Collaboration Across Linked Disciplines: Skills and Roles for Integrating Systems Engineering and Program Management

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Abstract

In new product development programs, systems engineers and program managers must often work together closely to define the product, the program structure and objectives, and allocate and define the focus of work effort. Poor communication and lack of integration between these two critical functions can often spell the difference between success and disappointment for the program and its stakeholders. Despite common and sometimes overlapping skills required for both disciplines, and their respective extensive practice and process models, effective integration and collaboration continues to elude many engineering efforts. Unfortunately, this failure of collaboration and integration negatively impacts program performance and outcomes. This study draws upon a large global survey of program managers and systems engineers to better understand the backgrounds, training, roles, and responsibilities of program managers and systems engineers. The analysis of the data identifies systems engineering and program management capabilities that are considered critical to program success, as well as those areas where both roles share key responsibilities. The implications of these findings for engineering students and for their engineering curricula will be discussed. For systems engineering students and future engineering leaders, having learned these principles and concepts may be critical to them as they prepare to enter a highly competitive workforce.

Introduction

What attributes and skills will be valuable to future engineering leaders? This is a central question for academic and professional engineering education and training programs. While not all trained engineers will assume leadership roles during their careers, many, if not most may reasonably expect to play a leading role in an engineering or product development effort at some point. Will they have the necessary preparation and skillset? And where should this preparation take place? These issues are the focus of this paper, which is based on a study of engineering leaders and the skills and roles that are essential to the work they do.

What skills will be required of an engineering leader? In a typical matrix organization leadership roles might involve permutations around project or functional, or technical or managerial (1). In a program, a program manager would fill the managerial role while a chief systems engineer might fill a technical role (although in some cases both roles might be combined.) In a functional organization, an engineer may work in roles from functional lead for a specific discipline area to director or vice president for all engineering functions. The potential skill set across these various roles is potentially large and diverse.

Background

Many of these skills will likely be acquired through work experience. Additionally, a number of professional development programs oriented toward engineering leaders have emerged in

recent years. In the field of engineering management, one web-based resource lists 422 international (though mostly US) degree programs in engineering management, including 63 certificate programs, 345 Master's degree programs, and 46 PhD programs (2). The same site lists 323 international (though mostly US) graduate programs in project management, including 95 certificate programs, 250 Master's degree programs, and 22 PhD programs (3). The International Council on Systems Engineering (INCOSE) Directory of Systems Engineering Academic Programs from July 2013 (4) identifies in the US alone 25 certificate programs and 30 degree programs offering a Bachelor's degree, 55 Master's degree, and 30 PhD degree programs in systems engineering.

More recent developments in engineering education involves a direct focus on engineering leadership. Entrepreneur Bernard Gordon wrote that "Too often, U.S. engineering is not cost-effective because the majority of today's engineering graduates do not have the broad background necessary to understand, take charge of and drive large-scale projects to completion in an economic fashion" (5). To the end of correcting these perceived deficiencies, Gordon has funded a number of engineering leadership degree programs in universities. One of them is at Northeastern University (NEU) in Boston, MA. Key elements of the degree program at NEU include experiential learning; distinguished speakers from industry to discuss and model leadership; mentoring from the program, an industry partner, and the technical faculty; cross-cohort learning (6). A similarly ambitious revision of engineering education has been on-going at the Massachusetts Institute of Technology (MIT) for some time, albeit at the undergraduate level. The Conceive-Design-Implement-Operate (CDIO) syllabus attempts to educate students in a broad range of technologies while simultaneously developing students' personal, interpersonal, and system-building skills (7). The thrust of the CDIO syllabus is that an engineering education should occur within the problem-solving context of conceiving-designing-implementing-operating of products, processes and systems, and that the educational program should have specific learning outcomes for personal and interpersonal skills, product, process, and system building skills, and disciplinary knowledge (8). The concept of both of these programs is to use product development or engineering program models to inform the overall engineering educational process through a broader perspective toward the development of skills and capabilities.

In addition to formal degree programs offered by universities, there are numerous professional certifications, often associated with professional bodies or organizations. In the field of systems engineering, the largest is the International Council on Systems Engineering (INCOSE) with about ten thousand members. INCOSE is a not-for-profit membership organization founded in 1990 to share, promote and advance systems engineering principles and concepts. INCOSE's members fill roles that range from student to senior practitioner and technical engineer to program and corporate management (9). In the field of project management the largest professional organization globally is the Project Management Institute (PMI) with over six hundred thousand members. PMI is a not-for-profit professional membership association founded in 1969 focusing on project, program and portfolio management professionals (10). Other organizations associated with standards and certifications in Project Management and Program Management are the Project Management Association of Japan (PMAJ), the International Project Management Association (IMPA), and the Office of Government Commerce (OGC) in the UK. Because the field of systems engineering is much smaller than the

field of project management, other SE certification processes tend to be associated with individual organizations. The most important international and commercial standards in the field of System Engineering are industry-spanning and include ANSI/EIA-632, IEEE and ISO/IEC 15288:2008. Each of these professional organizations manages standards, certification processes, and supports research and professional exchanges to advance their respective fields.

One important method for instilling and advancing skills and roles for professionals is through the promulgation of standards and certifications. For instance, INCOSE offers the INCOSE ASEP (Associate), INCOSE CSEP (Certified), and INCOSE ESEP (Expert) certifications. The list of program manager certifications in the much larger field of project management is more broad and diverse, as shown in Table 1.

CAPM® (Certified Associate in Project Management)	PRINCE2 Foundation
PMP (Project Management Professional)	PRINCE2 Practitioner
PgMP® (Program Management Professional)	IPMA Level A (Certified Projects Director)
PfMPSM (Portfolio Management Professional)	IPMA Level B® (Certified Senior Project
PMI-RMP® (PMI Risk Management Professional)	Manager)
PMI-SP® (PMI Scheduling Professional)	IPMA Level C® (Certified Project Manager)
PMI-ACP® (PMI Agile Certified Practitioner)	IPMA Level D® (Certified Project Management
PMI-PBASM (PMI Professional in Business Analysis)	Associate)
PMI-PBASM (PMI Professional in Business Analysis)	P2M (Project Management Specialist)
OPM3® (Professional Certification)	P2M (Project Manager Registered)
	P2M (Project Management Architect)

Table 1. Project Management Professional Credentials and Certifications.

An important role of professional (as well as academic) discipline communities is to increase the depth and specialization of knowledge within the community. Progressive certifications (and academic degrees) even encourage, enable, and reward increasing knowledge specialization. But increasing specialization carries the risk of creating greater distance between disciplines such as program management and systems engineering that must ultimately collaborate on product development projects. There is a growing concern that program managers and systems engineers view stakeholders' needs from within their own disciplinary perspectives, and as a result apply distinctly different approaches to the key work of engineering programs—managing the planning and implementation, defining the components and their interactions, building the components, and integrating the components. The resulting impact on engineering programs is unreliable cost and schedule targets, duplication of effort and wasted resources, and failure to meet stakeholders' expectations (11).

Has increasingly specialized knowledge in disciplines like program management and systems engineering created new challenges for those disciplines to work together? This question has implications not only for product development activities, but also for professional development and academic degree programs. Academic degrees are built upon the completion of a defined set of required courses, often originating from within areas of deep specialization. The only integrating experience to bridge across those diverse sources of knowledge may be in a capstone course, or perhaps in the few engineering programs that are designed to be integrative, such as those identified earlier in this section. If greater emphasis is placed on bridging and integrating across knowledge boundaries in order to improve product development performance (12), should new curriculum be developed beyond those already identified in current core discipline areas?

Approach

To better understand these issues and their impact on professionals in the project/program management and systems engineering fields, in the Fall of 2012 INCOSE and PMI established a joint working group to investigate the issues and challenges to developing closer working relationships between program management and systems engineering disciplines in organizations. One of the primary objectives of this alliance was to identify potential areas for improvement, from both a theoretical and a practical perspective.

To collect data from professionals in these disciplines, a joint survey was developed by members of the combined INCOSE and PMI joint working group. The objective was to conduct a preliminary investigation of the challenges to the integration of project management and systems engineering functions in projects. Topical coverage in the survey was developed from the working group members' professional experience as well as knowledge of issues that were surfaced in previous surveys of the professionals in each society, respectively, and was not based on prior peer-reviewed academic research. Specific items included identifying common job skills and responsibilities between the roles, understanding the level of interaction and integration between the two roles, investigating possible avenues to better align systems engineering with program management practices at the professional level, and describing the interactions between the use of standards, integration, formalization, level of effectiveness, and degree of unproductive tension between Program Management and Systems Engineering. The survey questionnaire that emerged contained 39 questions that explored the organization (e.g., industry sector, annual revenue, and location), program characteristics (size of the program, budget, duration and main result), processes (e.g., main standards and practices, tools and techniques adopted) and professional characteristics such as background, years of experience, and engineering and program leader responsibilities in the organization.

Data were collected during the fall of 2012. An invitation to participate in the study was sent to approximately 3,000 members of the INCOSE System Engineering community of practice and to approximately 5,000 members of the PMI Program Management community of practice. Bi-weekly reminder notices were sent to the community members who did not respond during the duration of survey (approximately one month). 68% of those who attempted to take the survey met the qualification requirements (i.e., to be a program/project manager (PM) or chief systems engineer (CSE) or both). Of those, 32% failed to complete the survey and provided an incomplete response. This resulted in 694 valid responses, representing a net response rate of 8.7%. The reported response rates for online surveys can vary significantly depending on a number of factors. This particular sample was drawn from a target population of individuals with significant professional responsibilities, which may explain the response rate somewhat lower than has been reported with other surveys. Of the respondents, 340 were functioning as a project or program manager, 222 as a chief systems engineer, and 132 were functioning in both roles. The data were analyzed using descriptive statistics and non-parametric analysis of variance.

The unit of analysis was primarily the organization, although some individual-level data were collected. The average size of the responding organizations is shown in Figure 1. The industry sector of the responding organizations is shown in Figure 2.
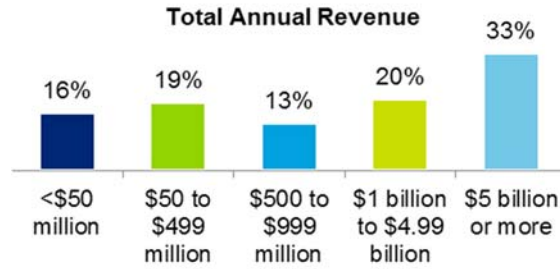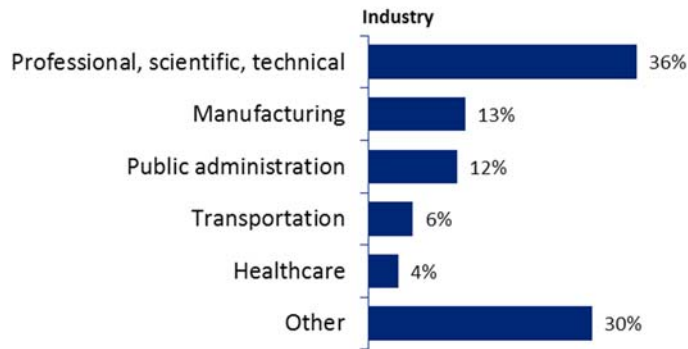
Figure 1. Size of Responding Organizations.

Figure 2. Industrial Sector of Responding Organizations.

78% of the respondents were from commercial organizations, 19% from government, and the remainder from non-profit or academic organizations. 55% of them had less than 5 years and 14% of them had greater than 10 years in their present job. Their average experience as a PM was 7.99 years, as a CSE 7.96 years, and as both 7.69 years. 69% of the sample had a graduate degree. Over half (56%) of the CSEs reported using the INCOSE standard as guidance, while a larger proportion (58%) of PMs reported using PMI standards as guidance. Both were significantly less likely to rely on a standard from outside their primary job domain, suggesting a strong orientation toward domain-specific specialization of knowledge.

Findings

The survey questions relevant to this paper asked specifically about the roles and skills required by program managers and chief systems engineers, respectively. All respondents were asked to indicate whether the PM, CSE, or both together were primarily accountable (the one who has the authority to make and implement final decisions) for each of these major areas of program responsibilities:

- External supplier relations
- Goals and objectives of the program (program benefits)
- Overall results of the program (benefits management)
- Technical requirements definition/management
- Configuration management
- Quality management
- Program/project risk

- Life cycle planning for the product
- System Definition planning
- System Retirement and/or Replacement Planning

Their responses are shown in Figure 3 in combined form to illustrate the relative importance of each role. To test whether one role predominantly belongs to either the PM, CSE, or both, the Goodman and Kruskal tau test was used to assess whether there was any association between the job classification of the respondent and the assignment of accountability of these program responsibilities. Only in the cases of Technical Requirements, Program/Project Risk, Life Cycle Planning, and Systems Definition Planning were the test statistics significant at the $p=0.05$ level. However, no particularly systematic insights were gained from these results.
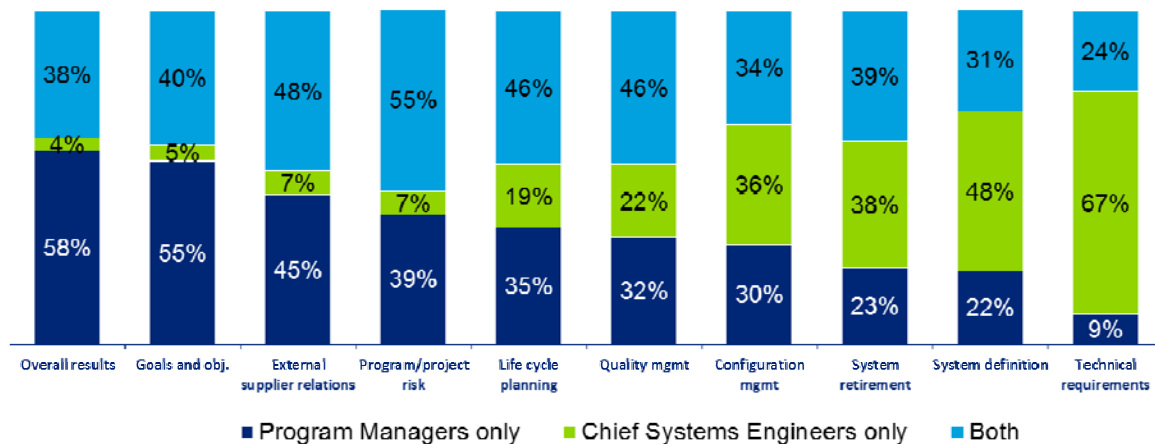

Figure 3. Primary Accountability for Key Program Responsibilities.

Overall, PMs are viewed as primarily accountable (i.e., much more so than CSEs) for managing overall results, goals & objectives, external supplier relations, program & project risk, and lifecycle planning. CSEs are viewed as primarily accountable for managing technical requirements, systems definition, system retirement, and configuration management. Both PMs and CSEs are viewed as jointly accountable for managing program and project risk, external supplier relations, quality management, and lifecycle planning. In these areas of shared responsibility PMs and CSEs must work together effectively while maintaining focus on their respective unique responsibilities, which may itself constitute an important skill.

Each respondent was asked to indicate which of these skills were most critical to them in their respective role as a PM or CSE:

- Negotiation skills
- Conflict resolution skills
- Team building skills
- System thinking/integrative thinking (Understanding interconnections; closed-loop thinking)
- Risk management

- Stakeholder management
- Communications skills
- Leadership skills
- Requirements management

Respondents were forced to prioritize their responses by selecting only up to three skills. The summary of their responses is shown in Figure 4.
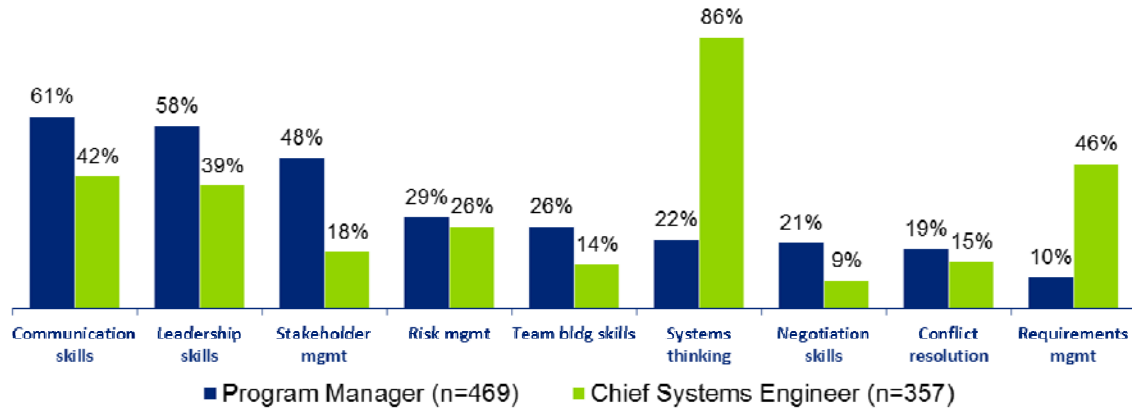

Figure 4. Skills Critical to Program Managers and Chief Systems Engineers.

PMs rated on average their most critical skills as being communication skills (61%), leadership skills (58%), and stakeholder management (48%). CSEs rated system or integrative thinking by far as the most important skill for themselves (86%) with requirements management (46%) and communication skills (42%) also seen, albeit to a lesser extent, as important skills. The Goodman and Kruskal tau test indicated significant differences between the PMs and CSEs in their responses.

Both the assessment of which leader is primarily accountable for a specific program function and the critical skills are confirmatory and support traditional conceptions of the roles of PMs and CSEs, respectively. PMs are primarily responsible for managing overall results, goals & objectives, external supplier relations, program & project risk, and lifecycle planning, and doing this using primarily communication, leadership, and stakeholder management skills. CSEs are primarily responsible for managing technical requirements, systems definition, system retirement, and configuration management, and do this using system or integrative thinking, requirements management, and communication skills.

Some of these roles and skills, such as, e.g., systems thinking, quality management, requirements management, might be found in a traditional engineering degree or leadership program, but some of the skills identified may not be. Nevertheless, if the only issue is a deficit of skills, then that deficit can be identified and the skill gap closed through targeted instruction and development.

There appears to be an element of integration suggested by the roles performed by both PMs and CSEs. That is to say, they must each bring their domain perspective together to produce a common solution. This integration of analysis and synthesis of a cross-domain solution perhaps represents an additional unarticulated set of roles and skills necessary for effective management of engineering activities. Might there be other challenges to engineering leadership that lie outside the traditionally-defined roles and skills?

Respondents were also asked to rate the degree of unproductive tension between program management and system engineers in their organization. It is natural to expect that there might be tension between different disciplinary specialties in a complex engineering development effort, particularly if there is a significant degree of innovation or novelty required. A well-functioning team might identify the existence of the tension, track the sources, and work to resolve the differences that precipitated the tension (perhaps in the process discovering new solutions to the challenges.) In the survey, nearly three out of ten respondents identified some (26%) or significant (3%) unproductive tension between program management and systems engineering (see Figure 5). The CSEs were significantly more likely to feel that there is unproductive tension between the roles in their organizations than were the program managers.
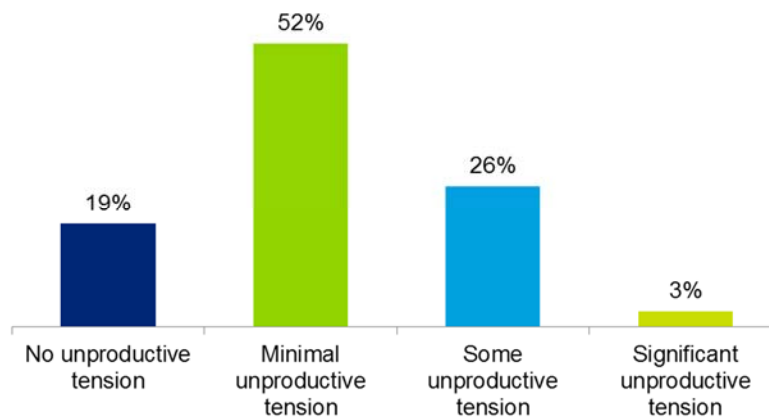

Figure 5. Degree of Unproductive Tension Between PMs and CSEs.

Respondents were asked about the potential sources of unproductive tension between the PM and CSE functions, with their responses shown in Figure 6. The top-rated sources of tension are lack of integrated planning, unclear authority, and conflicting practices across the functional boundaries. These challenges could reasonably be traced back to ambiguity and uncertainty around the relationships between the two functions. Making decisions under ambiguity or uncertainty (also known as choice under uncertainty) is central to decision theory. Decision theory informs us that in situations of uncertainty, decisions tend to bias and are referential (13). That is that rather than using an absolute reference to evaluate alternatives, the point from which options are assessed is the known or familiar state. In a strong discipline-based environment, perhaps the clearest reference point from which to make a decision will be established by the knowledge base, standards, certifications, tools, etc. which define the discipline. An additional complication is that these decision processes are social; they are part of a shared process that is affected by factors such as number and diversity of stakeholders, influence, representation, participation, power, and other factors not entirely in the control of individual disciplines. It is

not surprising then that the reported primary sources of unproductive tension between PMs and SEs might link back to uncertainty in the context of shared decisions and responsibilities.
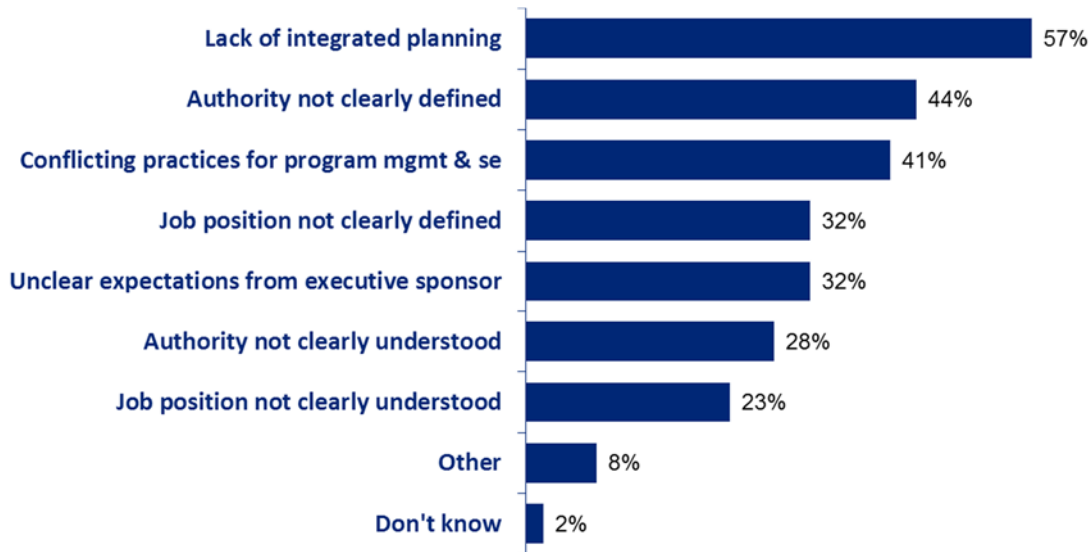

Figure 6. Sources of Unproductive Tension Between PMs and CSEs.

An engineering education generally provides many analytic tools to support decision-making, but typically they are based in rational processes. This assessment of unproductive tension suggests that processes that are not classically rational may have potentially significant impact on real-world engineering efforts and outcomes. The extent to which they are not represented in engineering curricula may represent a weakness in the preparation of future engineering leaders.

We finally asked the respondents specifically about the degree of integration between the PM and CSE functions in their organization. We used the Kruskal Wallis test to investigate whether there is a statistically significant relationship between the degree of integration and the level of unproductive tension between the PM and CSE functions. The Kruskal-Wallis Chi-squared test indicated that lower levels of unproductive tension were more likely at higher levels of integration between PM and SE, and higher levels of unproductive tension were more likely at decreased levels of integration ($p < 0.001$, n=610). This suggests that organizations that have made concerted and/or formal efforts to bridge the knowledge boundaries defining these functional disciplines are less likely to experience problems in program execution. Unfortunately, program performance outcomes weren't collected as part of this dataset, so a correlation between increasing levels of integration and improved program outcomes can't be established. Nevertheless, the potential link between program performance and organizational and interpersonal integration efforts is intriguing.

Conclusion

This analysis confirmed roles and skills for engineering program leaders (PMs and CSEs) that are consistent not only with traditional engineering education and training programs but also professional standards and certifications. This reinforces the notion that these roles are indeed part of functional disciplines based in specialized knowledge. While each of these domains has

unique roles and skills, there are significant areas of overlapping or shared responsibility, particularly with respect to PMs. Both PMs and CSEs are viewed as jointly accountable for managing program and project risk, external supplier relations, quality management, and lifecycle planning. In each of those areas (e.g., managing program and project risk) there are unique perspectives and analyses that each function brings to the shared responsibility. Nevertheless, successful integration may not be so much in the accumulation of multiple analyses as in the way in which one analysis or perspective informs the other, and ultimately shapes the unified program-level approach. This suggests the ability to synthesize integrated solutions from multiple perspectives is an important engineering leadership skill.

Whether through shared responsibilities or from the need to share knowledge derived from unique functional responsibilities, the respective functions need the ability to work together in an integrated fashion. The most important skills claimed by PMs include leadership and stakeholder management. Combined, these suggest the ability to bring together diverse interests to embrace a common objective and work collaboratively. The most important skills claimed by CSEs include system thinking and requirements management, which suggest an ability to link overarching objectives to detailed elements in a holistic integrated perspective. Both PMs and CSEs share communication as a key skill. An educational or professional development program may not necessarily need to develop all of these skills in its students, but it should nevertheless strive to develop an understanding and appreciation of the different roles that are required in an integrated program leadership team.

Innovative engineering leadership education programs increasingly emphasize the introduction of more elements of lifecycle processes and operations for engineered systems, including interpersonal skills and leadership. Yet, they still may not address some of the organizational and relational elements highlighted by this study. Particularly, integration across functional and organizational boundaries appears to be an important element of engineering program success. Unproductive tension between the PM and SE disciplines results when integration of the functions is informal, ad hoc, or just ineffective. The roots of unproductive tension may ultimately lie with poorly-defined roles and relationships in the program and organization. As engineering efforts became more integrated, as relationships become more explicit and formally-defined, the unproductive tension in organizations is seen to decrease. This suggests that organizational or program design may play a significant role in shaping the effectiveness of engineering efforts. While engineering students may learn a good deal about product design during the course of their education, they may not be exposed to much about the design of organizations and the relationships they embody. It is recommended that these issues be considered for addition in future engineering leadership curricula.

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