helped facilitate this in this case example. Project B has substantially less interaction during development, and a higher post frequency in the later stages was due to increased design changes coinciding with late deliverables on essential milestones. Project B experienced severe delays and cost overruns and had a more disjointed approach to design tools and CIT, including switching project management tools during the process. This certainly had an impact on team tool usage. Also, the use of a wide variety of platforms contributed to knowledge and information inefficiency during the project. While providing lower-cost design changes and prototyping costs, these tools can also be tempting a team to rush into detail design or increase the number of design iterations with decreasing returns, both effects potentially leading to a phenomenon called back-loading, and as a result

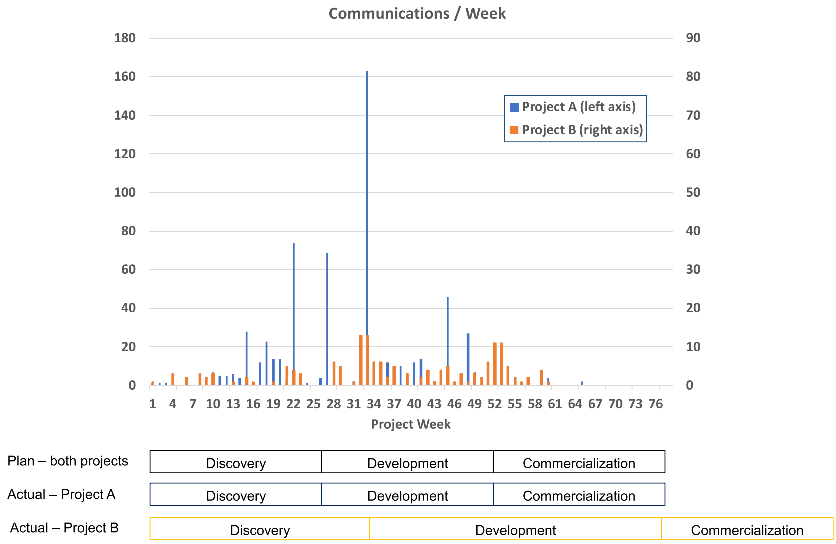

Figure 2. Frequency of Communication (Design and Project Management Posts) for Projects A (Left axis, Blue Thin Line) and B (Right axis, Orange Thick Line) [Colour figure can be viewed at wileyonlinelibrary.com]

to an overall increase in development time and cost. Back-loading can delay some design decisions combined with excessive, late phase iteration (Fixson and Marion, 2012). This was also noted by quotes from an engineer during research Phase 1 interviews. As one engineer noted: "*An issue we have with this constant iteration is that management looks at the early designs and thinks it's DONE. However, there is a lot more engineering to be done on these early models. You can keep design fluid for so long, constantly tweaking and changing*."

Effect on the organization. In terms of the organization, the rise and importance of these tools as a central factor in how teams and organizations are organized was observed. In one of our interviews from the last phase of research (Phase 4), the R&D manager noted the importance of a new, central software and analysis group. These individuals are creating custom real-time analysis software that helps the designers' direct development. He stated: "*We have a new computational design group. These guys developed the Grasshopper code* (Grasshopper is a visual programming language). *There are three people now, but the group wants to grow. The future for us is the Grasshopper solver. This will include the physics code. This will be the driver of* the *entire design process. The whole group is incubating 3D design computation.*"

In this investigation, it is clear that design and CIT tools have propagated into every facet and phase of the NPD process. The cumulative introduction of these tools over time gives the NPD team a large variety of different tools and platforms from which to choose. From design and simulation tools for specific engineering needs to project and knowledge management tools designed to improve team communication, the use of these tools influences how engineers and designers approach and manage the NPD process. This allows the organization to think about different ways of organizing workflow for its employees. The combination of tools and CIT provides for temporary and fluid forms of work. As one senior engineer at a well-known electronics firm stated: "*We have a central information systems (CIS) group, but we are allowed to do FEA ourselves. I am now in Process Engineering, and I play the role of internal design consultant on projects. I tell designers 'there should be ridges for adhesive there, more wall thickness here, etc.' I come in early into the process and advise*." Another individual at the same firm works from home and moves from project to project as a remote, virtual expert. The process engineer noted: "*He's just that good*." This engineer's design tool skill drives his fit and interfaces with the organization and its associated projects. We also have observed the increasing need for product developers to be skilled in a wide variety of tools, from coding packages to suites of analysis tools.

However, these tools also come with challenges. Design and CIT tools that are easy to adopt are also easy to move away from and replace with competitors.

J PROD INNOV MANAG
2021;38(1):192–215

Each new tool requires some investment, sometimes financial, but indeed time to learn and become skilled. In the case of project management CIT tools, switching tools can have an impact on team usage and effectiveness of the tool itself. Another issue is that there can be tool overload, just as we see in our personal lives with smartphone applications and social media platforms. In the cases examined, management mandated use of a tool, to beneficial effect, but the team returned to default collaboration (email) when the executive mandate was lifted. This was the case in Phase 3 Project A with Basecamp and, to a lesser extent, Google Sites during 2013.

A summary of the changes in tools juxtaposed with their impact on individuals, project teams, and the organization is shown in Table 7. For the individual, these tools allow designers and engineers to go right to digital concept development, change how they approach design and analysis workflow, try new tools quickly, share these changes easily with other team members. As tools now span every facet of NPD activities, the individual needs a broader perspective of tool use and its effect on the process. For teams, these easy design iterations can increase knowledge generation, but also challenge the team, not to over iterate and give a false sense of design maturity. While lower barriers to entry allow new tools to be adopted, this can also cause churn and issues with knowledge flow and loss during NPD. And with more tools to use, managing them properly can impact overall knowledge management. For the organization, increased knowledge generation and flow mean that process discipline is more important than ever. These tools allow for the formation of new organizational groups and changes to the expertise and access to that expertise within the organization. The tools also allow for a decentralization of IT sourcing and control of what types of tools are used during the process. This can be a positive from a knowledge creation standpoint, but a negative in terms of knowledge management (i.e., loss of information, drop off in use, training).

In the next section, theoretical and managerial implications is discussed.

Discussion

Theoretical Implications

In this research, the pervasiveness of digital design and CIT tools on NPD activities, impacting every

Table 7. Summary of Tool Changes and the Effect on Individuals, Project Teams, and the Organization

Digital Tool Changes		Individual	Team	Organization
Broader process integration	Digital tools used earlier and in all parts of the development process	Allows designers and engineers to go right to digital concept development	Teams can explore a wider variety of iterations, but must consider the condition of back-loading	Increased knowledge creation and speed in R&D. Continued need for process discipline
Higher performance	Increasingly capable, high performance digital design and analysis tools	Allows designers and engineers to shift the design and analysis workflow. Need for systems thinkers to best use and leverage tool capabilities	Changing team responsibilities, false sense of design maturity	Increased knowledge generation, speed, and development of higher performance products. Allows for changes in organization design (central digital groups, etc.)
Lower barriers to entry	Lower and no cost digital design and CIT tools, and low-cot services	Lowers barriers of entry for design and engineering activities. Allows individuals to try new tools with reduced consequences (cost, etc.)	Allows team to easily try new tools, but also switch frequently during project, affecting knowledge management and flow	Allows some non R&D employees to be involved in design activities, decentralizes some IT functions, some potential knowledge loss due to ease of switching, and switching costs
New types of tools for collaboration and workflow	New cloud-based forms of collaboration and project management tools, many developed by startups	Allows individuals to better share, create, and manage knowledge. Allows more virtual work	Increases the portfolio of ways to collect and share project information. Allows for easier virtual team management. Need to all team members to be active users. More platforms to manage	Reduction in total cost of knowledge creation and management. More data to review project performance

facet of the process and associated knowledge flow, is shown. Research has shown this knowledge flow is of great value and importance to innovation efforts (Marion et al., 2015; Nonaka and Takeuchi, 1995), and has become central to the associated activities and management of the process. However, knowledge management can be difficult during the NPD effort within large organizations with multiple departments or function groups dispersed globally (Carlile, 2002; Eppinger and Chitkara, 2006; Marion et al., 2016). Design and CIT tools have been specifically designed to enhance this knowledge creation and the ease with which information is transferred and acted upon. This influence on knowledge creation was observed first hand in the increased frequency of design related communication fostered by cloud-based wikis in our case examples (cf. Figure 2).

The number of tools available has increased dramatically, while costs and barriers to use them during the process have substantially been reduced. However, most studies on IT and NPD have not been focused on project-level use of the tools themselves and their influence on the process. This is particularly true in the case of the use of social media or cloud-based tools (Gilson et al., 2014; Marion et al., 2015). In our case firms, it was shown just how pervasive the use of the design and collaboration tools are for managing distributed development. In this research, it was found that the profound changes in capability and scope of digital tools and CIT have significantly impacted project-level NPD. Examples include tools used for project management, design and project communication, file storage, computer simulation analysis, and digital design used increasingly earlier in the innovation process. This goes to the heart of the KBV of the firm, as the tools themselves have become an essential part of knowledge creation. Their increasing power leads to faster development and better solution outcomes. Their increasing coverage of activities across the NPD process leads to increasing process integration of the work flow, in turn leading to more integrated units on the organizational level. Collectively, the strong influence of digital design and CIT tools on the creation of knowledge, has turned them into a competitive advantaged when managed properly. This is illustrated by the accelerated pace of the discovery and development phases in one of the case companies that had a broad and intense of these new tools. This research furthers the KBV by highlighting the contribution these design and collaboration tools have on project knowledge creation, sharing, and storage.

Our findings also contribute to recent research that shows that information technology intensity has a positive impact on innovation program performance and agility (Kroh, Luetjen, Globocnik, and Schultz, 2018; Lu and Ramamurthy, 2011). In this research, it was shown how multiple distributed projects were able to be enhanced through the use of new tools, especially in the most recent case studies, where knowledge creation and iteration dramatically increased with the use of new design and CIT tools. On the firm level, this study supports research that has shown that IT and the knowledge it creates can mitigate diminishing returns to R&D, especially under conditions of high geographic complexity and high technological complexity (Ravichandran, Han, and Mithas, 2017). The research shows how enmeshed and influential these tools can be on the individual, associated NPD tasks, and the network between these and the organization itself. In our interviews with engineers at multiple firms, it was clear that tool experts were extremely valuable to the organization, and some had their position designed to best leverage their individual talents across teams in the company.

Applying the framework of member, task, and tool (Argote and Fahrenkopf, 2016; Argote and Ingram, 2000) as reservoirs for knowledge concerning the tools, it was shown how the advancement in the power and sophistication of the tools has a direct effect on the knowledge of a firm and its competitiveness by extension. For example, the comparison of the features that CAD vendors added to their software over time (cf. Table 4), illustrates how the improved tool can lead directly to better outcomes, both in product performance (or quality) and in-process performance (consuming less cost and time to develop a new product). This effect is even more pronounced due to the increasing levels of competition that lead to a wide array of CIT tools on the market (cf. Figure 1), which in turn contributes to the decreasing costs of many CIT tools. Many platforms ranging from communication tools such as Slack to design software like Onshape offer free usage (e.g., to a certain level of functionality) to users. Increased performance combined with lower barriers to entry together has led to an increase in the use of CIT tools, both in increasing use per user as well as the total number of users. This has allowed individuals, teams, and the organization to maximize the acquisition, reconfiguration, and use of new IT resources within NPD (Lu and Ramamurthy, 2011; Sambamurthy and Zmud, 1997). In principle, this has allowed individuals and teams to become their own IT champions with increased autonomy for deciding which tools to use and when (Barczak et al., 2007). While research has noted the importance of champions, our findings suggest that autonomy of tool use and selection by the individual and project team may now play a significantly more prominent role in IT usage and its effect on NPD performance than previously understood (Barczak et al., 2007; Grover, 1993). In our case firms, the project managers predominantly made the decisions on the tools and their usage. In one case this benefitted the team with a focused, more stable adoption of tools and collaborative platforms. Conversely, evidence of a project manager that allowed too many changes to a team's IT tool suite during development, leading to inconsistent use and confusion within the team was observed.

While the direct effect of increasing tool use and tool power on the knowledge position of a firm is relatively straight forward, there are additional interaction effects that influence the individual, teams, and the organization. With CIT tools covering an increasing number of steps of the NPD process, they enhance the collaboration between those individuals working in NPD. In other words, the tools' advancements improve the member-member network as a knowledge reservoir. These tools increase the power of individual and team knowledge creation and coordination during the span of NPD efforts (Lyytinen, Yoo, and Boland, 2016). These tools also can be more transparent in their communication of changes, iterations, and project information. In essence, these new tools can improve the harmony within the organization (Song and Theime, 2006). Research has shown that increased harmony and collaboration within the organization can lead to better NPD outcomes (Souder, 1977, 1987), and collaboration that goes beyond interaction and can be a significant factor in NPD success (Kahn, 1996). Research provides evidence that increased cross-functional integration and collaboration can have a positive impact on new product performance (Nakata and Im, 2010). In our study of projects, it was observed that the intense use of CIT during the early phases of discovery and development can dramatically improve knowledge creation within the team. However, the investigation has shown with easy adoption of tools can come easy replacement, increasing churn within the project (e.g., the cost of switching, a decline in the use of tool replacements, and lack of training on new tools). There is also the potential for excessive iteration during design activities (Fixson and Marion, 2012). This was observed in two projects, where excessive iteration caused frustration within the team. Both churn and excessive iteration can have the possibility of decreased project harmony if not appropriately managed.

Managerial Implications

There are multiple implications for managers and their organizations. The increasing integration of features in the CIT tools (e.g., integration of FEA analysis into a CAD software) has a direct effect on the individual and the approach to NPD tasks. New tool features now enable a single engineer, the individual, to do the work that used to be contributed by two separate specialists. Over time, tools that once were used for different tasks (e.g. drafting, mechanical engineering, and analysis) required unique tools most likely in a specific sequence, but now a larger number of features inside of a single tool allows the reallocation of tasks to a single tool, often the reversal or even total integration of various tasks. An example of integration is the modeling of aircraft wing components with simultaneous analysis of areas of high mechanical stress during simulated flight conditions. Historically these tasks were sequentially performed by different individuals. Integration and reordering of design tasks give the team and organization more flexibility in the process and associated use of human capital. In one of the projects observed, these changes allowed a freelance single designer to quickly move from conceptual CAD to complex models by being able to perform a variety of tasks from industrial design, to engineering, to computational analysis by themselves, near simultaneously, at home.

The content of the design innovator's work is changing as well. Because more and more of the specific expertise across multiple areas of discipline is provided by the digital tool, the innovators' focus shifts from narrow and deep, to broader in scope and more oriented toward the performance of the entire system. These design engineers are moving to detailed design and engineering earlier, performing their own complex analyses, and working with CIT tools for knowledge management and flow during the process. Also, the increasing role of software adds another layer to the complexity. Whereas 15 years ago, each of these disciplines required the say and contribution from various specialists, today's digital tools provide a sophisticated level of integration. For example, ANSYS' newest version of its simulation tool, Twin Builder, enables users to explore quickly, analyze, and iterate design ideas to optimize the balance between power, performance, thermal reliability, and structural integrity.

The changing nature of individual design tasks signals that training in systems thinking and orchestration will be increasingly important to firms. This research indicates the increasing importance of this type of higher-level thinking during the project (Karmi and Naaranoja, 2015). Our findings also show that digital tools and CIT have a direct implication on problem-solving, technology affordances and constraints, and orchestration (Barley et al., 2017; Nambisan et al., 2017). When combined with the need for a more strategic perspective on the project and associated tool use, these skills of problem-solving and orchestration need to be learned, cultivated and practiced to be effective (Bonn, 2005). Our research has shown that online communities, such as GrabCAD, can foster a collaborative and instructive environment to practice and develop design skills. Software firms themselves are investigating ways to better interact with users and cultivate the next generation of users. As an example, in 2020, PTC made Onshape CAD platform available to high schoolers involved in the First Robotics Robots to the Rescue competition (PTC, 2020).

These trends also have implications for knowledge management at the firm level. From a knowledge management perspective, increasingly more capable tools change the role of the user from a solution generator to a solution selector. The types of tools used, how users are trained, and how teams who are using the tools are organized form a direct link to the foundational knowledge of any NPD effort. Firms are moving toward centralized analysis and digital design groups, who are increasingly seen as an essential part of modern NPD efforts. However, it was also seen that highly skilled individuals being used as mobile consultants during projects, "dropping in" to solve issues then moving to other challenges within the organization. Research has shown that how these knowledge bases (individually and collectively) are key determinants of competitive advantage and profitability for the organization (Deeds and Decarolis, 1999; Dröge, Claycomb, and Germain, 2003). As shown in this research, digital design and CIT are the fundamental levers used for design and engineering and associated knowledge creation—those firms that use them the most effectively will gain the most benefit.

An example of how firms can leverage these new capabilities is the global CAD director at a leading software vendor. He was specially trained and tasked to be an expert in all systems throughout the entire design tool value chain. His absolute role was to show internal employees and external customers the overall capability of every type of digital tool and how they can work in concert for the benefit of NPD efficiency and the development of transformative product features and service innovations. Digital tools and solutions explored included the use of real-time analysis, generative design, digital twins, edge computing, augmented reality, and others. His skills included software coding, electrical engineering, mechanical engineering, systems engineering, project management, and making. As these tools progress and the coordination of these digital knowledge generators become increasingly important, the skills and training of NPD professionals such as those described above will also need to be revised accordingly. Increasing the virtual intelligence of engineers and project managers needs to be addressed both in higher education and in corporate learning. For human capital planning, possessing these skills will be an important consideration in staffing decisions.

Today's teams can choose among all sorts of tools, but there is a switching cost as a result of changing to new tools and stopping the use of others during development that does affect the team and performance. Management needs to consider weighing this switching cost versus the gains that design and CIT tools may provide. The right balance between prescribing the use of specific tools (to minimize confusion and product churn), and letting the team explore new and better options needs to be a consideration. In these cases, management dictated tool use, which certainly had an impact on usage. The question remains whether it is more impactful to have the teams be empowered and have the autonomy to make their determination of worth. With this empowerment and autonomy, tool usage can be transient based on the whims of the team, with some tools losing favor with development teams and being replaced with other tools. It was also noticed that given the number of tools, it is easy for teams to adopt, but also to switch, which may have negative consequences for the project. The management of tool choice and implementation has become an increasingly important aspect of innovation management, given the direct relation to project design activities and cost. Our research has also shown that many of these choices are in the hands of the engineer or project team, circumventing centralized IT. This has ramifications for overall firm IT strategy, cost, and training. Who has responsibility of choosing the tools, getting appropriate training, and managing their use consistently during a project? This means that the engineer, project manager, and the NPD professional needs to be an expert at the management of digital platforms and strategy. They, in effect, will be the coordinator of the tools, platforms, and information flow. This higher level, systems level of thinking of tool strategy and use will only become more important over the coming decade.

Conclusions and Future Research

This research adds to a body of literature focused on understanding how IT can affect and influence the innovation and NPD process (Barczak et al., 2008; Durmusoglu and Barczak, 2011; Marion et al., 2015b; Marion and Fixson, 2018). This research represents an in-depth study of how these latest design and CIT tools shape the innovation process, and where project teams might benefit from their adoption. These tools assist and shape the way knowledge is created and shared during NPD and needs to be managed carefully due to their importance on project-level activities (Eisenhardt and Santos, 2002). Recent software developments, such as generative design, where the role of designer shifts from developing a small number of solution options to first specifying the problem parameters and then selecting one or more solutions out of the vast number the computer has generated, will only accelerate the need for continued research on the ramifications of tool use.

While this research represents a comprehensive study into digital design and communication tool changes and how these tool changes have impacted work in multiple projects, one limitation is that although cases were selected carefully, they represent a bias for electro-mechanical products. Future research could include other industries such as biotechnology or software development. Additionally, the increasing proliferation of design and communication tools will make the selection of who uses which tool a more dynamic process. Future research should explore how best to balance cost and benefits through autonomy, choice, training, coordination, and resulting team performance and satisfaction.

Finally, two major current developments will only accelerate the changes described in this paper. First, the accelerating pace of digital tool development will have significant implications for work and organizations. For example, the emergence of artificial intelligence solutions and their integration into various tools and systems will have substantial implications of what innovators do and how they work. It will require innovators to learn broader skill sets (Marion, Fixson, and Brown, 2020), and organizations to experiment with new governance structures. This research opportunity promises to connect multiple areas in the innovation management literature. Second, while working on the final revision of this paper, the Covid-19 pandemic is racing around the world. Its force to shift many work processes to a virtual and online format will only accelerate the effects described in this paper. Future research can explore how this natural experiment forces adaptation of skills, work processes, and organizational arrangements. Similarly, the explosion of offerings by new and established digital tool vendors suggests a fertile ground for research on the role of digital design tools reshaping competition and entire industries.

References

Alavi, M., and D. E. Leidner. 2001. Review: Knowledge management and knowledge management systems: Conceptual foundations and research issues. *MIS Quarterly* 25 (1): 107–36.

Appley, D. G., and A. E. Winder. 1977. An evolving definition of collaboration and some implications for the world of work. *Journal of Applied Behavioral Science* 13: 279–91.

Argote, L., and E. Fahrenkopf. 2016. Knowledge transfer in organizations: The roles of members, tasks, tools, and networks. *Organizational Behavior and Human Decision Processes* 136: 146–59.

Argote, L., and P. Ingram. 2000. Knowledge transfer: A basis for competitive advantage in firms. *Organizational Behavior and Human Decision Processes* 82 (1): 150–69.

Arnould, E. J., and M. Wallendorf. 1994. Market-oriented ethnography: Interpretation building and marketing strategy formulation. *Journal of Marketing Research* 31 (4): 484–504.

Bailey, D. E., P. M. Leonardi, and J. Chong. 2010. Minding the gaps: Understanding technology interdependence and coordination in knowledge work. *Organization Science* 21 (3): 713–30.

Barczak, G., E. J. Hultink, and F. Sultan. 2008. Antecedents and consequences of information technology usage in NPD: A comparison of Dutch and U.S. businesses. *Journal of Product Innovation Management* 25 (6): 620–31.

Barczak, G., F. Sultan, and E. J. Hultink. 2007. Determinants of IT usage and new product performance. *Journal of Product Innovation Management* 24 (6): 600–13.

Barley, S. R., B. A. Bechky, and F. J. Miliken. 2017. The changing nature of work: Careers, identities, and work lives in the 21st century. *Academy of Management Discoveries* 3 (2): 111–5.

Barley, W. C., J. W. Treem, and T. Kuhn. 2018. Valuing multiple trajectories of knowledge: A critical review and agenda for knowledge management research. *Academy of Management Annals* 12 (1): 278–317. https://doi.org/10.5465/annals.2016.0041.

Berger, P. L., and T. Luckman. 1967. *The social construction of reality*. New York: Anchor Books.

Bonn, I. 2005. Improving strategic thinking: A multilevel approach. *Leadership and Organizational Development Journal* 26: 336–54.

Brown, G. 2018. *Internal capabilities presentation*. Boston, MA: PTC.

Brown, S. L., and K. M. Eisenhardt. 1995. Product development: Past research, present findings, and future directions. *Academy of Management Review* 20 (2): 343–78.

Browning, T. R., and R. V. Ramasesh. 2007. A survey of activity network-based process models for managing product development projects. *Production and Operations Management* 16 (2): 217–40.

Bunduchi, R. 2017. Legitimacy-seeking mechanisms in product innovation: A qualitative study. *Journal of Product Innovation Management* 34 (3): 315–42.

Cardinal, L. B., S. F. Turner, M. J. Fern, and R. M. Burton. 2011. Organizing for product development across technological environments: Performance trade-offs and priorities. *Organization Science* 22 (4): 1000–25.

Carlile, P. R. 2002. A pragmatic view of knowledge and boundaries: Boundary objects in new product development. *Organization Science* 13 (4): 442–55.

Claggett, J. L., and E. Karahanna. 2018. Unpacking the structure of coordination mechanisms and the role of relational coordination in an era of digitally mediated work processes. *Academy of Management Review* 43 (4): 704–22.

Collier, D., and C. Elman. 2008. Qualitative and multi-method research: organizations, publication and reflections on integration. In *Oxford handbook of political methodology*, ed. J. M. Box-Steffensmeier, H. Brady and D. Collier, 780–3. Oxford: Oxford University Press.

Cooper, R. G. 2001. *Winning at new products: Accelerating the process from idea to launch* (3rd ed.). New York, NY: Basic Books.

Creswell, J. W. 2003. Advanced mixed methods research designs. In *Handbook of mixed methods in social and behavioral research*, ed. A. Tashakkori and C. Teddlie, 209–40. Thousand Oaks, CA: SAGE Publications.

Deeds, D. L., and D. M. Decarolis. 1999. The impact of stocks and flows of organizational knowledge on firm performance: An empirical investigation of the biotechnology industry. *Strategic Management Journal* 20 (10): 953–68.

Devaraj, S., and R. Kohli. 2003. Performance impacts of information technology: Is actual usage the missing link? *Management Science* 49 (3): 273–89.

Dröge, C., C. Claycomb, and R. Germain. 2003. Does knowledge mediate the effect of context on performance? Some initial evidence. *Decision Sciences* 34 (3): 541–68.

Duranti, C. M., and F. C. de Almeida. 2012. Is more technology better for communication in international virtual teams? *International Journal of e-Collaboration (IJeC)* 8 (1): 36–52.

Durmusoglu, S. S., and G. Barczak. 2011. The use of information technology tools in new product development phases: Analysis of effects on new product innovativeness, quality, and market performance. *Industrial Marketing Management* 40 (2): 321–30.

Durmusoglu, S. S., R. J. Calantone, and V. Sambamurthy. 2006. Is more information technology better for new product development? *Journal of Product & Brand Management* 15 (7): 435–41.

Eisenhardt, K. M., and F. M. Santos. 2002. Knowledge-based view: A new theory of strategy. *Handbook of Strategy and Management* 1 (1): 139–164.

Eppinger, S. D., and A. R. Chitkara. 2006. The new practice of global product development. *MIT Sloan Management Review* 47 (4): 22.

Eppinger, S., and K. Ulrich. 2015. *Product design and development*. McGraw-Hill Higher Education.

Fernandez, J. W. 1986. *Persuasions and performances: The play of tropes in culture* (No. 374). Bloomington, IN: Indiana University Press.

Fixson, S. K., and T. J. Marion. 2012. Back-loading: A potential side effect of employing digital design tools in new product development. *Journal of Product Innovation Management* 29 (S1): 140–56.

Forman, C., J. L. King, and K. Lyytinen. 2014. Information, technology and the changing nature of work. *Information Systems Research* 25 (4): 789–95.

Galunic, D. C., and S. Rodan. 1998. Resource recombinations in the firm: Knowledge structures and the potential for Schumpeterian innovation. *Strategic Management Journal* 19 (12): 1193–201.

Geertz, C. 1973. *The interpretation of cultures*. New York: Basic Books.

George, A., and A. Bennett. 2005. *Case study and theory development in the social sciences*. Cambridge: MIT Press.

Gibson, C. B., and J. Birkinshaw. 2004. The antecedents, consequences, and mediating role of organizational ambidexterity. *Academy of Management Journal* 47 (2): 209–28.

Gilson, L., M. T. Maynard, N. Young, M. Vartiainen, and M. Hakonen. 2014. Virtual teams research: 10 years, 10 themes, and 10 opportunities. *Journal of Management* 41 (5): 1313–37.

Given, L. M. (ed.). 2008. *The Sage encyclopedia of qualitative research methods*. Thousand Oaks, CA: Sage Publications, Vol. 2.

Gartner IT Glossary. Available at: https://www.gartner.com/it-glossary/digitization/.

Gopalakrishnan, S., P. Bierly, and E. H. Kessler. 1999. A reexamination of product and process innovations using a knowledge-based view. *The Journal of High Technology Management Research* 10 (1): 147–66.

Gordon, R. 2017. Reshaping computer-aided design. *MIT News*. http://news.mit.edu/2017/reshaping-computer-aided-design-instantcad-0724.

Grant, R. M. 1996. Toward a knowledge-based theory of the firm. *Strategic Management Journal* 17 (S2): 109–22.

Greve, H. R., and A. Taylor. 2000. Innovations as catalysts for organizational change: Shifts in organizational cognition and search. *Administrative Science Quarterly* 45 (1): 54–80.

Griffin, A. 1997. The effect of project and process characteristics on product development cycle time. *Journal of Marketing Research* 34 (1): 24–35.

Grodal, S. 2018. Field expansion and contraction: How communities shape social and symbolic boundaries. *Administrative Science Quarterly* 63 (4): 783–818.

Henderson, R. M., and K. B. Clark. 1990. Architectural innovation: The reconfiguration of existing. *Administrative Science Quarterly* 35 (1): 9–30.

Hopp, W. J., S. M. R. Iravani, and F. Liu. 2009. Managing White-Collar work: An operations-oriented survey. *Production and Operations Management* 18 (1): 1–32.

Jackson, P. 2000. Ethnography. In *The dictionary of human geography*, ed. R. Johnston, D. Gregory, G. Pratt, and M. Watts, 262–273. Oxford: Blackwell.

J PROD INNOV MANAG
2021;38(1):192–215

Ju, M., K. Z. Zhou, G. Y. Gao, and J. Lu. 2013. Technological capability growth and performance outcome: Foreign versus local firms in China. *Journal of International Marketing* 21 (2): 1–16.

Kahn, K. B. 1996. Interdepartmental integration: A definition with implications for product development performance. *Journal of Product Innovation Management* 13 (2): 137–51.

Kazmi, S. A. Z., and M. Naaranoja. 2015. Fusion of strengths: T-style thinkers are the soul savers for organizational innovative drives and the allied change processes. *Procedia-Social and Behavioral Sciences* 181: 276–85.

Khavul, S., H. Chavez, and G. D. Bruton. 2013. When institutional change outruns the change agent: The contested terrain of entrepreneurial microfinance for those in poverty. *Journal of Business Venturing* 28: 30–50.

Kogut, B., and U. Zander. 1992. Knowledge of the firm, combinative capabilities, and the replication of technology. *Organization Science* 3 (3): 383–97.

Krishnan, V., and K. Ulrich. 2001. Product development decisions: A review of the literature. *Management Science* 47 (1): 1–21.

Kroh, J., H. Luetjen, D. Globocnik, and C. Schultz. 2018. Use and efficacy of information technology in innovation processes: The specific role of servitization. *Journal of Product Innovation Management* 35 (5): 720–41.

Lee, T. W. 1999. *Using qualitative methods in organizational research*. Thousand Oaks, CA: Sage.

Lincoln, Y. S., and E. G. Guba. 1985. *Naturalistic inquiry*. Beverly Hills, CA: Sage Publications Inc.

Lu, Y., and K. (Ram) Ramamurthy. 2011. Understanding the link between information technology capability and organizational agility: An empirical examination. *MIS Quarterly* 35 (4): 931–54.

Lyytinen, K., Y. Yoo, and R. J. Boland Jr. 2016. Digital product innovation within four classes of innovation networks. *Information Systems Journal* 26 (1): 47–75.

Machlup, F. 1980. Knowledge: Its creation. *Distribution, and Economic Significance* 1: 3.

Maitlis, S. 2005. The social processes of organizational sensemaking. *Academy of Management Journal* 48 (1): 21–49.

Makarius, E. E., and B. Z. Larson. 2017. Changing the perspective of virtual work: Building virtual intelligence at the individual level. *Academy of Management Perspectives* 31 (2): 159–78.

Marion, T. J., G. Barczak, and E. J. Hultink. 2014. Do social media tools impact the development phase? An exploratory study. *Journal of Product Innovation Management* 31: 18–29.

Marion, T. J., K. A. Eddleston, J. H. Friar, and D. Deeds. 2015a. The evolution of inter-organizational relationships in emerging ventures: An ethnographic study within the new product development process. *Journal of Business Venturing* 30 (1): 167–84.

Marion, T. J., and S. K. Fixson. 2018. *The innovation navigator—Transforming your organization in the era of digital design and collaborative culture*. Toronto, CA: Rotman Toronto University Press.

Marion, T. J., S. K. Fixson, and G. Brown. 2020. MIT Sloan Management Review. 61 (2) (Winter 2020): 1–7.

Marion, T. J., S. K. Fixson, and M. H. Meyer. 2012. The problem with digital design. *Sloan Management Review*. Summer issue.

Marion, T. J., M. H. Meyer, and G. Barczak. 2015b. The influence of digital design and IT on modular product architecture. *Journal of Product Innovation Management* 32 (1): 98–110.

Marion, T. J., M. Reid, E. J. Hultink, and G. Barczak. 2016. The influence of collaborative IT tools on NPD. *Research-Technology Management* 59 (2): 47.

Marion, T. J., and M. Schumacher. (2009). Moving new venture new product development from information push to pull using web 2.0. In *DS 58–3: Proceedings of ICED 09, the 17th International Conference on Engineering Design, Vol. 3, Design Organization and Management*, Palo Alto, CA, 24–27 August 2009.

Markham, S., and H. Lee. Winning at NPD: Success drivers from the 2012 CPAS study. *Presentation at the 2012 Product Innovation Management Conference*, Orlando, FL.

Mauerhoefer, T., S. Strese, and M. Brettel. 2017. The impact of information technology on new product development performance. *Journal of Product Innovation Management* 34 (6): 719–38.

McGrath, M., and M. Iansiti. (1998). Envisioning IT-enabled innovation. Insight Magazine, Fall/ Winter, 2–10.

Meredith, J. R., S. J. Mantel Jr., and S. M. Shafer. 2017. *Project management: A managerial approach*. Hoboken, NJ: John Wiley & Sons.

Meyer, M. H., and T. J. Marion. 2013. Preserving the integrity of knowledge and information in R&D. *Business Horizons* 56 (1): 51–61.

Mills, P. K., and G. R. Ungson. 2003. Reassessing the limits of structural empowerment: Organizational constitution and trust as controls. *Academy of Management Review* 28 (1): 143–53.

Moorman, C., and R. J. Slotegraaf. 1999. The contingency value of complementary capabilities in product development. *Journal of Marketing Research* 36 (2): 239–57.

Nakata, C., and S. Im. 2010. Spurring cross-functional integration for higher new product performance: A group effectiveness perspective. *Journal of Product Innovation Management* 27: 554–71.

Nambisan, S., K. Lyytinen, A. Majchrzak, and M. Song. 2017. Digital innovation management: Reinventing innovation management research in a digital world. *MIS Quarterly* 41 (1): 223–38.

Nonaka, I. 1994. A dynamic theory of organizational knowledge creation. *Organisation Science* 5 (1): 14–37.

Nonaka, I., and H. Takeuchi. 1995. *The knowledge-creating company: How Japanese companies create the dynamics of innovation*. Oxford, UK: Oxford University Press.

Nordhaus, W. D. 2007. Two centuries of productivity growth in computing. *Journal of Economic History* 67 (1): 128–59.

Orellana, S. 2017. Digitalizing collaboration. *Research-Technology Management* 60 (5): 12–4.

Peng, D. X., G. R. Heim, and D. N. Mallick. 2014. Collaborative product development: The effect of project complexity on the use of information technology tools and new product development practices. *Production and Operations Management* 23 (8): 1421–38.

Perks, H., R. Cooper, and C. Jones. 2005. Characterizing the role of design in new product development: An empirically derived taxonomy. *Journal of Product Innovation Management* 22: 111–27.

PTC. 2020. *Press release*. Available at: https://www.ptc.com/en/news/2020/ptc-onshape-support-first-robotics-to-the-rescue-competition.

Quintane, E., R. Mitch Casselman, B. Sebastian Reiche, and P. A. Nylund. 2011. Innovation as a knowledge-based outcome. *Journal of Knowledge Management* 15 (6): 928–47.

Raghuram, S., Hill, N. S., Gibbs, J. L., and Maruping, L. M. (2019) Virtual work: Bridging research clusters. *Academy of Management Annals*, 13 (1): 308–341.

Ravichandran, T., S. Han, and S. Mithas. 2017. Mitigating diminishing returns to R&D: The role of information technology in innovation. *Information Systems Research* 28 (4): 812–27.

Roberts, D., and M. Candi. 2012. Using social media as part of product launch. *Proceedings of the 2012 PDMA Research Forum*. Orlando, FL.

Roemer, T. A., and R. Ahmadi. 2004. Concurrent crashing and overlapping in product development. *Operations Research* 52 (4): 606–22.

Sambamurthy, V., and R. W. Zmud. 1997. At the heart of success: Organization-wide management competencies. In *Steps to the* *future: Fresh thinking on the management of IT-based organizational transformation*. ed. C. Sauer and P. Yetton, 14. San Francisco, CA: Jossey-Bass Publishers.

Schrage, M. 1990. *Shared minds: The new technologies of collaboration*. New York: Random House.

Schumpeter, J. A. 1934. *The theory of economic development*. Cambridge, MA: Harvard University Press.

Snider, C., S. Škec, J. A. Gopsill, and B. J. Hicks. 2017. The characterization of engineering activity through email communication and content dynamics, for support of engineering project management. *Design Science* 3 (22): 1–31.

Song, M. X., H. Berends, H. Van der Bij, and M. Weggemen. 2007. The effect of IT and co-location on knowledge dissemination. *Journal of Product Innovation Management* 24 (1): 52–68.

Song, M., C. Droge, S. Hanvanich, and R. Calantone. 2005. Marketing and technology resource complementarity: An analysis of their interaction effect in two environmental contexts. *Strategic Management Journal* 26 (3): 259–76.

Song, M., and R. J. Thieme. 2006. A cross-national investigation of the R&D-marketing interface in the product innovation process. *Industrial Marketing Management* 35 (3): 308–22.

Souder, W. E. 1977. Effectiveness of nominal and interacting group decision processes for integrating R&D and marketing. *Management Science* 23 (6): 595–605.

Souder, W. E. 1987. *Managing new product innovations*. Lexington, MA: Lexington Books.

Spender, J. C. 1996. Making knowledge the basis of a dynamic theory of the firm. *Strategic Management Journal* 17 (S2): 45–62.

Taylor, J. R., and E. Van Every. 2000. *The emergent organization: Communication as its site and surface*. Mahwah, NJ: Erlbaum.

Taylor, S. J., R. Bogdan, and M. DeVault. 2015. *Introduction to qualitative research methods: A guidebook and resource*. Hoboken, NJ: John Wiley & Sons.

Tsai, W. 2001. Knowledge transfer in intra-organizational networks: Effects of network position and absorptive capacity on business unit innovation and performance. *Academy of Management Journal* 44 (5): 996–1004.

Ulrich, K. T., and S. D. Eppinger. 2016. *Product design and development*, 291–311. New York, NY: McGraw-Hill.

Wacquant, L. 2003. Ethnografeast: A progress report on the practice and promise of ethnography. *Ethnography* 4: 5–14.

Ware, N. C., T. Tugenberg, B. Dickey, and C. A. McHorney. 1999. An ethnographic study of the meaning of continuity care in mental health services. *Psychiatric Services* 50 (3): 395–400.

Wasko, M. M., and S. Faraj. 2005. Why should I share? Examining social capital and knowledge contribution in electronic networks of practice. *MIS Quarterly* 29 (1): 35–57.

Weick, K. E. 1993. The collapse of sensemaking in organizations: The Mann Gulch disaster. *Administrative Science Quarterly* 38 (4): 628–52.

Weick, K. E. 1995. *Sensemaking in organizations*. Thousand Oaks, CA: (Vol. 3). Sage Publications, Inc. 248

Weick, K. E., K. M. Sutcliffe, and D. Obstfeld. 2005. Organizing and the process of sensemaking. *Organization Science* 16 (4): 409–21.

Woodside, A. G., and E. J. Wilson. 2003. Case study research methods for theory building. *Journal of Business & Industrial Marketing* 18 (6/7): 493–508.

Yin, R. 1994. *Case study research: Design and methods*. Thousand Oaks, CA: Sage Publications.

Yin, R. K. (2003). Designing case studies. *Qualitative Research Methods*, 359–386. London, UK: Sage Publications.

Zahra, S. A., and A. P. Nielsen. 2002. Sources of capabilities, integration and technology commercialization. *Strategic Management Journal* 23 (5): 377–98.

Zhou, K. Z., and F. Wu. 2010. Technological capability, strategic flexibility, and product innovation. *Strategic Management Journal* 31 (5): 547–61.

J PROD INNOV MANAG 2021;38(1):192–215

Appendix A

Summary of Exploratory CAD Survey Conducted in 2008

Description	Metric
Firm size (no. of employees)	12
Average experience of employee (no. of years)	7.5
Use of a dedicated project manager (%)	81%
Average project duration (months)	18
Average project size ($)	$ 500,000.00
Use of a standard, structured NPD process (%)	9%
$N = 44$	

12. When does computer-aided-design (CAD) begin?	
Immediately	23%
After initial concept sketches	49%
After detailed concept sketches	21%
After some prototypes are constructed	7%
After several prototypes are constructed	0%
Total	100%

13. How often are CAD-based prototypes (example: FDM models and SLA models) used during development?	
Never	2%
Rarely	14%
Sometimes	19%
Often	36%
Always	29%
Total	100%

14. What software do you use during product development? Pick all that apply	
SolidWorks	52%
ProEngineer	45%
Adobe Photoshop	71%
Alias	26%
Microsoft Excel or other spreadsheets	55%
Microsoft Project	29%
MasterCAM	12%
Other, please specify	81%

15. Typically for a project, what percentage of total billed hours are CAD-related (both initial design and iterative modifications)?	
0–20%	15%
20–40%	34%
40–60%	29%
60–80%	22%
80–100%	0%
Total	100%