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Corning-Cornell Project to Evaluate Effectiveness of Systems Engineering Techniques: Results from a Literature Review and Interview Research

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July 7, 2009

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Executive Summary

This report summarizes findings from a three-year study conducted by the Systems Engineering Directorate at Corning, Incorporated, and the Systems Engineering Program at Cornell University, on the subject of Systems Engineering, or SE, as applied in commercial companies, versus those that traditionally serve military/aerospace customers. In the field of SE, it has become almost a cliché to say that "the value of SE is understood by systems engineers, even without needing to quantitatively prove its benefits." Our goal, therefore, has been to better validate this belief in SE, and also understand in more detail the connection between SE and project/program performance, for example to learn what SE techniques are effective in what situations.

In the first phase of the study, documented in Chapter 2, 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. Our research unearthed a total of eight instances where SE was documented to have contributed to improved product development success, in fields ranging from aerospace to automotive. Some of these were case studies of individual projects, and others were surveys of multiple projects. However, we did not encounter any documented studies of the effectiveness of SE in the commercial world that provided a methodology for studying the use of multiple SE techniques across multiple projects, nor evidence quantifying the benefits of SE in the commercial world.

We therefore created our own methodology (Chapter 3) and implemented within Corning (Chapters 4 and 5). The methodology is first presented in a generic form, that might be adapted to a wide range of technically-oriented enterprises including both original equipment manufacturers (a.k.a. OEMs, such as electronics or automotive makers) and keystone technology development enterprises like Corning. The generic methodology features the choice of SE areas from a list of eight possible areas, the development of questions about SE inputs and performance outputs to be applied to each project studied, evaluation of the extent of correlation between SE and performance, and the gathering of key interviewee quotes to accompany scoring of answers to interview questions.

After adapting the methodology to Corning's situation, we were able to conduct 19 usable interviews between April 2008 and March 2009 from which to gather data on SE and performance. The level of development in the stage gate process, scores for areas of SE input, and performance evaluation are shown in Table E-1. In the table, the four columns marked "mkt", "req", "verify", and "trade" represent four areas of SE input chosen for study in the project, namely market analysis, requirements analysis, verification & validation, and tradeoff analysis, respectively.

Num	Stage	Scores				Perf
		Mkt	Req	Verif	Trade	Overall	
1	III	100%	67%	67%	25%	64%	++
2	III	100%	67%	100%	0%	50%	OK
3	II	100%	67%	17%	50%	57%	OK
5	II	75%	83%	0%	62%	57%	OK
6	I	50%	33%	83%	62%	57%	OK
7	IV	87%	83%	0%	62%	61%	--
8	IV	87%	33%	33%	12%	36%	--
9	III	100%	50%	67%	75%	79%	++
10	III	50%	67%	67%	0%	43%	OK
11	II	50%	33%	100%	50%	57%	--
12	II	33%	37%	67%	62%	50%	OK
13	I	87%	67%	0%	50%	54%	OK
14	I	37%	100%	50%	75%	64%	OK
15	III	62%	33%	25%	75%	50%	OK
16	I	100%	83%	67%	75%	82%	OK
17	IV	100%	67%	100%	100%	93%	++
18	III	50%	50%	67%	50%	55%	OK
19	II	75%	67%	50%	0%	40%	OK
20	I	83%	33%	50%	37%	50%	OK

Table E-1. Summary results for individual projects, including development stage, individual and combined SE input scores, and project performance. Note: Due to scoring method, overall score does not equal arithmetic average of four areas. Performance code: "++" for superior, "OK" for satisfactory, "—" for struggling. Interview #4 does not appear in the table because it did not provide sufficient usable data.

Our first finding from the project is that a survey of randomly chosen 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 E-1. Even in a situation where many survey respondents did not use SE terminology to describe their approach to managing the project, they were found to be using SE, and some more than others. For example, the respondent 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.

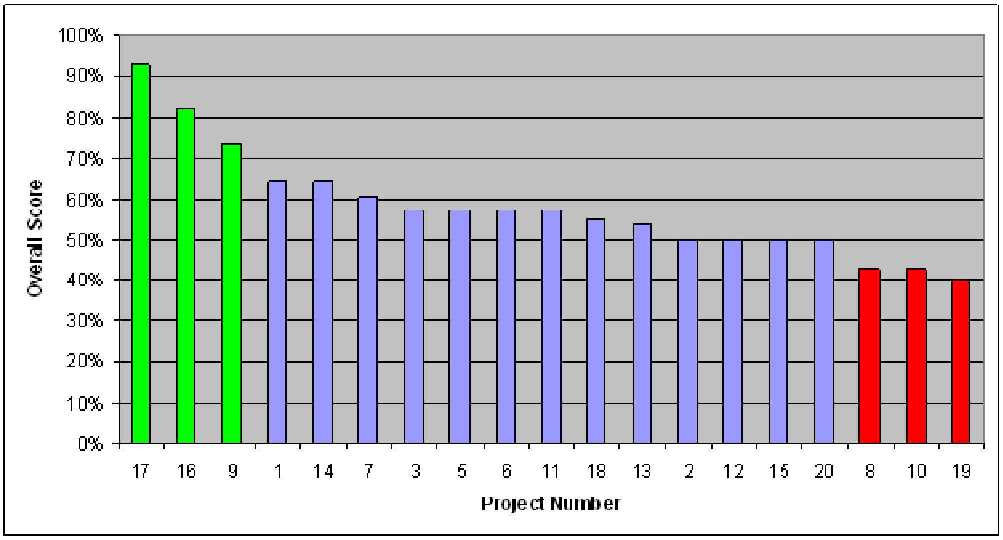


Figure E-1. Projects ranked in order of decreasing overall SE input score, with green, blue, and red bars to indicate higher, medium, or lower SE input, respectively. Mean and standard deviation = 58%, 13%, resp. Higher SE input = 1 S.D. above mean, lower SE input = 1 S.D. below mean.

The variability in amount of SE input provided an opportunity to see whether varying levels of SE had an effect on project performance. Since none of the projects interviewed were for products whose success in the marketplace was known, it was not possible to quantitatively evaluate project performance, so instead we use a qualitative scoring system, and found 3 projects to be "superior", 3 to be "struggling", and the rest "satisfactory", as shown above in Table E-1.

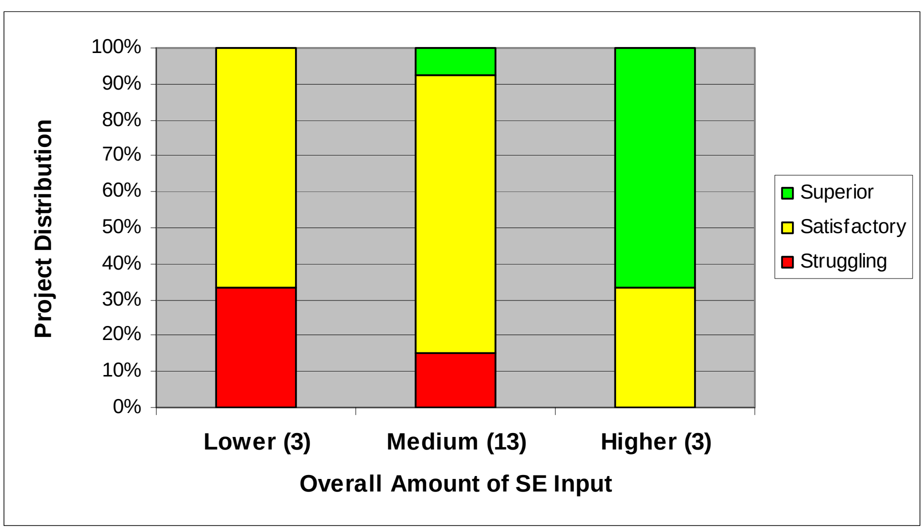


Figure E-2. Project performance as a function of overall SE input, for lower, medium, and higher SE input projects. Note: number in parenthesis shows how many projects fell into the category bar, e.g., 3 projects in the "lower SE input" category, etc.

When the answers to questions were analyzed, a correlation was found to exist between SE input and performance, supporting the hypothesis that SE is effective in improving project outcome. This correlation can be documented in both a graphical and case study form, as presented in Chapter 5. First, in a graphical form, as shown in Figure E-2, struggling projects all had lower or medium SE input, while superior projects all had medium or higher input. In terms of specific SE input areas, market analysis, requirements engineering, and (where applicable) verification/validation were found to be especially important.

Secondly, in case study form, the experience of specific projects can be used to validate the correlation between SE input and project performance. The three projects judged to have "superior" performance featured accelerated advancement through the Stage Gate process, excellent feedback from customers and prospective customers, and rapid growth in customer base as the product developed. These three projects also averaged an overall score of 80% for SE input, compared to the 58% average across all projects. Conversely, three projects judged to have "struggling" performance in each instance had gaps in SE input that contributed directly to their shortcomings. In one project, lack of a clear market analysis and value proposition prevented the project from moving forward through the Stage Gate process. In the second one, lack of clear translation of the value proposition into core requirements allowed the product to neglect characteristics that were critical to the customer, leading to a re-working of the product development that was costly in both time and financial resource. In the third project, problems with connecting the value proposition to project requirements or to translating requirements into a test plan and schedule led to lack of clear understanding between the project team, internal Corning stakeholders, and customers about the timing of the project and achievement of technical development milestones.

To summarize, 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. The strength of this finding for SE generally can be improved, for example by repeating this type of analysis in other firms and/or for additional projects. The recommendations in Chapter 6 include some practical suggestions for improving project performance. Among others, the recommendations include: 1) making up-to-date versions of the market analysis, value proposition, and key project requirements easily accessible at all times to the product development team in a standardized form and 2) retaining historical data from projects to enable retrospective and longitudinal analysis of project performance.

Acknowledgment

The authors of the report wish to acknowledge the assistance of support staff who helped make this project possible, including Amy MacDougall from the Systems Engineering Directorate at Corning, Incorporated, and Anitra Douglas, Michelle Dean, and Jonathan Froehlich of the Systems Engineering Program at Cornell University for their logistical support for the research project. They also wish to thank Professors Al George, Linda Nozick, and Frank Wayno for their input into the project. Lastly, they wish to thank Corning and the Cornell University Systems Engineering Program for financial support for the project. While this support is gratefully acknowledged, responsibility for any and all errors rests with the authors.

Chapter 1. Introduction

In the field of Systems Engineering (hereafter SE for short), it has become almost a cliché to say that "the value of SE is understood by systems engineers, even without needing to quantitatively prove its benefits." SE as a practice is widely used across many different industries (aerospace, automotive, and so on), and many individual enterprises have adopted a systems engineering standard, incorporated a systems engineering unit into their corporate structure, or both. This state of affairs is in itself a testament to the confidence that engineers have in the value of SE. However, more can be done to understand this benefit, which provides motivation for the research presented in this report.

The particular type of SE that is of interest in our research is what Sheard [2000] calls "Approach" SE, as opposed to "Discovery" or "Program" SE. The three types can be defined as follows:

1. "Discovery": the application of SE to cutting edge problems of great scientific complexity, such as the development of certain new aerospace applications not previously in existence.
2. "Program": the application of the complete SE package to mature but complex systems problems, such as the development of a new airframe for the commercial aircraft market
3. "Approach": the application of individual SE techniques to a wide range of fields in order to improve product development performance or economics, such as the application of requirements engineering or design for testability to improving the development of electronics, automotive products, etc.

In general, if one divides the creative process into three domains of "purpose", "product", and "process" [Corson, 2009], one could say that while all three types of SE serve the purpose of achieving a superior outcome, types 1 and 2 focus on the "product", while type 3 focuses on the "process."

The SE field is also an evolving one, and the adoption of SE techniques can be seen as transformational for enterprises that seek to bring SE to bear on new product development. Tichy [1983] identifies three dimensions within the strategic change process, namely technical, political, and cultural. While the focus of this report is primarily on technical dynamics within the organization, the effect of political and cultural dynamics on the evolution of new product development is important as well, and should not be overlooked.

Along with the definition of different types of SE, other terminology used in this report include "enterprise" to mean the firm whose use of SE is being researched; "investigator" to mean the researcher responsible for studying the use of SE; "interviewer" to mean the person meeting with representatives of a product development team to discuss their practices (the interviewer is often the same as the investigator); "interviewee" to mean the person or persons interacting with the interviewer; and "project manager" to be the person in a position of management within the product development project, whether or not they hold that exact title. Other terms used in the report are thought to comply with standard technical usage.

The components of the project consist of two main phases:

1. Examination of the use of SE in industry, and especially in the commercial (as opposed to government contracting) world, through a literature review, and
2. Examination of the use of SE within Corning incorporated, through on-site interviewing of Corning project managers and systems engineers on location in Corning, NY.

The project spanned the period from approximately 2006 to 2009. It was initiated by Dr. Richard Grzybowski, head of the Systems Engineering Directorate at Corning, who approached the Systems Engineering Program at Cornell University about undertaking the research to benefit both Corning and other members of the International Council on Systems Engineering (INCOSE).

Some of the major milestones in the evolution of the project are the following:

- June 2006: official launch of the project
- June 2006 – March 2007: literature review and drafting of literature review for publication
- April 2007: presentation on literature review findings at Cornell SE Day 2007
- May 2007: draft of literature review submitted for publication
- June 2007 – March 2008: development of research approach for studying use of SE within Corning
- January 2008: literature review accepted for publication in INCOSE journal
- April 2008: feedback session on draft guidelines for conducting research at Corning, presented at Cornell SE Day 2008
- April 2008 – March 2009: interviews at Corning
- January 2009: Presentation on interview research component of study to Finger Lakes Chapter of INCOSE
- April 2009: Presentation of preliminary findings at Cornell SE Day 2009
- May 2009: Draft final report and project closeout meeting

A detailed timeline can be found in Appendix A.

The rest of this report consists of the following parts. Chapter 2 provides the background and findings from the literature review. Chapter 3 presents the methodology for carrying out the research in general terms, not specific to the application to Corning. Chapter 4 discusses the ways in which the approach was adapted to the specific case of Corning, and provides background on the types of projects that were included among the field of projects interviewed. Chapter 5 presents the findings from application of the methodology to Corning, including the extent to which a correlation was found between use of SE and project performance, as well as caveats and limitations. Lastly, Chapter 6 presents recommendations based on the analysis, and suggestions for future research. Several appendices, a list of references, and a bibliography are attached as well.

Chapter 2. Literature review

As mentioned in the introduction, the first phase of the project was the literature review to look for evidence of the effectiveness of SE, and of studies that had investigated the use of SE, especially within commercially-oriented firms. The results are presented in this chapter, which also appeared in *Systems Engineering* in a slightly modified form (Vanek, Jackson, and Grzybowski, 2008).

The goals of this literature review are as follows:

1. To summarize studies of the impact of Systems Engineering (SE) on development efforts, with a particular emphasis on two key areas:
    a. The use of SE techniques in a range of commercial R&D and early stage engineering environments; and
    b. Metrics on SE activities and project performance.
2. To identify "best practice" implementations of SE in industry.

Previously published reviews most closely related to the topic are those of Brady and Allen (2006) on Six Sigma, and of Sousa and Voss (2002) on Quality Management. These are discussed in section 6, below.

Scope

As described above, the goal of our research is to study the application of SE in a variety of commercial R&D environments. Our specific focus is on commercial product development and early stage engineering, including not only materials products as in the case of Corning, Incorporated but also other commercial products such as automobiles or consumer electronics. In general, military and aerospace applications are excluded, since this type of R&D occurs in an environment that is significantly different from that of the development of products and materials for competitive sale in the open market. Exceptions are made where such applications are relevant. We also exclude the following SE applications:

1. SE applied to the improvement of industrial process, e.g., SE applied to the reduction of errors and improvement of quality on an assembly line (e.g., Ehie and Sheu, 2005).
2. SE applied purely to the solution of product design problems, not incorporating the relationship between product design and the product development process (e.g., Ashdown, 2007).
3. SE applied to the mathematical modeling of the product development process, in which the individuals or groups within the organization are treated as entities in the model, and their interactions are modeled using mathematical equations or flowchart diagrams (e.g., Koffi, 2005).

Also, all three types of SE are of interest to this literature review, since the core competence of the company is the solution of cutting edge scientific problems and converting new knowledge into successful products ("Discovery" and "Program"), while the individual SE techniques are applicable to improving performance and economics of the product development process ("Approach"). Therefore, the scope of the literature review cuts across all three fields.

Another possible categorization of reported findings is to distinguish between studies that are 1) formal experiments, in which the authors exert tight control over the conditions of the study in order to isolate the effects of key variables, 2) case studies, or studies of a single situation not structured as a scientific experiment, and 3) surveys, which are reviews of multiple case studies or experiments in order to extract general results (see Kitchenham et al, 1994). There are no papers that can be classified as formal experiments. Indeed, Kitchenham et al note that some publications on "experiments" in software PD were not true experiments, since they did not meet the criteria for isolating independent variables. Both Sheard and Miller (2000) and Frantz (1995) point to the difficulty of setting up a true scientific experiment to test the effect of applying SE. Therefore, our review considers case studies almost exclusively, with occasional reference to surveys, particularly literature reviews of subjects related to SE.

Methodology

Cooper (1989) advocates a "scientific" approach to designing and executing a literature review, in which at every step the researcher uses the scientific method as a guide, as opposed to an "intuitive" approach, in which the researcher uses her/his own judgment as the basis for selecting sources to be included in the review, the way in which to organize the presentation within the written review, and so on. We have adopted Cooper's approach in selecting sources for inclusion, and required that, in order to qualify for this review, the source must answer at least one of the following questions in the affirmative:

1) Does it describe or advance the practice of implementing SE metrics, or a related practice such as Design for Six Sigma (DFSS)?
2) Does it evaluate the use of SE metrics in an enterprise?
3) Does it evaluate some other aspect of SE practice that contributes to our understanding of how to implement SE metrics at Corning?
4) Is it a case study of SE best practice that is relevant to the Corning project?
5) Is it a case study of best practice not called SE but resembling SE in implementation, such that it is relevant to the Corning project?

Some comments are in order on the five criteria above. "Best practice," as stated in point 5, can include papers on organizational change, since effective SE implementation depends on the flexibility and adaptability of the organization. Also, under point 2, the type of enterprise is taken to be commercial, unless an exception is made.

SE metrics and best practice: Purpose and evidence of effect

The underlying purpose of the application of SE to product development is, simply stated, to improve the outcome. Honour et al (2004, p.3) state that the promise of SE is "to provide better systems in less time and cost with less risk." According to Frantz (1995), "Systems Design" can be contrasted with "Unit Design": a unit design looks at the most critical entity and assumes that all other entities will fall into place, whereas systems design considers interaction between major entities.

One means of using SE in product design or development is the use of metrics. The purpose of SE metrics in the product development process is to identify or create a quantitative measure based on SE theory or practice that indicates that the process is moving toward a successful outcome. Use of SE metrics implies that the firm is taking a "systems design" approach to product development. In addition, the application of SE need not be limited to technical objectives, as social objectives play an important role in overall project success, and technical excellence cannot save a socially unacceptable project (Miller, 2000).

Steps in the SE process

Whether or not the product development process is called "systems engineering", the systems engineering method can be recognized from the techniques employed. A partial list of SE steps includes the following:

- Customer, market, and context analysis
- Elucidation of testable requirements
- A life-cycle view of the system
- Translation of customer objectives to technical performance measures ("requirements analysis" / "requirements engineering")
- Development of modular architectures with clearly defined interfaces
- Consideration of the systems context and the relationship between the product and its environment
- Extensive tradeoff and optimization analyses ('trade studies")
- Development of test plans in advance of the development of designs
- Systematic exploration of the design space, using a design matrix or other technique
- Flow-down of requirements to sub-system and component design
- Design reviews by multiple stakeholders
- Detailed mapping and simulation of system behavior and reliability
- Creation of build and test plans with priorities and contingencies

Individual organizations may adapt these generic SE steps to their own circumstances, or add others. Product success cannot always be traced to the use of these techniques but product failure can usually be traced to their absence. Interested readers are referred to INCOSE (2006) for more information about the SE process.

Evidence of effectiveness of SE metrics and best practice

Evidence of the effectiveness of SE can often be difficult to obtain, due both to the challenges involved in isolating the effects of SE practice from other effects in a product development process, as well as the limitations on what information about a project can be published. Nevertheless, the following instances of SE success have been gathered since the 1990s (in chronological order):

1. Gruhl (1992, as quoted in Honour, 2004, p.10): This study of 32 major NASA projects showed that reduced cost overrun (measured in percent) was correlated with increased upfront spending on project definition (measured in percent of total budget). The optimum benefit was found to occur with percent of effort values between 5 and 10%; above 10%, benefits of additional spending on project definition were not shown.
2. Frantz (1995): Study of the development of three Universal Holding Fixtures (a.k.a. UHFs, equipment for holding complex aerospace components for precise machining, assembly, or other types of treatment) which took place at approximately the same time in the Boeing organization. UHF2 and UHF3 projects, which used SE best practices, were completed more quickly than UHF1, which did not use SE. This outcome was in spite of UHF2 and UHF3 being more complex devices. This case study is reviewed in greater depth below.
3. Malek (1995): study of automobile prototype development, which reports the delivery "in record time" of Dodge Neon, Ford Mustang, and Lincoln Continental prototypes by creating a close relationship between the OEM (Original Equipment Manufacturer) development team and the supplier company engineers. Such an approach requires increased communications effort between OEM and supplier (e.g., through co-located engineering teams) but improves the outcome by making both perspectives fully available early in the development cycle.
4. Miller et al (2000, as quoted in Honour et al, 2004): a study of 60 infrastructure projects found that the most important factor contributing to success was the presence of a coherent leadership structure.
5. Honour et al (2004): Study carried out by the Systems Engineering Center of Excellence (SECOE) of INCOSE of 44 projects of member organization found that for both minimizing cost and schedule overruns, allocating 15% of total effort to SEE (Systems Engineering Effort) was optimal. The results are similar to those of Gruhl (1992) in point 1 above.
6. Loureiro et al (2004): Comparison of two power train control systems (PCS) within the Ford Motor organization, one gasoline-powered and the other diesel-powered. The diesel-powered system was developed using SE techniques and required about half of the time and half of the resource of the gasoline system.
7. Kludze (2004, as quoted in Honour et al, 2004)): A survey of 379 valid responses from 900 forms sent out gave the result that those surveyed felt that the impact of SE on project cost was good to excellent. Respondents included members of INCOSE (64%) and those within NASA (36%). Although both members looked favorably on the effect of SE on cost, INCOSE members were more positive than NASA respondents.

8. Research & Technology Executive Council (RTEC) (2006): Conclusion #5 of six key conclusions for this survey of the RTEC membership finds that "high performing RD&E organizations tend to use more RD&E metrics than low performers to support RD&E decision making."

Based on these eight examples, two points will be discussed here. The first point is in regard to SE Effort, as studied in Gruhl (1992). One measure of effective use of SE is to allocate an adequate fraction of total technical effort on a project toward "SE Effort" and to ascertain that value of the ratio SE Effort/Total Technical Effort is in line with the range of historical optimal values. SE Effort and Total Effort are typically measured in the estimated number of person-hours allocated to SE, versus the total number of hours worked, respectively, over the lifetime of the project.

The amount of SE effort in the ratio of (SE Effort / Total Effort) might also be adjusted by the "quality" of the SE effort, so that higher quality SE effort hours count more heavily (Honour et al, 2004). In practice, this can be accomplished as shown in Figure 1, where a project with 0% SE Effort (intersection of lower curve with "y" axis) is still able to achieve some value. Also, at very low percentages of SE effort, the quality of the SE effort will be poor, so that its effect on overall value is negligible. However, as percent SE effort is added, its quality increases so that expected value rises, as shown by the thick curve, toward some upper bound on achievable value. Finally, once SE effort exceeds some optimal range (Gruhl's study suggests a value of approximately 10%), SE effort no longer adds to overall expected value, even at 100% quality, so that the maximum expected value declines towards 0 as SE effort increases towards 100%.

The second point is in regard to the contribution of different SE techniques to the overall improvement in the development process. Of all the papers reviewed, the paper by Frantz provides the most detail about this question, so we study it in greater depth here.

The comparison of UHF1 – UHF3 in this study is broken down into nine steps where SE techniques might or might not be applied. Highlights of this comparison are shown in Table 1.

Project Trait	UHF* 1	UHF 2 & UHF 3
Overall use of SE techniques	Not used significantly	Used significantly
Role of SE in relationship with project subcontractor	No significant role. Periodic design reviews.	Full-time systems engineer on site of major subcontractor
SE approach for requirements	Not significant	Complete, detailed, integrated requirements, written by multi-organizational team of customers
SE approach to design	Hardware and software specifications. Processes and interfaces not included.	Functional specifications driven by requirements specification. Specifications address hardware, software, processes, and interfaces
Unit/integration test approach	Based on design. Not a priority during early project life cycle	Based on functional specifications. Designed early in project life cycle.
Systems acceptance test approach	Tests defined in high-level project plan. Not as detailed as SE approach.	Tests defined directly from requirements specification acceptance criteria and functional specifications
Overall effect of SE, as reflected in time requirements for stages of projects.	Total duration 104 weeks. Time from design to production ready 52 weeks. Integration test 16 weeks.	Total duration 36 to 48 weeks. From design to production ready 20 to 30 weeks. Integration test 10 weeks.

UHF = Universal Holding Fixture. See text.

Table 1 Comparison of SE content of three comparable projects at Boeing as reported in Frantz (1995).

As an example of different techniques, in the SE case, engineers developed well-defined test specifications directly from acceptance criteria and functional specifications, and the test were developed in detail early in the product development cycle,. This is different from the non-SE case, in which test plans were developed initially only at a high level. The bottom line is that the UHF 2 and UHF3 projects finished much more quickly thanks to shorter time from design to production, and shorter testing time.

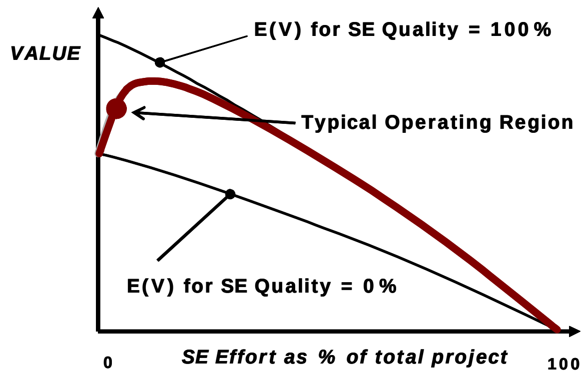


Figure 1 Effect of SE quality on the value of SE effort to project outcome.
Source: Honour et al (2004), p.9.

Available sets of metrics and processes for choosing systems of metrics

The preceding section focused on the effectiveness of SE generally. In this section, we focus specifically on SE metrics. First, we give a brief history of the emergence of SE metrics as they relate to the growth of the SE field in general. We then present available sets of metrics from the literature, and ways of choosing metrics for a project. A complete review of available SE standards appears in Honour and Valerdi (2006).

The history of the use of metrics in SE dates back nearly to the emergence of the field itself in the post-WWII era. Although no clear date for this beginning exists in the literature, two early milestones were the publication of *Systems engineering: an introduction to the design of large-scale systems* by Goode and Machol (1957), and of *A Methodology for Systems Engineering* by Hall (1962). A list of fundamental business measures from the General Electric organization around this time reflects an early interest in organization-wide issues beyond purely financial measures (Eccles, 1991). GE's list of six measures includes profitability, market share, productivity, employee attitudes, public responsibility, and balance between short and long-term goals.

Early peer-review papers also reflect an interest in using metrics to validate the pursuit of SE. For example, Jenkins (1969) identifies "information and data collection" as a key stage in the application of SE, in which the practitioner asks, "have all important persons and sources of data been interrogated? Has all relevant data been assembled and presented in the best way?" He further identifies six cost elements in the design of a system, namely performance, operation, capital expenditure, design, unreliability, and delay to build, noting that these objectives compete with one another and the practitioner must make tradeoffs between them. Among these six, the last three are particularly noteworthy as contributions of the SE field, in that the contribution of increased expenditure on design can reduce operating and unreliability costs, or capital costs as in the case studies of Gruhl or Honour et al presented above.

A final milestone in the evolution of SE metrics is the increased interest in broader, non-financial measures not just in systems engineering circles but also in enterprise generally since the early 1990s. Eccles' (1991) publication of "the performance measurement manifesto" signaled a significant expansion of corporate interest in non-financial measures, already evidenced by the GE measures of the 1950s. There is at present an awareness, especially among large organizations, and firms that either develop complex systems or are involved in the delivery of high-technology products and services, that in order to deliver desired broad financial results, it is necessary to focus on non-financial internal operational needs (e.g., Johnson and Kaplan, 1987, as quoted in Mahidhar, 2005).

The following terms are relevant to the subsequent discussion.

According to Kitterman (2005), *measurement* is the process of assigning numerical values to attributes. A "measure" is therefore the quantified value of an attribute. A *metric* is distinct from a measure in that it is a measure compared to what is expected.

Mahidhar (2005) defines a *performance measure* as a verifiable variable that is either quantitative or qualititative. All measures taken for quantifying SE metrics are performance measures, but not all performance measures fall within SE. For example, there are a number of performance measures familiar to most business decision-makers (e.g., sales per square foot of retail space in retailing) that are not SE metrics.

The following three dimensions can characterize performance measures such as SE metrics:

1. *Type*: financial versus non-financial. Any metric that does not use monetary value in some way is a non-financial metric. The growing interest in non-financial measures relative to financial measures is discussed above. Most SE metrics are non-financial.
2. *Tense*: lagging versus leading. A lagging metric compares the outcome of a project, once completed, to the expected outcome, or to previous similar projects. It is thus used to evaluate a project ex post facto. A leading indicator compares the current status of a project while it is underway to the level expected at that point, and is used to make both short- and long-term adjustments to the trajectory of the project.
3. *Focus*: internal versus external. An internal metric looks at measures inside of the firm to evaluate performance (e.g., percent overrun on budget or schedule), whereas an external metric looks at competitors or the overall market, outside of the firm (e.g., market share).

See Mahidhar (2005, pp.68-69) for further discussion. In addition, Loureiro et al (2004) posit that there are three areas to apply measurement: product (What is it?), process (How do we make it?), and organization (Who controls what part of the process?).

Characteristics of effective SE metrics

INCOSE (1998) gives seven attributes of effective metrics: relevance, completeness, timeliness, simplicity, cost-effectiveness, repeatability, and accuracy. These attributes resemble Garvin's (1984) eight dimensions of quality: performance, features, reliability, conformance, durability, serviceability, aesthetics, and perceived quality. DFSS also incorporates a list of five attributes for successful programs using the acronym "SMART": Specific, Measurable, Achievable, Relevant and Time-bound. Johnston et al (2002) further state that some characteristics common to successful users of performance measurement include 1) measures are simple and clear; 2) measures drive action; and 3) measurement doesn't get in the way of action.

In this section we present representative systems of SE metrics from the literature. The first, the set of 13 Leading Indicators from the Lean Aerospace Initiative (LAI), represent the efforts of an industry consortium, assisted by INCOSE. Subsequent examples are from individual firms.

LAI/INCOSE Leading Indicators

The following indicators have been published by Roedler et al (2007), on behalf of LAI's SE Leading Indicators team:

1. Requirements trends: rate of maturity of system definition against plan
2. System definition change backlog trends: degree of backlog in system definition changes
3. Interface trends: interface specification closure against plan
4. Requirements validation trends: progress in assuring customer that requirements are valid and understood against plan
5. Requirements verification trends: verification that design meets requirements against plan.
6. Work product approval trends: acceptable rate of internal and external approval of documentation during design process
7. Review action closure trends: Responsiveness of organization to carry out post-review actions
8. Risk exposure trends: evaluation of effectiveness of risk management and mitigation process against target.
9. Risk handling trends: evaluation of effectiveness of organization in implementing risk mitigation activities against target.
10. Technology maturity trends: evaluation of ability to avoid adoption of immature technology or to replace aging technology in a timely fashion.
11. Technical measurement trends: Progress toward meeting quantitative measures of technical progress, including Measures of Effectiveness (MOEs), Measures of Performance (MOPs), Key Performance Parameters (KPPs), and Technical Performance Measures (TPMs).
12. Systems Engineering Staffing & Skills Trends: evaluation of ability of organization to apply SE based on quantity of SE personnel assigned, skill and

seniority of personnel, and extent of involvement at different phases of project/program life cycle.

13. Process compliance trends: evaluation of quality and consistency of project-defined SE process.

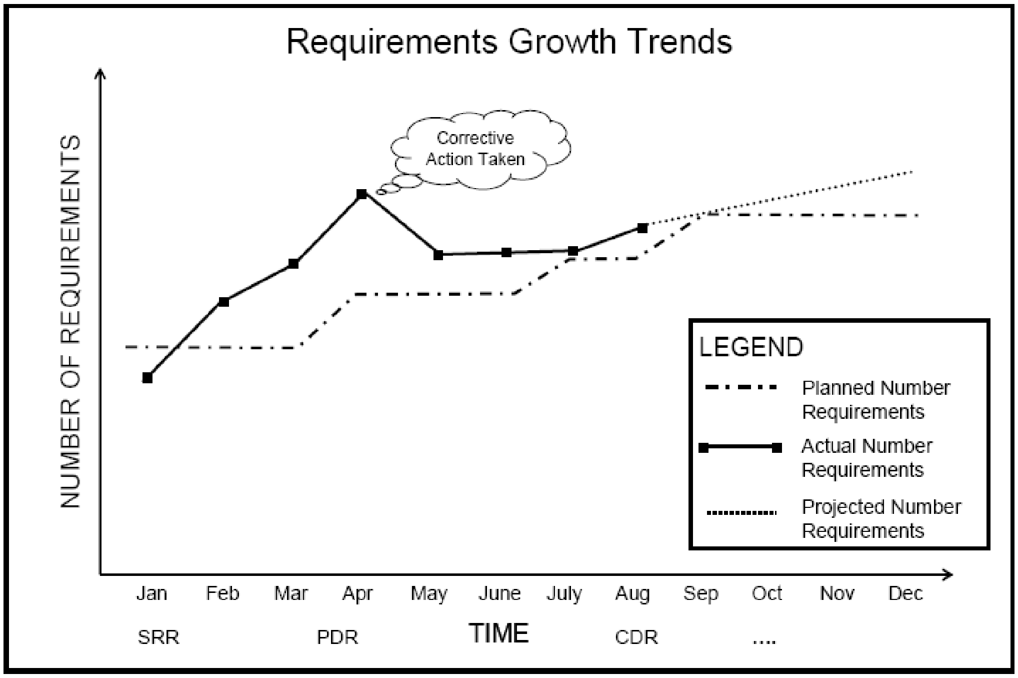


Figure 2 Application of "requirements growth trend" leading indicator during runtime of PD project, showing initial growth, overshoot relative to planned number of requirements, and effect of corrective action
Source: Roedler et al (2007), p.10.

To illustrate the application of these indicators, LAI's explanation of indicator #1, "requirements trends", is summarized here, as shown in Figure 2. The purpose of the indicator is to track the number of requirements generated by the project against a predicted number that is stipulated at the project's inception. Thus, for each phase of the project life cycle (e.g., LAI uses "concept refinement" – "technology development" – "system development & demonstration" – "production & deployment" – "operations & support"), a predicted number of requirements is set out, which will typically increase as the project advances. The project systems engineer then tracks the actual number of requirements against the predicted number. If the actual number grows more rapidly than predicted, the systems engineer in conjunction with project management takes corrective action and verifies that the number of requirements realigns with the target.

LAI'S five product development stages are particularly suitable for aerospace projects, but they are similar to the steps in commercial product development. For example, Whitaker (2005) uses the following five steps: 1) identify needs, 2) system-level design, 3) detail design, 4) testing and refinement, 5) production ramp-up.

Other systems of metrics

In addition to the leading indictors presented above, a number of enterprises have published their own internal systems of metrics. These systems typically have a smaller number of indicators and incorporate both leading and lagging indicators. The following sets are representative:

- *Boeing* (Elston, 1995): the Boeing SE metrics program has three objectives, namely to assess the health of the project, to look for process improvement opportunities, and to create a company-wide database for planning and estimating purposes. The actual SE metrics include seven points: 1) system specification requirements allocated, 2) system specification requirements To Be Developed (TBD), 3) requirements stability, 4) requirements volatility, 5) external interfaces defined and approved, 6) external interface definition TBDs, and 7) domain experience of engineering staff.
- *GTE* (Ross, 1995): GTE divides its system of metrics into three types: trends, completion, and earned value. Trends metrics are based on a factual number. Completion metrics are based on the completion of a specific activity. Earned value metrics are based on an estimate of the portion of the task completed. All three types are present in their overall system of nine metrics: 1) system design tasks versus time, 2) planned versus actual number of personnel, 3) Technical Performance Measure (TPM) requirements versus present estimate, 4) planned versus actual cost in hours, 5) planned versus actual test plan objectives, 6) planned versus actual test procedures, 7) systems integration tests versus time, 8) planned versus actual formal test procedures attempted/completed, and 9) Engineering Action Report and Program Trouble Report total number opened versus closed.
- *IBM* (Rhodes, 1995): IBM metrics are designed to address four objectives, namely productivity, quality, process compliance, and customer satisfaction. Five metrics are used to assess progress towards these goals: 1) Product requirements productivity, 2) product page productivity, 3) product defects, 4) compliance to product standards, and 5) customer satisfaction with product.

The examples of Boeing, GTE, and IBM, are only three among many firms that have adopted a standard for the application of SE. For example, Honour and Valerdi (2006) report on such systems within BAE Systems, General Dynamics, Lockheed Martin, Northrop Grumman, Raytheon, and SAIC.

Discussion of metrics

A comparison of the four systems of metrics above suggests two points. First, the metrics share many common characteristics. For example, progress in generating and meeting requirements is often used as an indicator of progress toward the overall goal of successfully completing the project. Also, in three out of four (LAI, Boeing, GTE) the presence and level of experience of SE staff is used as an indicator of the extent of application of SE within the project. The second point is that all systems of metrics are subject to adaptation to fit the purposes of the specific firm wishing to implement them.

In the case of the three business-specific systems, the three firms in question have each created a somewhat different set of metrics that fits their own circumstances. Similarly, the LAI system is not intended to be implemented exactly in its presented form to enterprises wishing to apply SE metrics, but rather, "government and industry organizations are encouraged to tailor the information…for their purposes (p.3)." Thus some metrics might not be used at all, and others might be modified to fit individual circumstances.

Guidelines for choosing metrics

INCOSE (1998, p.10) recommends two possible methods for choosing metrics, namely the practical systems measurement approach (PSM), and goal/question/metric approach (GQM).

In the PSM approach, the practitioner first identifies candidate measures from a number of possible sources, including the Practical Software Measurement guidebook, the INCOSE guidebook, published standards for system development, or textbook sources. Next, the practitioner identifies selection criteria, which may include some or all of the following six measures, as well as others:

1. Effectiveness of measure to provide desired insight
2. Applicability of measure to project's domain
3. Compatibility of measure with current management practice
4. Cost and availability of data to support the measure
5. Applicability of measure to particular project life cycle phase
6. Degree to which measure addresses external measurement requirements

Finally, the measures that are chosen are those that best meet the criteria.

In the GQM approach, the practitioner uses four basic steps to identify measures, as follows (See Figure 3):

1. State the information *goal*: Determine what stakeholders want to know and what they intend to do with the information, including both organizational and project goals.
2. Ask the *question*: Determine what question should be asked in order to decide whether the goal from step 1 is being met.
3. Determine the *measure*: Identify measures that can be used to answer the question from step 2, and either gather information necessary for these measures directly from the project, or gather the information needed to calculate the measure, as appropriate.
4. Do and evaluate: apply measures selected in step 3, evaluate their usefulness, and return to steps 1 or 2 if the measures are found to be inadequate.

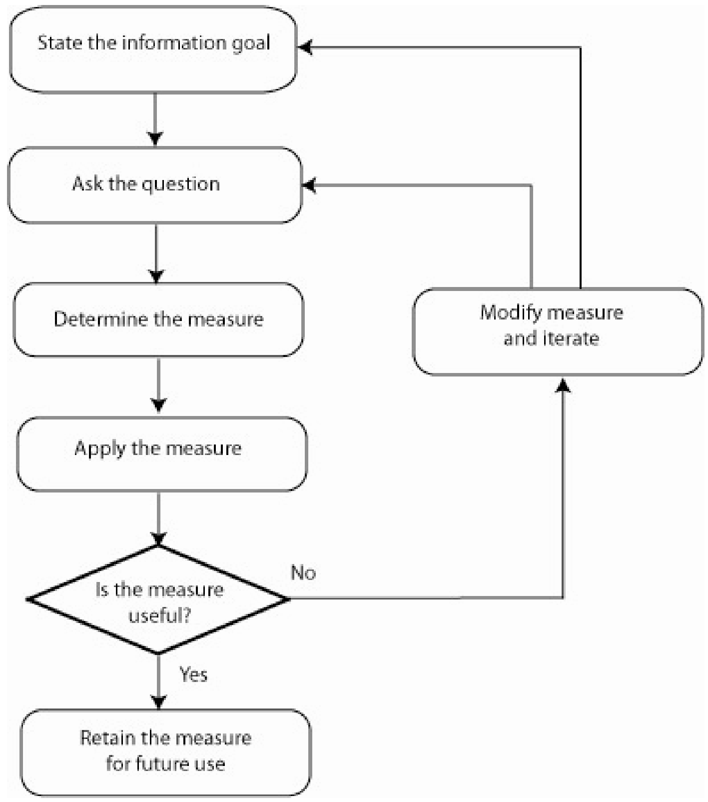


Figure 3 Flowchart showing application of GQM method

Thus the primary difference between the two approaches is that in PSM, one selects metrics from a list of candidate metrics, whereas in GQM, one generates the metrics in response to goals and questions about the project.

In addition, Kitterman (2005) provides the following list of five test questions to evaluate a metric:

1. Do people care about the value of a metric (good or bad)?
2. Would the metric drive a decision to take action?
3. If a decision were made to take action based on a metric, could that action actually be taken?
4. If action were taken, would it create a change?
5. If the change occurs, will it show up in a future value of the metric?

In order for a proposed metric to be worth adopting, it must answer positively to these questions. As the author states, "The only value of a metric is in giving an objective basis for a decision."

Programs and measurement systems related to SE metrics and best practice

As stated in the introduction, metrics and best practices are two fields within SE that are currently evolving and for which many questions remain unanswered. They are also informed and influenced by techniques and practices from related fields in the engineering and management literature. In this section, we review a number of papers on these techniques and practices (hereafter referred to as "performance management systems") that provide insights useful for SE. In the first part, we define each system covered and identify papers reviewed. In the second part, we list a number of lessons gained from this literature. It should be noted that these reviews of related systems are not based on exhaustive literature reviews, since this was judged to be outside the scope of our work; the reader is referred to other published literature reviews for further reading, where possible.

The list of performance management systems includes the following:

Six Sigma and Design for Six Sigma (DFSS): Six Sigma takes its name from a statistical quality goal of no more than 3.4 defects per million opportunities (DPMO); more broadly, the Six Sigma program comprises a set of customer-focused, quality control techniques that are applied on a project-by-project basis to the operations of a firm. DFSS is seen as an outgrowth, since 2000, of the evolution of Six Sigma in the 1990s. Sources used for our analysis of Six Sigma and DFSS include Goh (2002), Johnson and Swisher (2003), Rayner (1990), Fuller (2000), Bayles (2001), Kandebo (1999), Velocci (2000), Patterson et al (2005), Noble (2001), and Motwani et al (2004). Many of these sources are found in a literature review by Brady and Allen (2006).

Quality Management (QM) is a management philosophy and set of techniques (ranging from continuous improvement to zero-defect mentality) dedicated to improving the quality of product or service delivered to the customer, with an understanding that enhanced quality will lead to business success. Variants of QM include Total Quality Management, or TQM, and Quality Function Deployment, or QFD. Sources on QM that we reviewed include Garvin (1984), Capon et al (1990), Harari (1993), Dow et al (1999), Sousa and Voss (2001), and Crow (2002) . A number of these sources are chosen from the review by Sousa and Voss (2002); readers seeking further information about QM may also wish to read earlier reviews by Ahire et al (1995), Hackman and Wageman (1995), and Powell (1995).

Research & Development Management: The field of research & development management, or "R&D Management", is focused on improving the R&D process in order to develop successful products in less time and with less use of resource. Sources reviewed include Detz et al (1996), Cooper and Kleinschmidt (1996), Meyer and Lehnerd (1997), Meyer et al (1997), Smith and Reinertsen (1998), Gregory and Pearce (1999), Hoetker (2006), and Hwang and Park (2006). For more information on R&D Management, the reader is referred to Pendergrass (2004), which lays out the goals of the technical organization in regard to R&D.

Project Management: modern scientific project management entails the planning and execution of any type of project so as to maximize the likelihood of success. PD projects constitute a subset of all types of projects, so we have looked in the literature for examples of project management techniques applied to product development, or the relationship between project management and systems engineering. Sources covered include Azimzadeh and Koehn (1997), Hayward-Williams (1998), Dey (1999), and Heires (2001).

Other programs and measurement systems: Other programs and measurement systems that we reviewed, along with representative source(s) in the literature, include Lean Product Development (Oppenheim, 2004; Whitaker, 2005); Capability Maturity Model, or CMM (Herbsleb et al, 1994); Strategic Management and Reporting Technique, or SMART (Cross and Lynch, 1988); the Balanced Scorecard (Haskins, 2001); Performance Prism (Neely and Adams, 2001); and European Foundation for Quality Management model, or EFQM (European Foundation for Quality Management, 1997).

Lessons for SE metrics and best practice from related systems

We have compiled the following ten lessons learned from all of the related performance management systems, including some that pertain to more than one system.

1. *The literature supports the idea that systems such as Six Sigma, Quality Management, and Project Management are effective:* There is considerable evidence in the literature to back the common-sense intuition that deliberate pursuit of superior quality or scientific project management is positively correlated with superior business performance. For example, Capon et al (1990) carried out a meta-analysis of 20 published studies and found 104 out 112 cases with positive relationships between quality management and performance. The success of other techniques related to systems engineering such as business process reengineering (e.g., Dey, 1999) and benchmarking (e.g., Heires, 2001) are supported as well. We predict that as the volume of literature on SE effectiveness grows, a similar claim about the connection between SE and overall success will be supported.
2. *Top leadership support and customer focus is important:* For example, a study of the use of Six Sigma within Dow Chemical showed that the implementation of SS was able to achieve a company target of $1.5 billion in worldwide pre-tax earnings, one year ahead of schedule. The company attributed the success of SS to top leadership support and a focus on creating a customer loyalty advantage. The nature of top leadership support is important as well: management must go beyond platitudes and genuinely "change the infrastructure" to support the program in question. A case study of the Xerox organization showed that their quality management program succeeded when top management made a commitment to build the organization around quality, whereas preceding efforts were not successful because they were not comprehensive (Wayno and Milkovich, 1992, p.24). We believe that these lessons are transferable to the application of SE.
3. *A rigorous but flexible PD process improves the likelihood of PD success:* a study of the impact of ten success factors on the success of the new product

development process in 161 firms found that the single factor that contributed most to high performance was the existence of "a high quality, rigorous new product process", such as the Stage-Gate process used by many companies (Cooper and Kleinschmidt, 1996). The characteristics defining a successful NPD process in these authors' study are common to the SE process as well: front-loading investment of time in researching the product concept early in the process, clear early product definition, and rigorous Go/Kill decision points early in the process. Flexibility to adapt to new information as the product evolves is also advantageous (Smith and Reinertsen, 1998, p.110).

4. *Use of product platforms enhances PD success:* A proven approach to successful product development is the use of "product platforms" to leverage the investment required to develop new product concepts into multiple "derivative" products (Meyer and Lehnerd, 1997; Meyer et al, 1997). The "product families" created in this way allow the firm to maximize revenues from sales, and at the same time adapt quickly to changing markets and respond to new sales opportunities, since the time and cost for the development of an individual product is greatly shortened, compared to developing each product in isolation. This insight is relevant to many of the steps in the SE process, including context analysis and a life-cycle view of the system.
5. *Flexibility in application of the performance management system is beneficial:* Another common thread for many of the systems, that SE practitioners would do well to follow, is the emphasis on flexibility in adapting these systems to individual circumstances (e.g., Goh, 2002). Systems such as Six Sigma or QM are applied to a very wide range of businesses, so naturally the type of business will influence how generic elements are adapted. It is likely that any system of SE metrics, or method for creating metrics, must be used flexibly as well.
6. *There is a tradeoff between confidentiality of in-company results and mutual learning from peer organizations:* As with all techniques and programs that evaluate the quality of projects within private industry, there are limitations on the level of precision and details of what can appear in the published literature. Corporate databases of previous projects are typically confidential (Brady and Allen, 2006), so that a practitioner has access to the results of previous projects within her/his own organization, but not those outside. One solution is that of the Industrial Research Institute, which convenes industry-only workshops in which results are exchanged between partners but not published generally (Johnson and Swisher, 2003). Since information about peers' practices will be imperfect in any case, it is desirable to compile information about cost-effectiveness efforts into an in-house database in order to execute future efforts more effectively (Azimzadeh and Koehn, 1997).
7. *The effectiveness of specific sub-methods within a system may be context-dependent:* Most performance management systems incorporate a number of sub-methods, not all of which need be applied to any one PD project. This question has not been researched in great detail in the literature for the other systems covered, such as Six Sigma (Brady and Allen, 2006). In one study, it was found that only a subset of QM techniques were effective in a manufacturing setting (Dow et al, 1999), though this result cannot yet be generalized to other fields,

including SE. In the interim, since a rigorous method for evaluating which methods are appropriate in what context does not yet exist, an effort should be made when applying SE to use only those specific metrics and tools that are appropriate, and to avoid those that are not, on a case-by-case basis.

8. *In the use of any performance management system, maintain a "healthy skepticism":* Examples of inappropriate use of Six Sigma or QM from the literature lead us to believe that a healthy skepticism should be maintained when applying SE metrics or best practices. Techniques such as these often pass through an initial "hyperbole" phase, which is followed by a backlash against its shortcomings (Goh, 2002). Skepticism about the value of QM and TQM has been voiced (e.g., Harari, 1993; Powell, 1995), while Six Sigma has been criticized (e.g., Clifford, 2001) for being used in situations where it was not appropriate to use a statistical technique, or for rewarding organizations for minimizing errors at the expense of trying new concepts and inevitably making mistakes. As Goh (2002) states, "instead of unreserved raving of all things Six Sigma, a balanced view of the strengths and weaknesses…is in order." He gives the example of a "string quartet on the Titanic" to illustrate the danger of becoming preoccupied with narrowly-defined statistical performance on a project that may have fundamental and possibly irreversible "big picture" flaws. Thus, the SE practitioner should not blindly apply metrics and best practices, but instead think about each step before embarking upon it.
9. *Performance management systems must maintain a focus on the core of the methodology:* With any system, there is a danger that as it evolves, it will lose its focus on core features, whereupon its value to the practitioner will be lost. For example, Sousa and Voss (2002) warn of the possibility that QM might be diluted by being incorporated in overall business excellence programs, so that the emphasis on quality would be lost. The SE community would do well to avoid this pitfall in the advancement of the use of SE metrics.
10. *Six Sigma and QM provide models for the development of the SE literature:* Lastly, from our review, we posit that the body of literature on Six Sigma and QM is more advanced in terms of studying the overall effectiveness of each, and the prevalence and use of specific techniques within each field. These two bodies of literature provide a model for the field of SE metrics and best practices on how to build up a case for SE by accumulating empirical evidence. The SE field should gather and publish more case studies on the contribution of SE to successful product development. Such case studies should be published in such a way that they convey the general context for the PD effort, the types of techniques used, and the effect of using SE, without revealing sensitive information about specific products or the PD process within the firm studied.

Discussion

Based on the range of SE applications considered in this literature review, we surmise that complexity of product has an effect on what types of practices/metrics are relevant. Lloyd and Pagels (1988, as quoted in Thomas & Mog, 1997) define complexity as a "measure of how hard it is to put something together." Thus an aircraft or automobile is clearly a complex system, whereas a unit of packaged food product is not, although the initial development, manufacture, distribution, and marketing of the food product may constitute a complex system when taken as a whole. Among complex systems, Oppenheim (2004) classifies technological PD programs in four types: 1) complex large open systems (e.g., the internet), complex frontier systems (a groundbreaking aerospace application, e.g., Mars Rover), complex legacy-based systems (commercial passenger aircraft), smaller complex systems (light aircraft). This distinction between complex products and non-complex products is consistent with the discovery-program-approach nomenclature of Sheard, introduced above, in that all three areas of SE are relevant to complex systems, whereas primarily it is only the "approach" area that is relevant to non-complex systems.

We also propose that, among the candidate metrics we have studied, a distinction can be made between "bottom line" and "detail" metrics. The metrics of the greatest interest to top management are likely to be those with a long-term, external view. However, in order to succeed on these bottom line indicators, it is necessary to be successful on the detail indicators, in order to meet bottom line metrics. Using the LAI metrics as an example, three of the indicators, namely "Risk exposure trends", "Risk handling trends", and "Technology maturity trends", are bottom line metrics. In order to achieve positive results with these metrics, the remaining ten metrics must be positive as well.

Along with a general need for more documentation of the quantifiable impact of SE metrics and best practice on successful PD, some of the specific gaps identified in the literature follow.

Honour et al (2004) state that we know that SE is useful in general, but don't know "which practices are useful under what conditions." Clearly, given the range of possible applications to which SE can be applied, it would be useful for practitioners to be able to choose metrics, best practices, etc. from the list of those available based on the type of business, complexity of the product or service, size and scope of the project, and other factors.

These authors also warn against "gaming" of the SE metrics system by suppliers who work toward optimizing their metrics numbers rather than pursuing a "reasonable" definition of a successful project (ibid, p.22). In the early 1990s, certain software contracts contained specific clauses detailing the regular reporting of measures such as lines of code, error rates, etc. It was later found that software developers had been interpreting the requirements to report their work in the most favorable light possible, but producing data that in retrospect proved not to be useful.

Browning (2003) points out that the value literature is "poorly linked" to process modeling literature. The literature on evaluating and improving PD processes, of which the study of SE metrics and best practice is a part, ultimately is about improving value to customers. On the other side of the divide between process and value, a body of literature has developed to understand how product attributes deliver value to customers. Linkages between these two sets of literature should be strengthened.

Point 3 from McKinney (1995) in the previous section indicates another weakness, namely the inability of systems engineers to precisely quantify the dollar value of using SE in the product development process. McKinney gives the example of projects in which the systems engineer presents to business decision-makers the potential financial losses from not applying SE best practices. The decision-makers add up the total financial losses, find that the total exceeds the business value of the whole project by "one or more orders of magnitude," and conclude that SE is not credible. Such a pitfall is clearly to be avoided.

Lastly, there remains the debate about the limits on our ability to quantify ROI for the use of SE in the first place. For example, Sheard and Miller (2000) state that it "won't be possible to prove return on investment from use of metrics for the foreseeable future." They cite the lack of transferability of results from one firm to another, the confidentiality of many critical numbers, and the difficulty of isolating the effects of SE from "background" activities of the firm as reasons, among others, for the futility of such an undertaking. Honour et al (2004) counter that Sheard and Miller point out difficulties, but do not prove that it is not possible to develop an effective SE metric. Our review of the literature suggests that, as of this writing, there is no resolution to this debate in sight.

Conclusions

From the perspective of the Corning organization, the overall purpose of this literature review was to develop a set of metrics by which the benefits garnered by employing the SE approach to product development might be quantifiably demonstrated by becoming familiar with work that has gone before. In this regard, while confidence in the SE approach is well placed, this project has not yet yielded a particular set of key metrics. The existing body of literature inspires confidence in SE techniques, and at the same time provides room for Corning to "push the envelope" and not only enhance its own R&D capacity by accelerating the use of SE, but also cut a path in which other similar organizations can follow. Specific conclusions from the literature review are as follows:

1. There is widespread confidence in the ability of the use of SE to enhance the success of technological projects. This evidence includes surveys of practitioners, individual case studies, a limited number of "quasi-experiments" (e.g., those of Frantz at Boeing or Loureiro et al at Ford), and the existence of standards for SE practice in many industrial organizations (Boeing, Ford, AT&T, Airbus (Jeffroy et al, 1999), IBM, and others).
2. Given the amount of effort expended on SE in industry, there is a shortage of published case studies that quantify its benefits, or illuminate which SE practices are expected to lead to which results. Nevertheless, we have identified eight examples where SE practitioners have been able to document the success of SE in

3. The ability of a number of enterprises, as well as consortia such as the Lean Aerospace Initiative to establish systems of metrics with a common overall goal and common elements shows that the SE field as a whole has been successful in developing a common architecture for metrics and best practices that can be adapted to the specific circumstances of an enterprise or project.
4. Evidence from related fields, such as Quality Management or Design for Six Sigma, suggest that techniques from these fields that resemble SE techniques have already achieved success in contributing to project and organizational success. These results help to bolster the case for SE.
5. The SE field can also use the QM and Six Sigma literature as examples of how to assemble a body of evidence that supports the effectiveness of a technique related to PD. The SE field should expand the body of available case studies that support its effectiveness.
6. Given the relatively small number of definitive case studies of successful application of SE metrics and best practices to commercial product development, there is a clear motivation for our ongoing study of the use of SE within the Corning organization.
7. The ultimate value of SE is widely understood but difficult to quantify. It may be possible to carry out theoretical work in order to better understand the absolute limits, if any, to rigorously proving the value of SE to the bottom line.

At the end of the literature review phase and beginning the Corning-based research phase, we articulated the following assumptions as a starting point for developing metrics:

1. There are objective output metrics that are of interest to managers: these metrics include the product cost versus budget, the development process time versus schedule, and overall quality of the product. Quality might be measured in a number of ways, including the number of defects, the number of warranty claims, or the number of engineering change orders after delivery.
2. SE techniques can have an impact on the value of these output metrics: the extent to which systems engineers use techniques such as those presented in Table 1 in this paper (requirements driving functional specifications, design for testability, etc.) will have an effect on the extent to which the desired output metrics are achieved.
3. It is possible to measure the degree of use of SE techniques: in order to evaluate the connection between SE techniques and output metrics, it is necessary to evaluate not only whether a technique was used, but also the extent to which it was used. It is possible to quantify this gradation of degree of use.

As an additional note to accompany this summary of the literature review, the publication of the review in *Systems Engineering* resulted in communication with Prof. John Warfield, specialist in systems engineering at George Mason University. Prof. Warfield shared with us two reports on work with Ford Motor Company, one of which was co-published with John Staley from Ford, to develop a systems engineering system that could more effectively accommodate the complexity of integrating all components in vehicle development (Warfield, 2007; Staley and Warfield, 2007). The success of this program in improving Ford's vehicle development process can be seen as additional evidence of the effectiveness of SE.

Chapter 3. Generic methodology development for SE evaluation

The metrics development process began with the literature review discussed in the previous chapter. Since we did not encounter a published methodology for studying the effectiveness of SE in the commercial world, we judged that there was wide latitude to develop our own methodology, based on the materials reviewed during the literature review stage.

The parts of this chapter follow the stages of methodology development, as follows:

1. Choice of areas of SE metrics
2. Evaluation of project effectiveness
3. Evaluation of correlation between use of SE and project effectiveness
4. Other parameters for project interview process

Among the various sources reviewed, two sources in particular informed the development of our methodology. The first source is the final report of the National Defense Industry Association Study, or NDIA Study, published by Carnegie Mellon University (CMU, 2007). This source provides both up-to-date results and a thorough explanation of the methodology used to identify and study individual projects for effectiveness of SE. The second source is the collection of powerpoint presentations and publications of Eric Honour, and various co-authors, reporting on research on the correlation between SE activity and project success, primarily in the aerospace and government procurement sector. For example, Honour is coauthor, along with Eric Axelband and Donna Rhodes, of the Lean Aerospace Initiative (LAI) Report on the Value of Systems Engineering [Honour et al, 2004], which informed our study as well.

Choice of areas of SE metrics

Having broken out the components of an SE research methodology into steps 1 to 4 in the previous section, the first task is to define the range of SE metrics available in a structured way. We assume that, with limited time and resources, an investigator using our methodology may not be able to look for every SE metric in every project, so it is left to the investigator to choose the metrics thought to be most relevant to a particular situation. This selection process is illustrated for the case of studying Corning in the next chapter.

At the outset, from the universe of techniques and practices that can be construed as SE, Honour and Valerdi [2006] describe an "ontology", or structure of definitions and relationships, for SE that is common to five of the major published SE standards, ranging from ANSI/EIA-632 to MIL-STD-499C. Individual steps in the standards are divided into eight principle categories, as shown in Table 2 below.

Table 5. Systems Engineering Effort Categories Evident in the Standards

SE Categories	ANSI/EIA-632	IEEE-1220	ISO-15288	CMMI	MIL-STD-499C
Mission/purpose definition	Not included in scope	▪ Define customer expectations (Req Anlys)	▪ Stakeholder needs definition	▪ Develop customer requirements (Req Devlp)	Not included in scope
Requirements engineering	System Design ▪ Requirements definition	▪ Requirements analysis ▪ Track requirements and design changes	▪ Requirements analysis	▪ Req'ments development ▪ Requirements mgmt	▪ System requirements analysis and validation
System architecting	System Design ▪ Solution definition	▪ Synthesis	▪ Architectural design ▪ System life cycle mgmt	▪ Select product-component solutions (Tech sol'n) ▪ Develop the design (Tech sol'n)	▪ System product technical req'ments anlys/validation ▪ Design or physical solution representation
System implementation	Product Realization ▪ Implementation ▪ Transition to Use	Not included in scope	▪ Implementation ▪ Integration ▪ Transition	▪ Implement the product design (Tech sol'n) ▪ Product integration	Not included in scope
Technical analysis	Technical Evaluation ▪ Systems analysis	▪ Functional analysis ▪ Requirements trade studies ▪ Functional trade studies ▪ Design trade studies	▪ Requirements analysis	▪ Decision analysis and resolution	▪ Functional analysis, allocations and validation ▪ Assessments of system effectiveness, cost, schedule, and risk ▪ Tradeoff analyses
Technical management/ leadership	Technical Mgmt ▪ Planning ▪ Assessment ▪ Control	▪ Technical mgmt ▪ Track analysis data ▪ Track performance – project plans, tech plans ▪ Track product metrics ▪ Update specifications ▪ Update architectures ▪ Update plans ▪ Maintain database	▪ Planning ▪ Assessment ▪ Control ▪ Decision mgmt ▪ Configuration mgmt ▪ Resource mgmt ▪ Risk mgmt	▪ Project planning ▪ Project monitoring & control ▪ Measurement and analysis ▪ Process and product quality assurance ▪ Configuration mgmt ▪ Integrated project mgmt ▪ Quantitative project mgmt ▪ Risk mgmt	▪ Planning ▪ Monitoring ▪ Decision making, control, and baseline maintenance ▪ Risk mgmt ▪ Baseline change control and maintenance ▪ Interface mgmt ▪ Data mgmt ▪ Technical reviews/audits
Scope management	Acquisition & Supply ▪ Supply ▪ Acquisition	Not included in scope	▪ Acquisition ▪ Supply	▪ Supplier agreement mgmt	▪ Technical mgmt of subcontractors/vendors
Verification & validation	Technical Evaluation ▪ Requirements validation ▪ System verification ▪ End products validation	▪ Requirement verification ▪ Functional verification ▪ Design verification	▪ Verification ▪ Validation	▪ Verification ▪ Validation	▪ Design or physical solution verification and validation
In the standard, but not in agreement with other standards			▪ Operation ▪ Disposal ▪ Enterprise mgmt ▪ Investment mgmt ▪ Quality mgmt	▪ Organ'l process focus ▪ Organ'l process definition ▪ Organ'l training ▪ Organ'l process perf ▪ Causal analysis/resolution ▪ Organ'l innov/deploymnt	▪ Lessons learned and continuous improvement

Table 2 SE categories used in major SE standards [Honour and Valerdi, 2006]

For the purposes of our methodology, we have reworded the titles of the eight categories in the left column in the table, as follows:

1. Market analysis: analysis of the total market, market niches, market segmentation, competitor analysis, product value proposition, and other factors
2. Requirements analysis: analysis of the connection between customer objectives, product requirements, and technical performance measures (TPMs)
3. Systems architecting analysis: consideration of systems architecture and systems life cycle
4. Systems implementation analysis: implementation of the design solution as a system, or integration of the product into its environment in the marketplace
5. Technical analysis: analysis of system functions, analysis of decisions, choice of best option among multiple alternatives
6. Technical management analysis: evaluation of input of SE expertise and leadership into project
7. Scope management analysis: evaluation of ability to draw boundaries around project, manage interactions at defined boundary

8. Verification and validation analysis: development, scheduling, and execution of testing to evaluate product performance during the development process

Note that the table also includes some steps in some of the standards that do not fall among the eight categories. Similarly, our methodology does not preclude assessment of techniques and practices outside of the eight titles in the list above as a part of assessing overall use of SE.

The next step in the process is to choose which categories to test – our experience shows that if an interview format is used, it is not possible to thoroughly explore all eight categories in a reasonable interview length. Choice of categories can be made internally to the enterprise, based on the understanding of its strengths and weaknesses. It can also be made based on observation of outside experience at other enterprises or as published in the SE literature.

The last step is to develop interview questions that will be used to evaluate the level of SE penetration for each of the chosen areas. For example, if four areas are chosen, and three or four questions are developed for each area, we might arrive at a list of a total of 12 to 16 questions to be discussed during the interview. By implication, since the number of questions is not long, it can be expected that each one will be discussed in some depth. Not all areas need to generate the same number of questions. For example, some areas might generate three questions, and others four. However, by spreading the total number of questions somewhat evenly among the different areas, each area is guaranteed to be explored in sufficient depth to assess its application.

In addition to being asked a question and being expected to answer, interviewees are expected to provide evidence supporting their answer, in the form of powerpoint slides, project reports, spreadsheets, database download tables, or other documents. This requirement helps the interviewer to generate a more realistic and accurate picture of the true usage of SE in the project.

As a concrete example of choosing an area and then developing a question, suppose we take the area of market analysis. A typical question might be:

> "Provide evidence of competitor analysis, such as identification of price leader, technology leader, or growth leader, or the assessment of potential role of major competitors"

The interviewee would then indicate whether or not they had carried out any competitor analysis, and if they answered yes, present files that supported this statement. We do not require that the question be worded exactly as phrased above. Although this is different from standard survey question practice, in which questions are to be read exactly as written, in the interest of avoiding miscommunication (e.g., Groves et al, p.2004, p.221), it is thought that the subsequent discussion of the supporting documentation eliminates any possibility of miscommunication. Also, if exact wording is not required, the interviewer can use their judgment to adapt questions to the particular circumstances of a project.

The interviewer takes notes and documents names of files presented during the interview, but does not score the questions until after the interview ends. This approach not only allows the interviewer to focus on gathering information rather than making judgments about the information, but also allows the interviewee to remain more relaxed, and hopefully open to candidly sharing information.

Also, when interviewing, the interviewer asks the individual questions without communicating to the interviewee the underlying area from which the question is asked, so as not to influence their answer one way or another. Otherwise, the interviewee may seek to meet expectations about a given area by "spinning" answers in one direction or another, or otherwise introduce subjective preferences into the interview.

After the interview is over, the interviewer scores each question related to the use of SE on the basis of 1 point for a fully satisfactory answer, half a point for a marginal answer, and no points for an answer that is unsatisfactory, or if the interviewee responds that the technique was not used. At the interviewer's discretion, it is possible to rule that a question does not apply to a project, and take it out of the calculation of overall scoring. Otherwise, each project is scored on the basis of percent of total possible points earned for each area. An "overall SE input" score is calculated based on the percent of possible points across all questions. For example, if there are four questions total in the market analysis area, and the project earns two full points and one half-point, the score is a 62%.

Once interviews are complete, the average and standard deviation for each area, and for the overall score across all areas, is calculated. Projects that have percent scores one SD above the mean are evaluated as having "higher SE input" for a given area, those within one SD of the mean are considered to have "medium SE input", and those below to have "lower SE input."

Evaluation of project effectiveness

To evaluate the effectiveness of SE, it is not enough to establish the extent to which projects use SE techniques. It also necessary to have some measure of the effectiveness of the project, in terms of its efficiency as a new product development (NPD) process, its outcome product, or, ideally, both.

It is useful at the outset to consider in general terms what are the possible outcomes from a project. According to the Product Development Management Association, or PDMA, the outcome from each project need not be that it result in a mature product in the marketplace (PDMA, 2002). Instead, PDMA encourages starting a sufficient number of new projects to allow for the development of successful products from some of these, and that the enterprise should aim for the "early kill" of the weaker projects so that resources can be redirected into the next round of more promising project starts.

Projects can then be grouped into one of four outcomes based on both the process and the result, arranged in order of decreasing desirability from Corning's perspective as follows:

1. *Successful process with mature product outcome:* the process starts with an inherently strong concept, successfully develops the product to maturity using a process that is both time- and resource-efficient, and launches the product into the market place, with positive reception from customers and strong returns to the enterprise. This is the ideal outcome.
2. *Unsuccessful process with passable or successful outcome:* the NPD process is executed from concept to mature product stage, but because of deficiencies in that process, it is either delayed, too expensive, or results in product defects. The product may ultimately succeed, but it may also underperform financially, for example if delays in product launch lead to competitors capturing market share at the enterprise's expense. Also, from their point of view of productivity, the same endpoint could have been reached with fewer resources and/or more quickly, if mistakes had not been made.
3. *Successful process with early kill:* the NPD process is effective from the beginning and at an early juncture is able to recognize a fundamental weakness in the product concept (e.g., realistic potential market or market share, limitations on the ability of the enterprise to deliver a workable technical solution). The process is shelved with little or no delay, and any significant learning from it is archived for future reference.
4. *Unsuccessful process with eventual killing of product prior to launch:* weaknesses in the product are not uncovered early, or else an unsatisfactory process leads to poor product development so that the product, as it develops, is not acceptable in the marketplace. As a result, the project is eventually shelved, but not before some non-trivial amount of resource has been used unnecessarily. This is the least successful outcome of numbers 1-4.

We now take a closer look at the measurement of project success. For a retrospective study of projects that have matured and launched products into the marketplace, one of the most obvious metrics of effectiveness is the extent to which the product met the expectations of the enterprise, in terms of market share, profitability, return on R&D investment, or other measure.

For in-progress projects as well as completed ones, measures of effectiveness of resource management are of interest as well. These include budgeted against actual financial outlays, schedule, and use of human resources (e.g., measured in full-time equivalents or FTEs).

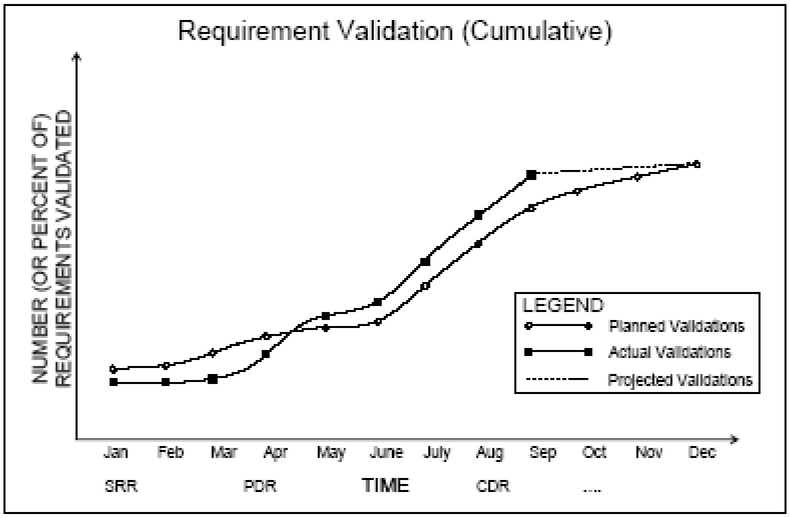


Figure 4 Example of requirements validation trend, comparing actual to planned validations, and projecting future validations going forward from the present (month of September in the example).
Source: Roedler and Rhodes, 2005, p.12

To project the future effectiveness of an in-progress project, it may be possible to use the project's trajectory against some target to provide a quantitative measure of anticipated success. For example, the *SE Leading Indicators Guide* from LAI (Roedler and Rhodes, 2005) provides a number of leading indicators whereby the project team can lay out a trajectory for a given metric at the beginning of a project, and then track actual progress relative to the trajectory during the course of the project (see Figure 4). Measures like these can be used to assess whether a project is performing well while it is in progress.

It may also be possible to use projections of future financial success to evaluate in-progress performance of a project, if the data allow. For example, the enterprise may have laid out ROI expectations from a product at the beginning of the project. Midway through the project, the project manager may be able to forecast an updated prediction of the ROI, based on how the product is actually evolving. The comparison of the initial to the updated ROI can then be used as a basis for evaluating project performance. Other indicators of this type include the actual versus anticipated satisfaction of key performance metrics (KPMs) or the actual versus anticipated value proposition for the product.

Table 3 below summarizes a wide range of quantitative measures that can be used to evaluate project outputs, from "detail-oriented" (adherence to financial budget and schedule) to "big-picture" (ROI to enterprise), as shown in the different rows. Across the table, the columns represent different ways in which the measures might be scored, including the goal for the measure or the minimum maximum threshold (benchmarks against which actual values can be compared), as well as the current and future projected values. The second column from the left ("weights") allows one to calculate an overall score by weighting different line items differently. Different KPMs and different components of the value proposition can similarly be combined into an overall weighted score. Usually the investigator would be able to find some data points for some of the elements in the table, so it should not be applied rigidly, but rather flexibly so as to adapt the cells used in an actual project to the data that are available.

	Weight	Goal	Budgeted Threshold	Current Achieved Value	Current Projected Value	Score
Development Cost						Ratio
Development Schedule (months)						Ratio
Technical (Person-hrs)						Ratio
System KPM (list of key performance measures by project, KPM1, KPM2, etc.)						Wtd avg of ratios
Customer Value Proposition (Capital cost, Op. cost, Life-cycle cost)						Wtd avg. of ratios
System ROI						Ratio
Total						Wtd avg. of scores

Table 3 Overview of Output Metrics Sought to evaluate project performance

Lastly, if data prove insufficient to support a quantitative assessment of project performance, the investigator may use a qualitative assessment of project performance instead, especially for ongoing projects where the final outcome of the product in the marketplace is not known. There is wide latitude in how such qualitative evaluation might be applied. One possibility is to group projects into three categories, as follows:

- *Superior project:* judged to be superior due to development speed, early indications of product promise, or other factors
- *Struggling project:* suffering from one or more process defects that are beyond the usual vicissitudes of product development
- *Satisfactory project:* not falling into either of the previous categories

In other words, almost any project will encounter some rough spots and unexpected turns, and project teams will make mistakes, but if the project either fares exceptionally well (Superior) or has more serious shortcomings (Struggling), the distinction can be made along those lines.

Some further indicators of project success might be the following for superior projects:

- Interviewee remarks on or can demonstrate that the product has developed a surprising level of interest from potential customers, or won praise from these customers on the basis of samples (beta versions, prototypes, etc.)

- Interviewee can demonstrate that the project timetable has been accelerated compared to initial expectations
- Interviewee remarks on or can demonstrate strong project team morale, team cohesion, etc. This indicator by itself may or may not indicate a truly superior project, but it can be used to corroborate other evidence.

Similarly, for struggling projects:

- Interviewee remarks on difficulties in reaching agreement with potential customers on product performance, beyond the usual give and take
- Interviewee comments on cost or schedule overruns.
- Interviewee discloses that there have been major mistakes made during the course of the project (e.g., failure to satisfy customers at later stages in development, leading to a return to earlier stages to rework technical mistakes)
- Interviewee remarks on weak morale, difficult interactions with clients or upper management, etc. Again, this indicator by itself may or may not indicate a struggling situation, but it can be used as corroboration.

To conclude, in comparing the quantitative and qualitative approaches, the former is more accurate and therefore preferred, but may or may not be supported by available date, whereas the latter is not as precise but thought to be applicable in almost all studies.

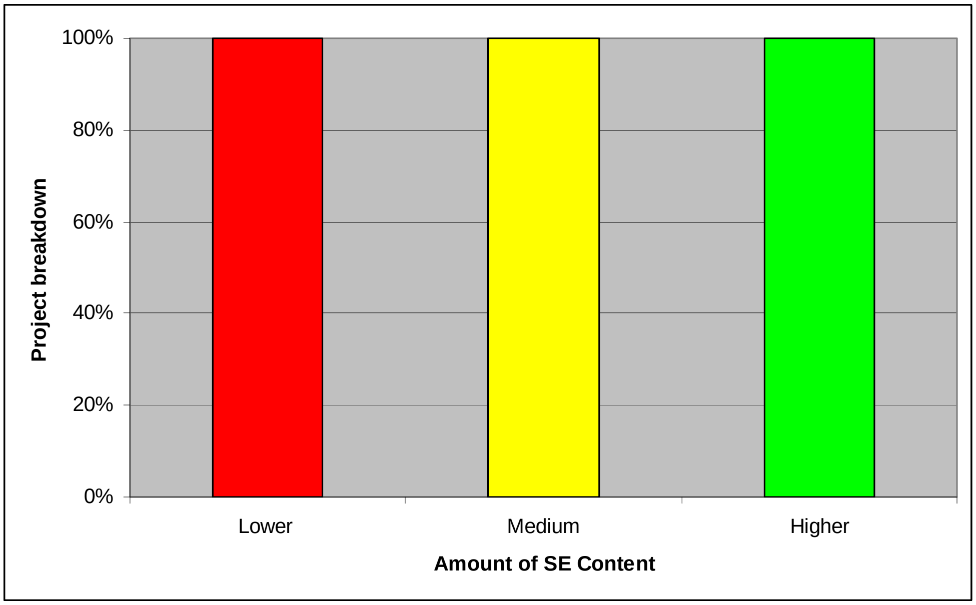
Evaluation of correlation between use of SE and project effectiveness

The NDIA report in its opening section sets forth the following hypothesis statement for their research:

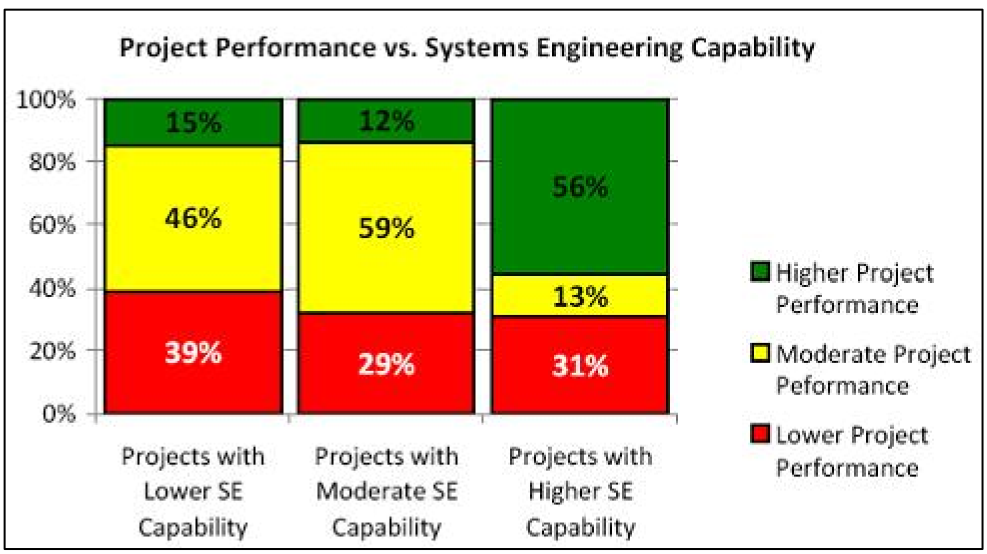
> "The effective performance of SE best practices on a development program yields quantifiable improvements in the program execution (for example, improved cost performance, schedule performance, technical performance)."
> Source: NDIA, 2007, p.19

This statement is a good fit for our own purposes and we have adopted it for our research as well.

The NDIA study has also demonstrated a visual tool for assessing correlation known as the "mosaic diagram", which we have adopted for our methodology as well, as shown in Figure 5 in both an ideal and realistic form. In the mosaic diagram, the total number of projects are divided along the x-axis according to the independent variable, or the amount of SE input in this case (lesser, moderate, or higher in this case). Then, of the total number of projects in each column, the percent of projects performing at a given level is broken out along the y-axis, so that each column adds up to 100%.



a) Ideal (red = lower performance, yellow = satisfactory performance, green = higher performance)



b) Realistic

Figure 5 Sample mosaic diagrams for a) an idealized case, and b) a realistic example taken from the NDIA study of aerospace projects.
Percentage values signify the percent of projects in a given column that correspond to a given condition. For example, in b), if 18 projects had lower SE capability, then 39%, or 7 of those 18 projects, had lower project performance. See text. Source for b): NDIA, 2007, p.xii.

The difference between parts a) and b) of the figure illustrate the idealized and realistic views of the correlation between SE input and performance. In a), project performance is exactly correlated with SE input: all of the projects with lower performance had lesser SE input, and so on. For a more realistic study of 46 projects across multiple enterprises from NDIA, all three types of performance appear in all three categories of SE input. However, the percent of lower performing projects decreases, and the percent of higher performing projects increases, from left to right, suggesting a relationship.

Individual SE areas (market analysis, requirements analysis, etc.) as well as overall SE input can be tested for correlation using the mosaic diagram. Typically, even if a correlation is observed at the level of overall SE input, not all of the individual areas will show this.

Recording and post-interview analysis of interviewee quotations

Our methodology relies on the interviewer recording statements made by the interviewee during the interview in a short-hand form, and then writing them out more fully as soon as possible after the interview, while the circumstances are fresh in memory. In theory, one could also make a sound recording of the entire interview, although the additional work of listening to and transcribing the interview in the post-processing phase may not merit the additional information gained.

Along with using the post-processing stage to determine scores on SE input questions and outputs from the project, the investigator may also encounter particular "pithy quotes" that shed further light on the use of SE, for which the meaning is not easily captured in the quantitative scoring portion of the analysis. It is the intention that these quotes be collected, revised or refined so that their context is clear to outside readers, and kept with the quantitative findings so that they accompany them when they are presented or read.

Some of the types of insights that might be discerned from these quotes are the following, though they need not be limited to this list:

- Reactions of the interviewee to SE, and revelations about the extent to which they either do or do not use SE techniques, whether or not they call them "systems engineering"
- Quotes that give further insight on the awarding of 0 to 1 point for a given SE input question, by illustrating how SE was or was not used.
- Quotes that highlight the successes or failures of a project
- Quotes that reveal the limitations of using a standard interview format to try to understand the function of an NPD process which is unique to both the enterprise and the product in question
- Quotes that reveal the attitude of the interviewee toward the corporate culture of the enterprise, including standard operating procedures, relationship between upper management and the rest of the organization, or other factors.

- Quotes that reveal the attitude of the interviewee toward the interviewer and the research goals of the project that the interviewer represents.

Other parameters for project interview process

Remaining aspects of the interview not covered in the input, output, and correlation sections are considered here.

Basic characteristics of interview

The interviewer needs to be someone with sufficient engineering experience to be able to understand a wide range of projects, both in terms of their technical content and their function as an NPD process. It is preferred that the interviewer could come from outside the organization, because interviewees may have concerns that if an internal person from the organization conducts the interview, the answers given may lead to repercussions. For example, the interviewer may at some later time find themselves in a position to affect the interviewees career path, and information candidly given in the interview may influence the interviewers thought process. These concerns would in general not arise with an outside interviewer, such as an academic or consultant. However, the organization may be able to take steps to use an internal interviewer while limiting any potential negative repercussions. In either case, steps must be taken to make sure that interviewees are comfortable with the interviewer, so that answers will be candid; see below. Ideally, a single interviewer conducts all interviews for consistency across the project; if a team of two or at most three interviewers were used, care would be needed to maintain consistency in scoring across projects interviewed by different interviewers.

The demeanor of the interviewer also affects the ability to effectively gather information from the interview. The interviewer must present themselves in a friendly and non-confrontational manner, so that interviewees will be comfortable discussing what are in effect sensitive pieces of information both about products and about the development process. Those representing the enterprise (or enterprises in case of multiple sites) should satisfy themselves that the interviewer has the necessary communication skills by spending time with them in person during the launch stage of the project.

In having interviewers speak directly to project managers (or other interviewees) about the project, we are avoiding a pitfall that was noted in the NDIA study. NDIA's approach was to have an intermediary within the target enterprises act as an agent on behalf of the investigators to find projects, obtain data from project managers, and return the data to the investigators. In their report, the authors questioned the effectiveness of this approach, since the number of projects for which they obtained data was lower than what they anticipated, given the number of enterprises participating and the number of projects potentially available within each enterprise (NDIA, 2007, p.93).

We decided to set a target duration for the interview of 2 hours. Less time was thought to be inadequate to fully explore the interviewee's project, and more was thought to be a deterrent to gaining participation in the project. Having a time limit implies that the number of questions may need to be adjusted so that the interview will not be too long. Also, the investigator should use judgment about gathering quantitative data about projects that interviewees are likely to have easily available, rather than data that will require significant extra efforts to calculate, lengthening the overall interview process.

As is standard practice with survey research, the first interview is thought of as a "pilot", preferably to be carried out with a project whose characteristics are well known or an interviewee who is familiar with the goals of the research. After conducting the interview, the investigator and any supporting persons on the project should meet to discuss how the interview went, and make adjustments as needed before conducting more interviews in the project.

Gathering follow-up information from the interview

In some instances, it may not be possible to gather all information in the time allowed, or an interviewee may be able to answer a question but may not have the required supporting documentation at their disposal during the interview. Two follow-up options are available. First, the interviewer and interviewee can arrange a Net Meeting on a different day for the interviewee to present the missing documentation, so that the interviewer can review it and determine the score for the question. This approach may raise information security concerns. Therefore, an alternative is for the interviewee to provide a hard copy of the documentation to put in a file for the project, which the interviewer can review at the interviewee's location at a later time.

It may also be convenient to download financial information about a project from a central location after the interview, rather than taking limited interview to unearth this information. If so, the investigator may wish to request a batch download for all projects at the end of the interview period, in which case the staff of the enterprise can enter the financial database and gather standard for all relevant projects simultaneously.

Gathering supporting information about the nature of the product and NPD process

As background for analyzing the responses from individual projects to questions about SE input to and output from the NPD process, it is useful to gather background information for categorizing projects into different groups. This background information can reveal factors that influence the performance of individual projects in comparison to one another.

One such factor is the nature of the product itself. In one dimension, products can be aimed at either an existing market (to displace the incumbent leading technology, where customers pull the product into the marketplace) or a potential market (to create a new market, where the enterprise pushes the product into the marketplace. These two dimensions can be referred to as "customer pull" and "technology push", respectively. In another dimension, the product may build on "process excellence", in which its competitive advantage is derived from a process that the enterprise has developed that competitors cannot emulate. It may instead build on "product integration excellence", in which the enterprise combines processes and components that are well understood, by both itself and its competitors, but in a novel way that creates competitive advantage. Thus fiber optic cable is an example of the former, while an i-pod is an example of the latter. These two dimensions can be combined into a 2x2 matrix to categorize NPD projects into four quadrants. Table 4 illustrates these four cells visually, and also gives a rationale that the enterprise may employ in developing products in each of the quadrants.

Rationale:	Technology-push	Customer-pull
Process focus	Perceived large market opportunity, but must educate customer about product (= push)	Customer depends on enterprise's process expertise to deliver keystone component
Product focus	Use the underlying process to create a new market in an adjacent product, so as to leverage expertise	Custom device demanded by the customer depends on ability to package discrete product, not process expertise.

Table 4 Mapping of technology-push versus customer pull and process versus product focus into quadrants, and product development rationale in each quadrant.

The other important characteristic of project development projects has to do with their status in the maturation process from "fuzzy front end" to full-scale maturity in the marketplace. From the perspective of the investigator, projects can either be completed (the product is "out the door" and the NPD process is no longer active), shelved (the project was terminated prior to maturity), or active. Among the active projects, the project can be rated according to its place in the Stage Gate process, or other measure of maturation, if the enterprise uses some other system to mark advancement.

Developing and maintaining rapport w interviewee

The first step in developing rapport with interviewees comes at the inception of the project, with the non-disclosure agreement (NDA). If the interviewer is someone from within the enterprise, non-disclosure is assumed, but for outside interviewers, a binding document guaranteeing that all discussion is confidential, and that only findings approved by the enterprise can be shared in the literature, reassures the interviewee that the confidentiality of their project will not be compromised.

Once an interview has been schedule, a short pre-interview phone call (5-10 minutes maximum) helps to further establish rapport. This phone call allows the interviewer to find out the identity of the project, make sure the interviewee understands the format of the interview (e.g., the need to call up supporting documentation, which may be different from other interview formats), and to make certain that the interviewee is comfortable with discussing sensitive project information.

A further step is to give each project a number, and refer to the project by the code rather than by its name or product description in any reporting about the research. If interviewees are confident that their statements will not be later taken from internal reports on the research to put their work in a bad light, they are more likely to talk openly. When asked about future prospects for a given potential product in the interview, interviewees may nevertheless be reluctant to predict sales on the high end, so any numbers given should be seen with this in mind.

Conclusion

This concludes the presentation of the generic methodology for researching SE metrics, which, it is thought, can be adapted for a wide range of technical enterprises that stand to benefit from the use of SE. The next chapter takes this generic methodology and applies it to the case of Corning, Incorporated

Chapter 4. Application of methodology to case of Corning, Incorporated

The methodology presented in Chapter 3 for evaluating the connection between SE input and project performance is generic in the sense that it can potentially be adapted to any technology-oriented organization that has a role in the delivery of products to the commercial marketplace. It may also be useful for organizations that specialize in infrastructure systems (e.g., civil engineering firms), although in general it is oriented more toward discrete products that are mass marketed. In this Chapter, we illustrate the process of applying the methodology to a specific firm by considering new product development at Corning, Incorporated

The application in this chapter and analysis in Chapter 5 are based on project interviews conducted between April 2008 and March 2009. In all, 20 interviews were conducted at the Sullivan Park site outside Corning, NY, of which 19 delivered usable results for the analysis. All interviews adhered to the two hour time limit more or less, with a few requiring an extra 10 or 15 minutes. Hereafter the projects are referred to by number, rather than by name, to maintain anonymity of the interviewees.

Choice of areas of SE input for analysis

One of the first steps taken in preparation for the interviews during early 2008 was the selection of SE input areas for investigation. Based on documentation from the NDIA study and powerpoint presentations obtained from Eric Honour stemming from his work on the value of SE, we chose four areas from the list of eight, and developed interview questions for each. The list of chosen areas and number of questions asked in each area are the following:

- Market analysis: four questions
- Requirements analysis: three questions
- Verification and validation analysis: three questions
- Technical analysis: four questions

The complete list of 14 questions is given in Appendix B. The technical analysis portion of the interview focused on tradeoff analysis, and the order was switched with verification and validation analysis, compared to Honour and Valerdi's framework (as given in Table 2) since it improved the flow of the interview questions. The list of questions in the appendix is the final list after piloting the interview process and making adjustments; the original list had 14 questions.

Before final adoption of the chosen list of areas in advance of beginning the interviews, the list was vetted against Corning's strategic objectives to ascertain that they would lead to the exploration of areas that are important for project success within Corning. From Corning's perspective, the four areas can be interpreted as "careful and thorough consideration of the market", "translation of the value proposition into appropriate requirements and product tests", and "thorough consideration of multiple objectives and alternatives before choosing the best option (e.g., for partnering with an outside organization, for choosing a design solution, etc.)." The choice of the four areas was approved between the Corning and Cornell sides of the project prior to launch of the interviews.

On the project performance side, we adopted two sets of three questions, the first three revolving around the short-term concerns of budget-schedule-personnel, and the second three around long term concerns of product performance, delivery of value to customer, and deliver of value to Corning. During the interview question development process, we observed that although the latter three questions are of main interest to upper levels of management, positive results for the former three questions are usually a necessary condition for success.

Background information on projects interviewed

The character of the projects interviewed varied widely in terms of level of development, status (active or inactive), nature of the product, and project performance. Since projects were interviewed as interviewees became available and agreed to schedule an interview over the 11-month run of this stage of the process, the overall composition of project characteristics was evident only in retrospect. These differences between projects are summarized here.

First, of the 19 projects included, 7 had been shelved (and therefore were being interviewed retrospectively, since they were no longer active) and the remaining 12 were currently active. We did not interview any finished projects that had run to maturity. Including both active and shelved projects, the projects were broken down by their stage between stage gate reviews, or equivalent in cases of two projects that did not adhere to the Stage Gate review process. In the case of discontinued projects, the stage gate position at the time the project was discontinued is used. The breakdown is shown in Table 5.

Stage	Number of Projects
I	5
II	5
III	6
IV	3

Table 5 Breakdown of projects interviewed by level of Stage Gate advancement

The products also constituted a mix of products developed for either new or existing markets, with the majority based on process excellence, and a smaller set based on product integration excellence. For one project, it was agreed that this nomenclature did not apply. The breakdown of the remaining 18 projects is shown in Table 6. From the table it is clear that most of the products were based on process excellence, with just two based on product integration excellence. This situation is consistent with the market niche of a company like Corning, which specializes in developing keystone components for customers to use in discrete OEM products (e.g., LCD screens for laptops or televisions), while occasionally using its expertise to integrate components into a discrete product of its own.

Number of projects	Existing Market	New Market
Process excellence	11	5
Product integration excellence	2	0

Table 6 Breakdown of projects by market type and area of excellence (process excellence versus product integration excellence).
One of the 19 projects is intentionally omitted, see text.

Background information on project performance

At the beginning of the project, we planned to gather quantitative information on project performance, including budget and schedule performance as well as delivery of value proposition and return on investment to Corning. For products that were undergoing development as opposed to launched in the marketplace, this meant gathering data on projections of how well the value prop would be met and what the return on investment would be.

However, the data proved to be insufficient on two counts. First, budget information, and to some extent schedule information as well, suffered from what Honour calls the problem of "sitting on the line." (Honour, 2008) That is, if the project is progressing slowly and requiring a larger budget to continue to make progress at a satisfactory rate, the enterprise can simply increase the budget during the current fiscal year or the following one. The project therefore appears to be adhering to budget (i.e., sitting on the line where the ratio of actual to budgeted expense is 1:1), but in fact the underperformance of the project leading to increased expense is masked. As a second point, since all projects interviewed that were not discontinued prior to launch were product development in progress, the analysis would have relied on projections of future returns on investment to make judgments about project performance in terms of developing a successful product. These projections were available for only 3 out of 12 active projects (numbers 7, 8, and 17), which does not provide an adequate basis for analysis.

We therefore turned to the qualitative analysis of project performance, as outlined in Chapter 3. Of the 19 projects, 13 were found to have satisfactory performance, meaning that they were judged to be moving forward in a satisfactory way (or had been moving forward prior to being shelved in the case of discontinued projects), though not without the predictable range of imperfections and minor mistakes that accompany most projects to some extent. We will not provide further analysis of these 13 projects here; instead, we focus on the three projects that were judged to be superior and the three that were judged struggling. Recall that this is an evaluation of the projects performance and not the extent to which they use SE techniques, since otherwise the result is self-fulfilling, with projects that perform well in terms of using SE also earning high scores in the four SE areas.

The three superior projects are described in the following way:

- *Project 1*: This project featured relatively rapid advance through the stage gate process, ahead of what was predicted in the early stages of development. Although it started as a project with no existing market ("technology-push"), it rapidly transitioned to being a "customer-pulled" project, with 50 members of the project team's customer data base expressing interest in the project once it reached maturity. Lastly, the interviewees, without prompting, expressed the opinion during the interview that the product was developing well.
- *Project 9*: This project is divided into three phases, and phase 1 out of 3 was adopted enthusiastically by customers, ahead of the interviewees' expected timing. The goal was for 80% of the target market to adopt the product in the desired timeframe, but the actual adoption was close to 100%. Lastly, praise from individual customers for the business value of the product was mentioned during the interview.
- *Project 17*: This project featured rapid, accelerated advance through the stage gate process. The principal customer for the product issued a strong endorsement after successful 'red flag' testing. Documentation presented in the interview suggested that the ROI might eventually amount to somewhere between 278% and 416%, depending on which scenario unfolded. It had also won an internal Corning award for product development excellence. Lastly, the interviewee expressed an unsolicited opinion that the product was developing well.

In the same way, descriptions of the struggling projects can be given as follows:

- *Project 7:* This project encountered several problems, including the reworking of a primary component in mid-development which could have been avoided with proper initial development, according to the interviewee. It also encountered delays and an inability to meet interim deadlines, beyond the norm based on the range of projects interviewed in our study. The project at one point encountered a large cost overrun, requiring a request for a budget supplement that triggered a review of its financial operations by outside management. Lastly, the project team was not able to carry out planned tests because the resources needed for the tests (staff, financial resources) were diverted to other purposes.
- *Project 8:* This project suffered from lack of clear communication, in that, according to the interviewee, higher levels of management have ongoing

unrealistic expectations about the ability to meet targets for technical development milestones. The project's customer also expects that the product will meet durability expectations, although the interviewee expressed some doubt that the product would meet the target. The project also suffered from delays beyond the norm.

- *Project 11:* Although this project generated some interesting engineering learning over its lifetime, it violated the PDMA principle of "move forward or kill early", and, as such, appeared to "wander" for years in search of a clear value proposition. It spent a long time first in stage 1, then passing to stage 2, then returning to stage 1. The project was eventually shelved, although at the time of its discontinuation, according to the interviewee, the product was making progress. This circumstance is also judged to be an attribute of a struggling project, since the progress could have come earlier to help the project to succeed, or the potential of the project could have been communicated better to outside stakeholders in order to convince them to continue it.

As a commentary on these six projects, it should be noted that although in general financial ROI data were not available during the interviews, they were available for projects 7 and 8, and these two projects presented financial data with breakeven coming only several years in the future, and at a time that was uncertain, contrasting with the strong financial performance and early breakeven of project 17. As a second comment, for both projects 7 and 11, interviewees described the level of technical challenge of the project as being particularly high. We did not use this factor to modify the scoring of the project, which is discussed at the end of the analysis in Chapter 5.

Corroboration by Systems Engineering Directorate

The responsibility for interviewing projects in the case of this research fell to the Cornell side of the research team. In general, the Cornell interviewer worked independently from the Corning side to carry out the interviews and analyze the answers afterward.

On two occasions, however, the two sides also took steps to compare notes about impressions of different interviews, to ascertain that the perceptions of the Cornell side were generally realistic (i.e., not overrating or underrating projects, or missing key information in assessing project performance). In the first instance, the team discussed the interview for Project 1 after it had taken place, and agreed that it would be used as a benchmark for a high-performing project. In the second instance, the team discussed the case of Project 7. The Corning side knew in advance that this project was struggling, and the Cornell side recognized this fact as well during the interview. In discussing Project 7, the two sides compared notes about what the interviewees had revealed about the problems encountered by the project. One slight divergence was that the interviewees gave a more optimistic assessment of the future prospects for the project than was the impression of the members of the Systems Engineering Directorate. Otherwise, it appeared that the interviewees had been candid about the limitations of the project. From the purposes of the methodology, this was a useful test of the ability of an outside interviewer to gather potentially negative information about a project, and its result was encouraging.

Conclusion

This chapter has focused on the adaptation of the general methodology to the application within Corning, and also on the background information gathered about the various projects. This information serves as a foundation for the analysis of the information gathered in the next chapter.

Chapter 5. Analysis of findings

In this chapter we turn to the results from the analysis of the 19 projects interviewed at Corning. In the first part, we look at differences in levels of SE input to projects, and possible explanatory factors for variations in these levels. Next, we evaluate the level of correlation between SE input and project performance. Thereafter, we discuss some findings from looking at quotes from the interviews. We conclude with limitations and caveats for the findings.

Differences in levels of SE input

The 19 projects differed widely in the amount of SE found to be in use, although all projects had at least some SE. Most projects were able to earn a maximum of 14 points, although for some, questions were ruled out as not relevant, so that the maximum number of points available was less; in addition, some projects earned half points for some of the questions. As shown in Figure 6, the number of points earned ranged from 40% (project 19) to 93% (project 17). The mean and standard deviation values for the projects were 58% and 13%, respectively. Therefore, the 13 projects in the range from 45% to 71% (blue bars in the figure) were considered to have medium SE input, with those outside of this range to have lower and higher input (red and green bars, respectively).

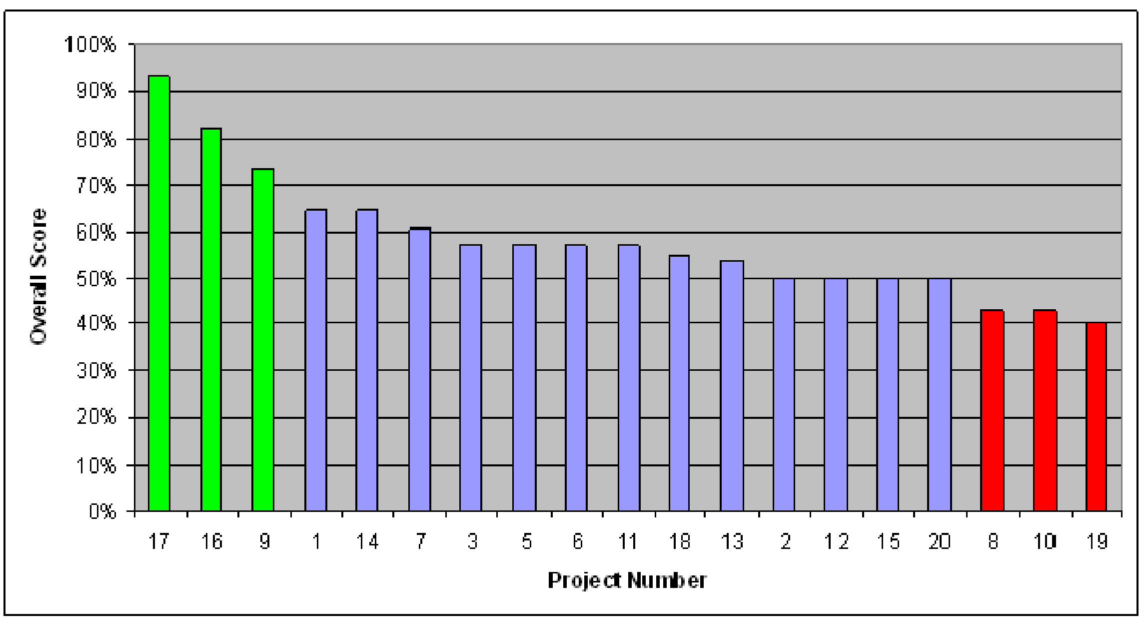


Figure 6 Projects ranked in order of decreasing overall SE input score, with green, blue, and red bars to indicate higher, medium, or lower SE input.
Note: higher = μ + 1 S.D., lower = μ - 1 S.D. See text.

Projects also varied by average number of points earned in each of the SE areas. Figure 7 shows the average percent of points earned, with market analysis labeled "market", requirements analysis labeled "TPMs", verification/validation labeled "Testing", and technical analysis labeled "Tradeoffs." As shown, market analysis was highest at 75% earned on average. Since the projects were all either in-progress or shelved, they would have had more opportunity to carry out market analysis than the other areas. Conversely, some early stage projects had not had as much opportunities to earn the technical points, some interviews stated that they were aware of tradeoff analysis but had not yet had an opportunity to use it.

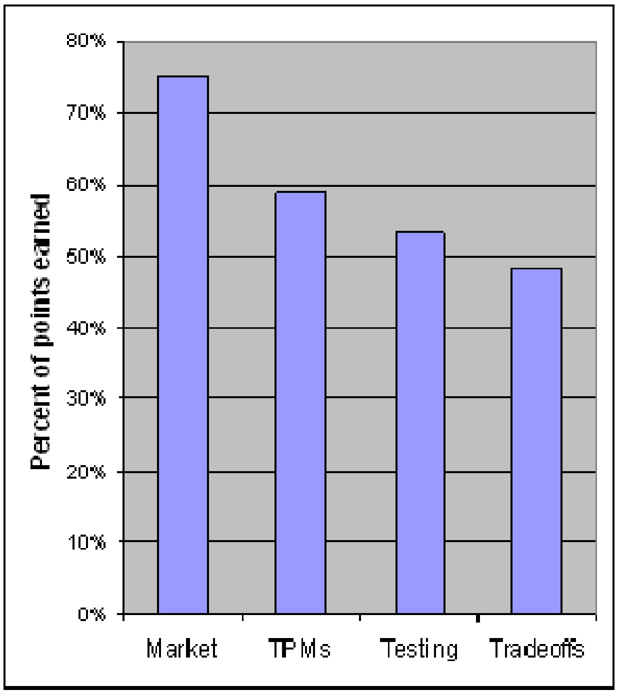


Figure 7 Average points earned in each of the four SE input areas

The results from comparing total scores of individual projects and amount of SE input from different areas can be combined into a single figure, as shown in Figure 8. This figure resembles Figure 6 except that the colors in each bar now represent the contribution of each area to the overall score attained by the project. From visual inspection, it can be seen that the darker blue bars of market analysis are dominant and appear for every project, whereas for some other areas, the color does not appear at all, i.e., the project earned 0% in that area.

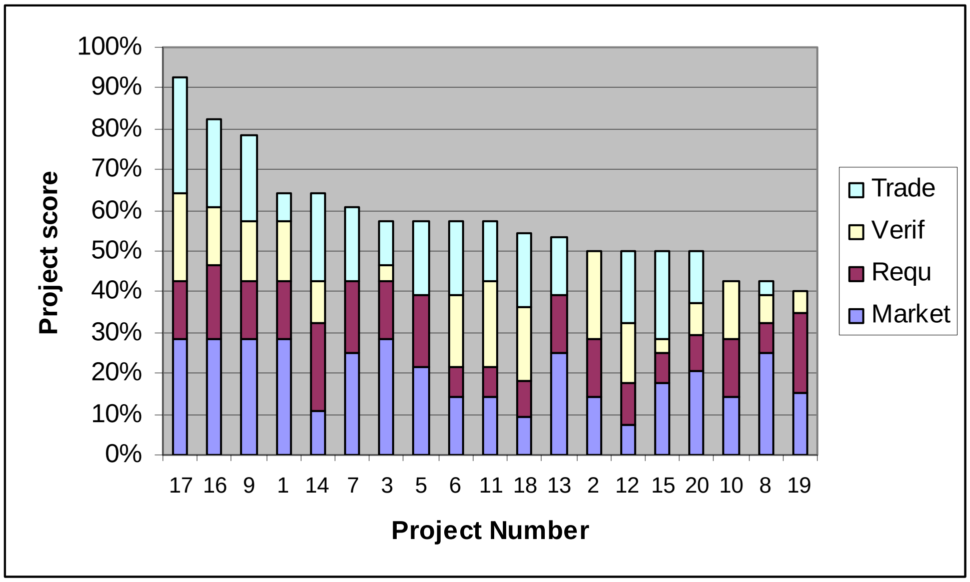


Figure 8 Projects in order of decreasing score, showing contribution of SE areas to overall score.

At the beginning of the project, we planned to analyze the effect of the "process versus product integration, new versus existing market" matrix on level of SE input. However, since there were only two product integration based projects in the mix, we focused only on the difference between new versus existing market projects. As shown in Figure 9, existing market projects on average earned slightly more points than new market projects (59% versus 52%), but in the case of the projects in our study, they had on average been under development longer. In any case, the difference between the existing and new groups is not thought to be significant, and we did not pursue further analysis of it.

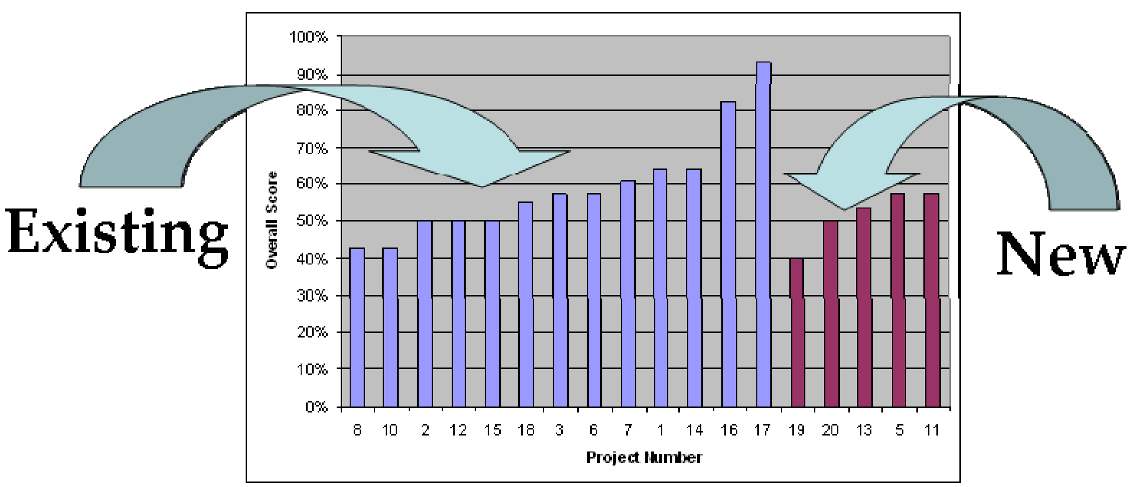
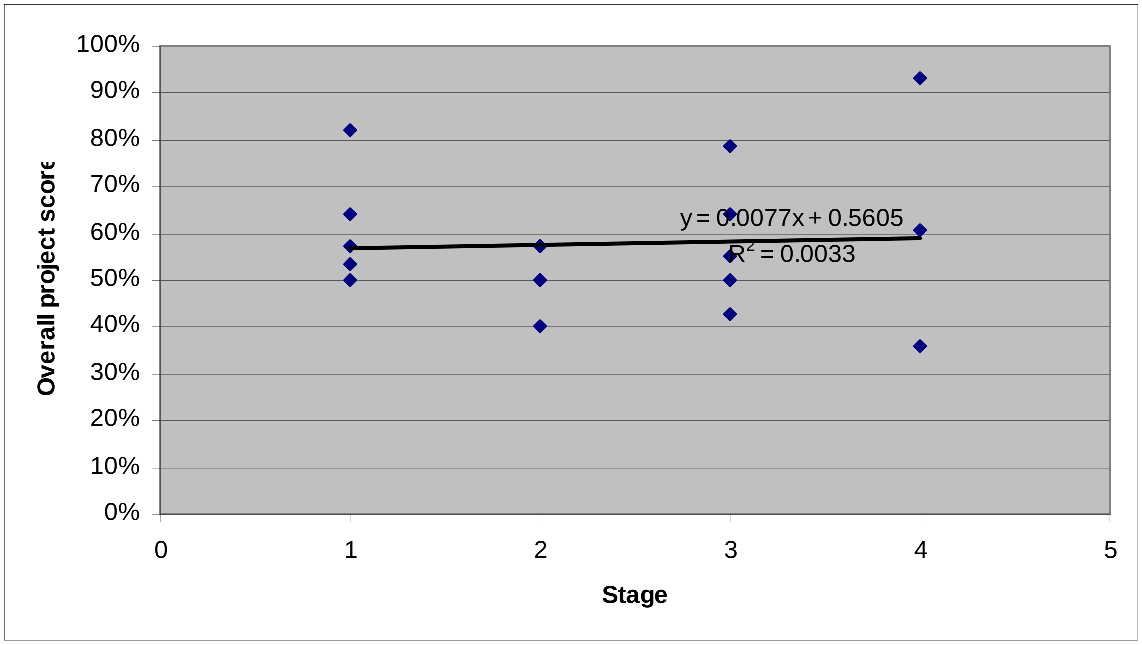


Figure 9 Comparison of ranking of existing market projects (blue) versus new market projects



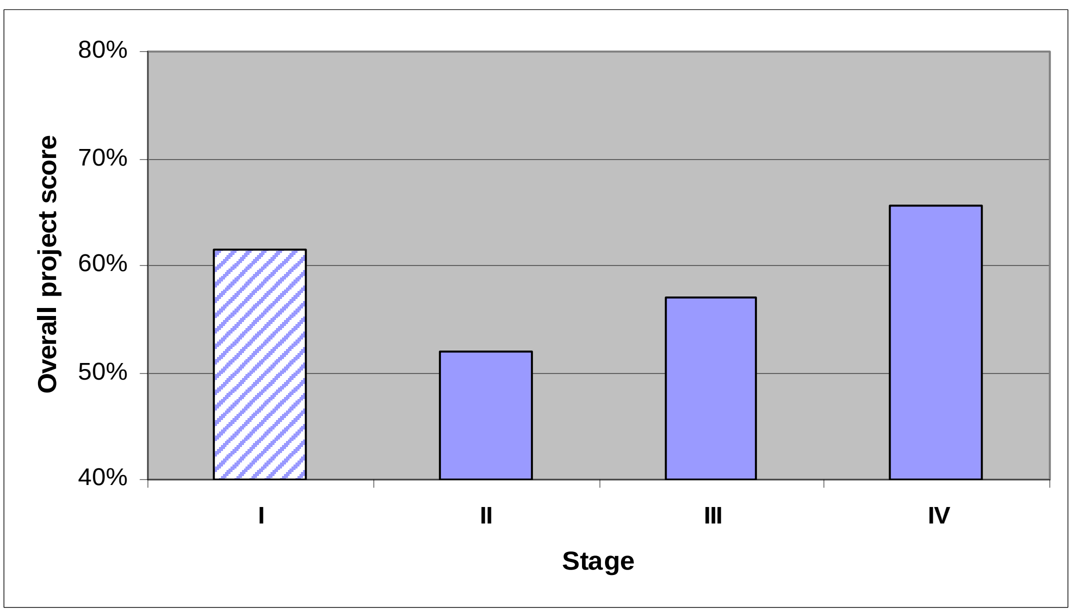


Figure 10 Project score by degree of stage gate completionin stage gate development process: a) individual project score scatter chart, and b) average score by stage gate category.

As a final piece of background about points earned for SE input, we tested the relationship between stage of development of the project and number of points earned. This relationship is illustrated in Figure 10 for both the individual data points (scatter chart) and for the average value earned by projects in each category (bar chart). In the scatter chart, the labels on the x axis correspond to increasing degree of advancement in the Stage Gate process, i.e., 1 = not yet passed Stage I review, 2 = passed Stage I review, and so on. The results of this analysis were mixed. On the one hand, the scores for Stages I to III indicate that with increasing number of stages passed, the projects scored higher. However, the Pre-I projects had an unusually high score, so that the overall trend was not clear. The goodness of fit value in the upper chart is $R^2 = 0.01$, however, if one removes the Pre-I points from the chart, the value improves to $R^2 = 0.15$ (this is not shown in the figure). Thus it appears that for many projects, use of SE increases with project evolution, but it is also possible to have a project that uses a full suite of SE tools early in the process: market analysis, requirements engineering, verification and validation, and tradeoff analysis.

To conclude this section, the findings for individual projects in terms of their level of development, use of SE, and project performance can be summarized in Table 7 below. In the table, the four SE input areas are marked as "mkt", "req", "verify", and "trade" for the four areas of market analysis, requirements analysis, verification & validation, and tradeoff analysis, respectively. Note that the overall score is based on the percent of total points available earned, and is therefore different from the arithmetic average of the four areas. In the rightmost column, the projects are marked "++" for superior, "OK" for satisfactory, and "—" for struggling.

Num	Stage	Project Scores					Perf
		Mkt	Req	Verif	Trade	Overall	
1	III	100%	67%	67%	25%	64%	++
2	III	100%	67%	100%	0%	50%	OK
3	II	100%	67%	17%	50%	57%	OK
5	II	75%	83%	0%	62%	57%	OK
6	I	50%	33%	83%	62%	57%	OK
7	IV	87%	83%	0%	62%	61%	--
8	IV	87%	33%	33%	12%	36%	--
9	III	100%	50%	67%	75%	79%	++
10	III	50%	67%	67%	0%	43%	OK
11	II	50%	33%	100%	50%	57%	--
12	II	33%	37%	67%	62%	50%	OK
13	I	87%	67%	0%	50%	54%	OK
14	I	37%	100%	50%	75%	64%	OK
15	III	62%	33%	25%	75%	50%	OK
16	I	100%	83%	67%	75%	82%	OK
17	IV	100%	67%	100%	100%	93%	++
18	III	50%	50%	67%	50%	55%	OK
19	II	75%	67%	50%	0%	40%	OK
20	I	83%	33%	50%	37%	50%	OK

Table 7 Individual results for Projects 1-20, including stage, individual and overall SE input, and project performance.

Effect of SE on project performance: graphical relationship

Limited sample size notwithstanding, there appeared to be a correlation between use of SE and overall project performance. Before introducing the mosaic diagrams, the correlation can be observed by adapting Figure 6 above and color-coding projects by project performance instead of amount of SE input, as shown in Figure 11. As shown, the superior projects (green bars) are at or near the top in terms of project performance. In addition, Project 1 (64%, Stage II) might have scored higher, but the interviewees had not yet made extensive use of tradeoff analysis tool, so the project scored low in this area. During the interview it appeared that there would be opportunities to use this technique later in the project; if so, the score would be even higher, and in line with Project 17 (93%, Stage III). Scores for the struggling projects were less clear: these projects were not necessarily at the low end in terms of overall SE score. Note, however, that Projects 7 and 8 were both Stage III projects, so compared to a superior Stage III project such as Project 17, they appear to be underperforming and to have less SE input. We return to this issue in the discussion of individual SE areas in the next section.

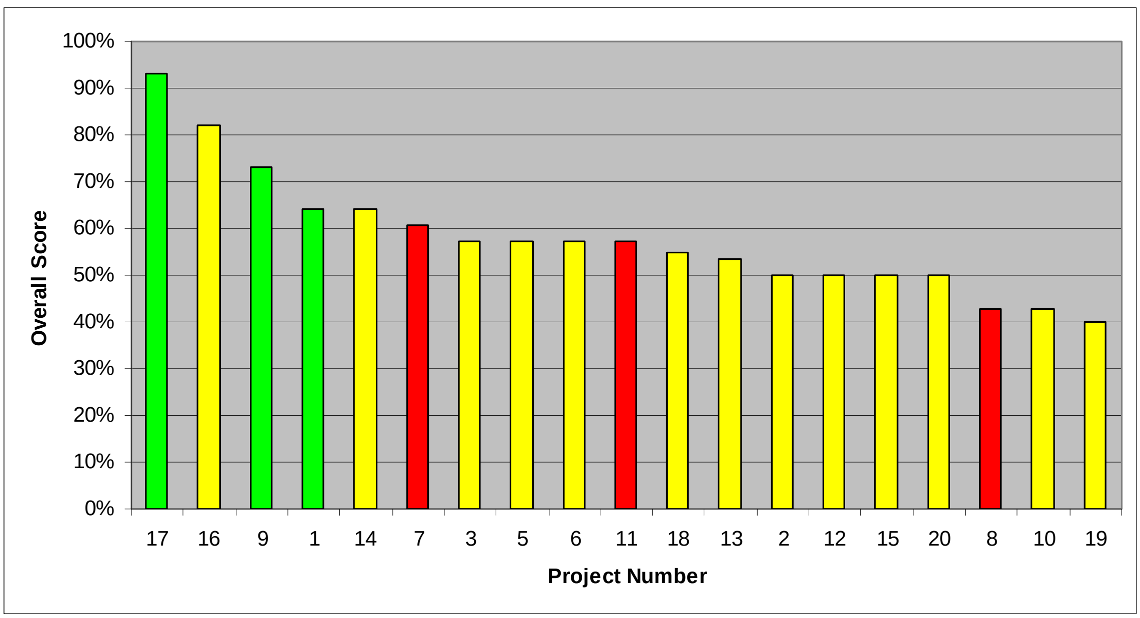


Figure 11 Projects ranked by decreasing overall SE score and color-coded by project performance
Note: green = superior, yellow = satisfactory, red = struggling.

The correlation between overall SE input and project performance is also evident in the mosaic diagram in Figure 12. As mentioned above, the projects are clustered in the middle band, with 13 out of 19 projects having medium SE input. Most of these also have satisfactory project success, with two projects struggling, one superior, and the rest satisfactory (10 total). The lower SE input bar had only satisfactory and struggling projects, and the higher SE input bar had only superior and satisfactory projects, which was consistent with expectations. Visually, the diagram gives the appearance of correlation, with decreasing red color and increasing green color as one moves from left to right.

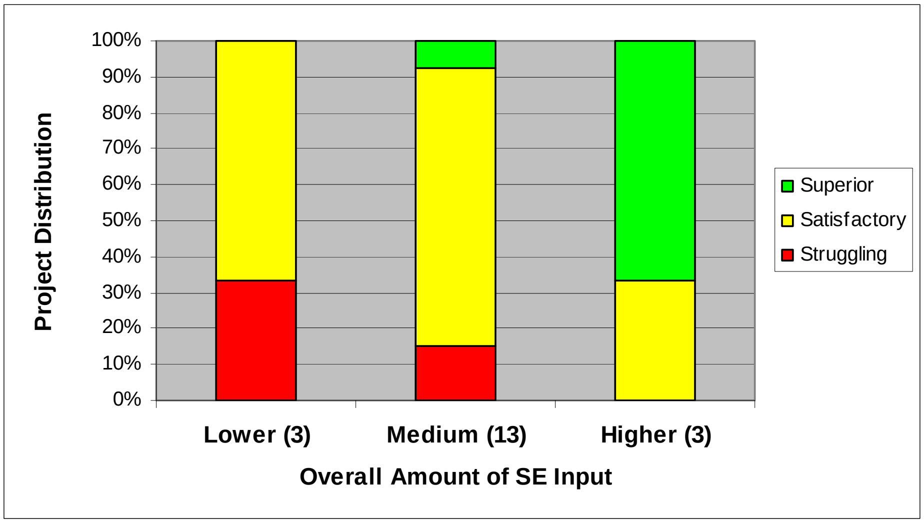


Figure 12 Mosaic diagram of project performance as a function of overall SE input.

To further investigate the correlation between SE input and project performance, a scatter chart was developed using a scoring system from 1 to 6 points as the basis for the dependent variable, as shown in Figure 13. In order to further disaggregate project performance, each performance category is divided into two point levels, i.e., struggling projects can earn 1 or 2 points, satisfactory 3 or 4, and superior 5 or 6. A judgment was then made for each project about how many points should be awarded, based on the interview. Although there is a fair amount of scatter around the trend line, a loose correlation can be observed in this way as well ($r^2 = 0.30$).

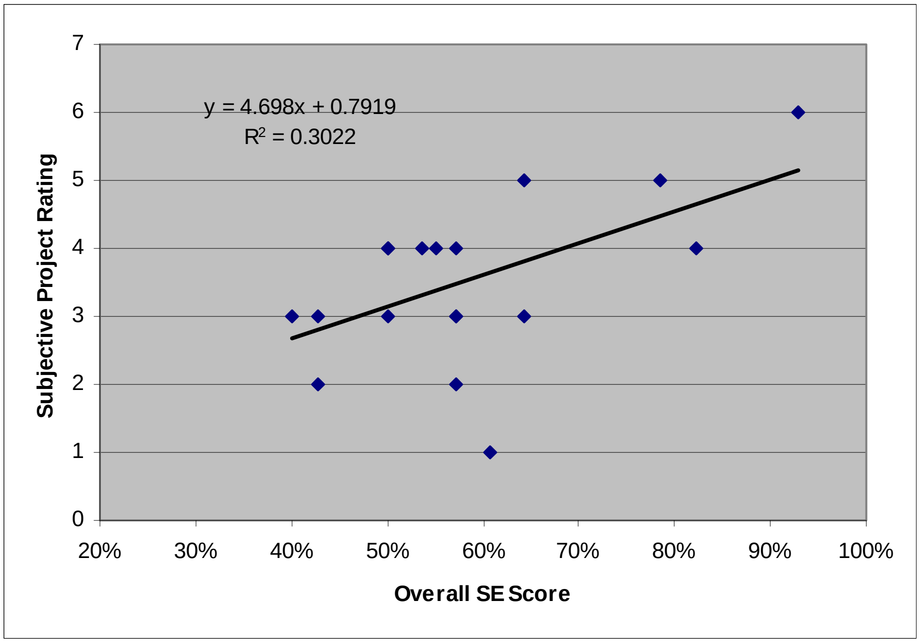


Figure 13 Scatter chart of project performance as a function of overall SE score, with project performance evaluated on a 1 to 6 scale.

Along with analysis of overall SE input, the Corning projects are analyzed for correlation between SE input in specific areas and project performance. For each of the four SE areas, calculation of mean and standard deviation of scores for that area leads to a new breakdown of the 19 projects into lower, medium, and higher input areas. Also, analysis of specific SE tools sometimes revealed in which specific areas a struggling project might have a lower score and, based on the notes from the interview, the underlying "story" would support the point that a missed step contributed to problems in the conduct of the project.

As an example, the market analysis mosaic diagram in Figure 14 shows the breakdown of the projects into three roughly equally sized groups of lower, medium, and higher input projects. For some of the areas like market analysis, the projects were not as concentrated into the "medium input" bar. Visually, the figure shows a rough correlation, with all of the superior projects and none of the struggling ones in the higher input bar. The struggling project in the lower input bar is Project 11, which earned a 50% score on market analysis, compared to the overall average of 75%. In particular, the project earned a half point on each of the market segmentation and customer analysis questions in this area, and no points on the value proposition (refer to Appendix B for the text of individual questions). This finding was consistent with the observation that the project lacked a clear focus (see Chapter 3). In general, many projects scored well in this area, among them all three of the superior projects, which scored 100%.

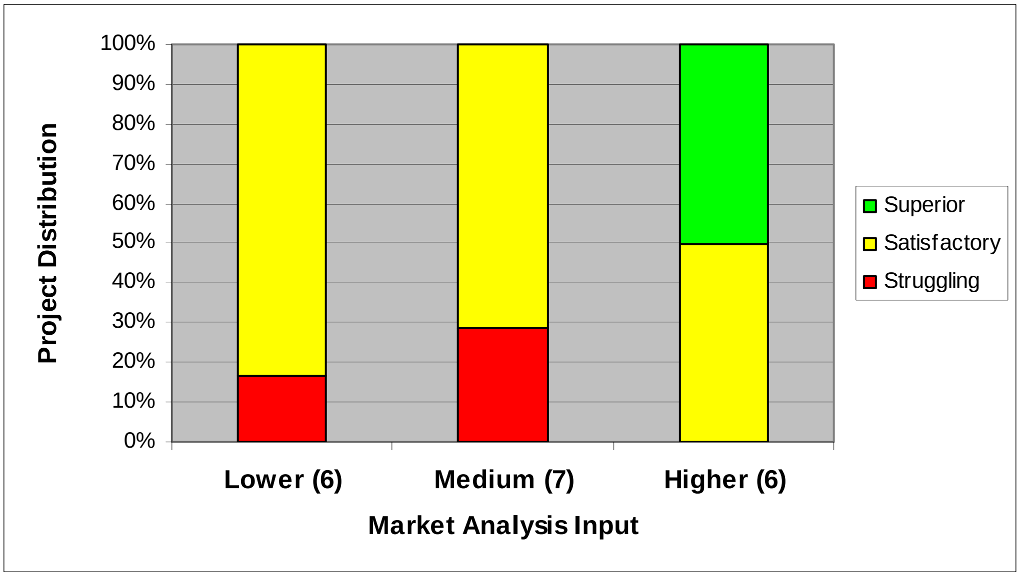


Figure 14 Distribution of project performance values as a function of market analysis input.

For requirements analysis, the mosaic diagram was less clear, as shown in Figure 15. All three of the superior projects clustered in the "medium input" bar, while one of the struggling projects (Project 7, requirements score 83%) was one of the four projects in the higher input bar, i.e., the red portion of the bar in the lower right. Project 7's overall high score is possibly misleading, however, because a weak statement of the key technical performance measures (TPMs) was, in our view, directly responsible for the rework that led to cost and schedule overruns. Other struggling projects behaved more "rationally", i.e., the two other projects had lower input in this area (red bar in lower left). Both of these projects presented TPMs that they used in the project, but these TPMs were not clearly connected to the value proposition or to a schedule for making sure they were met during project development. The overall mean and standard deviation for this area are 59% and 21%, respectively, whereas Projects 8 and 11 each scored 33% in this area.

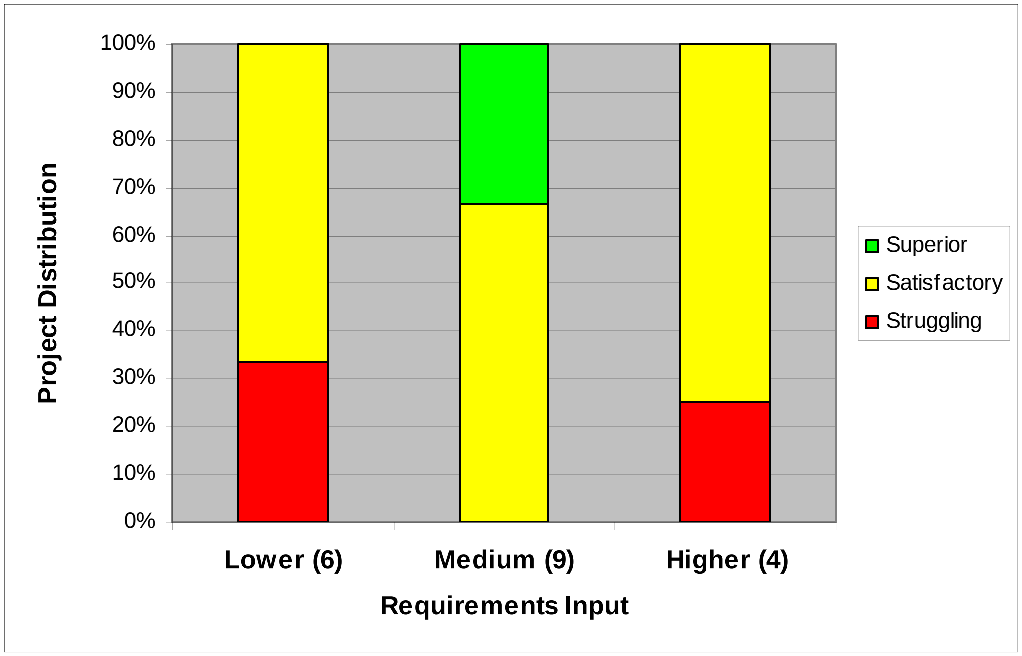


Figure 15 Distribution of project performance values as a function of requirements analysis input.

Like requirements analysis input, verification/validation input had a less clear pattern (Figure 16). The mean and standard deviation for this area were 53% and 33%, respectively. The three struggling projects distributed themselves evenly across the three bars (red portion). Project 11 earned 100% of the points available in this area, indicating once again that it was possible for projects to do well in some of the SE areas and still struggle over all. Project 7, on the other hand, did not earn any of the points available in this area due to problems with test planning and execution in the project. Of the superior projects, Project 17 had a higher level of input in this area while the other two had medium input.

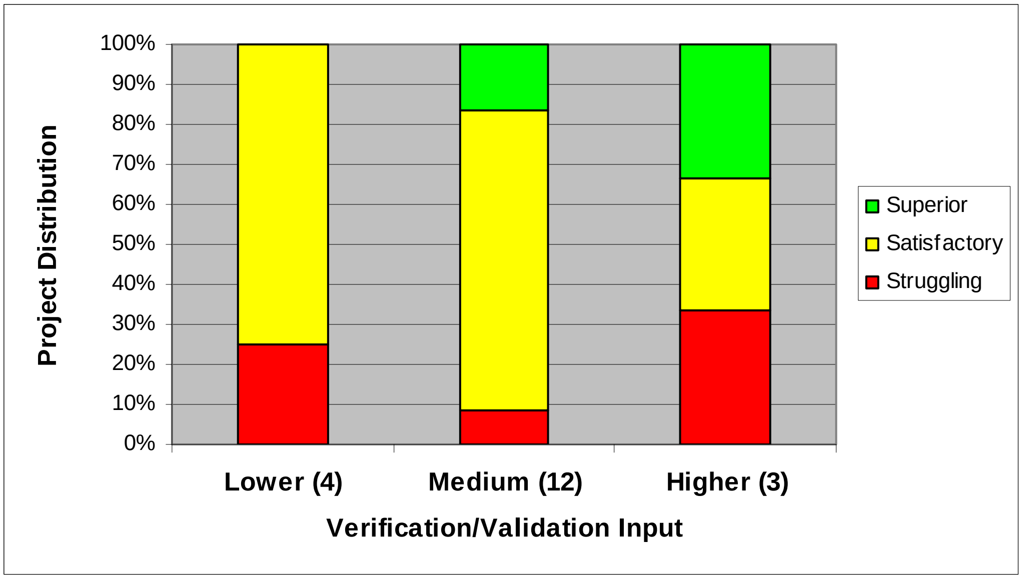


Figure 16 Distribution of project performance values as a function of verification and validation input.

Finally, the tradeoff analysis area showed a more intuitive pattern for correlation between input and performance, with all struggling projects in the medium column, and all superior projects in the medium or upper columns, as shown in Figure 17. (Note that this category is called "Technical Analysis" elsewhere in the literature.) The mean and standard deviation values for this area were 49% and 29%, respectively. In general, tradeoff analysis was not as commonly used in the projects interviewed as some of the other techniques, and only one project, Project 17, earned 100% of the points available (green bar on the right). All three of the struggling projects had medium amounts of tradeoff analysis input (scores ranging from 25% to 62%), so it is not possible to discern any pattern of low tradeoff input leading to poor project performance.

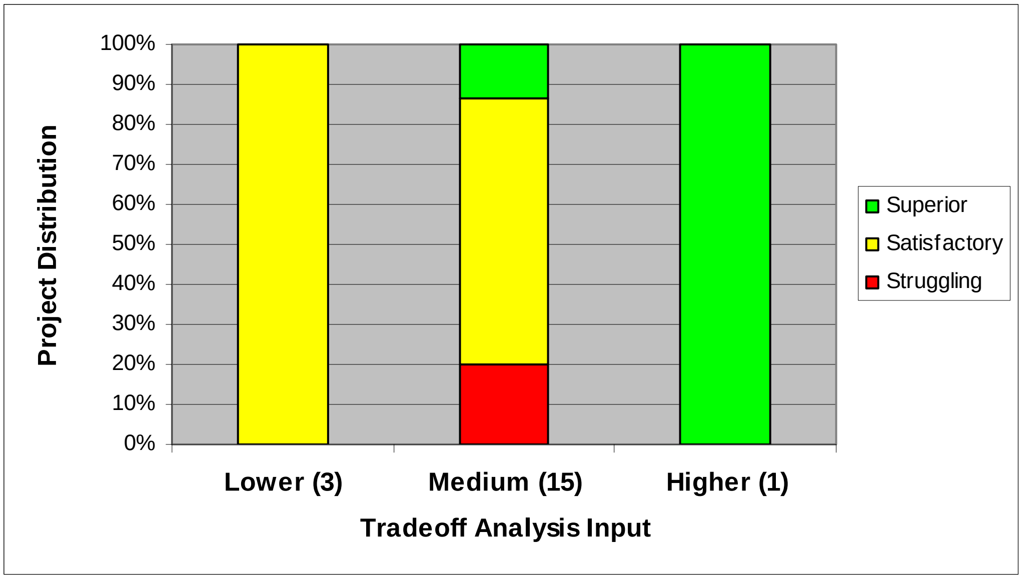


Figure 17 Distribution of project performance values as a function of tradeoff analysis input.

To conclude the discussion of individual SE areas, it is worthwhile to review which areas stand out as having had an impact on performance. The most general statement that can made regarding the struggling projects is that none of them underperformed across all of the four areas, but each of them were subject to problems that could be traced to one or more of the four areas. In these cases, the project might score poorly across all of the questions in the area, or it might score poorly on just one of them. For example, projects 8 and 11 scored low across all the requirements questions, and project 11 scored low across the marketing ones, while project 7 scored well overall in requirements but had problems with one of the questions, which correlated with problems in the project. Project 7 also struggled with verification and validation, and this was correlated with struggles in the project to complete testing of the prototype. In this way, analyzing the answers to the areas of marketing, requirements, and verification/validation revealed how problems in product development could be linked back to shortcomings in the use of SE. The situation with tradeoff analysis was different, at least in terms of the projects studied: while the mosaic diagram shows a relationship between tradeoff analysis input and project performance, there was no single instance of a failure to use tradeoff analysis creating problems in the development path.

The results regarding the superior projects are more general. We did not note any instance of the particularly skilled execution of one of the SE areas leading to breakthroughs or advances in the product that made it stand out among the range of projects interviewed. Rather, the three superior projects all carried out the SE areas competently across the board. All projects scored in the 50% to 100% range in all four of the areas. The only exception was Project 1 scoring 25% on tradeoff analysis. However, based on the conversation during the interview, we have the impression that opportunities to use tradeoff analysis may arise during the subsequent run of the project (they may have done so already, since the project was interviewed more than one year ago). Given the overall success of the project leadership in managing its course effectively, they would probably take actions that would earn most of the points in this area, were the interview to be conducted again in the future.

Effect of SE on project performance: case study relationship

In the previous section, the relationship between use of SE and project performance is established graphical, using mosaic diagrams to cluster projects into one of three SE input areas and then observe the effect on project performance. In this section we connect the description of superior and struggling projects introduced in Chapter 4 to anecdotes about the degree of use of SE that were revealed in interviews. One of the strengths of the interview process is that, with enough time spent discussing the background for the questions asked, sufficient information is supplied to be able to write about the projects in a case study format.

The superior projects had common elements of a strong understanding of the market for the product, crisp translation of the value proposition into the product requirements, and a disciplined approach to testing that led to successful prototypes praised by customers. As a result, all three projects scored very well in the first three SE areas. Internal stakeholders within Corning would likely agree that the development paths of these three projects reflect strong project management. What many of these stakeholders may not realize is that the steps taken to ensure a successful pathway are in fact elements of the SE approach to product development.

Whereas the superior projects were successful for similar reasons, the struggling projects were more different from one another, and need more careful consideration in turn. Project 7 appears to score reasonably well (though not 100%) on both marketing and requirements. However, both the value proposition and the technical performance measures were weakly represented in the interview, and the project earned half points on each of these questions. These missteps set up the project to de-prioritize some of the key requirements of the customer, and the product developed in a wrong direction. When the project team was forced to re-work much of the product development, resources were redirected toward correcting earlier errors, and as a result, sufficient resources were not available for verification and validation, leading to low scores in this area.

Unlike project 7, for project 8, less than full points on the market analysis and hence less than perfect handling of this stage of product development appeared not to affect the course of product development. In other words, the market analysis seemed strong enough. Instead, problems began to develop in the requirements and testing stages. From the interview, neither the product requirements nor the test plan were clearly linked back to the value proposition, and there was no clear schedule for meeting requirements or carrying out tests. These gaps contributed to differing expectations between the project team and internal Corning stakeholders about the ability to meet scheduled targets going forward, and between the project team and customers about the ability of the product to meet requirements. Hence the description of "lack of clear communication" as mentioned in Chapter 4.

Finally, for Project 11, problems began in the market analysis stage and continued through requirements. The lack of focus described in Chapter 4 is attributed to the lack of detail in the market analysis stage (market segmentation, Corning's target segment within the larger market) that would allow the project to either focus in on a target product that would allow the product to advance through the Stage Gate process, or conclude early that there was no appropriate market for the product and shelve the project (which was ultimately the result, although after many years of effort). Interestingly, Project 3 faced a similar situation, but a clear market analysis and conclusion that the initially perceived market was not sufficient to support the development of a technology led quite rapidly to that project being shelved. Thus Projects 11 and 3 faced similar circumstances, but had different outcomes. Although Project 11 earned respectable points in verification/validation and tradeoff analysis, these stages were in vain, because the product was not built on a solid value proposition.

In looking at all three struggling projects, a similar conclusion can be reached to that of the superior projects. A technical person who is not a systems engineer could look at these projects and see that they are struggling. However, the new information is that the struggles of these projects were brought about by failures to use, or use effectively, key SE tools that can keep a project on course.

Analysis of quotes obtained from interviews

Along with scoring of answers to individual questions posed in the interviews, we have retained a number of quotes (sometimes referred to as "pithy quotes") from interviewees that shed further light on the answers given, beyond what can be easily captured in the direct answer to a question. A total of 16 quotes that merited retention are given in Appendix D. In this section we will present and discuss a limited number of these quotes. Note that the words of the speaker may not have been captured exactly, 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, as follows. First, the quotes were read through once to see what general categories emerged, resulting in the following list of three categories:

1. Quotes that supported the benefits of using SE
2. Quotes that illustrate the challenges with using SE generally
3. Quotes that illustrate the challenges with using SE in the specific case of Corning

We then place each of the quotes in one of the three categories, and found that all 16 could be categorized in one of these ways. The breakdown of quotes was 3, 5, and 8 quotes for categories 1 through 3, respectively. In the remainder of this section, a sampling of highlight quotes are presented and discussed.

Quotes that supported the benefits of using SE

In general, these quotes gave further details about how using SE made a difference in project performance.

> "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."

This quote speaks to SE at work in making projects perform better. As in this case, SE is not always present in a project from its inception. Here, the interviewee joins the project with the expressed purpose of bringing SE to it, sees that one area of weakness is verification and validation, and introduces the concept of "design for testability" with immediate positive results.

> "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."

Like the previous quote, the interviewee shows how introducing SE can bring rigor to the market analysis and help the project management and its stakeholders to make the sometimes tough decisions to terminate a project, consistent with the PDMA philosophy of "bring forward or kill early." Although not discussed in the quote, the interviewee went on to discuss how some within the project resisted this decision in the hopes that the project might continue and eventually find a market. However, this situation only serves to illustrate how, without a strong connection to market analysis, members of a project team can become invested in the unjustified continuation of a project because of the work they have already put into it.

Quotes that illustrate the challenges with using SE generally

Some of the quotes illustrate the challenges with implementing SE techniques in general. These challenges are thought to be applicable across all types of organizations that might implement SE.

> Q: "Given that the market analysis outcome for the product (Interview #16) was that the market was not large enough, wouldn't it have been better to wait for market analysis results before continuing development?" A: "You have to pursue market analysis and development simultaneously. If you wait for the market analysis answer to come back before starting development, you're too late."

This quote shows the challenges that the product development team faces in deciding how to allocate resources. A product needs a solid market analysis in order to know whether or not it is viable to go forward with development. On the other hand, timing is important as well: if the market analysis is positive, the team needs to be ready to move forward as rapidly as possible in order to launch the product in a timely fashion, given the competitive nature of the marketplace. Note that not all products interviewed had the same pressure to launch quickly, some products had more leeway to take as much time as necessary to find a solution that works.

> “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 SE is not a priority for the stakeholders, the resources are diverted elsewhere, and the problems in the project continue to fester. We expect that this situation is likely to be encountered in other enterprises as well.

Quotes that illustrate the challenges with using SE in the specific case of Corning
Along with quotes that illustrated challenges for SE that transcend the specific organization, some of the challenges encountered were specific to the characteristics of Corning. These characteristics include the focus on developing keystone technologies for a diverse range of applications (from optical electronics to life sciences), the focus on materials science as a key competency, and the strategic emphasis on developing breakthrough technologies as opposed to incremental improvements (i.e., “home runs” rather than “base hits”).

> “The project was budgeted to experiments, not to deliverables. It's all learning, which is different from meeting statements of deliverables.”

This quote shows the difficulty of using adherence to budget as a measure of project performance in some situations. Sometimes it may be the right thing to do to spend more on a project than was budgeted to thoroughly learn about some aspect of a project, as a necessary foundation for eventual product success. When projects overrun their budgets in this situation, it may be difficult to tease out how much was due to the need for learning, and how much was due to mis-execution that might have cost less if it had been done differently.

The following two quotes convey a similar meaning and are presented together:

> “The moment you try to lock research scientists into a rigid timetable of test schedules and deadlines, they start running for the exit.”
> "How do you plan and schedule testing when you don't even know enough about the topic to know what it is you are going to test?"

These quotes show the challenges associated with coming up with test plans and schedules in a research-oriented environment. Looking back across all the interviews, it is clear that, in some situations, there simply is not enough known to design for testability at the outset. Furthermore, attempts to force a plan and schedule onto the research scientist may indeed stifle innovation. At the same time, in other situations the information was there, and the project earned high marks in the verification and validation area. Perhaps a reasonable compromise is to always consider design for testability, and implement it where possible.

In summary, this section has illustrated how SE has been both beneficial and challenging for the projects interviewed. At the same time, it also illustrates how retaining quotes from interviews as part of the methodology is a useful activity to increase the amount of learning possible from the interviews and their analysis.

Conclusions and caveats

The learning gained from the implementation of the methodology within Corning can be summarized in the following five conclusions:

1. *The methodology is feasible.* Based on the Corning experience, it was feasible for a team to draw up an interview format and then have a single interviewer gather the information needed to support analysis of the use of SE techniques. We interviewed 20 projects in the space of about one year, and all but one of the interviews provided useful information. Also, from the Corning Systems Engineering Directorate side we learned that when the purpose of the research was explained to prospective interviewees, there was widespread interest in and support for our project, and no reservations expressed about taking the time to participate in an interview. Since to the best of our knowledge of the literature and of previous SE research, this exact type of study had not been implemented before, the feasibility of carrying out this kind of study constitutes the first of our conclusions.
2. *Varying degrees of SE input were observable between projects:* although some interviewees were more familiar with SE than others, all projects were using SE tools to some degree (whether they used SE names or not), and some were using these tools significantly more than others.
3. *Correlation was observed between SE input and project performance.* For both superior and struggling projects, correlation was observed between better performing projects having more SE, and lower performing projects having less SE. This conclusion supports the fundamental claim that SE has a positive effect on project performance.
4. *Projects with lower performance had specific SE weaknesses rather than being weak across all areas of SE.* The three projects judged to be struggling were not scoring poorly across all four SE areas, and in some instances scored well in certain areas. Instead, the weaknesses in the project that were affecting it as a product development process could be tied to limitations in its use of techniques in one or two of the areas (e.g., lack of a clear market analysis leads to lack of focus in the project).
5. *For project success, the most important linkage of SE tools is between market analysis, requirements engineering, and testing.* In other words, each project

6. *The research begun in this report is worthy of continuation both within Corning and outside of Corning.* The findings in Conclusions 1 to 5 above support continuing the research by following the evolution of the projects studied and applying the learning to other projects. Also, the research should be expanded by implementing similar studies in other enterprises, both to assist these other enterprises with their use of SE, and to learn more about SE generally. Specific recommendations will be made in Chapter 6.

Several limitations and caveats arise from the study as well, outlined in the following five points:

1. *Limited number of interviews:* 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, this approach necessarily limits the number of interviews that can be completed in a finite amount of time (one year in this case), due to the need to find time for interviews for both interviewer and interviewee. Ideally, it would have been helpful to have more interviews, so as to strengthen our findings. For comparison, the NDIA study was able to incorporate 46 projects across multiple participating enterprises.
2. *Evaluation of project performance based on quantitative success of final products in the marketplace was not possible*: before beginning the interviews, our goal was to gather data on product success in the marketplace for completed projects (i.e., Stage V), or gather data on project performance that would allow us to project future product success for ongoing projects. However, we did not end up with any Stage V projects in our interview mix, and data for projecting future performance proved not to be available in sufficient quantity to support an analysis. We have therefore opted for a subjective evaluation of performance instead. Although the reasons for labeling certain projects as superior or struggling are given in Chapter 4, they are based on the interviewer's best judgment of the information presented, and might be disputed by others. Also, since all projects are either discontinued or in progress, the ultimate fate of the

ongoing projects in the marketplace is unknown, and projects that are struggling now may eventually result in successful projects, and vice versa.

3. *Level of difficulty and stage of evolution of projects not explicitly incorporated*: our methodology in its current form does not explicitly consider weighting project scores by level of difficulty or stage of development. (Where applicable, observations about these characteristics are made but not scored in the body of the text in Chapters 4 and 5.) For example, Projects 7 and 11 were judged to be struggling, but the interviewees also stated in the interview that they thought the content of these projects was particularly difficult. If these factors were to be incorporated, projects that are judged to be the most technically challenging, or projects that are in earlier stages, might be expected to score lower than projects that are technically less challenging or are further along. A system of weights or "handicapping" might be used to compensate for this.
4. *Nonlinear nature of stage gate development process complicates interpretation:* As an additional observation related to point #3, the evolution of products through the Stage Gate process within Corning is more complicated than a simple linear, uniform path, and a number of actual examples of this came to light in the interviews. For example, a project may stay in Stage 1 for an extended period of time so that it can spin off new projects that subsequently advance through the Stage Gate process. The fact that the "parent" project remains in Stage 1 for its entire duration should not be judged as a failure of the NPD process, it is in fact desirable from Corning's point of view.
5. *Information from archiving of shelved projects not inspected:* while the research was underway, we realized that the 7 out of 20 projects interviewed that had been shelved might be assessed in terms of the extent to which learning during the project had been archived (through reports, standard operating procedures, intellectual property, etc.). This archiving is consistent with Corning's strategy of drawing on shelved projects for restarting or for new applications that eventually lead to successful projects. This aspect could have been explored further than was accomplished. For each of the 7 projects, we asked the interviewees to confirm that information had been archived, but did not inspect the information or evaluate its extent or quality. Had we looked at this documentation, we might have learned more about the performance of these projects relative to one another, based on the quality of the archives.

Chapter 6. Recommendations and future steps

Following from the conclusions at the end of Chapter 5, we have the following recommendations for improving the methodology, for product development practices within Corning, and for the broader systems engineering community.

Recommendations for the methodology:

1. Maintain anonymity and rapport-building as part of interviews: having an NDA, making contact with the interviewee in advance of the interview (preferably by phone or if not possible by email), informing the interviewee about the NDA, and masking the identity of the project in subsequent reporting about the research are all important steps toward gaining the trust needed for discussing detailed and potentially sensitive information about projects. These should be kept.
2. Adjusting SE areas as research evolves: if the research on the use of SE goes on to a new round of interviews of new projects, it may be possible to adjust the areas chosen, or questions within an area. For example, in this case it appeared that trade studies did not reveal as much about the connection between SE and performance as the other areas. The questions might be rephrased or, given the opportunity to use limited interview time more effectively, a different area from the original list of eight might be chosen instead.

Recommendations for Corning:

1. Apply the learning from this project to adjustments to project metrics: based on the observations from the projects interviewed, a set of standard questions can be asked about each project, including 1) what is the market potential for the product, in precise terms as possible? 2) what is the value proposition that will help the product attain this market potential? 3) how is the value proposition reflected in the key project requirements, and 4) how do the planned tests reflect the requirements? (Note that for projects focused on fundamental learning, it may not be possible to plan precise tests, for reasons discussed in Chapter 5.) Many project teams are already pursuing these questions, but the organization could be even more effective in avoiding NPD pitfalls if they were to enforce them universally and with rigor.
2. Make the information used in Recommendation #1 available in a standardized, easily accessible format: during interviews, we sometimes spent a considerable amount of digging through data files to find the most recent version of the market analysis, the value proposition, the list of key project requirements, or the plan and schedule for testing. More than once, the interviewee observed that it would be useful to have this information at their fingertips, so that it would be easier to keep focused on the most important goals of the project. Corning could streamline the availability of this data.
3. Maintain more archival data about projects to allow retrospective analysis: investigation of available data within Corning on past project history revealed that

some data that could be useful for looking retrospectively at projects and which must have been available at one time, was no longer available. For example,

Recommendations for continuing the research:

1. Continuing to study the relationship between SE and performance within Corning: in the first instance, it will be useful to track the 12 ongoing projects to see how they move through the stage gate process, whether they result in mature products, and if so, the extent of their success in the marketplace. The Cornell Systems Engineering program requests in advance that this information be shared in a year or two. Also, if resources allow, Corning might study other projects outside the 20 interviewed in order to strengthen or refine the findings related to SE effectiveness.
2. The methodology should be made available to other enterprises: these enterprises can use the methodology to learn about how to use SE more effectively within their own systems, and also to contribute to the development of a body of knowledge about SE that spans multiple firms. Each study could stand alone, as the Corning study does currently, or the data could be pooled to create a single multi-firm study of SE and performance, similar to the report from the NDIA. Among Corning's regional peers in the northeast, Pitney-Bowes and Xerox have been identified as being interested in studying SE, based on conversations at Cornell Systems Engineering Day in 2008 and 2009.
3. The findings should be made available to the SE community: with Corning's review and approval, this report should be made available to the members of the INCOSE Finger Lakes Region chapter and elsewhere so that peers can understand the methodology and apply it to their own organizations.. Also, a shorter version of the findings should be compiled into a research paper and submitted to the INCOSE *Systems Engineering* journal for review and publication if accepted.

Appendix A: Project timeline

Project timeline at a glance:

6/30/06 Kickoff meeting
6/06-12/06 Literature review, assembling results, writeup
1/19/07 Update meeting at Corning: discuss literature review, initial discussions of research on use of SE within Corning
3/19/07 Meeting at Corning: discussion of Corning's NPD process
4/19/07 Presentation at SE Day at Cornell: literature review findings
5/07 Submit manuscript for literature review
7/5/07 Update meeting at Corning: discuss metrics w Bruce Kirk and Jim Stamatoff
9/28/07 Meeting at Corning: discussion of metrics
10/05/07 Telecon: discussion of technical/political/cultural dimensions
2/18/08 Telecon: discussion of content of metrics interviews
3/26/08 Update meeting at Corning: present plan for metrics research to Bruce Kirk and Jim Stamatoff, get feedback
4/25/08 Presentation at SE Day at Cornell: brainstorming about metrics interviews, feedback session
4/30/08 First interview at Corning: Peter, Matt, Rich Wagner, Francis
6/12/08 Telecon: discuss first 3 interviews, make adjustments in format
10/31/08 Update meeting at Corning: presentation of interim results from interviews
3/19/09 Last interviews conducted (19 and 20)
4/17/09 Presentation of findings at SE Day

Highlights from project timeline:

The metrics development process began with an extensive literature review which was published in the journal Systems Engineering (see Vanek, Jackson, and Grzybowski, 2008). Thereafter, choice of areas of metrics on which to focus continued with review of recent studies of SE effectiveness to uncover findings on which metrics are best correlated with project success. Among these, the results of the National Defense Industry Association, or NDIA, published by Carnegie Mellon University (CMU, 2007), proved to be the most thorough and up-to-date, so their findings, along with our own judgment and interpretation, were used in the choice of metrics.

After review of documents and discussion regarding the situation at Corning, the team concluded that the four areas presented in Chapter 5 were most promising as areas of SE practice that might yield a positive correlation with project results:

In the next phase, the team gathered feedback on individual questions to be used in interviews of Corning project managers through a launch meeting held at Corning on

March 26, 2008, and a presentation at Cornell University Systems Engineering Day on April 25, 2008.

Launch meeting at Corning, March 26: this meeting was held in two parts, first with Jim Stamatoff and Bruce Kirk, and then with just Rich, Matt, Peter, and Francis. Jim and Bruce were supportive of the four metric areas that were chosen, although they did not have particular input on which metrics were or were not particularly important. We incorporated a number of points from Jim and Bruce's advice into writing the initial list of questions to be used in the interviews

Feedback session at 2008 SE Day, April 25: at this session we presented draft metric areas and specific metrics to attendees, including both faculty colleagues and representatives from other local enterprises (Lockheed-Martin, Pitney-Bowes, ITT, GM, etc). We incorporated suggestions from this session into further refinement of the questions.

Trial interview at Corning, April 30: based on our first interview in the project, we made several observations and adjustments, as follows:

- We decided to set a target duration of the interview of 2 hours, and that we would ask for reservations of this length. Less time was found to be inadequate, and more time is likely to be a deterrent to gaining agreement from PMs to participate in the project. Accordingly, we reduced the number of input metrics questions from 19 to 14.
- We decided that the face-to-face interviews should focus on input metrics, with output metrics discussed at the end of the interview, time permitting, or in a NetMeeting follow-up if needed.
- The interviewees suggested that we should evaluate the project team's assessment of competitors' performance under the heading of market analysis.

Further refinements to the interview process, made during summer 2008:

- Use of NetMeeting discontinued for security reasons
- All interviews begin with a pre-interview phone call. This phone call allows us to find out the identity of the project, establish with the interviewee the format of calling up supporting documentation, and reiterate the existence of the NDA and need to look at secure information.

Appendix B. List of questions asked during interviews

There are three types of questions asked: preliminary, input, and output. For input and output questions, the interviewee is required to show a computer file supporting the answer ("documentation"), and the interviewer writes down notes about the content ("comments"), so that after the interview s/he can evaluate the answer and decide whether or not to award points.

Preliminary Questions:

(to be filled in advance if possible, or else on the day of the interview):

P1. Number of project & name(s) of contact person(s):

P2. Stage and date (month/year) at last stage gate review:

P3. Approximate anticipated date (month/year) of next stage gate review:

P4. Project is (choose one): currently active / completed & successful / killed before completion

P5. Brief description of product:

P6. "Is the value of the product to Corning built around process excellence or product integration excellence? Is the product aimed at an existing or potential market?"

Input Questions:

I-1 "Evidence of market analysis, including total market size, market segmentation (by geography or customer type), target share, and/or market testing"

- Documentation:
- Comment:

(Documentation and comment are provide for each of questions I-2 to I-14)

I-2: "Evidence of customer analysis, such as customer surveys"

I-3: "Evidence of competitor analysis, such as identification of price leader, technology leader, or growth leader, or the assessment of potential role of major competitors"

I-4: “Evidence of ‘Value proposition’ presented at the last review (or developed for product)”

I-5: “Evidence of Technical Performance Measures, or TPMs, currently used for this project” (Since not all teams used the term TPM, other terms such as Product Characteristics or Product Specifications were also accepted)

I-6: “Evidence of trace of the TPMs to the value proposition, if any”

I-7: “Evidence of a schedule of anticipated TPM targets available”

I-8: “Evidence that the testing procedure was traced to TPMs”

I-9: “Evidence of a testing plan for the project”

I-10: “Evidence of a testing schedule (of future anticipated tests) available”

I-11: “Evidence of tradeoff analysis including alternatives and criteria carried out”

I-12: “Evidence that tradeoff analysis criteria were traced to requirements or product objectives”

I-13: “Evidence of research and data collection before and documentation of selection rationale after tradeoff analysis”

I-14: “Evidence of stakeholder involvement in selection process for tradeoff analysis”

<u>Output questions</u>

For output questions 1 to 6, filenames were not recorded as “documentation”, however documents were reviewed and inferences about performance of project were recorded by the interviewer during the interview. Comments were also recorded.

Questions O-1 to O-3 focus on short-term execution of the project in terms of adherence to non-personnel budget, schedule, and allocation of personnel (measured either in full-time equivalents, also known as FTEs, or dollar expenditure on personnel)

Question O-1: “Development cost against current or projected target”

O-2: “Development time against current or projected target”

O-3: “Technical input (person-hours or FTEs) against current or projected target”

Questions O-4 to O-6 focus on longer-term delivery of value from the project in terms of meeting expectations for product performance, meeting customer expectations in terms of the value proposition, and meeting Corning’s expectations in terms of the return on resources invested in developing the product.

Question O-4: “System TPM performance against current or anticipated target” (Record answers for as many TPMs as there are available data to answer the question)

O-5: “Customer value proposition against current or projected target”

O-6: “System return on investment from Corning’s perspective (project benefit compared to input), either actual or projected.”

Appendix C. Distribution of answers and ratings

Notes:

1. Interview 4 not included since data were not accepted for study
2. Greyed boxes indicate that question was not relevant to project and therefore answer was not included in scoring
3. Table of project performance evaluations follows answers to questions

Projects 1-6:

	Project				
Question	1	2	3	5	6
1	1.0	0.0	1.0	1.0	1.0
2	1.0	0.0	1.0	1.0	0.0
3	1.0	1.0	1.0	1.0	1.0
4	1.0	1.0	1.0	0.0	0.0
5	1.0	1.0	1.0	0.0	0.0
6	1.0	1.0	1.0	1.0	1.0
7	0.0	1.0	0.5	0.5	0.0
8	1.0	0.0	0.5	1.0	0.0
9	1.0	1.0	0.5	0.0	0.5
10	0.0	1.0	0.0	0.0	1.0
11	1.0	1.0	0.0	0.0	1.0
12	0.0	0.0	0.5	1.0	1.0
13	0.0	0.0	0.5	0.0	0.0
14	0.0	0.0	0.5	0.5	0.5
Max poss	14.0	14.0	14.0	14.0	14.0
Earned	9.0	7.0	8.0	8.0	8.0
Percent	64%	50%	57%	57%	57%

Projects 7-11:

	Project				
Question	7	8	9	10	11
1	1.0	1.0	1.0	0.5	0.5
2	1.0	0.5	1.0	0.0	0.5
3	1.0	1.0	1.0	1.0	1.0
4	0.5	0.5	1.0	0.5	0.0
5	0.5	1.0	0.5	1.0	1.0
6	1.0	0.0	1.0	0.0	0.0
7	1.0	0.0	0.5	1.0	0.0
8	0.0	0.0	1.0	1.0	1.0
9	0.0	1.0	1.0	1.0	1.0
10	0.0	0.0	0.0	0.0	1.0

11	1.0	0.5	1.0	0.0	1.0
12	0.0	0.0	1.0	0.0	0.0
13	0.5	0.5	0.0	0.0	1.0
14	1.0	0.0	1.0	0.0	0.0
Max poss	14.0	14.0	14.0	14.0	14.0
Earned	8.5	6.0	11.0	6.0	8.0
Percent	61%	43%	79%	43%	57%

Projects 12-16:

	Project				
Question	12	13	14	15	16
1	0.0	1.0	0.0	0.5	1.0
2	1.0	1.0	0.0	0.0	1.0
3	0.0	0.5	1.0	1.0	1.0
4	0.0	1.0	0.5	1.0	1.0
5	1.0	1.0	1.0	1.0	1.0
6	0.5	1.0	1.0	0.0	1.0
7	0.0	0.0	1.0	0.0	0.5
8	0.0	0.0	0.0	0.0	1.0
9	1.0	0.0	1.0	0.5	0.5
10	1.0	0.0	0.5	0.0	0.5
11	1.0	1.0	0.5	0.5	1.0
12	0.5	0.0	1.0	1.0	1.0
13	0.0	0.0	0.5	0.5	0.0
14	1.0	1.0	1.0	1.0	1.0
Max poss	14.0	14.0	14.0	14.0	14.0
Earned	7.0	7.5	9.0	7.0	11.5
Percent	50%	54%	64%	50%	82%

Projects 17-20:

	Project			
Question	17	18	19	20
1	1.0			1.0
2	1.0	0.0		
3	1.0		0.5	0.5
4	1.0	1.0	1.0	1.0
5	1.0	1.0	1.0	1.0
6	0.5		0.0	0.0
7	0.5	0.0	1.0	0.0
8	1.0	1.0		
9	1.0	1.0	0.5	1.0
10	1.0	0.0		0.0
11	1.0	1.0	0.0	1.0
12	1.0	0.0	0.0	0.0

13	1.0	0.0	0.0	0.5
14	1.0	1.0	0.0	0.0
Max poss	14.0	11.0	10.0	12.0
Earned	13.0	6.0	4.0	6.0
Percent	93%	55%	40%	50%

Rating of projects as “struggling”, “satisfactory”, or “superior”, by project number:

Project	Rating
1	Superior
2	Satisfactory
3	Satisfactory
5	Satisfactory
6	Satisfactory
7	Struggling
8	Struggling
9	Superior
10	Satisfactory
11	Struggling
12	Satisfactory
13	Satisfactory
14	Satisfactory
15	Satisfactory
16	Satisfactory
17	Superior
18	Satisfactory
19	Satisfactory
20	Satisfactory

Appendix D. Complete record of all highlighted quotes recorded from interviews

List of quotes from interviews thought to be worthy of further analysis, in the order that they were incurred. Note that because there was no sound recording of the interview, the wording of the quotes is approximate. However, in each case, the quote as presented is thought to accurately represent the intention of the interviewee.

Interview 2:

"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 SE." Technical people responsible for testing responded positively to the change: they could see its appeal right away."

Interview 3:

"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."

Interview 7:

"For the project, we created a document of top level requirements, action items, and priorities. The document includes a map of system components. However, during 2003-2006, we had to focus on making it work, so, unconsciously, we decided to ignore the other requirements."

"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."

"We missed every milestone except for the last one in Sept 2006. The 10-12 missed milestones were because stakeholders asked for accelerated development. We had only had 30-40% chance of success for each milestone, but the stakeholders did not complain, they had intended to give us challenging milestones."

"The moment you try to lock research scientists into a rigid timetable of test schedules and deadlines, they start running for the exit"

Interview 8:

(Regarding setting targets for schedule adherence:) "Ultimately, the managers are the ones that set the objectives, and they do this independent of the reality of the progress of the research. In the case of this project, the objective for the milestone is the end of 2008, but it won't happen."

Interview 11:

"The project was budgeted to experiments, not to deliverables. It's all learning, which is different from meeting statements of deliverables."

On budget adherence: "Competing objectives [of making research progress and adhering to budget] worked at cross purposes. If many people got excited about what they are doing, we would have a bad month, budgetarily speaking."

On System TPM performance: at the beginning, the PM "lays out goals with project principles. Once the project starts down the road, then you would begin to learn. All of a sudden would have a result that was baffling, experts didn't agree. Sometimes it took 6-12 months to come up with an answer."

On interview questions related to design for testability: "how do you plan and schedule testing when you don't even know enough about the topic to know what it is you are going to test"

Interview 16:

Question from the interviewer: “Given that the market analysis outcome for the product (Interview #16) was that the market was not large enough, wouldn’t it have been better to wait for market analysis results before continuing development?”

Answer: “You have to pursue market analysis and development simultaneously. If you wait for the market analysis answer to come back before starting development, you’re too late.”

Interview 18:

“The list of requirements from stakeholders…is a wish list that has propagated through time. The options come out of requirements that have rolled along through years and years of measurement work.” [Implication: not all of the requirements are realistic or well thought out, they appear as if by inertia or osmosis]

Interview 20:

“Management-based objectives (MBOs) are adopted each year, and we meet or exceed them each year, but they are not helpful, because the unknown eclipses the known – what we learn that we did not expect proves to be more useful.”

Question from the interviewer: “Can the process you are developing go all the way through the Stage Gate development process without getting tied to a specific product?”

Answer: “Systems are in place to bring new processes into the Stage Gate review process through specific products. This has the potential to be stifling of true innovation, since the steering committee begins to dictate what the inventor does.”

On the interviewees expectations prior to the interview: “I’m surprised. I thought I would not be found to be using any SE, and therefore the interview would be a complete waste of time. Actually, I really was able to provide some useful information!”

Appendix E. Introductory letter to interviewees

Note: this letter was sent to interviewees once they had agreed to be interviewed, but before the pre-interview phone call.

To: Corning project managers
From: Corning/Cornell Systems Engineering Research Project

Dear colleague,

On behalf of the Systems Engineering Directorate at Corning, Incorporated, and the Systems Engineering Program at Cornell University, I would like to thank you for agreeing to participate in our survey of product development practices and outputs. Since June 2006, Corning and Cornell have been collaborating on an effort to assess the impact of certain practices in the product development process on the outcome of that process, whether it is measured in terms of adherence to Corning's internal goals or success of the product in the marketplace. Your cooperation in this interview process is greatly appreciated, and we are making every effort to insure an efficient process that gives us the information we need to develop useful results for Corning, while minimizing the impact on your time. By participating in this work, you are contributing to making Innovation and Project/Program management at Corning more effective and competitive in the future. Ultimately this work will benefit you in your capacity as project manager: we aim to produce from the survey a set of tools that deliver useful results in return for manageable commitment of time and resources. The interview process yields immediate benefits as well, according to comments that we have received so far, since the process of reflecting on the process by which decisions are made leads to new insights that can be used right away.

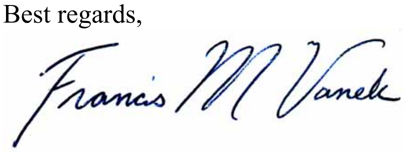
At the outset, we wish to assure you that confidentiality of the information you provide is absolutely guaranteed. The Cornell University participants in the project are bound by a Non-Disclosure Agreement (NDA) and may not reveal documents or information to anyone outside the project. Also, the project that each interviewee represents is given a numerical code at the beginning of the research, and by using the code for the project and not its name in any subsequent internal reports or communications, we will be able to make comparisons and draw conclusions from our research without revealing the identities of the projects studied. By maintaining the anonymity of your project in both internal and external reviews, we aim to make it possible for you to provide responses that are as candid and complete as possible, to maximize the value of our research to Corning's New Product Development process.

During the interview, we will gather data on both inputs (i.e., use of certain product development techniques) and outputs (i.e., the technical and financial performance of the resulting product) to and from the project. Inputs and outputs are to be evaluated at the most recent stage gate review (Stages I to III), and possibly previous stages, if they are relevant. The attached page gives more information about the nature of the questions asked, and the type of supporting data sought.

Lastly, depending on the nature of your project, it may not be possible to provide data for all of the questions that we will pose during the interview. We anticipate this outcome and intend to obtain data for as many questions as possible, while leaving some questions unanswered.

Thanks, and we look forward to meeting with you soon.

Best regards,



Francis M Vanek, PhD
Research Associate, Systems Engineering Program, Cornell University

Attachment: description of questions and data

Attachment: Description of questions and data

Examples of input and output questions:

One example of each type:

> Inputs question on the use of a *customer value proposition*: "Please provide the statement of the customer value proposition that was presented at the most recent stage gate review." (Appropriate evidence: slide in Powerpoint show that states the value proposition, or value statement in interim report)
>
> Outputs question on adherence to schedule: "Please provide the target and actual schedule (e.g., measure in months since the beginning of the project or the previous stage gate review) data for the project" (Appropriate evidence: date of project beginning, date(s) of stage gate reviews completed, or document showing target schedule for stage gate reviews)

There are approximately 20 input and output questions in all.

Questions about Technical Performance Measures (TPMs):

In addition to questions about project schedule, budget, and person-hours, we are also asking you as project manager to identify TPMs used in evaluating the technical progress of the project, if possible, since these measures are different in each product under development (e.g., "percent yield" from a new process, such as 85% or 90% successful, etc.). We are asking you to provide both the target and actual value of TPMs, and a subjective weight that you give to different TPMs in evaluating overall performance. For example, if you identify 3 TPMs, you might weight two of them 30% and one at 40%, for an overall score of 100%. If you cannot provide the numerical scores of the TPMs, a ratio of actual/threshold or actual/target TPM is sufficient.

Project documentation sought

Since the interviews will take place in your office, we hope that you will be able to show as much of the documentation requested as possible. We will only need to see it and record a small amount of information from it, we do not need to retain or photocopy it. Some of the documentation of interest includes but is not limited to:

- Powerpoint presentations from stage gate reviews
- Written progress reports at the time of review
- Feedback from stage gate review committees
- Documentation of market surveys and market test
- Documentation of customer profiles
- Reports from experiments that show TPM values
- Test plans and test schedules
- Documents from trade studies conducted
- In any format, data may include records/results of any risk analysis & mitigation plans; requirements and verification/validation plans; trade-off analyses, DoPP, QFD, VOC etc.

Appendix F. Supporting product matrices for Chapter 3

Note: these matrices were developed in addition to the matrix in Chapter 3, "Mapping of technology-push versus customer pull and process versus product focus into quadrants, and product development rationale in each quadrant."

Matrix that provides examples of specific products for each of the quadrants. The Fiber-optic cable is in the technology-push column because it is a technology that Corning developed at first without a market, using process expertise, and for which eventually markets were found. LCD screen is in the customer pull column because this is a mature market where customers demand improved products that Corning can deliver. Scratch-resistant PDA glass is in the product focus because it makes possible the PDA, which is a product-integration success. The RFID system is in the product focus column because it uses known components (radio-frequency technology) reconfigured into a new product that customers are demanding.

Examples:	Technology-push	Customer-pull
Process focus	Fiber-optic cable	LCD Screens
Product focus	Scratch-resistant PDA glass	RFID Systems

Matrix that illustrates differences in how each quadrant is approached in terms of experimental process, customers, etc. Note that for customer + process and technology + product, technical performance measures dominate, but for customer + product, interface requirements dominate.

Differences	Technology-push	Customer-pull
Process focus	Customers are not completely identified Experimental process, not completely understood May be reliant on other developing technologies (only some of which Corning develops)	Customer's customer is known Technical performance measures dominate Interfaces not important
Product focus	Customers are not completely identified Existing process Novel application creates opportunity Technical performance measures dominate	Customer context is extremely important Many interfaces and interface issues Interface requirements dominate

Practices within projects, and means of allocating projects to quadrants. In the upper figure, the likely most important SE areas are given for each quadrant. In the lower figure, questions that can be asked about a project to determine its location are given.

Examples:	Technology-push	Customer-pull
Process focus	•Market/customer analysis and validation	•Requirements analysis and verification
Product focus	•Market/customer analysis and validation	•Requirements analysis and verification •Trade studies

Examples:	Technology-push	Customer-pull
Process focus	•Are specific customers engaged? (no) •Is process mature? (no)	•Are specific customers engaged? (yes) •Is customer's customer known? (yes) •Are multiple external stakeholders involved? (no) •Is interoperability a major focus? (no) •Is process mature? (no)
Product focus	•Is process mature? (yes) •Is space currently occupied by other technologies? (yes)	•Are multiple external stakeholders involved? (yes) •Is interoperability a major focus? (yes)

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