THE BENFITS AND PITFALLS OF DIGITAL DESIGN TOOLS

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ABSTRACT
Digital design has become pervasive to all aspects of the development process. The potential benefits of digital design include rapid iterations, the development of quick prototypes, and the ability of the team to virtually model entire systems without expensive physical prototypes. Digital design has now migrated to the beginning of the development process during ideation and conceptual design. Through empirical and case-base research we report on the challenges and opportunities of employing digital design early. We find that digital design can lead to back-loading, a condition in which digital design can short-cut valuable conceptual iteration. We also find that the integration of digital design into the development process needs to maintain distinct phases and firms must maintain a balance of creative iteration with process discipline. Finally, we find that there is a direct correlation between firm R&D efficiency and their strategy for IT infrastructure, process discipline, and use of digital design support tools.

Keywords: New product development, computer-aided design, digital design, front-loading

1 INTRODUCTION

Computer-aided design (CAD), or digital design, has become pervasive over the last twenty years in industries that produce physical products. Digital design has migrated from a computer-aided drafting solution implemented at the end of the product development process to an integral part of early ideation. The ability for engineers and designers to develop, share, and collaborate with digital design representations has altered the landscape of traditional engineering – promising to reduce innovation cycle times and improved efficiencies throughout the design and launch process.

This article reports on the use of digital design tools and their impact on the R&D process. Our research indicates that the pursuit of digital design earlier in the process, combined with increasing capabilities of the tools is not a panacea for the R&D team. We find that there are benefits and pitfalls to the overarching use of these tools on the process, design iterations, communication, and resulting effort projects teams exert at different phases of R&D. Early execution of concepts in CAD can cut-short valuable concept development phases, fostering early termination of the 'fuzzy front-end' of design. The ability for teams to execute fast design changes and associated rapid prototypes, while seemingly invaluable in today's environment, can cause engineering teams to be 'caught' in costly cycles of revisions, keeping the design fluid much longer than needed. Our research indicates that contrary to popular notion, these tools do not necessarily shorten total work time, but rather shift engineering resources into different phases. However, we show that firms that invest and adopt a robust IT infrastructure, maintain a disciplined focus on up-front development phases, and embrace digital design for its benefits concomitantly reducing side effects, can see substantial gains in development efficiency. In the pages to follow, we describe our findings based on field and empirical work, noting challenges and opportunities for the R&D organization that span from process to team training. We note several areas where firms can embrace and implement comprehensive, early digital design methods that address common issues while increasing potential for innovation with the R&D process.

2 DIGITAL DESIGN (history and current state-of-the-art, future trends)

Since the 1980's, new product development has migrated from co-located, traditional engineering teams to one that is more global and virtual [1]. What has enabled this transition is the propagation of digital design tools. These tools include the proliferation of highly capable, yet increasingly less expensive CAD packages (e.g., Solidworks[i]), pervasively used electronic mail (e-mail), rapid prototyping technologies, and new communication tools such as Internet-based video conferencing (e.g., Skype).

Research on digital design began in the 1950's, and migrated to industries such as automotive and aerospace in the 1960's. By the 1980's, the use of 2D drawing packages such as AutoCAD had begun to replace traditional hand-drawn layouts and control drawings used by manufactures and suppliers. However, this was a minor change in engineering process that just replaced the final deliverable of the engineering team. The traditional engineering team paradigm remained, i.e. engineers would develop designs and prototypes, and transfer this knowledge to a draftsman. The draftsman would express these in highly detailed drawings and this end product then would be transferred to manufacturing resources and suppliers. Beginning in the 1990's, in tandem with the rise of fast, powerful workstations and capable 3D software (such as Pro/ENGINEER or Solidworks), development teams began a shift to marry the engineers to the final product design, allowing them to conceptualize and complete a production ready design – essentially eliminating the engineer/draftsman workflow.

This paradigm shift in team workflow – enabled by digital design tools - occurred at the same time as the rise of email, corporate intranets, and the Internet. These electronic files could now be emailed and stored on corporate data vaults – allowing distributed teams the ability to easily modify and change designs during the course of the project. One of the first complete digital designs was the Boeing 777, in which the entire airliner was designed, modeled, and tested virtually by an extended development team [2]. The benefits of this approach included identifying interference and fit issues before expensive physical prototyping and having different members of the organization view and participate in the design process (manufacturing representatives, vendors, service and maintenance individuals, etc.). Over the next ten years, this model became pervasive. The cost of the software decreased, and inexpensive computing power allowed even the smallest of firms to implement virtual design methods similar to those used on the 777.

Today, capable CAD packages can cost as little at several hundred dollars, and can run efficiently on laptops costing a fraction of cost of machines of similar performance from several years earlier. Since the time of the 777, the use of IT technologies and services has accelerated the proliferation of support tools that aid in digital design. An example is low cost rapid prototyping. Low cost rapid prototyping machines can print near functional parts in a matter of hours from CAD packages, allowing near real-time physical validation of engineering designs. Early in the design process, designers can vet concepts virtually and physically, with little cost and effort. This can continue throughout the design process into production ramp. IT tools such as project Wikis and social networking foster team communication and iteration. Lastly, communication tools such as the Internet-based video conferencing system Skype foster global communication and team collaboration, at very low or no cost. In summation, today's design is nearly all digital – allowing teams to go from idea to precise parts quickly, then continually revise and validate throughout the development process. The trend continues, with ever increasing adoption of new software, collaboration tools, and services.

What does this mean for the R&D Manager? First, digital design tools have enabled a paradigm shift in engineering processes and workflow. Early designs can be done quickly, and these designs can remain fluid longer. Engineers can conceptualize, create, and finalize these designs virtually. R&D Managers need to understand how to manage and optimize this process more efficiently – as a majority of engineering man-hours are spent developing and refining CAD. The sober reality of modern day product development 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 [3]. This is supported by other research that shows that in some cases the actual cycle time of development has not decreased substantially in the past ten years [4]. In terms of product development effectiveness, research indicates similar stagnancy [5]. Product failure and success rates have changed little over the past several decades. Recent issues with digital design also highlight the challenges R&D organizations face. Airbus suffered severe delays in the development of its new A380 due to issues with CAD revision levels [6]. The successful implementation and management of digital design on product development efficiency and effectiveness has become – due to its impact and pervasiveness – critical to the R&D Manager.

In order to understand pitfalls and benefits of digital design implementation, we undertook a longitudinal study that combined empirical and case field research. We surveyed and interviewed 145 firms[1] that use CAD systems in the design of development of their products. In the next section, we report on our findings.

3 BENEFITS AND PITFALLS OF DIGITAL DESIGN, AND THE PROBLEM OF BACK-LOADING:

Given that fact that a majority of engineering time is spent in front of a computer revising CAD files, we focused our lens on the engineering *bullpen*[2]. We surveyed and interviewed engineers and managers to understand how CAD and digital design is performed and how information technology supports the process. From this research, we developed an understanding of the benefits and pitfalls of using these tools. Interestingly, we found that the implementation of digital design can have a substantial impact, both negative and positive, on the efficiency and effectiveness of product development. We find that while these tools can be invaluable for visualizing ideas and quickly developing a detailed design, and conducting fast iterations. However, when not carefully managed these tools also carry the potential to actually reduce performance. This can lead to short cutting the conceptualization process – limiting the scope and integrity of the final product. This points to the continued need to strive for balanced process discipline, and continued focus on maintaining the traditional phases of product development. We also found that there are substantial issues in the quality of CAD work performed, delays and mistakes caused by different revision levels and packages used, noting the need to focus on training and ensuring commonality along the development value chain. Lastly, we find that digital design completion does not mean the product design is ready for production. Engineering teams tasked with design tend to race to 'completion', when in reality the 'finished' design needs substantial virtual revision before commercialization – sometimes during tooling fabrication – which can be costly. We review the issues in detail in the next sub sections.

3.1 Rush to CAD

Modern parametric CAD systems allow fast iterations of design features and dimensions – once a CAD is built. This ability for fast iterations creates a strong pull for product development teams to jump to building CAD models right at the start of the project. In our research we have identified an interesting phenomenon that can be a downside to this heavy, early adoption of digital design. In contrast to using CAD systems for fast iterations later in the development process – an effect that has been called *front-loading* [7] because it allows to shift task to earlier in the development process – the very early and heavy use of CAD systems in the early stage can actually be counterproductive. We have found that the heavy use of CAD early in the process can lead the R&D team to shortchange valuable activities such as concept development and system design at the front-end of development. Because CAD is a precise tool, the 'fuzziness' of wide-open concept exploration can be eschewed for very detailed design early, potentially eliminating innovative designs that would result from longer, traditional concept exploration. The lower quality early decisions then can lead to more work downstream. It creates a form of *back-loading* [4] in that design changes – due to the ease of CAD enables engineers to 'tweak' designs – are now processed throughout detailed design and production ramp, in essence at the rear of the development process, rather than a focus on iterations up-front during the fuzzy front-end. Traditional engineering completed and tested a design, then finalized the project via control drawings. CAD has enabled the process to be fluid throughout the development process – raising the possibility for rushing to suboptimal early design decision. Figure 1 illustrates both effects that CAD enables: frontloading (from I to II_ideal), and backloading (from II_ideal to II_real)).

[1] This empirical study was conducted with the assistance of PTC Corporation.

[2] An engineering bullpen is an area in an office with workspace for a number of employees and engineers.

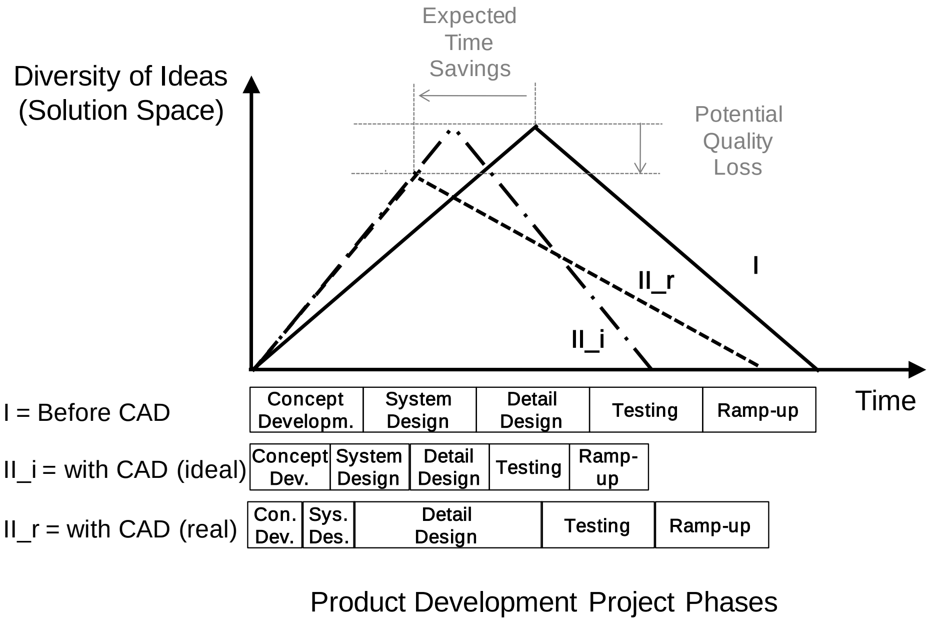

Figure 1: Idealized and real effects through rushing to CAD

In our in-depth interviews, we explored this issue further. A leading design and engineering firm noted the dangers of short-cutting up-front development phases: "*sometimes CAD is too precise… sometimes CAD is not worth it for concepts. Sketching is an Ideation tool, not an engineering tool (like CAD).*" Another firm noted the importance of protecting the front-end of design. They focus on hands-on prototyping and iteration in these early phases. An lead engineer at the firm adds: "*Systems design and engineering are important to us, but we approach it very differently. We do a lot of rough physical models and bread boarding. We lay things out with simple prototypes. This phase really combines usability, design, and technology – all overlapping. If there are lots of systems, we identify them and break them into smaller chunks. Each team member might take a chunk and go make a rough model, we get right into prototyping. There might be some early CAD done here, really depends on the team. Old school people tend to work in physical models.*"

We also found a significant correlation between efficient[3] use of R&D resources and well-defined conceptual and systems design phases and the implementation of management reviews during these early phases. The most successful of these firms maintained a disciplined focus on the process, protecting the front-end, even though digital design tools were used in-phase. A large defense firm noted that: "*We don't see a ton of back-loading here because we are so focused on process. We spend a great deal of time planning the product. We're very rigorous up-front, especially during planning*." In summary, while heavy CAD system use provides powerful effects in later stages, it also carries performance reducing potential when used too heavy too early..

3.2 Changes made (too) easy

Related to protecting the front-end of the process, is maintaining an environment of creativity balanced with process discipline [8]. Modern CAD systems allow running design changes much more easily, leading ideally to a higher rate of problem-solving (compare process II_i vs. I in Figure 2). However, unmonitored the number of these changes can increase dramatically, leading to a problem-solving rate that is lower than ideal (compare process II_r with II_I). Consequently, an appropriate design process and process discipline prevent the number of unnecessary iterations to mushroom just because they are easy to do. A large number of unnecessary changes can eat in the performance gain initially provided through higher iteration speed afforded by CAD systems.

[3] We define engineering efficiency as the use of fewer company resources and lower development cost.

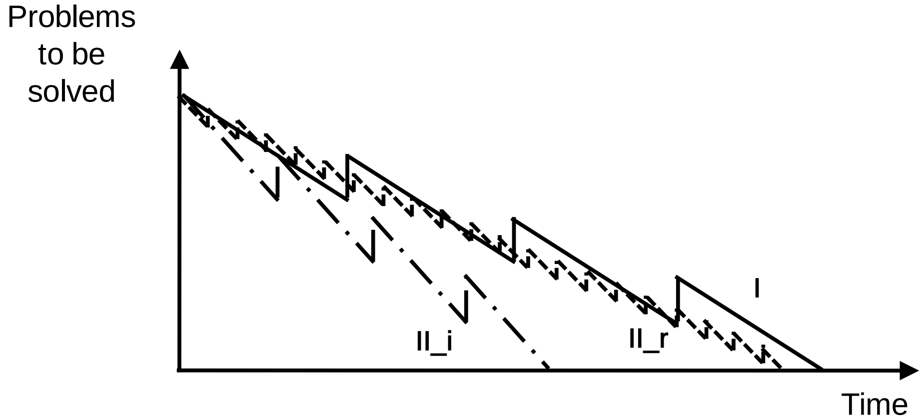

Figure 2: Idealized and real effects through CAD via process discipline

In our empirical study, we found confirmation for this effect, i.e., a significant correlation between the use of systematic planning in up-front phases and early cost engineering with improved engineering efficiency. Firms that focus on systems engineering processes have a healthy respect for maintaining a focus on process, and thus avoid a large number of late changes. This focus on process is juxtaposed by a significant correlation in improved engineering efficiency through an increased focus on information sharing. Firms that fostered communication among R&D team members, focused on shared goals and vision, encouraged team meetings (be it in-person or virtual), and pervasively used prototypes early in the process exhibited more efficient R&D. This balanced focus on process is aided by the integration of IT tools, including CAD. Many of the most successful firms in our study had dedicated systems design and engineering teams, tasked with overseeing the R&D process. As one aerospace firm R&D manager notes: "*We have a dedicated Systems Engineering group, and separate Hardware and Software groups. Each is a well-defined area. I work on Systems applications on a daily basis. Systems Design begins up front, driven by customer requirements. These may be well-defined, as we respond to Request for Quotes. We then translate these Customer Requirements into functional specifications. We consider this up-front portion Systems Design. Partway through Systems Design we bring in mechanical and electrical – so there is an overlap.*"

To facilitate this process discipline, the most successful firms leveraged an extensive IT infrastructure. This included use of software, such as IBM Rational DOORS®, a software package that enables the R&D team to track requirements throughout the process. We found that firms that place an emphasis on IT infrastructure have a significant, positive correlation on engineering efficiency. This includes access to the latest tools and ensuring proper use of the tools. Tools that had a significant impact on engineering efficiency were the use of support tools (like systems requirements packages) and design repositories. The need for strong project management was pervasive throughout our study. Often, a good project manager was seen as the key figure to stop back-loading from occurring. As one technology firm explains its approach to project management and impact on the process: "*We don't see endless iterations in design. This is up to the project manager. We go through the necessary iterations and not overdo it. In the old days you couldn't change the design after a certain point, so sometimes poor designs might have been released. Our process is project management driven. We aim for discipline and efficiency.*" In sum, powerful CAD systems need to be matched with appropriate process discipline, supported by a relevant IT infrastructure.

3.3 Effective resource use hinges on resource compatibility and training adequacy

As we have reviewed, digital design tools allow sharing designs much faster and to a far broader circle engineers ever could with paper-based designs. Today, these tools touch nearly all aspects of development from concept iteration to finalizing point of sale packaging, and as with any tool critical to development and production, these need upgrading to current standards and to remain compatible with partners, as well as training to keep users abreast of the latest features. We have recently seen severe issues with projects that do not maintain commonality on revision level throughout the supply chain. For example, the Airbus A380 experienced substantial delays due to CAD software revision issues between different facilities and suppliers [6]. Incompatibilities between CAD systems of collaborating partners or between CAD systems and workforce carry significant cost because they can cause major setbacks in a project, leading to a process II_r instead of a process of II_i (Figure 3).

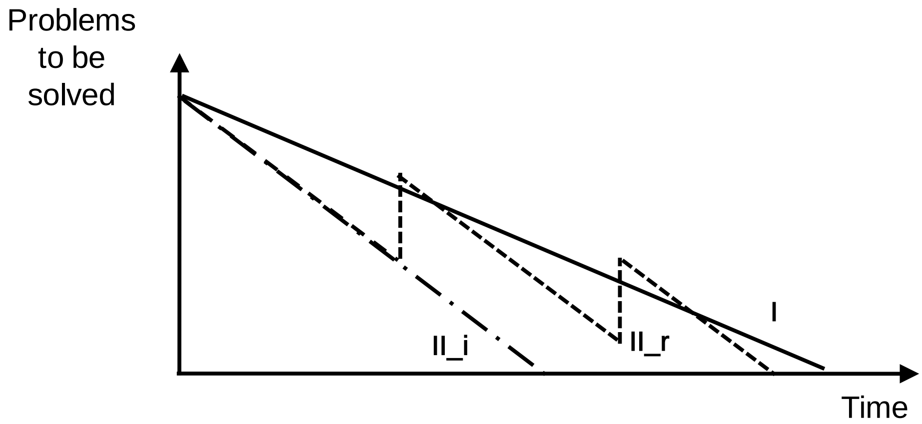

Figure 3: Software incompatibility and workforce mismatch can eat productivity gains

In our empirical research, we found that firms that focus on implementing and maintaining a top-level IT infrastructure are significantly better in terms of engineering efficiency than those that do not. It is imperative that internal departments, vendors, and suppliers maintain consistent levels of software revision and training, and that issues such as tolerances are clearly communicated. One engineer at a high technology firm explains: "*It used to be that vendors, people making sheetmetal parts or injection molded parts, would receive dimensioned, 2D drawings, and check their parts versus samples, etc. Thought went into tolerances, fit, etc. Now, these vendors work right off the 3D solid models. The parts come back to us, and they don't fit well."* This causes unnecessary tooling and design revisions during production ramp. Poor IT infrastructure and data management, as described here, can lead to back-loading.

Another issue revealed from our research is the necessity of training, from engineering core principles to CAD proficiency itself. Since up to 75% of project time can be directly related to CAD hours, users of CAD are directly responsible for the efficiency of process. A large aerospace firm noted that CAD designers are the real experts, and they need to be trained accordingly. Thus, training and proficiency are critical the R&D success. One R&D manager noted that training was all-important to the process. Another lead engineer noted a lack of basic engineering knowledge among younger engineers (who incidentally, will most likely be spending the greatest percentage of time on CAD). He explains: "*I grew up in a machinist town. You started as an apprentice, became a draftsman, then an engineer, then a chief engineer. There was tradition and a learned process of engineering methods once you became an engineer. Now, you have to deal with new hires that have no engineering tradition. They have to figure it out.*" In our interviews, we found that these new engineers were heavily reliant on CAD, and were not fully vetted in engineering methodology. These less seasoned engineers went right to solving the problem digitally, without full defining and exploring the problem first – a surefire contributor to back-loading. Firms would be well served to ensure engineers and CAD designers are well vetted before employment, and have their skills continually improved through training.

3.4 A fast rendering is NOT a complete product design

Digital design, and more importantly the migration of digital tools to early in the development process has caused an interesting issue for the R&D Manager. CAD, being a very precise tool, allows to produce very realistic looking concepts very quickly, much earlier in the process than ever before. Cut-away models, photo realistic renderings, engineering simulations – all providing design details which are close to what near-production ready projects were ten years ago. While this enables amazing communication opportunities, therein also lies the pitfall for the R&D team. While these designs look finalized, they are not. This can result in upper-level management perceiving the design as near completion, putting further pressure on the R&D team(assuming, in Figure 4, the process of II_i to be true, rather than II_r). As one aerospace firm explains: "*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.*" Another firm states that a downside is having management look over the shoulder of the designers, trying to have input on design changes. Their solution is to only show pictures of the parts and assemblies (rather then the CAD models themselves), intentionally limiting upper-level management input on engineering decisions. As the head of R&D states: "*We do not show the CAD model because when you show the model, people try to have technical input on the project when they don't have technical knowledge. This is a big issue.*" Another firm states: "*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.*" R&D managers need to take head that a detailed early CAD concept can open a Pandora's box of gratuitous design input.

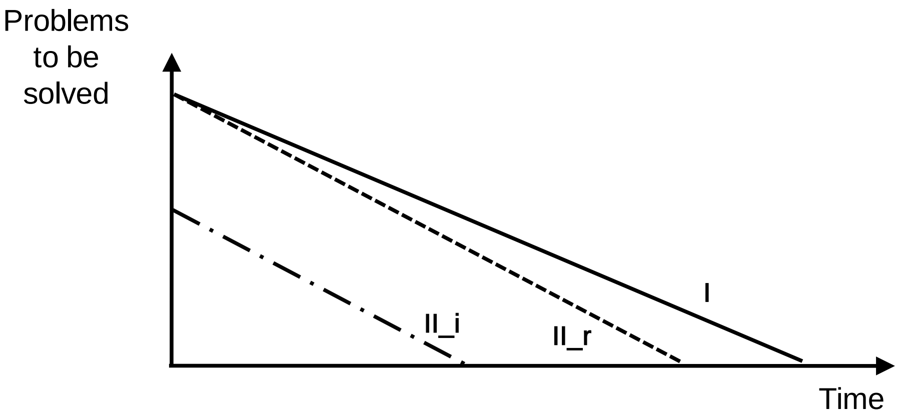

Figure 4: Early CAD models can be misinterpreted as almost complete (II_i) even though in reality they are not half as complete (II_r)

Within the organization, product development process, and management reviews, all should understand the benefits of digital design and also its limits. In the next section, we review challenges and opportunities for the R&D manager.

4 CHALLENGES AND OPPORTUNITIES FOR THE R&D MANAGER

4.1 **Opportunity: Use CAD early wisely and protect the fuzzy front end**

In our research, two things became clear. One is that the migration and pervasive use of digital tools has occurred, and is not reversible but actually accelerating. The second is that firms must protect the front-end of development, and not race to a premature detailed design, which may cause back-loading. For firms wishing to use digital design tools very early during conceptualization and research, we consider this an opportunity to maximize the benefit of digital tools, namely the ease of iteration and the development of fast prototypes to vet concepts. As one firm noted: "*Today, we do go right to CAD earlier, mocking-up designs very quickly – often during Systems Design. We call this the 'Imagineering stage.' You can do analysis faster. Rapid prototyping is used heavily. We have Laser Sintering machines and SLAs.*" This agile methodology of rapid iteration and testing – up-front – can also be used in conjunction with early cost evaluation. As noted, we found significant connection between firms that heavily prototype up-front and continued R&D efficiency. Since 70% of development costs are decided in the very early stages of development [9], having detailed costs estimates derived from detailed concepts can be a benefit. This is particularly important in the current economic climate.

4.2 Opportunity: Use digital tools and maintain process and process discipline to enhance the process

While CAD is an essential digital tool in design and engineering, the power of CAD is truly realized when combined with digital support tools. These include communication, collaboration, and project management tools and applications. Reviewing a CAD model on Skype with global vendors can reduce communication errors, reduce travel time and expense, and leverage global time changes. For example, a firm in our research had Skype calls nightly with their team in China, who were exactly 12 hours apart. This enabled a near 24-hour development cycle, truncating total time-to-market. As one firm noted: "*We use WebX meetings a lot. We also have dedicated video conferencing capabilities.*" Our empirical research showed a significant connection between the use of IT support tools and R&D efficiency.

For project management and team collaborations, more firms are using Wiki's. These allow distributed team members to share a common development space. The team members can comment, edit, and revise designs in a socially networked environment [10]. Interestingly, we found no significant connection between the use of collaboration tools on R&D efficiency, but we did see a significant correlation between improved efficiency and increased communication and knowledge sharing among team members. Many firms still have challenges though, particularly with product lifecycle management (PLM) software. These systems can be cumbersome for teams to use to their desired effect, and result in layers of old part revisions, duplicate files, and mismanaged data. As one firm states: "*We use PLM, but it's really a messy vault system. We have 27,000 variations in the vault. So say you want to look for a design – you have to go back and look at all the revisions. There are multiple copies saved. There is no structure – it's really extremely big and complicated.*" Often, instead of reusing a design, this firm will just design a new part because it's more efficient.

As such, R&D managers need to ensure discipline not only in the development process, but in the maintenance and use of stored data. One large firm ensures that all files are properly maintained and stored in a secure intranet vault. It is interesting to note that this firm also is the closest to a traditional firm – with their process being relatively unchanged since 1980. Our empirical research supported this, noting a significant connection between the use of a design repository and R&D efficiency. R&D managers should note the importance of these tools, but also understand the needs of the organization as to not overburden the R&D team with tools and policies.

4.3 Opportunity: Ensure compatibility across partners and workforce

One of the challenges of firms adopting heavy use of digital design is software revision level and data commonality throughout the value chain. These are often issues with design revision levels, e.g. part files not containing information on tolerances and desired materials and finishes, and a reduced reliance on control drawings. Issues with vendors can grind the development process to a halt. As one engineer notes: "*Often these vendors don't look for these potential problems (shrinkage, fit, sinks). I wish these vendors would push back. They just make the part, then we have to review, it doesn't work, then they have to rework the molds and the cycle continues. We pay a higher price for parts because of this. Another issue is these vendors will take the 3D parts and change them without telling us.*" R&D managers need to ensure the CAD files contain the proper data, and more importantly, not eschew important control drawings for the sake of 'just sending the file.' Similarly, training new engineers not only the latest CAD software version, but also in fundamental engineering methods is key. Staying current in both underlying engineering know-how and the latest application software both are ingredients to high performance.

4.4 Opportunity: Use early CAD to the benefit of the project, not to use CAD

Early digital design has many benefits as discussed in this article. It also presents challenges to the R&D team, some of which can impact efficiency of the total process. The R&D manager needs to maximize the positives of digital design while shaping the process to reduce the negatives. For the former, CAD allows the team to have early management exposure to the project, fostering empowered support through visualization. But this can result in active management support and R&D funds throughout the project. This also presents a challenge as discussed earlier: some may perceive the project as complete when being shown digital images. Consequently, senior management needs to be educated about the difference between a photorealistic rendering and completed design. In addition to conceptualization, digital design can be used for sales, management approval, customer feedback, etc.

Iterations proven by prototypes, team communication and collaboration, and maintaining the front-end seem to be an assured bet for the R&D team. We conclude with final thoughts in the next section.

5 CONCLUDING REMARKS

Digital design has forever changed the way R&D teams approach innovation development. The benefits are clear – rapid design and iterations, the ability to transmit design electronically to global sources, etc. However, there are downsides. First, early use of CAD can lead teams to prematurely select and design a concept, leading to more iteration at the end of the process. This can impact both efficiency and effectiveness of the development process. The issue of back-loading is an important one for the R&D manager. However, these are steps one can take to maximize the benefit of digital design while reducing the side effects. These including investing in a world-class IT infrastructure, deploying the latest support tools, and fostering team communication and collaboration. Secondly, the R&D manager must maintain the front phases of development. A balanced process between creative iterations and discipline can foster the benefit of CAD's rapid design and prototype capabilities while focusing on the importance of systematic systems design. Third,, since CAD efficiency is directly proportional to engineering efficiency, it is import to hire and train the best, most capable individuals who understand engineering methodology and the tools themselves. Digital designs can get 'real' very quickly, but *realness* does not equate to *completeness*. The R&D manager must understand this and arrange her/his organization around the benefits and pitfalls of these new development tools.

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