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A Potential Side Effect of Employing Digital Design Tools in New Product Development

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Abstract

Over the past twenty years, the use of digital design tools such as Computer-Aided-Design (CAD) has increased dramatically. Today, almost no product development project is conducted without the use of CAD models. Major advantages typically ascribed to using CAD include better solutions through broader exploration of the solution space as well as faster and less expensive projects through faster and earlier iterations. This latter effect, the shifting of simulation and testing traditionally accomplished with help of physical prototypes late in the process–a slow and expensive activity–to doing similar activities with virtual prototypes faster and earlier in the process, has been identified as a key aspect of *front-loading*, an activity shift promising to enable superior product development performance (Thomke & Fujimoto, 2000).

Given CAD's recent pervasive use, our research questions for this paper became how CAD use has actually changed the way in which product development is conducted, and through which mechanisms and pathways can CAD impact product development performance, especially with respect to the idea of front-loading? To address these questions, we study in a longitudinal comparison in detail two similar product development projects, one conducted in 2001, the other in 2009. The second project exhibits substantially higher levels of CAD use and significant improvements in prototyping costs but only marginal changes in project time and project engineering labor cost. In-depth analysis reveals that the use of CAD affected how the product development was executed, with both positive and negative consequences. In addition to, and separate from positive aspects of front-loading we also observe unintended consequences in the form of *back-loading* work. We discuss theoretical implications of our observations and propose a simple framework to convert our findings into managerial advice.

1 Introduction

Despite the importance of designing and successfully commercializing innovative new products (Cooper, 2001), product development (PD) performance in many companies remains unsatisfactory. The fraction of products that fail after launch in the market place remains astonishingly high (Adams, 2004), and many product development projects do not meet time and cost targets (Cooper, 2005).

Given that the product development process touches upon a broad range of activities and decisions across strategy, marketing, operations, organizational behavior, psychology, engineering, and design, an equally broad range of success factors for R&D and product innovation has been explored, ranging from factors related to markets and technology, to techniques and tools, to organizational structures, processes, and decision mechanisms (Balachandra & Friar, 1997; Krishnan & Ulrich, 2001; Hauser, Tellis, & Griffin, 2006; Barczak, Griffin, & Kahn, 2009). We focus this paper on the intersection between digital design tools and product development processes. More specifically, we explore the effects of the increasing use of digital design tools such as Computer-Aided Design (CAD) on product development efficiency by shifting critical simulation and experimentation work upstream in the project (Thomke & Fujimoto, 2000).

Over the last twenty years most industries have seen a transition from traditional product development that was local, face-to-face, and sequential to one that is more global, more virtual, and more concurrent (Eppinger & Chitkara, 2006). Broadly speaking, the digital tools supporting these changes include less expensive and user-friendlier CAD packages (e.g., Solidworks[1]), pervasively used electronic mail (e-mail), rapid prototyping technologies, and new communication tools such as Internet-based video conferencing (e.g., Skype). The predominant

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[1] Solidworks (www.solidworks.com), founded in 1995, today sells one of the most widely used CAD packages.

presumption is that these new tools have revolutionized product development in terms of efficiency, allowing designs to be iterated, vetted, tested, and transmitted extremely quickly– saving time and cost before product launch. However, in the reality of modern day product development this relationship is not always clear-cut, and recent research suggests that the detailed, daily activities of engineers designing products virtually, i.e., the hours spent building CAD models and running virtual design iterations, can themselves be costly: these virtual design rounds can account for 75% of total project development cost (Marion & Simpson, 2009).

To investigate how increasing use of a major digital design tool, CAD, can impact product development performance, we explore in detail two product development projects that exhibit different levels of CAD use. We collect and analyze both qualitative and quantitative data on a micro-level in order to study the mechanisms through which CAD use may make one product development process superior to another. Specifically, we investigate how the increased CAD use can impact the product development process itself, and how it in turn can affect its outcome performance. We find that increasing use of CAD can lead to inter-phase workload shifts with both positive and negative consequences. In addition to and separate from the advantageous results through front-loading from the back-end of the process, we also observe an unintended consequence in form of back-loading work away from the front-end of the process.

The remainder of the paper is structured as follows. In the next section we develop the theoretical background, and in section three we present our research design. In section four we provide micro-level data of the two projects' product development processes, unpack project performance data, and present our interpretation of the observations. In section five we discuss theoretical implications and develop a framework to convert our findings into managerial guidelines. Section six concludes.

2 Theoretical Background

2.1 Product development performance measures

The success of product development efforts has been measured with a multitude of metrics. At the firm level a wide range of product development performance measures exists that consider customer, financial, and technical dimensions. Which of these are appropriate to be used depends on a firm's business and project strategy (Griffin & Page, 1996).

On the project level, product development performance typically comprises three dimensions: product performance, development time, and development cost (Clark & Fujimoto, 1991; Brown & Eisenhardt, 1995; Reinertsen, 1997). Product performance here encompasses several performance dimensions such as innovativeness, conformance to user needs, quality, manufacturability, reliability, etc. Product development time is simply the time it takes to convert an initial idea into a sellable product, in some industries this is referred to as lead-time. Finally, product development cost refers to the resources required to execute the product development project. Personnel expenses, in addition to expenditures for materials, equipment, and tools, typically dominate product development costs.

Most existing project-level research measures product development performance only once per project, e.g., (Tatikonda & Rosenthal, 2000; Swink, Talluri, & Pandejpong, 2006). That is, product development projects are often assumed to be internally homogeneous, i.e., potential variations of product performance, development time, and development cost across phases *inside the project* remain unconsidered. To gain additional insight in the performance driver-outcome relationships, in this paper we further unpack performance measures beyond the project level and investigate the *within-project* performance dimensions such as cost, time, and iterations on the phase-level of the product development projects.

2.2 Product development performance drivers

The literature stream that has investigated the drivers of superior product development performance is vast and covers a broad set of factors, including *product, people, process,* and *tools*. For example, product characteristics such as ‘newness’ (i.e., the product’s degree of innovativeness) and ‘project difficulty’ (sometimes approximated by product complexity) have been found to impact product development time (Griffin, 1997). Similarly, the product architecture, i.e., the way in which the product function is allocated to its components and the ways in which the interfaces are defined (Ulrich, 1995) and its multi-dimensional structure (Fixson, 2005) can affect product development performance. More integral product architectures can lead to cascading and iterating product development activities that prolong the product development project and make it more costly (Mihm, Loch, & Huchzermeier, 2003; Clarkson, Simons, & Eckert, 2004; Fixson, 2006).

Other studies have identified people-related factors such as team communication, team composition, and senior management support as affecting product development performance dimensions such as lead time and cost (Brown & Eisenhardt, 1995). Especially for innovation related activities such as product development, the use of cross-functional teams has become commonplace over the past two decades, and a substantial body of research has accompanied this development (Edmondson & Nembhard, 2009; Sethi & Sethi, 2009). Similarly, not only senior management support but also clear senior management decisions to kill underperforming projects at control points, or stage gates, have been identified as critical for superior product development performance (Cooper, 2001, 2008).

Third, the process structure of product development projects has been identified as playing a key role for product development performance. For example, representing product development projects typically as an interconnected network of tasks and activities, the modeling literature has identified several strategies to affect the performance dimensions product development cost and product development time. ‘Crashing,’ for example, attempts to shorten development lead-time by compressing activities, typically by expending additional resources, or by trading off product performance and time-to-market (Cohen, Eliashberg, & Ho, 1996). The extent to which this approach is possible obviously depends on the degree to which work is dividable into ever smaller units. Brooks (1995) discusses the limits to this approach for software engineering. Another process change to reduce product development time has been labeled ‘overlapping,’ also termed ‘concurrent engineering.’ As the name suggest, overlapping aims at reducing overall product development time by starting an activity before its predecessor has been completed, and executing some activities in parallel rather than sequential. A potential downside of overlapping is the increased uncertainty under which some of the work proceeds, exhibiting a higher risk for rework. Work in the project scheduling literature has explored time-cost tradeoffs between crashing and overlapping (Roemer, Ahmadi, & Wang, 2000; Roemer & Ahmadi, 2004).

A fourth set of factors is represented by advanced virtualization and simulation tools, sometimes broadly referred to as Information and Communication Technologies (ICT). In the product development context these tools and technologies range from systems enabling computer-aided-design (CAD) and computer-aided-manufacturing (CAM), both recently in more realistic three-dimensional (3D) applications, to programs to simulate and test product functions (e.g., Computer-Aided-Engineering - CAE) and manufacturing processes (e.g., Moldflow^{TM}, which helps engineers analyze the plastic injecting molding process), to project management, workflow, and data management systems (e.g., Product Data Management (PDM) and Product Life Cycle Management (PLM)), as well as general methods for electronic communication (e-mail, instant messaging, Wikis[2], etc.) (Büyüközkan, Dereli, & Baykasoglu, 2004; Chryssolouris et al., 2009). Because of the central role that the geometric information created with CAD systems plays in product design, we focus here on the use and impact of CAD systems.

2.3 CAD and front-loading

The previous section presented for brevity the four sets of product development performance drivers as quasi-independent. In reality, there are often interactions between them, e.g., between tool use and people, or between product and process. One of these interactions, the one between the tool 'CAD' and the inter-phase process structure is at the heart of this paper.

While the origins underlying modern CAD systems go back to the 1950s (Weisberg, 2008), substantial improvements in affordability and usability of modern CAD tools have led to their widespread use in product development only over the past twenty years. The affordability improved not so much through falling purchasing (and licensing) prices for commercial CAD packages[3], but rather through phenomenal increases of computing power, resulting in a decrease of the deflated price per unit computing power annually between 20% and 55% (Nordhaus, 2007). This vast improvement of computing power allows running relatively complex CAD programs today on inexpensive personal computers instead of expensive engineering workstations. In addition, the usability of the software has also improved substantially over the past two decades. Whereas early CAD programs required months-long user training and were essentially digital representations of 2D-drawings (Kappel & Rubenstein, 1999), modern CAD packages employ graphical user interfaces (GUIs) that enable steep learning curves, model products directly in solid geometries, and offer a wide range of add-ons for various analysis,

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[2] Wiki's are Websites that can be easily edited by multiple participants. These are increasingly used to foster collaboration between distributed development teams. Websites such as Trac and Basecamp are examples (Marion & Schumacher, 2009).

[3] In 2009, purchasing prices for single-seat entry-level CAD packages ranged from $1,000 to $5,000, often associated with an annual maintenance fees between $500 and $1,000 (Johnson, 2009).

rendering, and visualization purposes. This combination of dramatic decrease in the price of computing power and significant increase in breadth and depth of the software programs has not only led to CAD systems being ubiquitous today in almost all product development settings[4], it has also been suggested to enable front-loading, "a strategy that seeks to improve development performance by shifting the identification and solving of [design] problems to earlier phases of a product development process" (Thomke & Fujimoto, 2000:129). In other words, made possible through low cost computing and sophisticated CAD applications, front-loading has been claimed to improve both effectiveness and efficiency of product development processes.[5]

Regarding product development effectiveness, "faster and less costly problem-solving via simulation can open new possibilities for learning and design innovation" (Thomke & Fujimoto, 2000:137). This claim of virtual technologies carrying the potential for the exploration of broader solution spaces, and consequently for producing more, newer and better solutions has also been made by Baba and Nobeoka (1998) and Becker *et al.* (2005). Extending this line of argument, some studies suggest that the *virtualization* of knowledge-based processes not only results in new product solutions but also enables new forms of knowledge creation. For example, studying two R&D projects in the automotive industry, Vaccaro *et al.* (2009) find that simulation activities enabled through modern computer programs such as CAD systems have resulted in collective socialization processes, directly transferring tacit knowledge into new tacit knowledge without the detour of making the knowledge explicit. In summary, front-loading via CAD systems can enable better and newer products, and potentially more capable organizations.

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[4] "In very simple terms, virtually no product, building, electronic component or system or factory is designed today in a developed country without the use of this technology." (Weisberg, 2008:2-21)

[5] In addition to 'rapid problem solving using advanced technologies and methods,' Thomke and Fujimoto list as a second element of front-loading 'project-to-project knowledge transfer,' i.e., to avoid renewed solving some of the same problems as during the last project.

Front-loading has also been suggested to improve product development efficiency. Taking a problem-solving perspective, Thomke and Fujimoto describe product development as a sequence of problem-solving cycles. Each cycle begins “with problem recognition and goal definition and continues with an iterative process of experimental search through alternatives” that are designed, built, tested, and analyzed (Thomke & Fujimoto, 2000:130). The purpose of this process of building and testing models is to identify and solve various design and manufacturing problems. Concurrent engineering, i.e., the organization of work in parallel and simultaneous flows, which includes, according to Koufteros *et al.* (2001), also the use of cross-functional teams and the early involvement of constituents, is suggested to support finding and solving these problems early. There are two reasons for why solving problems early is better than late. First, if product development is understood as a series of problem solving activities of often interconnected problems, then the degree of freedom for each problem solving process decreases with the number of decisions already made. In other words, problems addressed early face fewer constraints by the solutions already generated for other problems in the project. Second, problems late in the PD process often involve prototypes and tests with higher degree of fidelity, i.e., they are more expensive to solve on a per experiment basis. The promise of CAD tools is the acceleration of problem-solving activities by increasing the rate (and lowering the unit cost) of individual iterations, and by shifting some of these prototype tests and simulations from the physical to the virtual world (Thomke & Fujimoto, 2000). For example, a stress analysis of a component conducted with a help of a virtual model may help to identify and remedy a potential functional problem of the product, an activity that tends to be more expensive when conducted with physical prototypes. Similarly, a virtual manufacturing analysis using the CAD model may help reduce the probability for expensive rework of manufacturing tools. In sum, CAD systems are expected to allow front-loading the problem solving process and thus reduce some of the late and expensive problem solving activities. The expected performance consequences are lower total project cost and shorter total project duration. Thomke and Fujimoto (2000) conceptualize this effect as depicted in Figure 1.

Insert Figure 1 about here

2.4 Research questions

Given the broad diffusion of digital design tools such as CAD in many industries in recent years, and the strong enabling effect for front-loading associated with these tools (Thomke & Fujimoto, 2000), our research questions became the following:

(1) Has CAD changed the way in which product development projects are actually executed?

(2) How does increased CAD use affect product development performance? And more specifically, what are the mechanisms and pathways through which CAD use impacts product development performance, especially with respect to the idea of front-loading?

3 Methods and Data

3.1 Research Design: A comparative case study

To explore in detail how increased levels of CAD tool use can change work processes and affect product development performance, we take a longitudinal perspective and compare two carefully selected product development projects in detail. This careful selection and detailed study of a small number of cases to isolate the effects of interest has been suggested as useful for this type of exploratory research (Yin, 1994), following the idea of theoretical sampling rather than statistical sampling (Eisenhardt, 1989). The longitudinal aspect in particular has been called for in studies on work systems (Sinha & Van de Ven, 2005). The limitations of small-*n* studies notwithstanding, other research has successfully employed this research approach in studying various aspects of product development such as designing visual recognition for a company's brand (Karjalainen & Snelders, 2009), interpersonal cohesiveness in NPD teams (Brockman, Rawlston, Jones, & Halstead, 2010) and product introduction lead times (Mabert, Muth, & Schmenner, 1992). Similar to those studies, we focus on the in-depth details of a few projects, given our research interest in the mechanisms at work *inside* of product development projects.

The following logic guided us in the careful selection of two product development projects for our comparative study. First, we made sure that the two cases differed substantially on our 'independent variable,' i.e., CAD use. Our two selected product development projects were executed eight years apart, one in 2001 (project A), the other in 2009 (project B), and the latter made substantial more use of CAD than the former. Second, we tried to control as much as possible for other variables regarding product and organizational structure. Both projects focused on consumer goods, specifically multi-parts hand tools (U.S. Industry Classification Code 3423), and across the two cases the customer needs and product specifications were nearly identical. For an example of a product of comparable complexity, an office stapler, see Marion and Simpson (2009). We deliberately chose consumer products of limited technical complexity for two reasons. One reason is that these types of products best correlate with existing NPD research regarding pre-development market planning and user-centered-design (Cooper, 2001; Cagan & Vogel, 2002; Norman, 2002). Thus, our cases are a good representation for typical consumer products, products which must have a good value proposition by meeting or exceeding customer expectations in terms of design and functionality (Marion & Meyer, forthcoming). The other reason for choosing products with limited complexity is that it enabled us to compile comprehensive data sets of both projects to develop a deep understanding of the inner workings of both projects. In addition to the product similarity, both projects were also executed in similar organizational set-ups: Both products were designed and manufactured in the U. S., and sold in retail outlets primarily in the U.S. Both products have been marketed by the same firm, working on similar projects for the past ten years. In addition to the focal firm, both projects involved an external design firm and multiple external specialists. The design firm is itself a small company, focused on user-centered design, and works primarily with small and early-stage firms. Both project teams had similar levels of experience, and both development projects were run by the same project manager. Finally, the second case, relative to the first, does not show the overall project performance improvement on the project level anticipated through the increased use of CAD. This makes our case combination somewhat of an anomaly, a recommended starting point for exploring phenomena of interest (Eisenhardt, 1989; Carlile & Christensen, 2005).

3.2 Data collection

For both projects, we collected quantitative and qualitative data, on both project- and phase-levels. Collected data included archival data such as cost and time data, e-mails, Wiki entries, CAD models, notes on phone calls, design iterations, prototypes built, and tooling development; as well as interview data on motivation, skills, and decision making rationales of the product development teams.[6]

4 Unpacking the Black Box: Inside of two Product Development Projects

4.1 Performance comparison

To explore potential effects increased CAD usage may have on product development performance, we begin our project comparison with a look on project-level performance data.

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[6] We could access this level of detailed data since one of the authors was actively involved in PD activities in both projects.

Since both of our projects exhibit similar levels of product performance (e.g., manufacturability, durability, and functional performance)[7] we focus our analysis on the performance measures PD cost and PD time. To measure PD cost we break out the cost for engineering labor, for prototypes, and for production tooling. To measure PD time we consider engineering person-hours and schedule time, i.e., duration in project weeks. Note that while the two measures person-hours and schedule time highly correlate, they are not identical, because in both our settings the team members did not spend 100% of their time working on these projects, a situation not unusual for distributed development teams. On the project level, project B outperforms project A with respect to total PD cost ($100k vs. $150k , both in 2009 dollars), whereas both projects exhibit similar performance levels with respect to PD time. Total development hours (which include for both projects hours worked by team members and manufacturing vendors) for project A were 1,066, and 1,150 for project B. Similarly, project A was completed in 28 weeks, project B in 31 weeks.

To better understand these results, and in particular the absence of significant superior project-level PD performance of project B with respect to PD time due to higher level of CAD usage we next unpack the performance data down to the phase-level. Figure 2 and Figure 3 compare phase-level costs and time of both projects. Figure 3 also shows communication frequency profiles as an additional proxy for management attention that each project required.[8]

A detailed look at the individual costs shows that the cost differential between the two projects originates from production tooling and prototyping, but not from engineering labor. The substantial difference in production tooling cost is primarily driven by two factors outside of the

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[7] There is one caveat to this statement: reliable sales data for the product B are not yet available, i.e., product B's ultimate market performance relative to product A's is as of yet unknown.

[8] It is instructive to compare the communication frequency profiles across the two projects to understand which phases required substantial management attention. However, direct comparisons of absolute numbers are difficult as the mode of communication (phone, e-mail, wikis, etc.) has changed between the two projects.

actual project: first, the financial arrangements for timing and size of payments differed significantly, and second, the downturn economy in 2009 resulted in a far more competitive environment for the tool maker. The savings in prototyping costs for project B on the other hand is a clear result of the advancements of rapid prototyping technologies, in association with more capable CAD systems. Finally, cost profiles due to engineering labor of both projects are dominated by high expenditures in the production ramp-up phase. This is due to the number of person-hours handled by the team completing engineering design changes and the manufacturer developing production tooling and associated modifications.

Direct comparison of the phase-level data of the two projects allows several interesting observations. First, while project-level performance data for engineering hours (and PD time) across the two projects are similar, the two projects exhibit different inter-phase distributions of labor and time spent. Second, during the last project phase, production ramp-up, project B spent more engineering person-hours (770) than project A (630). This high-level of PD engineering labor effort for project B is surprising as the idea of front-loaded problem solving via CAD use is that it leads to problem solving earlier in the process so that more expensive problem solving later in the project is reduced or even eliminated. Third, project B does exhibit, as expected, a higher level of person-hours during detailed design phase due to extensive CAD use, but this expenditure apparently did not lead to less work and better efficiencies in the production ramp-up phase. To search for an explanation for these unexpected observations we unpack the process details below, comparing both projects using as a baseline a generic product development process (Ulrich & Eppinger, 2008) which includes five phases: 1) concept development, 2) system design, 3) detailed design, 4) testing, and 5) production ramp-up (Table 1). To map out specific tasks during these phases, we relied on the Continuum[9] development process which denotes specific tasks and deliverables by phase (Marion, 2009).

Insert Figure 2, Figure 3, and Table 1 about here

4.2 Process comparison

Planning and concept development. Project A commenced in early 2001. The project team included a dedicated project manager, a CAD engineer, a mechanical engineer, and an industrial designer. The project team was distributed, and all project items were communicated through methods predominant at the time (e-mail, phone, and fax). The project team spoke to several users, and did competitive research through store visits and tear-downs of competitive products to gain a better understanding of product specifications, market price points, and functionality. From this research, lists of customer needs and product attributes were developed and vetted by the development team, and ultimately condensed into a short punch list of target specifications. Based on this list, the industrial designer developed over a dozen hand-drawn product sketches to ideate and explore different solutions. These sketches were evaluated by the project team and down-selected to three leading concepts, which were ultimately reduced to a winning concept. Concurrently with the hand-sketched concept, two wooden models were fabricated to test size and rudimentary functionality of the design. The development team felt mock-ups were the most efficient way to gauge user feedback on size and ease of use.

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[9] Continuum (www.dcontinuum.com) is a world-leading design and innovation firm headquartered in Boston, MA.

Project B started in early 2009. The project team included a dedicated project manager (who also acted as the mechanical engineer), a CAD engineer, and an industrial designer. The project team was also distributed, and communicated primarily through phone, e-mail, and a Wiki. A dedicated project Wiki was created to foster team communication and the sharing of files. The distributed team did not meet in-person often – but did meet three times at critical decision points. The project team did not speak directly to users, but did do competitive research via Internet searches on competitive products and pricing. Competitive products were also purchased to evaluate materials, functionality, and pricing. As with Project A, lists of customer needs and product attributes were developed and vetted by the development team, and ultimately condensed into a short punch list of target specifications. From these specifications, the industrial designer developed three hand-drawn product sketches. These sketches were reduced to one leading concept based upon the team’s assessment of its ability to meet customer needs and product attributes. The leading concept was then translated into Adobe Illustrator, a digital illustration program, to ease the transition to CAD. As opposed to project A, models were not developed to test functionality with the exception of one foam mock-up to validate the ergonomics of a new handle design. Project B spent only half the schedule time and less than 30% of the cost on this phase compared to project A.

System-level design. For project A, the team spent significant time thinking about the product architecture and how to reduce the number of components from the winning concept sketch to strive for lower manufacturing costs. Integral to this process was the industrial designer, who produced a series of detailed hand drawings noting connection points, important design features, and aesthetic call-outs. From these drawings, another more accurate prototype made of hand-machined plastic was constructed. This conceptual and system-level design work was conducted without CAD.

For project B, the team communicated infrequently through email and Wiki postings on the issue of product architecture. Apart from the foam mock-up that was produced to gauge effectiveness of a new handle shape, little engineering effort was focused on system-level design, as the team of project B was confident to do this work directly in CAD. In direct comparison, team person-hours of project A during system-level design surpassed project B's by a factor of 16, primarily due to the effort spent on creating detailed drawings to be used to prepare the scale drawings during detailed design. Project A's schedule time was twice that of project B's.

Detail design. In project A, using the mock-ups and hand sketches as a guide, detailed scale line drawings were produced by hand on a drafting table. These drawings were dimensioned, three-view two-dimensional product prints, and copies of the prints were mailed to the project manager and mechanical engineer. These drawings also specified connection points, material thicknesses, and part geometry details. Using these drawings, the CAD engineer translated the information into a CAD model in SolidEdge (a popular 3D CAD package at the time). The translation of part specifics and their geometry was a manual process – with the CAD engineer taking measurements off the scale drawing and then recreating the geometry digitally. The CAD engineer was the only team member with access to the CAD program. No renderings were produced from the CAD as the team sought to avoid additional development cost (at the time, the renderings would have to be created using a separate illustration software package, e.g., Alias). Finite-Element-Analysis (FEA), or computer simulation of part strength and durability, was used to assess critical points of stress, resulting in some design modifications.

In project B, since the winning sketch had been translated into Adobe Illustrator, the design team skipped detailed scale drawings and directly began to design and iterate the 3D-CAD model. All team members had the CAD program on their computers, and could directly review and comment on recent model changes. Revisions of the model were continuously posted on the project Wiki. Once the design was deemed to be mostly representative of the final product, a prototype was fabricated using a Stereolithography Apparatus (SLA). As opposed to project A, a more refined mock-up was not vetted – changes were made directly to the CAD model and associated rapid prototype iterations. During this iterative design phase, ten CAD iterations resulted in four physical prototypes that were tested. In addition, realistic renderings were produced from the CAD model. Similar to project A, Finite-Element-Analysis (FEA), or computer simulation of part strength and durability, was used to assess critical stress points. Some design modifications were made to the design based on the FEA results. The person-hours spent in project B for detailed design were more than twice those of project A, and the phase duration was three times as long, a result of the development team going directly to CAD, bypassing some of the manual system design work. In addition, project B exhibited a peak in its across-phase communication profile, whereas project A did not (Figure 3). Finally, only project B created prototyping cost in this phase, albeit they were modest.

Test and Refine. In project A, three design modifications were made, and from CAD models rapid prototype (SLA) parts were produced in conjunction with third-party prototype vendors. These parts were then used to create urethane molds to simulate actual production parts. Testing was performed on these parts and two design modifications were made to the product. Prototypes were tested to failure in actual use scenarios, and the design team captured the required changes in design project books. Also in this phase, vendor quotes were evaluated and a manufacturer was selected. Detailed bill-of-materials (BOM) quotes were compiled and evaluated against the customer need and product attributes list developed in the conceptual phase. BOMs were developed in MS Excel and distributed to the team via email.

For project B testing was performed on the prototype parts and six design modification rounds were initiated. At this phase, the vendor quotes were evaluated and the existing manufacturer (who also produced project A), was brought onto the design team. Detailed BOM quotes were compiled and vetted against the initial cost targets. Total man hours and schedule time for project A in this phase were about half of those spent for project B. However, the cost for prototyping for project A in this phase was almost ten times higher than for project B.

Production Ramp-up. For project A, tool development began approximately three months after the initial concept drawings were drafted. From tooling start to production approved parts it took about fourteen weeks, consuming 630 man-hours. Upon first article sampling, three design modifications were made to the tooling and the product. The total time from first sampling to production approved parts was approximately 3 weeks.

For project B, the manufacturer began to tool for the project approximately five months after the initial concepts were drafted. Tooling start to production-ready parts took approximately eleven weeks, expending 770 person-hours. Upon first article sampling, ten design modifications were made to the tooling and the product. Of the ten issues noted by the development team, four were design related and six were manufacturing related. Project team B communicated extensively to try to resolve these issues, creating a second peak in its across-phase communication profile (Figure 3). The tooling debug time between first sampling and production approved parts was approximately 6 weeks. In total, project B consumed for this phase about 22% more person-hours (the inflation adjusted engineering labor cost were similar) and 21% less schedule time that project A.

4.3 Results from case comparison: the linkages between tool, process, and performance

In this section we return to our research questions: has increased CAD use changed how PD is executed, and what is the linkage between increased CAD use and PD performance? As for changes of PD execution, the previous section clearly presented how increased CAD use altered the PD process in our case comparison. First, in the project with higher CAD use (project B), the design was transferred much earlier into digital models. Second, more design iterations and prototypes were built throughout the process, a process made easier through CAD (and associated prototyping technologies). Both of these process changes reflect the idea of front-loading. Third, the process as a whole was more fluid, i.e., decision points that were clear in project A, were more amorphous in project B. The ability to quickly review and change digital models across all team members enabled this less rigid process structure.

To explore the effects that increased CAD use had on PD performance measures PD cost and PD time in our case comparison, we return to the observation that on the project level project B did not exhibit substantially superior project performance with respect to engineering labor cost and PD time, relative to project A. This suggests that there have been some performance degrading effects – in addition to the performance improving effect through front-loading. The key for finding these additional effects lies in how the work content of the individual PD phases is linked across phases, and how this link is affected by CAD tool induced inter-phase workload shifts. Consider the profiles of design iterations and prototypes for both projects (Figure 4). For our discussion, we define design iterations as substantive changes to an existing design, including new designs and concepts, and prototypes as physical prototypes for exploration and testing purposes. It becomes immediately clear that during the production ramp-up phase the number of design iterations of project B was three times as large, and the number of prototypes two times as large, both relative to project A, which explains the higher number of person-hours. But why does project B exhibit so many late design changes although clearly CAD use during detailed design led to the exploration of more virtual designs and prototypes in project B than in project A?

In our case comparison, we observe an unintended side effect that is enabled by the increased use of CAD and contributes to the performance deterioration. We label this side effect *back-loading*. In our data we find two types of back-loading. A closer inspection of the design iteration and prototyping profiles at the beginning of the projects provides an explanation for the first type of back-loading. Whereas project team A thoroughly explored different designs and their implications on the conceptual and system design level, project team B spent little time in these first two phases. Instead, in project B the first two phases were rolled into the third phase, detailed design. In fact, the development team’s view was that it handled the conceptual design phase, the system design phase, and the detailed design phase concurrently. The result of condensing the front-end of the PD process in project B led effectively to shortcutting concept development. As a result, some initial choices were left unquestioned and the team settled on a solution space that was less advantageous compared to one that could have been created with a more thorough concept development process. Ultimately, more iterations were then required to arrive at a satisfactory design. The second type of back-loading is a side-effect of the ease with which CAD allows design iterations, and consequently encourages a more fluid PD process. In project B, the team postponed some of the design decisions, kept running several designs in parallel for longer in the process, resulting ultimately in more iterations during tooling and production ramp-up. Combined, these two back-loading effects counterbalanced the performance improvement through front-loading in our case comparison.

We have sketched out these separate work-load shifts in Figure 5. The figure’s top portion restates the advantageous form, front-loading, enabled through digital design tools, i.e., it presents the time saving effect made possible by moving test and experiments upstream to the digital design realm where the tests and experiments can be conducted at a faster pace (indicated by the initially steeper slope of line B, compared to line A). The bottom portion of the figure describes the disadvantageous form of CAD-enabled work-load shifts, i.e., back-loading. Two types of back-loading occurred in project B. First, lured by the possibilities of digital design tools, project team B rushed to the detail design phase, and by inadvertently not questioning some initial assumptions effectively raised what in Figure 5 is labeled the ‘100%’ of problems to be solved. While using a fraction of problems solved as a measure of project progress is conceptually convenient, what these 100% really are is often only known ex-post. Initial poor choices at the start of the process can create a product development trajectory that makes it relatively more difficult to arrive at a satisfactory solution at the end of the process, i.e., the initial choice effectively increases the total number of problems to be solved in the project (from ‘old’ 100% to new ‘100% in Figure 5). This higher number of problems to be solved then led project team B to having to solve problems at an even higher rate to stay on schedule (steeper slop of line B’), which ate into the expected savings from increased CAD use and resulted in higher than expected expenses for engineering person-hours and management attention. If the rate, and consequently the cost, had not been increased, it would have resulted in later project completion (see line extension B’’). The second type of back-loading, caused by the ability to make late changes, led to postponing design decisions to late in the process, effectively slowing down the project progress late in the project, and causing a need to rush the project at the end (see line B’’’).

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Insert Figure 4 and Figure 5 about here

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5 Theoretical and Managerial Implications

In this paper, we study two development projects, separated by nearly a decade. Within this timeframe, the migration of digital tools such as 3D-CAD to earlier in the development process has been pervasive. This migration has followed the conceptual lead of Thomke and Fujimoto (2000), who proposed that *front-loading* a project with faster iteration activities fostered by digital tools is likely to improve development efficiency and effectiveness. Our data show that these digital tools have changed the PD process dramatically. While we observe increases in the number of digital and rapid physical prototypes constructed and a lowering of associated physical prototype costs as predicted by Thomke and Fujimoto (2000), in our study we find that these digital tools can have unintended side effects of substantial magnitude, in this case eliminating most of the anticipated productivity gains. Our two projects are far too few to produce representative results in any statistical sense, but we argue the observed effects and linkages between tool use, inter-phase workload shifts, and project performance allow a discussion of potentially broader theoretical and managerial implications.

On the theoretical level, it appears as if viewing product development projects only on the project-level, i.e., neglecting any heterogeneity throughout their duration, masks important intermediate effects that are relevant for explaining overall project performance. Past research has typically pursued either studies of micro-level processes qualitatively without performance data, or collected performance data and project aspects only on the project-level, often through categorical measures via questionnaires. We believe our finer grained micro-level process data linked to both intermediate and overall project outcome performance data can bridge this gap and help sharpen theoretical constructs such as front-loading by illuminating their limitations and boundary conditions.

More specifically, the original front-loading idea viewed the entire product development process as one entity, and proposed to push as much problem-solving upstream as possible via advanced digital tools. While this idea is conceptually very powerful, it seems as if there are at least two potential side effects to be considered. The first is that effectiveness of digital tools such as CAD for problem-solving processes can vary depending on the individual process phase. Research in the creativity literature has a long tradition in describing creative activities such as product development as consisting of two very distinct parts: a divergent and a convergent portion, e.g., (Gordon, 1961). To be conducted successfully, each portion requires the teams to engage different thinking modes. The downstream part, the convergent portion, has as its goal to select and refine solutions. It is this portion that is best described as a technical problem-solving process. Moreover, it is here where the replacement of expensive tools (physical prototypes, perhaps even full-scale) with digital tools (e.g., CAD) that are – on a per experiment basis – less expensive and much faster, can generate dramatic benefits. This is where CAD use strongly supports the original idea of front-loading.

The upstream part of product development, however, i.e., the divergent portion, requires a different approach. Here the goal is to explore the solution space and to generate possibilities. Others have recognized these qualitative differences that the early phase of product development – sometimes called the Fuzzy Front End (FFE) – exhibits relative to the downstream part (Kim & Wilemon, 2002; Reid & de Brentani, 2004). The designers von Elk and Holwerda describe this difference in thinking modes that is associated with the technical means for creating drawings and models as follows: "During sketching you react directly to the drawing on the paper, whereas with CAD you execute a designated plan and react to the outcome later. These two ways of visualizing imply different moments of reaction and decision making." (Van Elk & Holwerda, 2007:164)

Given this qualitative difference, the focused problem-solving approach that is so successful downstream, might actually backfire when used in the same way upstream. We suggest that the precision afforded by modern CAD models can potentially be hindering to an exploration process that could create a better 'initial framing' of the problem, which subsequently would require fewer prototypes (both digital and physical). Concept development is – by definition – more qualitative in nature, but CAD models are – also by definition – very precise. In other words, CAD models assume a level of precision that in the early-stages is not available, and if assigned, can remove a number of options from the solution space. This can occur unrecognized by the participants of the product development teams.

The second potential side effect that needs to be considered is that the ability to postpone decisions due to faster iterations can lead to a decline in process discipline. In other words, the tool's ability allows postponement of decisions, although this postponement is not necessarily the best choice from the perspective of project performance. While postponing design decisions can maintain flexibility if, for example, new information about customer needs is expected to arrive later, but it can also lure PD teams to simply postponing decisions simply because they can, which effectively slows down project progress. In that sense, the design tools ability can induce sub-optimal decision making behavior.

On a managerial level, the availability of powerful CAD systems has created its own challenges. The strong advantages of current CAD systems sit really in the middle of the product development process. One result that we observed in our study: activities are front-loaded from the back of the process to the middle of the process, but unconsciously some are also back-loaded from the front of the process to the middle of the process. An unintended casualty of this effect has been a truncated concept development phase. In our study, project B migrated very quickly to detailed CAD, effectively shortcutting the organic development of sketches, rough models, and detailed line drawings so prevalent in these early design activities. While for the R&D manager, at first glance, eliminating portions of the project through the use of the latest tools may seem attractive, our data shows that shortcutting these early phases may actually increase development time and cost later in the project. Consequently, management would be well-served to protect these early-stages, even if new tools enter into the organization replacing traditional routines such as sketching. But which measures are helpful to do this well? In their paper focusing on this fuzzy-front end (FFE), Kim and Wilemon (2002) call for better ways to measure and manage FFE activities. Following this call, we suggest managers study cost and iteration profiles of their projects to learn about the inter-phase relationships in their own industry and company settings.

As an example, consider the cost and iteration profiles in Figure 6. For this discussion, the cost profiles can be considered a composite of engineering hours (labor cost), managerial attention, and materials and equipment for prototyping. The cost profile III in Figure 6 represents the distribution of a rather poor product development project. Large cost outlays towards the end of the process hint to many rework and iteration activities late in the process.[10] Shifting some of that work to earlier in the process via advanced digital design tools can lead to profile II, which exhibits a peak in the middle of the project where CAD tools are particularly powerful. One question then is whether a more in-depth up-front work could create the cost profile I, which does not exhibit large variation across the project phases. However, the cost profiles alone cannot answer this question.

To shed additional light on the internal workings of a product development project now consider the design iteration profiles in Figure 6. Again, iteration profile III can be associated

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[10] Note that the cost profile is also determined by actual production technologies. Certain manufacturing processes that require very expensive tooling might make it very difficult to create a cost profile that differs from profile III.

with a poorly run project, a project that exhibits much iteration late in the process. In fact, together, cost profile III and design iteration profile III confirm a project with major problems. Introducing CAD to this situation could lead to design iteration profile II: a substantial portion of iterations has been pulled forward so that the peak of iterations now occurs around the middle of the process. In fact, the design iteration profile of our project B is very similar to the iteration profile II. In contrast, a process execution that creates the iteration profile I would be truly front-loaded in that the largest number of iterations would occur early on in the process. Interestingly, that is not what the increased CAD use in our project B created. In contrast, our project A's iteration profile looks very similar to profile I, despite the fact that it made much less use of advanced CAD tools than project B.

Three general insights emerge for managers of product development projects. First, a tool should not drive the process. Our results argue for an appropriate use of new design tools, i.e., to employ digital design tools where they make sense, but not simply because they are available. Second, our study lends support for the often-claimed value of sufficiently funding and protecting the fuzzy-front end of product development projects. Because detailed evaluations are by definition difficult in a phase with high ambiguity, perhaps the focus on iterations can serve as a better lever to manage the concept phase successfully. Third, the ability to postpone design decisions can have unintended negative consequences for the process discipline which need to be managed.

Insert Figure 6 about here

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6 Conclusion

Over the past twenty years, product development teams' use of digital tools has increased dramatically. Paper-based traditional development, spearheaded by draftsmen and engineers, has migrated towards a nearly total digital environment. The trend continues with the aim to fully having the ability to digitally design and modify effortlessly, much as word processing has changed writing and publishing. However, our study suggests that the effortlessness of digital design can have unintended side effects. These side effects of digital design come from its major strength, the ability to iterate detailed models. Our study illustrates that the different thinking modes that underlie divergent and convergent phases in product development as well as process discipline effects need to be considered when applying the idea of front-loading via extensive use of digital design tools such as CAD. In short, front-loading the downstream process should not result in a quasi back-loading of concept development work into the detailed design phase; the different thinking modes that are appropriate for each phase make this merger counter-productive. Nor should a quasi back-loading occur due to pushing detailed design issues into the tooling phase just because it is possible.

Our study results are subject to limitations similar to all studies building on a small number of cases. While we carefully selected our two cases to improve the internal validity of the comparison, the external validity is limited by the small number of cases. That said, we conjecture that our observations from product development projects of products with relatively low levels of complexity, are likely to hold true for products with higher levels of complexity. Higher degrees of product complexity should make both the careful execution of the early concept development phase and increased process discipline even more important.

We see two directions to extend this research. First, it will be useful to test our findings with a larger number of cases, perhaps including projects with various levels of complexity.

Second, following our call for more micro-level studies to improve our understanding of cause and effect of managerial actions in the product development environment, studies that would observe ongoing product development projects could focus on which managerial interventions lead to better performance outcomes. For example, does the upstream concept development phase need particular protection? Could this be achieved through better guidelines when and how to implement and use new virtualization tools? And how can process discipline be maintained?

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Figures and Tables

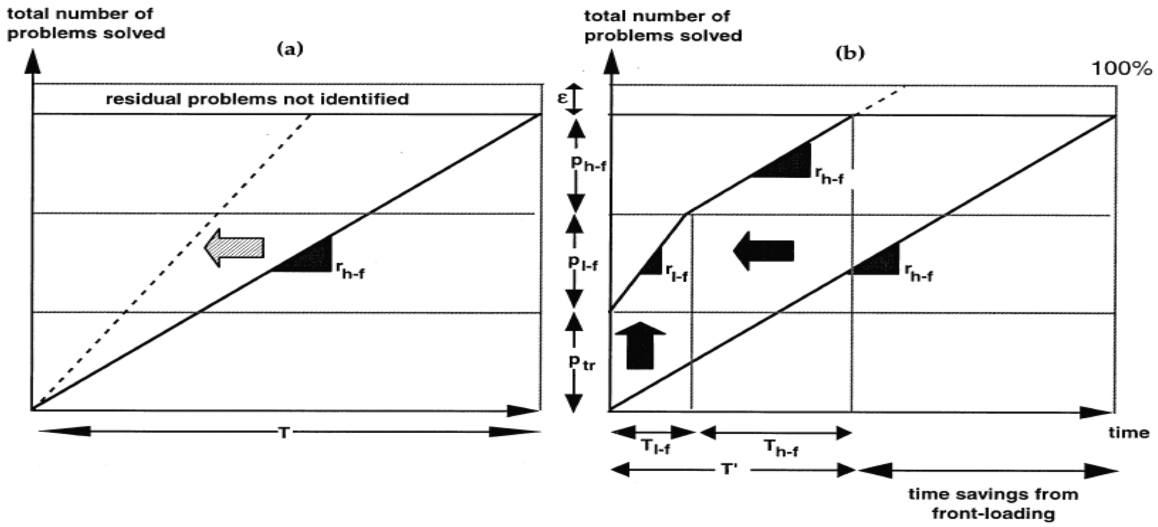

Figure 3. Problem-solving cycles with (a) a single high-fidelity (*h-f*) mode and no project-to-project knowledge transfer; and (b) two modes (*l-f* and *h-f*) with knowledge transfer (for simplicity, trajectories are shown to be linear).

Source: Thomke and Fujimoto (2000, p. 133)

Figure 1: Conceptualization of front-loading by Thomke and Fujimoto (2000).

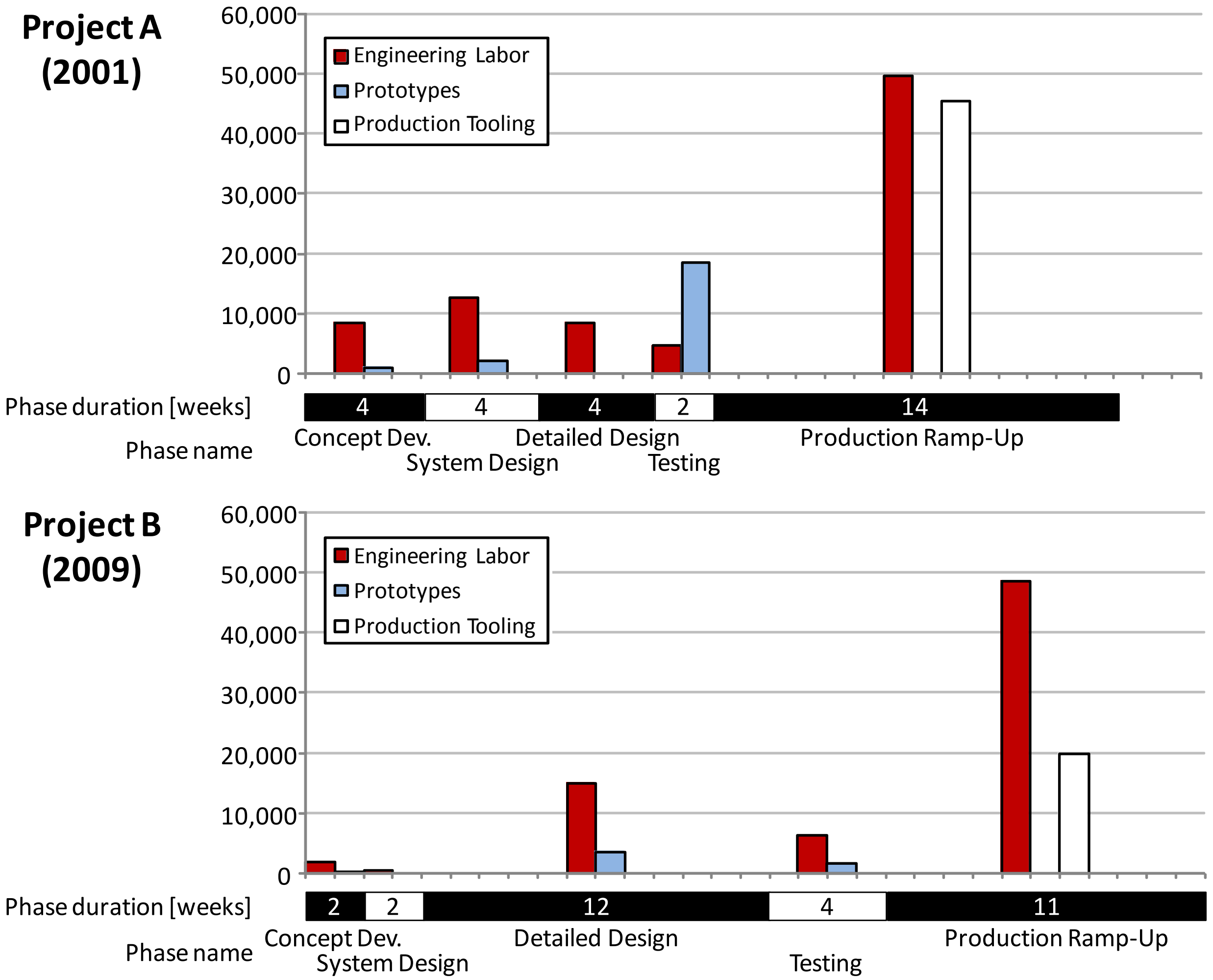

Figure 2: Phase-level PD performance comparison for PD cost (in 2009 dollars)

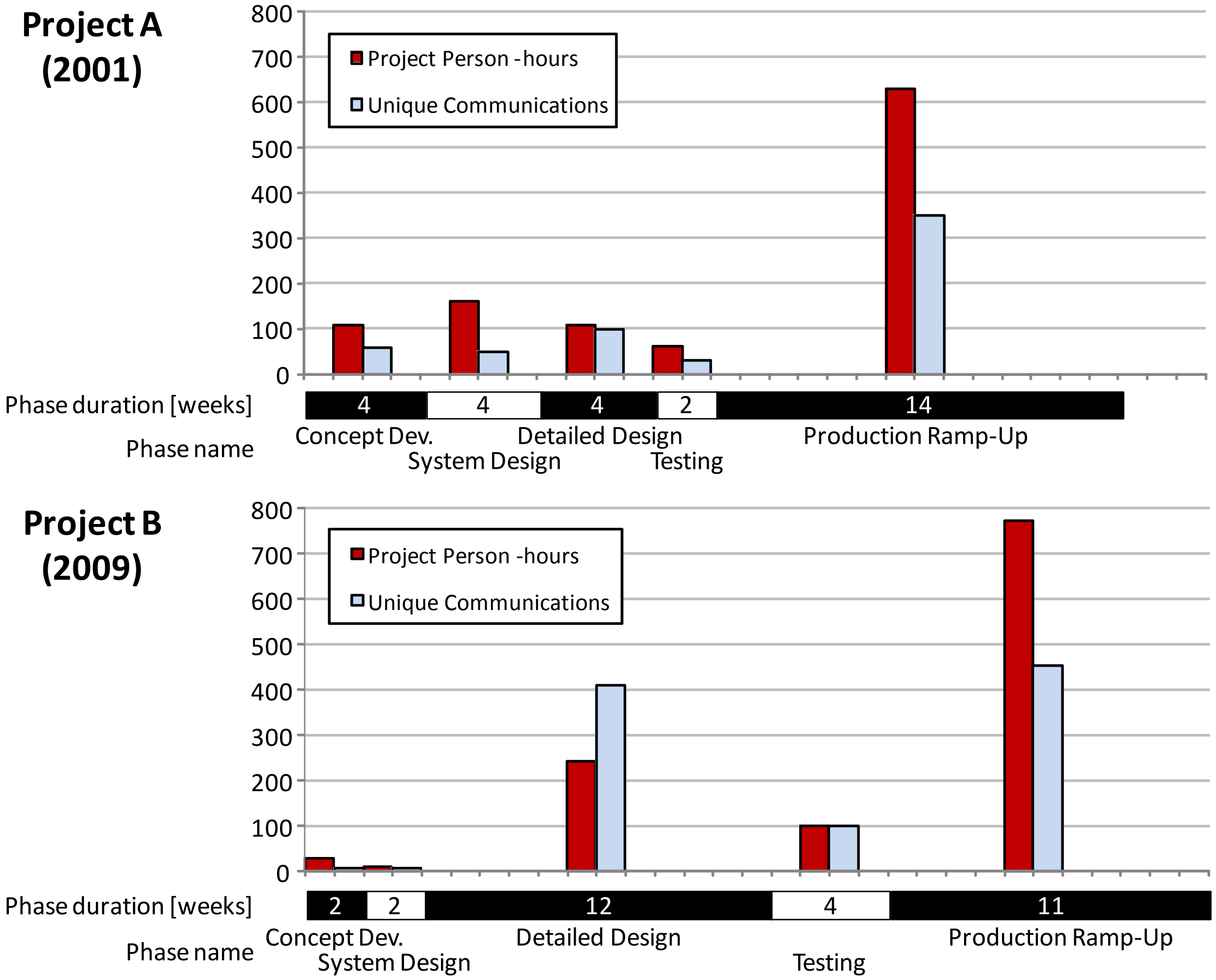

Figure 3: Phase-level PD performance comparison for PD time

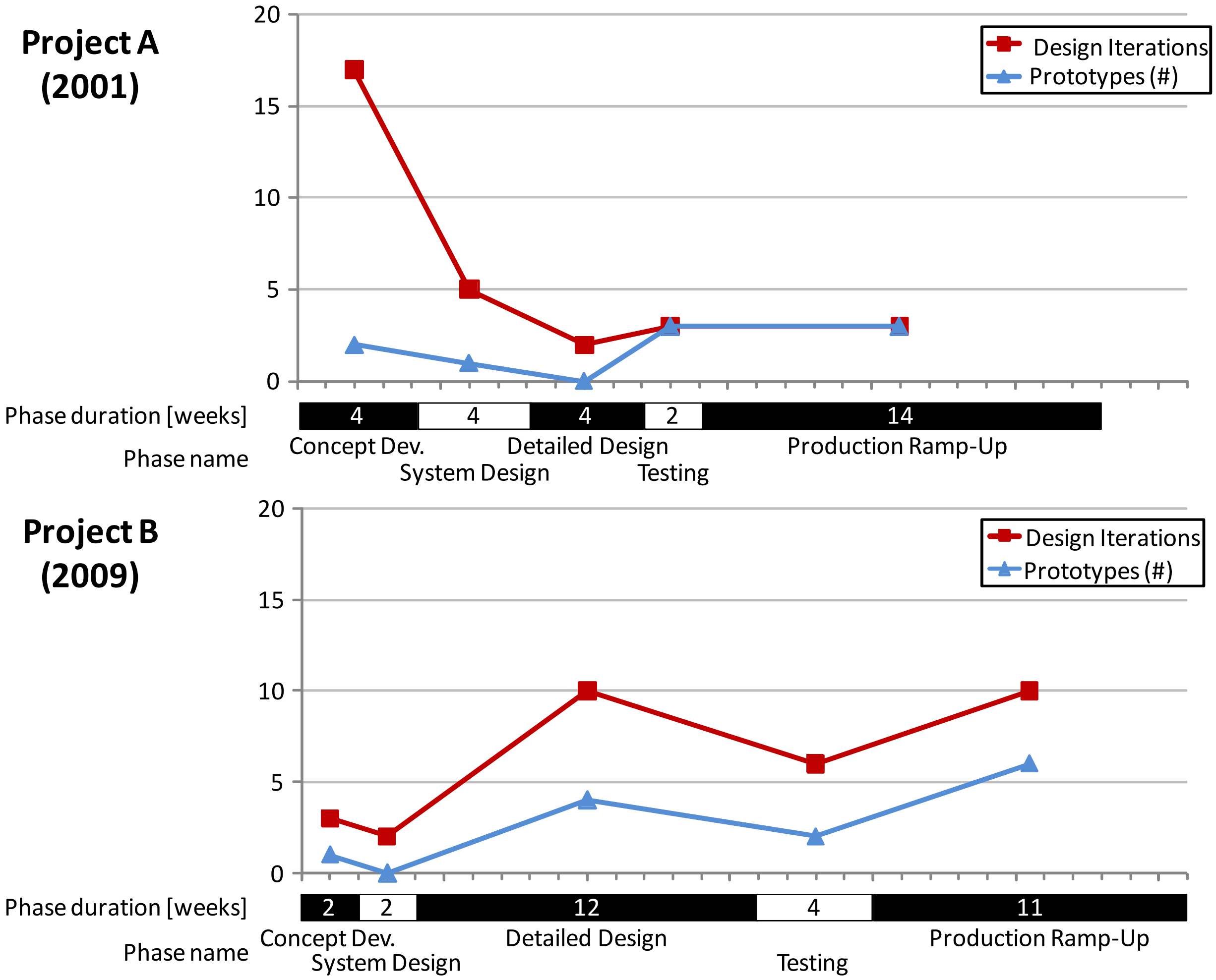

Figure 4: Design iteration and prototyping profiles

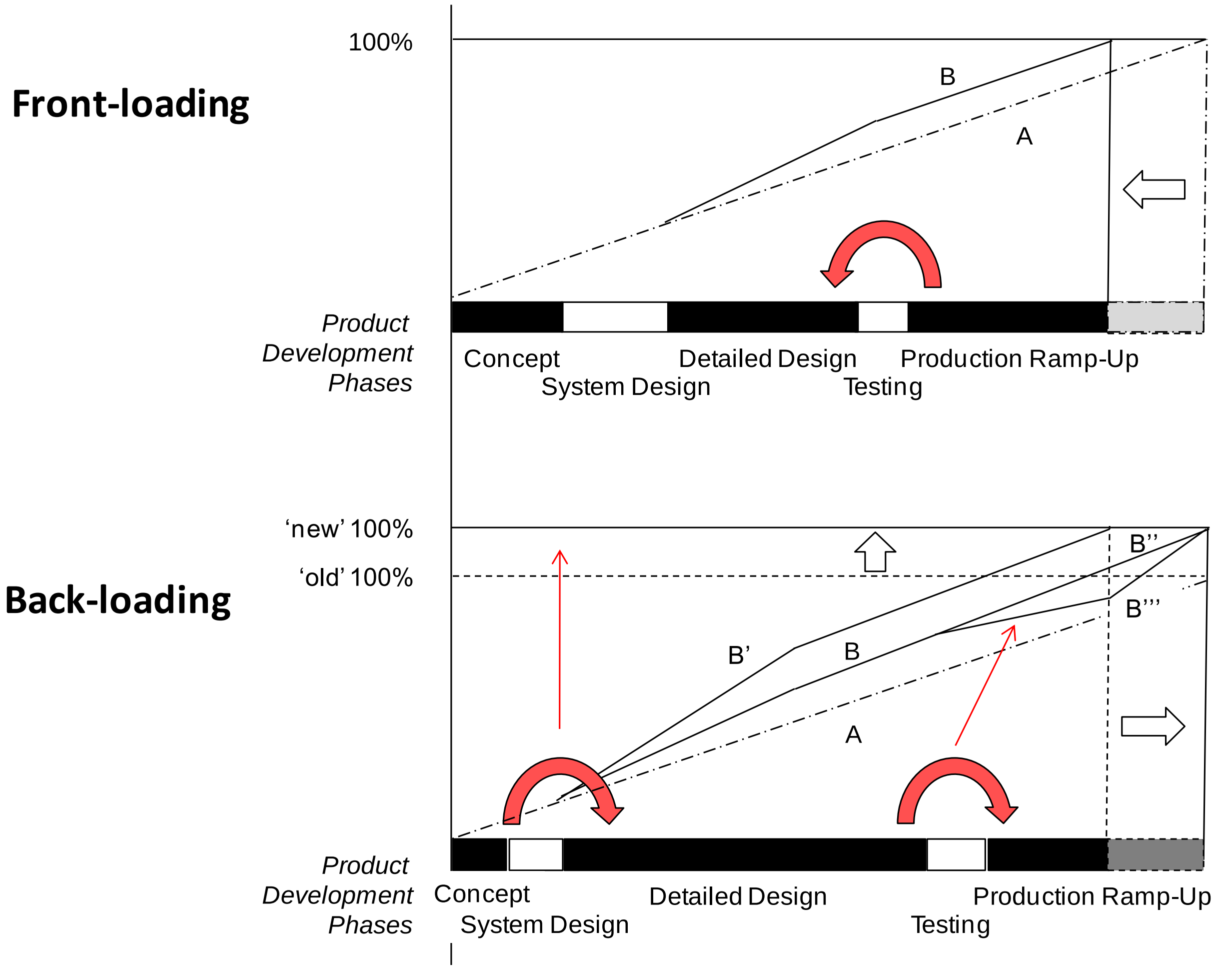

Figure 5: Separate work load shifts: Front-loading (top) and two types of back-loading (bottom)

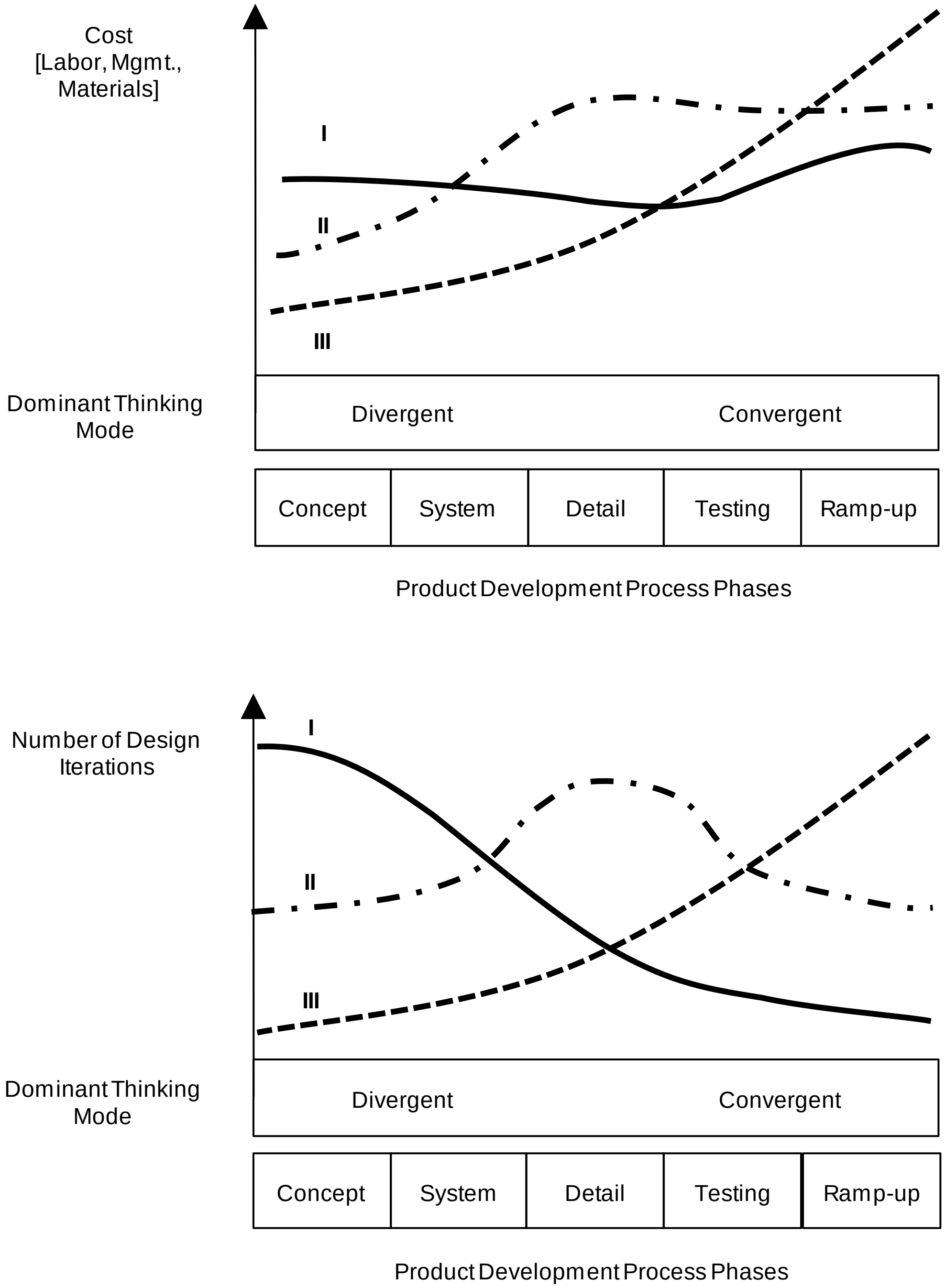

Figure 6: Cost and iteration profiles

Table 1: Detailed PD activity comparison between Project A and Project B

Phase	Task/Tool	Project A	Project B
Planning and Concept Development	User Research	Limited discussions w/potential users	No discussions w/potential users
	Comp. Analysis	Competition purchased, segmented, and analyzed	Competition segmented, not reviewed
	Attribute Definition	List of Customer Needs and Specifications developed	List of Customer Needs and Specifications developed
	Industrial Design Sketches	17 paper-based concepts developed	3 paper-based concepts developed
	Digital Industrial Design	Digital industrial design not used	Digital design rendering used
System-Level Design	Architecture Definition	Product architecture defined	Product architecture defined
	Component Layout	Rough layout of components sketched	Rough layout of components not sketched
	Rough Mock-ups	3 rough mock-ups developed	1 foam mock-up developed
Detailed Design	Scale Drawings	Scale drawings used for all parts	Scale drawings used on (1) part
	Computer-Aided-Design	Product designed in SolidEdge	Product designed in Solidworks
	Realistic Renderings	No realistic renderings produced	Multiple renderings produced
	CAD-based Prototypes	3 CAD-based SLA's produced	5 CAD-based SLA's produced
	Breadboard Test	Testing on rough working model performed	No test performed on rough working model
	Analysis Tools (FEA)	FEA used to analyze critical areas	FEA used to analyze critical areas
	System Integration	Not Applicable	Not Applicable
	Prototype Testing	Tests performed on CAD-based prototypes	Tests performed on CAD-based prototypes
Test and Refine	Design Refinement/Iterations	One design change after prototype testing	6 design changes after prototype iterations
	Vendor Selection	Manufacturer selected during development	Manufacturer selected during development
	Bill-of-Material Generation	Bill-of-materials generated to verify cost targets	Bill-of-materials generated to verify cost targets
Production Ramp-up	Tooling Development	10 weeks	7 weeks
	Tooling Debug	Tooling needed revision after first article	Tooling needed revision after first article
	First Article Assessment	First article assessed per Attributes	First article assessed per Attributes
	Product Refinement	Product needed refinement based on analysis	Product needed refinement based on analysis
	Iterations	3 tooling and testing iterations performed	10 tooling and design iterations performed
	Pre-Production	14 weeks from tooling start to production	11 weeks from tooling start to production
	Testing and Evaluation	4 weeks testing and evaluation of production units	4 weeks testing and evaluation of production units