

Systems Engineering as integrator between engineering and business

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Abstract—The primary aim of business is to make money from services and/or products. Increasing system complexity and level of technology of engineered systems has seen an increased integration of systems engineering and program management activities. However, at large, systems engineering and program management is still seen as separate engineering functions remaining at logger heads with systems engineering being responsible for the technical decisions and program management for the business decisions of the project. As pressure mounts on performance, schedule and cost due to the trend of better faster cheaper, integration of engineering and business towards achieving company objectives is becoming increasingly important when aiming towards business excellence. Successful integration is reliant on management support and it is therefore becoming increasingly important to include the importance of systems engineering into management training. This article subsequently discusses the importance of systems engineering as integrator between engineering and business and how the School of Engineering Management at the University of Johannesburg has included it into their management education program.

Keywords—systems engineering; integrated management; management education

I. INTRODUCTION

The primary aim of business is to generate income from offering services or products to its customers. Engineering is, however, key in producing these products or services and it therefore stands to reason that integration of business and engineering is essential when aiming towards business excellence. Despite Deming's success in miraculously recovering the Japanese economy after WWII by integrating business and engineering concepts, engineering and business has to a large extent remained opposite poles in supplying products or services to customers until the relative recent past. The increasing complexity of engineered systems together with increasing level of technology, competition and pressure on time to market serves as motivation for integrating Systems Engineering and Program Management as essential tools in remaining competitive [1]. As the value of the product to the customer including the operating and dispersal costs is to a large extent determined by design decisions, Design Management is developing into a discipline applying systems engineering principles to integrate business and design [2]. As

the principles are generic, it is applicable to all engineering disciplines as well as other industries.

Doug Hall from the Innovation Engineering Leadership Institute indicates that innovation is about the integration of more profitable products/services with more profitable customers/markets through more profitable processes [3].

Confirming the need for an integrated approach to management education led to the creation of the Marcel Desautels Institute for Integrated Management (MDIIM). The aim is to educate management students in breaking down barriers between disciplines encouraging holistic, cross-functional approaches to management to address the increasing need for managers who can articulate and reconcile issues from multiple perspectives [4].

In order to align their effort with industry need the Postgraduate School of Engineering Management at the University of Johannesburg has subsequently echoed the need to include formal training in applying the principles of systems engineering as part of their Masters in Engineering Management Program. The single module is aimed at challenging the traditional way of engineering thinking and exposing the students in engineering management to the generic concepts of systems engineering and creative problem solving. This paper discusses the motivation for the focus of the module.

II. INTEGRATION OF DISCIPLINES

In essence systems engineering is about risk management. Originating as a formal discipline in the 60's its primary function is to manage all activities that may potentially impact the success of achieving the required outcome. The first of this is knowing exactly what the required outcome is, i.e. managing the user requirements. This not only includes the stated needs, but also the implied needs, but even more importantly, the expectations. Only once this is clear does it make sense to continue. Once the outcomes have been determined it is important to compare this with the company objectives to ensure that they are aligned. If satisfactory alignment can be obtained the rest of the systems engineering process can be initiated to manage the technical aspects of the project.

Technical performance not only includes technical performance of the product, but also of the resources required to successfully obtain the product or produce the service. It therefore includes required skills and capabilities, facilities and equipment, acceptable performance levels, quality management, verification and validation. These aspects in turn all impact the required funding as well as the time required to successfully achieve the required outcome. The above therefore necessarily involves the functions of human resource planning, logistics, operational management, maintenance, financial planning, program management, strategic planning, quality management, procurement, i.e. each and every function required to run a business successfully. Successful achievement of the required outcome is therefore only possible through successful integration of the required functions as a whole rather than the individual functions on their own [5]. Without this integration the different functions tend to operate in silos with the stronger personalities dictating the level of service delivered to the project and subsequently also the focus of the team.

III. SYSTEMS ENGINEERING AS INTEGRATOR

Project requirements placed on the different functions are, however, determined by a thorough understanding of the technical requirements to be met throughout the complete life cycle of the project and its related outcome, i.e. product or service. Systems engineering in essence is about reducing risk by addressing potential problems through smaller manageable steps. This is only possible if the role of the system or impact of the problem is understood as part of a bigger system. A sound understanding of the real problem and the project as a whole then enables the definition of the work break down structure (WBS) identifying the most suitable lower level deliverables required to ensure that the high level outcome is achieved to the required level. Analyzing and prioritizing the requirements through scientific decision making removes bias when identifying the most suitable solution to address a problem. Integrating lessons learned on previous projects with other risk management tools is essential to identify and prioritize risks that could impact on achieving the intended outcome. Systems engineering is generally the discipline involved in the identifying the lessons learned and therefore, having defined the technical requirements, is the discipline most capable for performing this integration.

Defining the required outcomes and deliverables, systems engineering determines the technical skills required for analytical modelling, design, manufacturing, testing, and commissioning as well as the product/service to be delivered. It therefore acts as a key contributor in negotiating the correct combination of project budget, performance and schedule. Based on the above it therefore stands to reason that systems engineering is the most suitable discipline to act as integrator between the different functions.

Due to the perceived cost and effort associated with the systems engineering process as applied to regulated industries such as that of defense and nuclear, the commercial industry

developed a resistance to the application thereof in a commercial environment. The main reason for the increased effort is, however, generally driven by the complexity of the systems and the fact that the defense and nuclear industries are mainly driven by safety requirements which is a lot less so in the commercial environment. Successes obtained by application of the generic principles as sound engineering has, however, proven the value of the principles to all industries with the approach gaining popularity. A serious challenge for traditional systems engineers is therefore to shift their minds from the bulky document centred approach of highly regulated environments to developing light footed lean processes ensuring that all the important elements are addressed as early as possible, yet only covering what is essential to limit risk and ensure repeatability, i.e. keeping it as simple as necessary. Understanding the importance of integrating design and business in any industry has led to the development of the relatively new discipline of design management.

IV. DESIGN MANAGEMENT

The Design Management Institute defines design management as the integration between business and design [2]. Realizing that in practice there are always conflicting requirements between performance, cost and schedule, Botha [6] defines design management as:

Relating to the effective application of management and design activities, methods and skills necessary to optimize and manage the design process to deliver the most suitable solution meeting business objectives within predefined constraints in a technically defensible and sustainable manner.

This suggests the aim to be, although not necessarily optimized, finding the most suitable technically defensible solution given the limitations of schedule, budget, technology, business objectives and even customer preference. However, it also suggests that the limitations/requirements should be challenged if it results in significantly reduced performance. It therefore requires effective integration of design thinking into the business strategy. This is echoed by the significantly increasing trend of high level companies acquiring design firms to improve their competitiveness [7].

Effective application of systems engineering principles is one of the most important aspects in supporting the “Faster, Better, Cheaper” trend. The less time and money there is the more important it becomes to do the right things right the first time. Design management is aimed at defining an as lean as necessary scientific approach to consistently arrive at the most suitable solution to support business objectives given the same requirements and limitations while optimizing the use of resources. It also includes the identification of potential failure modes to improve reliability and customer experience while reducing the risk of warranty claims. Although essentially developed to address the challenges of the fast moving consumer goods (FMCG) industry, the principles are, true to

systems engineering, generic and therefore applicable to any environment.

V. COMPANY CULTURE

The direct value of systems engineering is, as with quality management, difficult to quantify early in the project. Successful application depends on a strong belief in the principles and allowing sufficient time and money to do what is required. As the budget and schedule (project) is not managed in the same place as the performance (technical) the initial delay in producing artifacts during the early stages of a project is often perceived as a threat to program management. It therefore often results in a misalignment to meet personal agendas for producing artifacts, whether important or not. This is not only counterproductive, but results in a high risk of accepting a wrong course of action in order to produce results.

Following the traditional approach, increased pressure on either time or budget generally results firefighting and subsequently in reduction of the time or budget allowed for the seemingly “less important documentation” of systems engineering. This is exactly the opposite reaction from the required. The tighter the budget or schedule the less time and money is available to accommodate an error and therefore the more important good planning and decision making becomes to ensure that the right solutions is produced right the first time. Checklists have proven to be an important tool to ensure that nothing is missed when reviewing a design or checking an artifact. The importance of developing a sound system for any repetitive task cannot be over stressed. It not only reduces the risk when required but often also the level of skilled resource required to perform the task freeing the higher skilled resource to address more pertinent issues.

Changing the culture to invest more time in the early stages to ensure the right outcome therefore is a function of senior management. Due to the high successes achieved when applying systems thinking line management often feel threatened by the possible exposure of their ignorance. It therefore has to be driven from the top down and cannot be implemented successfully without visible support from senior management. This was already emphasized by Demming [8].

VI. EDUCATING MANAGEMENT

With reference to the well-known statement by Peter Drucker, “Management is doing things right, leadership is doing the right things”, systems engineering is about first identifying the right thing to do and then doing it right [9]. Without formal management training engineers from the traditional disciplines generally have not been exposed to systems engineering and systems thinking during their education. Their education generally focusses around the accuracy of the answer rather than the accuracy of the solution, e.g. a technically highly advanced sports car is far less valuable in working a piece of land than a low end tractor, i.e. a hundred percent accurate wrong answer is less valuable than a fifty percent accurate right answer. This, however, does

not negate the importance of developing the most accurate answer given the limitations once the right solution has been identified. The challenge in educating engineering managers therefore lies in changing their thinking from the traditional engineering thinking to systems thinking where the primary focus in the initial phases is to identify the most suitable solution and then finding the most accurate answer. It is also important to let them understand that the decision to apply the principles should, as with quality management, not be based on how much it costs to implement, but how much it can cost if not implemented. This understanding is important to ensure the relevant management support essential for allowing sufficient time and money on any project.

Due to the encompassing nature of systems engineering it is impossible to train students in engineering management as competent systems engineers in a course not specifically designed for this purpose. With only a single module, the challenge was therefore to identify the important aspects to create a sound awareness and understanding of the value of systems engineering in general to engineering projects. The aim was therefore to equip management students from different engineering disciplines with sufficient knowledge to be supportive of systems engineering as an essential engineering discipline when they return to industry. Detailed information is freely available on the internet with numerous courses covering the different topics in more detail. Content was therefore aimed at challenging the traditional engineering thinking and triggering consideration of systems thinking to find the most suitable solution to any problem.

VII. USE OF MINDMAPS

Although not formally taught, mindmapping offers an invaluable tool to engineers to simplify complex problems into their various sub-problems and tracking the status of each element. The ease of adding, deleting and shifting elements allows easy generation of logical structures while collapsing and expanding of element sub-structures simplifies the creation of the “larger picture” as well as the detailed content. This makes it suitable as an initial planning tool to all aspects of engineering whether it be project/program management, technical project planning, documentation or research. Once the important issues have been identified and allocated it serves as input to the more traditional engineering tools. The simplicity of use and visibility of issues, however, reduces the time identifying and risk of missing important issues.

Although not formally assessed on the use of mind maps the students were sensitized as to the value of using commercially available mindmapping software to simplify complex problems.

VIII. COURSE CONTENT PLANNING AND LAYOUT

As a post graduate course, students are generally from industry with some practical experience in applying their knowledge. The challenge of the course was to get them to think differently to the traditional engineering mindset and

view the bigger picture to find a balanced solution offering the highest value satisfying both customer and company objectives. The content was developed based on experience, the Systems Engineering Handbook of INCOSE and trends found in industry and at other academic institutions. As shown in Fig. 1, it includes the essence of systems engineering in addressing systems engineering in context, operational concept development and systems engineering management. This is followed by discussing various tools for application of the most common generic principles. The students are then given the opportunity to demonstrate their understanding of the principles by applying the most common tools in group assignments to a system of their choice. Students are grouped randomly to force interaction between students from different environments and disciplines to work together to improve cross pollination and maximizing the learning experience. The course is then closed with an explanation of how systems engineering interacts with other project functions.

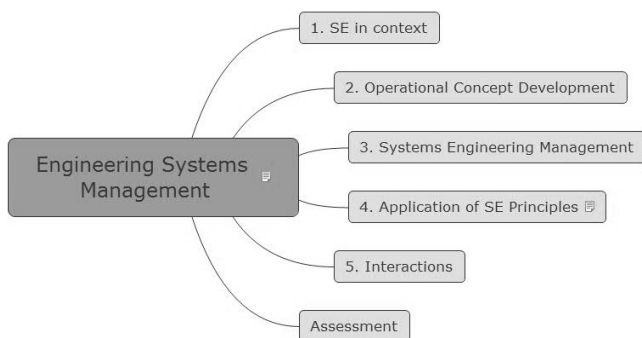


Fig. 1. Course layout

Course development was done in collaboration with practicing systems engineers in order to ensure relevancy of content as well as assessments. It was also benchmarked to other courses for content and relevancy. With the course benchmarked against industry it was then evaluated against the needs of the engineering management program and interaction with other modules.

As the needs for the other management modules are impacted by the technical requirements of engineering projects, systems engineering once again plays an important role as integrator between the content of the different modules. (see Fig. 2).

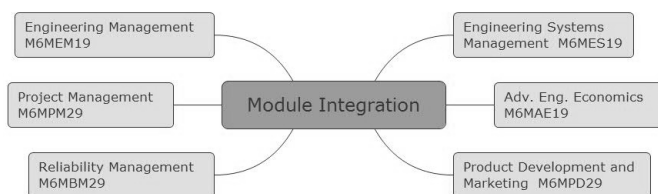


Fig. 2. Module Integration

Placing systems engineering in context therefore gives a brief discussion as to how this module integrates with the other engineering management modules shown in

Discussing the module integration is followed by discussing the fundamental principles of systems engineering to form a common basis of understanding to work from. It includes the concept of a holistic view to the problem, seeing an element as part of a bigger picture and considering the whole life cycle from initiation to decommissioning. It covers important engineering processes and system architecture. Finally it gives an overview of the Systems Engineering Body of Knowledge (SEBOK) covering system fundamentals, systems science, systems thinking and following a systems approach to engineered systems.

Operational concept development primarily focuses on the importance of requirements engineering in identifying the customer needs and expectations and integrating this with the company objectives to define measurable technical requirements both for systems/sub-system requirements as well as interface requirements. The main topics covered include:

- requirement types,
- requirements elicitation,
- requirements analysis,
- requirements specification including characteristics of good requirements,
- requirements validation and review, and finally
- requirements management.

Requirements engineering is followed by system analysis addressing the governing principles and general process approach to system analysis in identifying the most suitable concept solution.

Systems engineering management discusses the systems engineering processes throughout a product life cycle as well as management processes to ensure that the identified solution is obtained. It includes identifying the different standards applicable to systems engineering.

The application of the principles addresses the importance and value of modelling when moving from a document centric environment to model based systems engineering. This is followed by a discussion of the importance of a scientific approach to decision making to prioritize characteristics scientifically and limit bias in the decision process. Discussing the work break down structure or WBS then focuses on identifying the deliverables required to achieve the intended outcome. This is followed by emphasizing the importance of a systems engineering plan to plan how the project is to be managed technically before formally commencing the project.

As systems engineering essentially is about risk mitigation the different risk types are discussed after which the risk mitigation tools of Root Cause Analysis and Failure Mode, Effect and Criticality Analysis (FMECA) are addressed as tools to identify and prioritize potential risks as input into the

decision process. This is followed by a discussion on the various technical reviews to be performed throughout the project to reduce the risks impacting on the potential to achieve the required outcome. Configuration management discusses the importance of change management to reduce risks and maintain relevant documentation while quality assurance addresses the process of ensuring that the outcome will be achieved by identifying and monitoring relevant indicators. Verification and validation addresses the importance of a test plan defining tests to measure each requirement prior to starting the project. Finally the importance of understanding the contributors to the overall life cycle cost is stressed to eliminate the risks of hidden costs impacting the feasibility of the project at a late stage.

In closing the course discusses the interaction with and supporting role systems engineering has to other engineering disciplines as well as the different sub-disciplines of systems engineering developing into disciplines in their own right.

The course is presented in seven lecturing sessions of three hours each. Assignments are selected to support the course content requiring additional work from the students. Group assignments allow interaction between students from different disciplines as well as level of exposure in industry resulting a cross pollination between disciplines. As students are generally from industry, work responsibilities sometimes prevent them from attending class. For this reason the School of Engineering Management has in 2016 embarked on recording the lectures and making them available to registered students electronically.

IX. ASSESSMENT

A. Student Assessment

Assessment is done on a continuous basis through group assignments and a final assessment on an individual basis. During the group assessment each group is required to identify a simple multi-disciplinary system of sufficient complexity to allow at least three subsystems three levels deep in order to develop a feel for the repetitive nature of higher level system requirements to be satisfied through defining lower level requirements to be satisfied.

For the *first assignment* they are required to”

- develop a functional architecture and
- develop a set of technical requirements including both system requirements as well as interface requirements.

Using the same system and the requirements derived in the first assignment, the *second assignment* requires them to develop:

- a Work Breakdown Structure (WBS) indicating the required deliverables
- a Systems Engineering Management Plan (SEMP) defining how the project will be managed technically
- a Test and Evaluation Management Plan (TEMP) defining tests for the different requirements, and

- a Failure Mode, Effect and Criticality Analysis (FMECA) identifying and prioritizing various potential failure modes as well as mitigation strategies to reduce the risk.

Group assignments are submitted electronically and then evaluated according to a rubric communicated to them prior to submission. The rubrics are developed to emphasize the aspects generic to all engineering disciplines for the topics covered in each assignment. These include, but are not limited to:

Assignment 1

- Multi-disciplinary system
- Multi-level system consisting of at least three sub-systems three levels deep
- Decision making and concept selection
- Definition of requirements focusing on lack of ambiguity
 - *Functional* – focusing on the “what”
 - *Technical* – defining level of acceptable performance, realism and tolerance
 - *Interface* – requirements for interaction

Assignment 2

- SEMP – Evaluate definition of SE activities related to the system selected in Assignment 1.
- TEMP – Evaluate definition of appropriate test type, nominal value, relevancy to sub-system level and cross-reference matrix for the system selected in Assignment 1.
- WBS – Evaluate WBS for relevancy and being deliverable based and not activity based for the system selected in Assignment 1.
- FMECA - Evaluate suitable definition of failure to satisfy a predefined function (as defined in Assignment 1), modes, effects and criticality for at least three failures and multiple modes and effects for three items per level and indicating the criticality thereof.

During the final assessment students are required to individually apply some of the tools (randomly selected) to a simple system to demonstrate their ability for applying the different tools. The assessment standard is moderated by an external moderator active in industry in the field of systems engineering. This is done prior to submission of the assessment to the program coordinator. The assessment takes the form of a closed book assessment done under normal exam conditions with university invigilators.

Once marked the marks are moderated by the external moderator as per normal university rules applicable to exams.

As indicated before the aim of the course was to create a general awareness as to the importance of systems engineering principles in supporting management decisions. Assessments were subsequently not aimed at developing systems engineers per se, but as an introduction to develop basic capabilities and support.

B. Course Assessment

During the last lecture the students complete a teaching and module evaluation as per the normal practice implemented by the university. The students then evaluate both the lecturer as well as the module content and relevancy.

X. FEEDBACK

Although the teaching and module evaluation was performed, the outcome was unfortunately not yet available by the submission due date.

Feedback from the students during the course indicated that they have developed an appreciation for systems thinking and the value of the application of systems engineering principles in different engineering disciplines. They indicated a basic understanding and valued the assessment methods in underpinning the basic knowledge.

As this was the first presentation there were also lessons learned which included:

- Students appreciated the format of the assessments supporting the course content.
- Students indicated the relevance of the content to multiple engineering disciplines and confirmed it to be aligned to their experience in industry.
- Students confirmed the value of the recordings, both for when work responsibilities prevented them from attending class as well as listening to the recordings again in order to improve their grasp of the content covered.
- Students indicating that they used mindmapping in the initial stages confirmed the value of this technique to simplify complex problems and quickly gain an overall picture supporting effective planning of subsequent activities.
- As an introductory course aimed at exposing the student to the larger picture of the importance of systems engineering the content covers a large volume of work to lesser detail. Although the intent was that the students gain additional knowledge through the assignments the final assessment suggests that this was not successful in all cases. The course content will therefore be re-evaluated and potentially adjusted to improve the capability on the most essential topics.
- Due to the volume of the course content limited time was available to discuss assignment requirements or results in much more detail than that indicated in the assignment definition and rubric. Although students generally showed an understanding of the principles the final assessment results suggest that feedback on the group assignments should be improved to ensure that students improve their understanding of what level of capability is required for the final assessment. This will be done by a summary of the common mistakes found

as well as the deviation from what was required. This can then be used together with the individual group feedback to align themselves. This will also be kept in mind when re-evaluating the volume and detail of the course content.

- The weighting of the continuous assessments resulted in students potentially passing on the results of the group work while not personally mastering the capability to the intended level. This was apparent judging by the marks achieved in the final assessment indicating two distinct groups, i.e. those who were involved in the detail execution of the activities in the group assignments and those who clearly were not. Based on the subject being an introduction to the importance of systems engineering and the fact that it forms part of a multi-module curriculum it was deemed acceptable for this year. However, the weighting will be adjusted to ensure that students have to demonstrate a stronger personal capability in the final assessment.

XI. A FINAL WORD

The increased successful implementation of Deming's leadership principles to different industries serves as proof of the validity thereof. This has become the corner stone of total quality management (TQM) and promotes the principles of objectives and measures to obtain objective satisfaction, integrated systems management, a life cycle approach to product development through organizational teamwork, statistical control, and achievement of customer satisfaction [8]. The essential feature is that of a holistic or "total" approach including efforts at the level of strategic planning, management control and operational and task control addressing both process and product issues. This also supports the underlying principles of systems engineering as integrator as discussed in this publication. Development of the systems engineering module at the University of Johannesburg was done considering the intended outcome of the engineering management course together with the trends identified in industry and other academic institutions. It is therefore believed that the course offers a sound basis to developing managers to understand the principles of systems engineering and the importance thereof in successfully finding suitable solutions to complex problems within the limits of the required level of performance, budget and schedule.

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