Effectiveness of Systems Engineering Techniques on New Product Development: Results from Interview Research at Corning Incorporated

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Abstract

This paper reports on the findings from interview research conducted by a joint team from the Systems Engineering Directorate at Corning Incorporated and the Systems Engineering Program at Cornell University to test for systems engineering (SE) effectiveness in product development in a commercial setting. Between April 2008 and March 2009, the team conducted 19 interviews of systems engineers and project managers within Corning to evaluate the extent to which they used a range of systems engineering techniques, and the effectiveness of those techniques in improving project performance. Both quantitatively and anecdotally, the expectation of a correlation was met, with strongly performing projects having generally higher use of SE, and struggling projects having difficulties that could be traced back to shortcomings in the use of SE. Both the findings and the underlying methodology are discussed, with the aim of interesting others in the field in repeating this type of research within other enterprises.

Introduction

Across many disciplines of engineering, there is widespread confidence in the benefit of using systems engineering (SE) as a core component of the new product development process. However, this confidence can benefit from further research to expand the empirical evidence connecting SE practice with project success. Such evidence would help systems engineers to better make the case within the enterprise for allocating time and financial resources to SE activities. It would also help systems engineers to understand in more detail the connection between SE and project/program performance, for example to learn what SE techniques are most effective in what situations.

Our goal, therefore, as members of the Systems Engineering Directorate at Corning Incorporated and the Systems Engineering Program at Cornell University, has been to better validate this belief in SE through a joint research project from 2006 to 2009. An earlier stage of the research, namely the literature review, was reported in the INCOSE journal *Systems Engineering* (Vanek et al, 2008). The content of this paper deals with the second part of the project, namely results from survey interviews of systems engineers and project managers within Corning in which our team looked for correlation between the presence of SE and project performance. The full final report for this project is available to interested readers electronically from the Cornell University server (see Corning Systems Engineering Directorate, 2009). Also, preliminary findings from the interview stage of the project were reported earlier in INCOSE *Insight* (Vanek et al, 2009).

This paper is organized as follows. In Part 2, we provide background for the interview research, focusing on the findings from the literature review and how they have informed the interview methodology. Part 3 describes how the interview and project evaluation format was developed and carried out. Part 4 gives the results of the analysis of projects studied within the Corning organization. Lastly, Part 5 discusses insights about the methodology gained from the application to Corning, as well as ways to extend it in the future.

Project Background

Genesis of the project.

The decision to study the use of SE in general and its effectiveness within Corning in particular came out of collaboration within the INCOSE Finger Lakes Chapter. The Cornell University Systems Engineering Program has existed since 1998 and the Systems Directorate at Corning since 2005. During this time, the Cornell program has been developing relationships with regional partners that have a strong interest in SE, such as Corning, and in 2006 a decision was taken to study the use of SE within Corning, both to help the Corning side with their internal efforts and also to allow the Cornell side to make a more general contribution to the body of knowledge surrounding SE effectiveness. As such, the project represents the first instance of Cornell's Systems Engineering Program conducting sponsored research.

Conceptual foundation of the project

Corson (2009) divides the design process into three distinct elements: 1) Purpose, 2) Product, and 3) Process, as shown in Figure 1. While much systems engineering work is concerned with the product and whether the product meets the requirements of the purpose, deliberate consideration of the process is an essential component as well, since failure to deliver a product that meets the purpose can often be traced to problems in the structure or execution of the process that connects the two.

In a similar vein, Sheard (2000) divides SE applications into three categories: 1) Discovery, 2) Program systems engineering, and 3) Approach. Whereas 'discovery' and 'program' applications focus on complex systems with an emphasis on the product, i.e., the systems engineer is focused on capturing and designing the physical and logical relationships within a complex system, an 'approach' application is often (though not exclusively) focused on evaluating and improving the process of developing new products or systems that solve a problem. Thus our interest falls primarily in the area of 'process' according to Corson's categorization, and 'approach' according to Sheard's structure of different types of systems engineering.

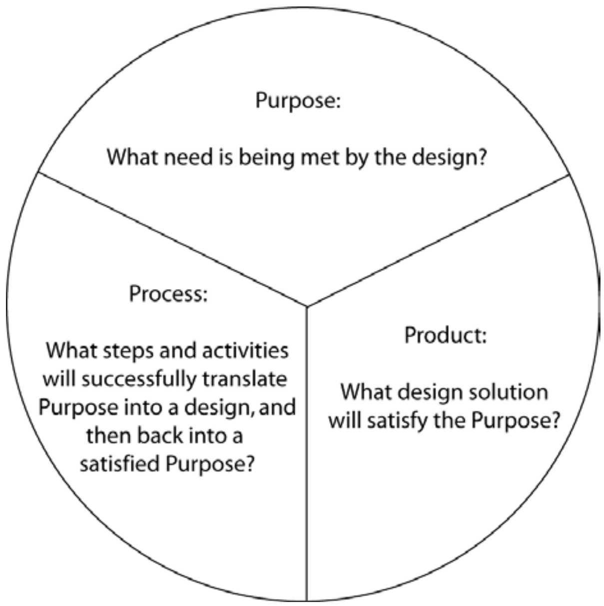

Figure 1. Relationship between Purpose, Product, and Process

(After Corson 2009)

Literature review

In the first phase of the study, we conducted a literature review of both the SE literature and of papers and reports from related fields that might include discussion of techniques common to SE, such as Total Quality Management or Six Sigma. We noted several instances where SE was found to have contributed to improved new product development (NPD) success in the commercial world. For example, Loureiro et al (2004) studied the development of two powertrains in the automotive industry and found that the powertrain development process that used more SE tools finished sooner and required fewer resources. Similarly, Staley and Warfield (2007) describe the advantage gained by implementing a systems engineering framework for vehicle development at Ford in the 1990s.

These examples reaffirmed the value of SE in developing new products for the commercial marketplace. More in-depth studies of SE effectiveness in commercial NPD, however, were found to be lacking. We searched for papers or reports that described the systematic assessment of SE effectiveness across multiple projects, either within a single enterprise or across multiple enterprises, in part to gain more detailed evidence of effectiveness and in part to find examples on which we could base a research project within Corning. We also searched for studies that evaluated longitudinally the benefit of introducing SE across multiple projects or enterprises, i.e., looking at the before-and-after effect of such a change. Our literature review did not reveal any such published studies

As part of the literature review, we also reviewed publications in the military/aerospace domain, and these were found to be more advanced in terms of testing for and documenting SE effectiveness. This body of evidence included both case studies of individual instances (e.g., Frantz 1995) and surveys of multiple projects that showed correlation between SE input and project performance (e.g., Honour et al 2004, National Defense Industry Association 2007). The publication from NDIA reported results from 46 projects across several member organizations. This publication was particularly useful to us, not only as evidence but also because of its detailed description of the methodology used to survey project managers and then evaluate project effectiveness. The methodology presented in Sections 3 and 4 below is based in part on the NDIA approach.

Organization and execution of interview study

Structure of interview research. In the first half of 2008, through brainstorming and tradeoff analysis sessions, the Corning-Cornell team developed a framework for conducting the research. We agreed that the study would entail interview research in which the members of the Cornell team, as impartial researchers, would conduct on-site interviews of NPD team participants with the title “project manager” or “systems engineer” (hereafter referred to as “interviewees”) to assess the extent of use of SE and to evaluate project performance. A non-disclosure agreement (NDA) provided reassurance to interviewees that they could openly share observations from their projects. (All results reported in this paper have been generalized so that they do not reveal sensitive information about new products.)

We considered introducing SE techniques to projects that were not currently using them and then testing for improved performance. This presented too many measurement difficulties. Instead, the scope of the project was restricted to considering only *existing* use of SE in either ongoing or completed projects. Also, since many interviewees had little familiarity with the language of systems engineering, we tested for the presence of specific techniques in a project (e.g., market analysis, tradeoff analysis) without regard for the particular name the respondent gave to the technique or even if the respondent was aware of applying a technique.

The specific process used to conduct an interview was divided into preparation, interview, and post-process stages. In the preparation stage, we sent the interviewee a 2-page document to introduce the study, and then followed up by phone to establish a personal rapport in advance of the interview, as well as to answer any questions arising out of the pre-read.

The interview itself took approximately two hours. One of the key features was that we asked interviewees to display documentation to support their answers in regard to their use of SE techniques, usually by opening and displaying electronic files related to the project. For example, if the interviewee were discussing the extent of their ‘competitor analysis,’ they might present a PowerPoint slide showing a comparison of offering between competitors’ products in the marketplace and their own proposed new product. During the interview, we took notes on the information drawn from the documents shown, as well as taking down in a condensed form the gist of any interesting statements the interviewee made either supporting or discounting their use of SE techniques.

During the interview, we also took steps to avoid ‘telegraphing’ to the interviewee the underlying SE technique that we were trying to detect, so that the interviewee would not be able to skew the results one way or the other, based on their opinion of that technique, desire to promote or discourage that technique, or other subjective factors. We asked each question about the project independently, without indicating whether it had to do with market analysis, requirements engineering, and so on.

As part of the post-process after the interview, we first evaluated, for each question in the interview, whether the interviewee earned full credit (1 point), partial credit (1/2 point), or zero points for the SE technique under consideration. On occasion, as part of this post-process evaluation, we followed up with interviewees to arrange to be shown additional information that might help us to better score the answer to a question. In general, however, the two-hour interview concluded the interviewee’s input into the research. The two-hour target was chosen weighing two considerations: by our judgment, more time would be too burdensome on prospective interviewees and they would be less inclined to make a commitment to participate, and less time would not allow us to thoroughly investigate the project.

Development of content.

Given our requirement that the interviewee provide evidence of using a technique, and given the two-hour limit to the interview, we had to severely restrict the number of questions posed to the interviewees. Specific areas of SE content were chosen for development into interview questions from Honour and Valerdi’s (2006) ontology of systems engineering. Their ontology (as presented in Table 5 of their paper) includes a structure of eight areas of systems engineering that are common to all or most of the major published SE standards, including ANSI-EIA/632, IEEE-1220, ISO-15288, CMMI, and MIL-STD-499C. As an indication of how consistent the standards are in using these eight topical headings to organize content details, out of five standards, two of them incorporate all eight, one incorporates seven, and two incorporate six.

Our interview content development process entailed selecting areas of greatest interest from among the eight topical headings and then developing interview questions that would elicit information about the extent to which interviewees were considering the topic in question in their NPD process. As shown in Table 1, the four headings chosen are “market analysis”, “requirements analysis”, “technical analysis”, and “verification & validation.” Just as the individual questions asked under a topical heading varies between SE standards, as shown in Honour and Valerdi’s table, the number and content of individual interview questions can be tailored to the specific enterprise or enterprises in which the research is being conducted. In our case, we ended up with either three or four questions under each of the four topic headings.

Table 1. Description of SE Categories Available for Inclusion in Interview Content (Source: adapted from Honour & Valerdi, 2006, Table 5. Note that where the original table uses “Mission definition”, we use “Market analysis” as being more appropriate for commercial world applications.

SE Category	Typical content	Included in Corning study?
Market analysis	Define customer	Yes

	Define customer needs	
Requirements engineering	Requirements development, based on customer input Requirements tracking	Yes
Systems architecting	System design System life cycle management	No
System implementation	Product realization Product integration	No
Technical analysis	Functional analysis Tradeoff analysis	Yes
Technical mgmt & leadership	Performance tracking Process management (resources, risks, decisions, etc.)	No
Scope management	Acquisition & supply Supplier agreement management (boundary management)	No
Verification & validation	System verification & validation Design for testability	Yes

On the project performance side (i.e., output from the project, as opposed to SE input), our method is to gather quantitative information on project performance, including budget, schedule, and human resource performance as well as delivery of value proposition and return on investment to Corning. For products that are undergoing development as opposed to launched in the marketplace, this means gathering data on projections of how well the value proposition will be met and what the return on investment to the enterprise will be, where sufficient data are available. We also gather qualitative information about project performance (e.g., expressions of confidence or lack thereof in the project by the interviewee, descriptions of how the project is or is not proceeding well) to complement the more quantitative information.

During the launch of the project, we built in opportunities to pilot and adjust the “script” of the interviews, before continuing the full application of the interview methodology to the remaining schedule of interviews. We first piloted the script on a project in which one of the members of the Corning Systems Engineering Directorate also had a managerial role, and made an initial round of script changes. We made additional adjustments after completing three more interviews, resulting in a final version of the script that was maintained for the duration of the project. Since the adjustments to the script were minor, we were able to re-score the first four interviews to fit the revised script without needing to repeat the interviews.

Findings

Finding #1: Methodology feasible

The first and most basic finding was that it was possible to pursue an ‘interview with documentation' format, which we have not seen previously in the literature, and gather analyzable information about the various projects. Between April 2008 and March 2009 we were able to complete 19 interviews with sufficient usable information from answers to questions that the project could be included in the cross-project analysis. A 20th project was also interviewed, but the answers obtained lacked sufficient detail to be useful, so this project was dropped from further consideration. For the most part, however, once an interviewee joined the interview schedule, we were almost always able to follow through and complete the necessary data gathering for their particular project.

Finding #2: Variability in SE input detected

Our second finding from the project is that a survey of a large number of distinct projects results in detectable differences in SE input, as the 19 projects ranged in percent score from 40% to 93% in terms of their use of SE ("Overall" column), per Figure 2. Even in a situation where many interviewees did not use SE terminology to describe their approach to managing the project, they were found to be using SE, and some techniques?) more than others. For example, some interviewees may not use the term "design for testability", yet their documented actions reflect proactive thinking about how to plan and schedule testing to evaluate whether a requirement has been met, from the point in time that the requirement is introduced onward. Other interviewees clearly had not engaged in proactive thinking about design for testability, based on the project documentation they presented.

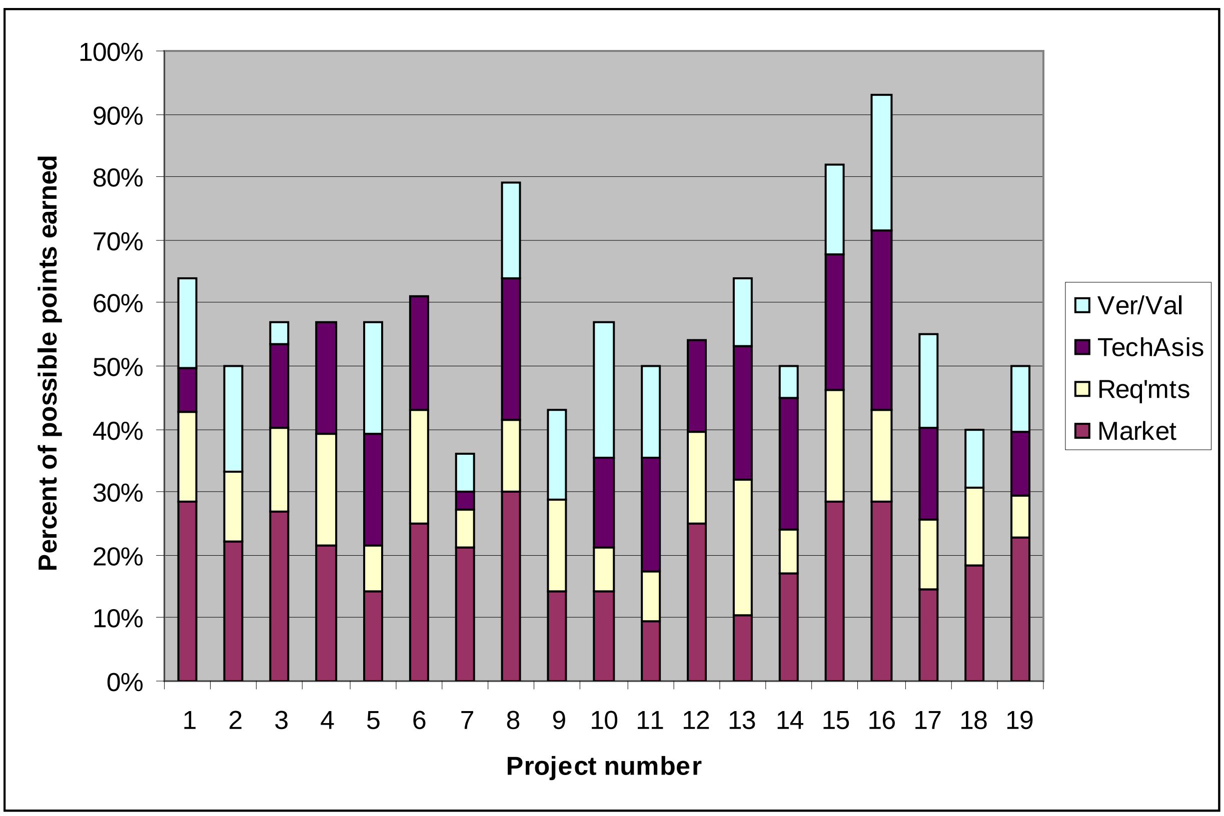

Figure 2. Comparison of percent of total possible points earned by numbered project, including contribution from SE category. (Notes for figure: "TechAsis" = technical analysis, "Ver/Val" = verification & validation, "Req'mts" = requirements engineering,

"Market" = market analysis. Stack order is the following: for each bar, the topmost bar is Ver/Val, next is TechAsis, etc.)

Finding #3: Correlation found between SE & performance

As a third finding, the projects studied were found not only to have differences in SE input, but also in project performance, and *superior project performance was correlated with increased SE input.* None of the projects studied were for products whose success in the marketplace was known, however we were able to use a mixture of qualitative evaluation of in-progress project performance together with quantitative evaluation of the project's progress to date and future prospects to classify their success. Using this admittedly subjective approach, we classified 3 projects to be "superior", 3 to be "struggling", and the rest "satisfactory". The variability in amount of SE input provided an opportunity to see whether varying levels of SE had an effect on project performance.

The relationship between SE input and project performance can be combined into the mosaic diagram shown in Figure 3. As shown in the figure, the 19 projects are divided into higher, medium, or lower SE input projects, with higher and lower input projects having percentage scores (see Figure 1) either one standard deviation above or below the mean score across all projects (μ=58%, σ=13%). Then the height of each bar is color-coded to reflect the performance of the projects represented in that bar. To illustrate, in the bar on the left of the figure, three projects had scores at or below 45% (= μ - 1SD), and of these, one was struggling and two were satisfactory. Based on the color-coding, the presence of superior projects increases and struggling projects decreases as SE input increases from left to right across the figure. Since project management of product development teams is a highly individualized experience, it is not surprising that the correlation between SE input and performance output is not completely precise, i.e., in the middle bar, a "medium" amount of SE input occurs in a superior project in one case and a struggling project in two cases. However, within the range of variability that can occur between projects, it is clear that SE input is having an effect on performance.

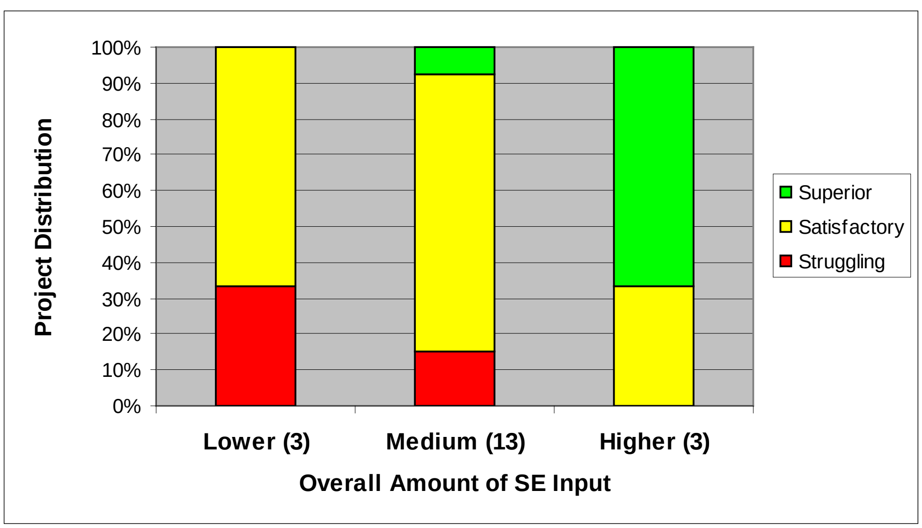

Figure 2. Project performance as a function of overall SE input, for lower, medium, and higher SE input projects. Note: number in parenthesis shows how many projects fell into the category bar, e.g., 3 projects in the "lower SE input" category, etc. See text.

For each of the four individual SE categories tested, there was more variability in scores (higher coefficients of variation), with some correlation between SE input and project performance. (For brevity, the four mosaic diagrams are not included here.) Since there are fewer questions on which to score a project in an individual SE category (3 or 4 as opposed to 14 questions total), the higher CV is not surprising. One way to address this problem would be a larger number of projects in the pool, which might provide a clearer picture.

On an anecdotal level, the three superior projects scored at the average level or at a very high level (up to 100% of possible points earned) across all four SE categories; interviewees described characteristics within the project that fit the profile of successful development, such as accelerated advance through the stage gate process, or winning of internal awards for project excellence. The three struggling projects were deficient in one or more of the following: market analysis, requirements engineering, or verification/validation. These deficiencies in turn led to project development problems, such as cost or schedule overruns. Problems with technical analysis did not appear to have a major negative impact on any of the 19 projects studied. This may suggest that technical excellence is more uniform across project teams than systems engineering excellence. One caveat is that it is entirely possible that with a larger pool of projects interviewed, some instances of a cause-and-effect relationship between deficient technical analysis and project underperformance might be uncovered.

Finding #4: additional benefits from reviewing interviewee quotes

Along with scoring of answers to individual questions posed in the interviews, we have retained a number of quotes from interviewees that shed further light on the answers given, beyond what can be captured in scoring a response to a question. In this case, the words of the speaker are not captured exactly, since we have no recording or transcript of the interview, but the quotes are accurate enough to represent the intended meaning. To analyze the overall meaning of the collected quotes, we conducted an affinity grouping exercise, where the quotes were read through once to see what general categories emerged, and later grouped into three categories by affinity grouping. We retained 16 quotes for reference in the final report.

Some of the quotes illustrated the challenges that project teams face as they strive to bring SE to projects. For example:

> "We created a plan for systems level acceptance testing (SLAT) but did not follow through… SLAT won't happen because product engineering resource has been sucked into other activities …. resources are always being taken away for customer purposes."

This quote illustrates the quintessential 'catch-22' for systems engineering: if resources were made available to carry out the testing, the outcomes would likely rectify the problems, but because the stakeholders are not convinced to make SE a priority in this case, the resources are diverted elsewhere, and the problems in the project continue to fester.

Other quotes illustrate a more positive experience with using SE to make a difference in project performance. For example, for a project where the interviewee's role is that of project systems engineer and joins the project already in progress:

> "I came onto the project in midstream as a newly added systems engineer. When I started, I found the approach to testing to be unfocused and responded by introducing 'design for testability': A general test description would appear as soon as requirements were set out. I considered bringing focus to the testing process to be the job of the systems engineer. Technical people responsible for testing responded positively to the change: they could see its appeal right away."

In this instance, the effect of SE is to bring focus to a project and to help it perform better. At other times, SE helps stakeholders to recognize that a product under development is not viable:

> "The motivation for the project was based on an early value analysis, which showed potential value to customer, and value to Corning. But the early value analysis was a projection only - when, in the final more realistic value analysis, the actual value of the product was negative, management decided to shelve the project."

This quote shows how introducing SE can bring rigor to the market analysis and help the project management and its stakeholders to make the sometimes tough decision to terminate a project. This decision need not be seen as a negative; it is in fact consistent with what the Product Development Management Association calls a philosophy of "bring forward or kill early (PDMA, 2005)." In a cutting edge technology firm like Corning, it is necessary to try many diverse technology concepts – the successful firm is the one that can accurately and without great delay discern which ideas are the most promising.

To sum up, the extra effort of recording and grouping interviewee quotes yields the benefit of a more complete picture of the body of projects studied, beyond what can be captured in quantitative scoring of interview questions. Since the information on the quantitative side is gathered through extensive one-on-one interviews (as opposed to postal questionnaires) it is advantageous to explicitly include a discussion of quotes in presenting the results of the survey, rather than ignoring the anecdotes that interviewees convey because they are not quantitative.

Discussion

In the preceding two sections we have presented an interview methodology and shown how its application within Corning yielded evidence for the effect of SE on product development. Because of the benefits to the field of SE of reproducing this research within other enterprises, we make the following observations about the methodology here:

1. *The approach can be adapted to meet the needs of other firms:* we have presented in this paper a framework for how to create the interview research process, and not an exact set of questions that must be asked. Thus another enterprise, if it were to pursue this research internally, would have latitude to choose a different set of SE categories from the original list of eight, to suit their needs. They might also choose to study all eight, although with limited time and resources, it may be difficult to study each in sufficient detail to yield meaningful results. Having chosen categories, the enterprise is also free to create their own questions to be asked, rather than using questions that were posed within Corning.

2. *Repeat application in other firms will serve multiple purposes:* first, it will help other firms justify to themselves the value of using SE techniques in product development. It will also help them to tailor their own internal use of SE to their own needs, as the research will uncover which techniques have the most effect of project performance. Lastly, a body of research built up around these interviews will help make the case for the benefit of systems engineering across industry in various sectors.

3. *The structure of the interview process matters:* we found that having an NDA in place helped interviewees to talk openly about struggles as well as successes, and it was good to remind the interviewee of its existence at the beginning of each interview. The interviewer should make every effort to develop and maintain a good rapport, by making contact some days in advance of the interview, and by accepting during the

interview that some subjects may not be open to discussion even if there is an NDA in place. Also, it will inevitably not be possible to find all the documentation that the interviewee would like to present – in some cases, the information never comes to light, but in others it is good to have a mechanism in place to look at the information after the interview, to fill in missing pieces of information after the fact. Lastly, our experience indicated that having the outside, impartial team of academic researchers helped to establish rapport. Although the Corning team assisted with the analysis of the results, the interviews were conducted by team members solely from Cornell. Use of in-house staff to conduct the interviews might raise concerns in the interviewee's mind that the interviewer may have connections in the organization that will limit the ability to answer questions candidly, for fear of repercussions later.

4. *The interview approach has advantages, but other methods may also work:* the choice of a time- and data-intensive approach to data gathering about projects, compared to, e.g., a mailed questionnaire, leads to large amounts of high quality information available about each project included. However, the interview approach necessarily limits the work that can be completed in a finite amount of time due to the need to find time for interviews for both interviewer and interviewee. It may well be possible to gather interesting results on the use of SE in the commercial world through a larger number of shorter answers to a mailing.

The next steps for the research presented in this paper are to find other enterprises who can repeat the interview process elsewhere. Also, since many of the projects interviewed were ongoing, it would be beneficial to check with the projects in 24 to 36 months to see how they had fared in the marketplace, so as to see whether the most promising projects according to our interviews were also the ones that had fared the best in the marketplace.

Conclusion

This paper reports on interview research conducted on the effectiveness of SE techniques in improving project performance in new product development. We conclude that, based on the interviews included in this study, 1) projects varied in amount of SE input and 2) improved project performance was correlated with increased SE content. Based on our research, our recommendations include: 1) making the methodology available to other commercial firms so that they can study their use of SE techniques and 2) building a stronger quantitative, empirical case for SE through repeated application across multiple firms.

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Matthew Whiting: Matt has been with Corning Incorporated for 26 years and is a Senior Systems Engineer and Technical Lead in the Systems Engineering & Program Management directorate in Corning's Science & Technology division. Prior to his current assignment, Matt held a number of engineering, project management and functional management positions in Corning's Corporate Engineering and Science & Technology divisions, with primary responsibility in the areas of controls, software engineering and electronics. Matt holds BSCS, BSEE and MCE/Structural Engineering degrees. In his current role, he is responsible for the technical leadership and systems engineering of an early stage research project involving RFID technology. This project involves technologies that are complex themselves, but will yield products that will be a key component of an even larger customer system. Matt is a member of several professional societies including INCOSE (where he is Past President of the Finger Lakes Chapter), IEEE, ACM, and NSPE. He is author or co-author of 15 invention disclosures, co-inventor on 8 patent applications and holder of two patents. Matt is a licensed professional engineer in NY and PA and when not working enjoys flying, motorcycling, camping, shooting and other outdoor pursuits.

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