Impact of System Engineering Practices on the Performance of R&D Projects – Initial Results

Umar Hamid, Muhammad Kashif Raza, and Raza Faisal Naqvi

Abstract—**The paper highlights the significance of applying system engineering in R&D projects. The research shows that system engineering in R&D projects not only facilitates the management process but also enhance the project performance in terms of requirements development and management, technical solution, system design development and testing, planning and monitoring of system engineering activities along with system engineering reviews and audits. This paper investigates the effectiveness of system engineering in R&D projects by focusing on different public sector R&D organizations. The research examines the knowledge and understanding of the working professionals in system engineering domain and its value addition in managing R&D projects for achieving better performance. The research is based on a survey in the form of a system engineering questionnaire. Project managers and team members involved in 15 projects of different R&D organizations participated in this survey. Results of this survey indicate a strong relationship between system engineering processes and the overall success or failure of the project in terms of satisfaction of the organization, user/customer, technical requirements, budget and schedule.**

Index Terms—**System engineering, project management, R&D projects.**

I. Introduction

Boarder has established a framework that defines system engineering. System engineering is a goal directed process addressing the issues of purpose, performance, product, and process with respect to customer requirements and end-user needs. It requires extensive engineering knowledge and skills [1]. Lightfoot identified the major phases of the system engineering process and highlighted its tools and techniques. The main milestones in system engineering are Systems Requirements Review, Preliminary Design Review, Critical Design Review, and System Integration Review. He suggested system engineering tools such as WBS, Gantt and PERT Charts, Configuration Management Plan, Integrated Logistic Support plan, System Test Plan, Acceptance Test Plan and System Engineering Management Plan. These tools help in overcoming the challenges of system engineering and to undertake the project in an orderly manner in which resources are used effectively in the development of a solution which meets the user needs [2]. Hayward has emphasized on requirements management in order to handle technical and performance risks. The process of requirements management includes defining performance requirements, functional requirements, safety requirements, and requirements traceability in the context of a railway project. He defined system engineering as a disciplined application of processes and tools to specify, document and manage the delivery of a system [3]. Burks highlighted some generic capabilities that are required by most system engineers such as requirement traceability, functional and detail design capture, design validation, documentation of results, and dynamic response to changes. According to Burks, the transformation of customer requirements into working requirements is essential to drive the whole system. System engineers are responsible for continuous refinements until all ambiguities are resolved to their satisfaction [4]. Lann found out that real causes of failure of the Ariane 5 flight 501 are the faults in capturing application/environment requirements, in design and dimensioning of the on-board computing system. These faults result from not following a rigorous System Engineering approach [5]. Project managers can reduce the chances of software project failure with the help of comprehensive planning, adequate requirements and proper documentation, user involvement at low level, team members with good technical and communication skills, and reliable resource estimation [6]. A project manager is responsible for failure factors such as unclear requirements, scope changes during project, lack of reviews at the end of each phase, and aggressive schedule [7]. Requirements engineering and reviews mentioned above can help in reducing the chances of failure factors. The study in [8] revealed some important project management issues related to project success such as proper planning, estimating, project life cycle, clear requirements and documentation, deliverables at each stage, and availability of skillful team members. It also presents a positive relationship between project success and project planning and scheduling techniques [8]. Lightfoot in [2] has suggested tools and techniques for planning and scheduling the system engineering activities and can facilitate project managers for better planning. Three common success factors related to project success are technical performance, schedule performance, and budget performance. Moreover level of satisfaction of the organization and customer/end-user should also be taken into consideration [9]. The study in [9] revealed that system engineering processes showed positive relationship with overall project success. The results came from surveys conducted for NASA space flight hardware projects. Results of study in [10] revealed that projects having highest overall system engineering capabilities have shown best performance for both low challenge and high challenge projects. In addition it pointed out that system

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engineering practices such as requirements development and management, product architecture, and trade studies have shown strong relationship with overall project success [10]. System engineering includes both scientific and engineering processes and tools to ensure that optimum system is designed and developed which meets all the requirements within cost and schedule. The study in [11] showed that application of system engineering in UK automatic light railway systems has proven to be a success. Project management requires inputs from the system engineering for planning, monitoring and controlling along with management of risks, configuration, and quality. System engineering is responsible for requirements definition and analysis, design implementation, integration and maintenance needs collaboration of project management throughout the project life cycle. System engineering is considered costly and is given less importance before the contract which leads to many problems at later [12]. Project management is a sequential process focused on planning, execution, delivering of the requested outputs. It also concentrates on reducing deviation from the plan, getting the things done, and is accountable for the success of the entire program. System engineering is an iterative process that focuses on requirements, design, and verification. It is about doing the right things, delivering what is required and is responsible for the technical success of the program [13]. According to Kostek and TekSci, use of both system engineering and project management tools and techniques can be key to the success of a project [14]. Project management and system engineering processes need to be combined for managing highly technical and complex projects [15]. To be successful, project management and system engineering shall be well integrated in technical, cost and schedule factors. This approach will have a very positive impact on project performance as well [16].

II. Research Methodology

The research is based on a survey in the form of a system engineering questionnaire. The questionnaire has been developed with the help of two requirement engineering questionnaires and the system engineering literature. One requirement engineering questionnaire is by Sari Kujala, 2003 [17] and the other by Stuart Anderson and Massimo Felici, 2001 [18]. The purpose is to investigate the effectiveness of system engineering in R&D projects by focusing on different public sector R&D organizations.

The survey questionnaire consists of 80 items. 72 out of 80 items address 08 system engineering dimensions such that there are 15 items for requirements development, 08 items for requirements management, 07 items for technical solution, 10 items for subsystem design development and testing, 08 items for system integration and testing, 06 items for planning of system engineering practices, 06 items for monitoring of system engineering activities, and 12 items for system engineering reviews and audits. Project performance in terms of success or failure has been measured in various dimensions such as organizational satisfaction, user/customer satisfaction, technical requirements satisfaction, budget, and schedule satisfaction. There are 08 items that address project performance. We have asked respondents to answer the questions based on the project in which they participated in system engineering. We have also asked the respondents to answer whether they consider the project success or failure.

All 80 items have been assigned scores ranging from 1 to 5 point scale which shows the presence or absence of system engineering processes. Score 1 to 4 represents 'strongly disagree, disagree, agree, and strongly agree' respectively. Score 5 represents 'no opinion' and has been assigned zero value in data analysis. We assured respondents that data collected from received responses will be kept confidential and is anonymous and not attributable to an individual organization or respondent which is a necessary requirement for obtaining maximum participation.

III. Data Analysis

We distributed the questionnaires in different public sector R&D organizations. We received completed questionnaires describing 15 R&D projects. Project managers and team members participated in this survey. 12 out of 15 projects have been reported a success whereas only 3 projects as failure. We received 47 complete survey responses and used them for data analysis. Each project included at least two respondents. Most of the sample (N = 47) are males which consist (91%) of the sample where the females consist only (9%) of the sample. In case of work experience of the project team members, the high portion went to (5 – 10 years) which consist (53%), (less than 5 years) consist (36%), and (above 10 years) consist (11%) of the sample. The sample size is small but adequate and exhibits sufficient variation that is required for identifying the statistical relationships between variables.

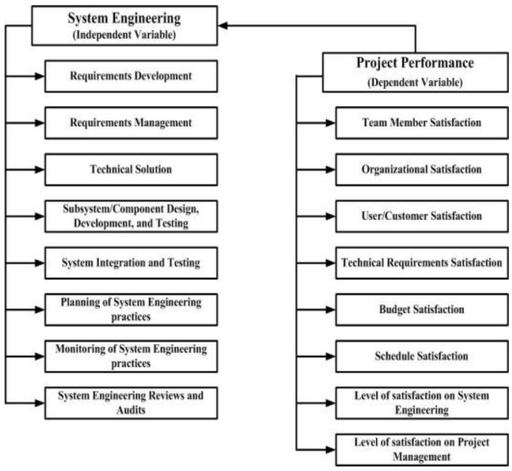

Fig. 1. System engineering and project performance dimensions

We have defined 08 variables for 08 system engineering dimensions mentioned above. Each variable is computed as the mean of the items corresponding to a particular dimension. System engineering has been defined as a separate variable which is the mean of the 08 variables corresponding to 08 dimensions mentioned above. Project performance has been defined as a separate variable which is the mean of the 08 items given in the questionnaire.

Fig. 1 shows the two most important variables of this research i.e. system engineering and project performance along with their dimensions. In this paper, system engineering has been taken as the independent variable and project performance (in terms of success or failure) as the dependent variable.

IV. Survey Results

A. Reliability Test

The reliability test has been carried out for all 80 items in the questionnaire. The value of Cronbach's Alpha is 0.958. This shows that the survey questionnaire is highly reliable.

B. Descriptive Statistics

System engineering variable has values i.e. Min = 1.91, Max = 3.46, Mean = 2.93, and Std. deviation = 0.44. Project performance variable has values i.e. Min = 1.50, Max = 3.75, Mean = 2.86, and Std. deviation = 0.45.

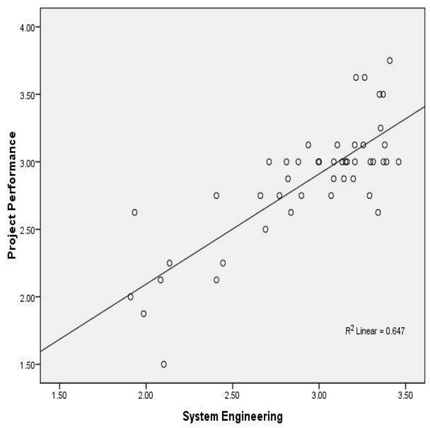

Fig. 2. Regression plot showing linear relationship between system engineering and project performance variables

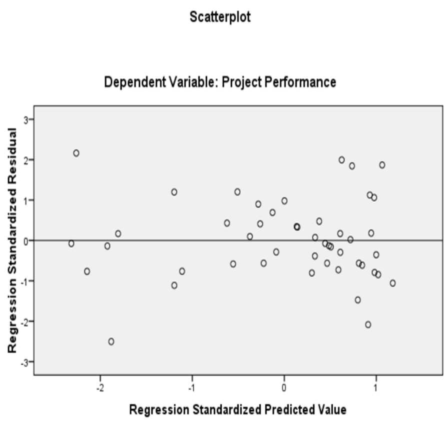

Fig. 3. Scatter plot showing residuals statistics

The skew ness and kurtosis values for system engineering are -1.04 and 0.036 respectively. The skew ness and kurtosis values for project performance are -0.771 and 1.3 respectively. These values have been calculated for satisfying the initial conditions required for regression.

C. Regression

Fig. 2 below shows that there is a linear relationship between system engineering and project performance.

The value of Pearson Correlation between system engineering and project performance is 0.804 which shows a strong positive relationship. The value of R-Square (coefficient of determination) is 0.647 which means that 64.7% variation in project performance is because of system engineering.

ANOVA shows that significance is 100%. Coefficient analysis was carried out which results in the following equation for linear regression:

$$pp = (0.817 \times se) + 0.460$$

where

pp = project performance
se = system engineering

Fig. 3 above shows the residuals statistics in terms of a scatter plot around the mean value of 0.0. All the outliers are within the acceptable regression value of ± 3.

D. Correlations

Correlation matrix was developed for the 08 system engineering dimensions. A strong correlation exists among all dimensions.

E. Factor Analysis

Factor analysis was carried out for all 08 dimensions of system engineering. This test explained the total variance for the 08 dimensions using principal component analysis. A single component was identified that represents the 08 dimensions in a manner as shown in Table I below:

TABLE I: The 08 Dimensions in a Manner

	Component 1
Requirements Development	0.722
Requirements Management	0.750
Technical Solution	0.859
Sub System Design Development and Testing	0.884
System Integration and Testing	0.844
Planning of System Engineering Practices	0.737
Monitoring of System Engineering Practice	0.732
System Engineering Reviews and Audits	0.785

V. Limitations

There are certain limitations to our study. The first was the relatively limited number of R&D projects that were reported. Secondly, survey based research is usually based on self-reported data which reflects people's perceptions, not what might have actually happened. We surveyed engineers and scientists working in different public sector R&D organizations, hence our results are limited to their knowledge, attitudes, and beliefs regarding the projects and project managers with whom they were involved. The items in our questionnaire are based on both the literature and some standard questionnaires that highlight important day-to-day activities on real projects.

VI. Conclusions

The system engineering activities described in this paper provide the systems engineer with an approach for moving a project from problem definition through design to implementation in an effective and orderly manner. System engineering ensures the delivery of the optimum system that best meets all requirements and provides the proper balance of technical performance with cost and schedule. This study has been designed to explore the relationship between project performance and system engineering and it shows that the success of the project is influenced by the use of system engineering processes. The survey data clearly shows that projects with better system engineering capabilities have an increased likelihood of delivering better project performance. There exists a strong relationship between overall project success and system engineering. This demands an early application of system engineering practices in the project. This research serves as a starting point in motivating continuing research related to system engineering for large and complex technical projects and project performance factors. We intend to continue with this research in the future to investigate more R&D projects.

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