Developing Systems Engineering for Sustainable Infrastructure Projects

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Abstract. Globally, Sustainability is very quickly becoming a fundamental requirement of the construction industry as it delivers its projects; whether buildings or infrastructures. Throughout more than two decades, many modeling schemes, evaluation tools, and rating systems have been introduced on route to realizing sustainable construction. Many of these, however, lack consensus on evaluation criteria, a robust scientific model that captures the logic behind their sustainability performance evaluation, and therefore experience discrepancies between rated results and actual performance. Moreover, very few of the evaluation tools available satisfactorily address infrastructure projects. The research introduces a system engineering model that abstracts the environment, the construction product, and its production system as three interacting systems that exchange materials, energy, and information. The model utilizes this setup to capture and quantify essential flows exchanged between such three systems, to evaluate sustainability. The research walks through the development of a generic case of the model, and then demonstrates its utility in evaluating the sustainability performance of civil infrastructure projects. The developed model will address an identified gap within the current body of knowledge by considering infrastructure projects. Through the ability to simulate different scenarios, the model will enable identifying which activities, products, and processes impact the environment more, and hence potential areas for optimization and improvement.

Keywords: Infrastructure, sustainable Infrastructure, systems engineering, realizing of systems.

1. Introduction

This paper is part of a series intended as brief introductions to the application of systems engineering approaches to infrastructure projects. It was developed by the International Council on Systems Engineering (INCOSE) Infrastructure Working Group in the interest of aiding industry [1-3]. Another characteristic in the construction of infrastructure projects has increased the complexity and number of stakeholders. Unlike other types of projects, construction of Infrastructure projects is often funded by government agencies. In many cases, there are multiple funding agencies at different levels of government. Add to this the many groups affected by the project, from local communities to utilities and transit systems that must be crossed or relocated, along with potential land-use restrictions and environmental impacts, and the requirements list grows exponentially.

The codes and standards that form part of the requirements add another layer of complexity in the construction of infrastructure projects. the construction of Infrastructure projects can cross into different jurisdictions, leading to varying and sometimes conflicting requirements for the different physical locations of packages of work [4]. There are several unique aspects of systems engineering on large infrastructure construction projects. One difference is that the system elements are often completed by different firms under separate contracts, and often at different times. This makes it even more difficult...
to integrate the work (as it’s done across projects), and to complete the verification and validation that all of the requirements have been met (as each contract is only a part of a larger system).

Design-Build projects have some unique characteristics of their own that have the potential to increase project risk. On design-build projects, there is a shift in responsibility for the quality of the work, including the development of final requirements and specifications, away from the agency and towards the contractor. The design is initiated by one firm but completed by another: this handoff increases the potential for misinterpreted requirements or incomplete incorporation of requirements. Internal integration is much more complex, as the work is broken down into much smaller packages to enable a more continuous construction effort [5].

2. Systems Engineering Fundamentals

Systems engineering is an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, and conducting design synthesis and system validation. SE considers both the business and technical needs of customers to provide a quality product that meets user needs. Systems engineering involves multidisciplinary teams working together to define project requirements, identify alternative designs, select the optimal solution, build the product, conduct testing to ensure the product meets stakeholder needs and requirements, and operate and maintain the product through its lifecycle [6]. Many of these steps are undertaken on traditional design projects. The systems engineering approach differs in a few fundamental aspects:

- Requirements are thoroughly defined, refined, and allocated to lower-level system elements, assigned to suppliers and subcontractors, and tracked, through the testing and verification phase of the work.
- The product is viewed from a system perspective: links between requirements are identified so that changes to any one area can be analyzed for impacts to the requirements for the system as a whole.
- The entire product lifecycle is considered from the start of the project, including the disposal of the final product.

3. Process of System Engineering

Figure 1 provides a simple context diagram showing design engineering as a process. The design engineering process gathers inputs from the specifications and system requirements, identifies and specifies all systems, structures, and major components to be designed and produces an integrated design with interface requirements and descriptions of the system elements [7]. From a system engineering perspective, effective design management requires the following activities to be well executed:

Figure 1. Design SE process.
3.1. Define
Describe a high-level system consistent with stakeholder requirements and specifications. Refine and allocate the system requirements to lower-level system elements as appropriate. Identify interfaces between system elements, and between the system and other external systems [7].

3.2. Analyze and Evaluate
Analyze the system as a whole to determine how best to achieve user and client requirements. Establish criteria for selecting from among the design alternatives. Evaluate design alternatives and decide on the best option [7].

3.3. Integrate
Define and manage interfaces with external systems. Define the strategy for integrating system elements. Ensure the design elements are integrated throughout the effort, from preliminary engineering through final design.

3.4. Document and Control Change
Document the preliminary engineering phases and the baseline design. Establish traceability between requirements and system elements. Analyze design changes for their full impact on the integrated design and the requirements. Approve changes through a prescribed process and appropriate levels of authority. Understand the impact on the rest of the system before committing to the change. Ensure approved changes are propagated to all affected items [7].

3.5. Provide Oversight
Manage the resulting information and the processes being implemented. Develop metrics useful to show the quality of the design management activities.

4. Benefits of Systems Engineering
As infrastructure projects become more complex about the size of the systems, the number of requirements and stakeholders involved, and the sophistication of the associated technology, the risks of project failure increase [8]. The application of systems engineering can help ensure these projects are delivered on time and budget, and that they meet requirements. Systems engineering improves project outcomes by:

4.1. Improving System Quality
Systems engineering involves an increased focus on thorough planning at the start of the project, including identifying stakeholder needs, documenting how the desired system will operate, and establishing system requirements, including tracing all requirements to their source documents. It also provides a detailed approach for ensuring those requirements are tracked through the testing stage and verified in a disciplined manner, through the use of a requirements verification traceability matrix (RVTM).

4.2. Gaining Increased Stakeholder Participation
Systems engineering requires the involvement of all stakeholders throughout the project to ensure the project continues to meet stakeholder needs. This continuous involvement helps the project team identify and document any changes to the requirements as early in the project as possible. The use of a standard systems engineering project process helps stakeholders actively participate in the development of the system, and facilitates the involvement of new stakeholders by reducing the learning curve.

4.3. Ensuring Design Integration
The thorough and detailed documentation of requirements in a requirements matrix provides a good foundation for design integration. The matrix documents the connections from the source files, such as contract documents, down to very detailed requirements for smaller system elements. It also documents interfaces and traceability between requirements, both internal and external. It also helps document
changes in requirements, and enables the team to identify impacts of the changes on the requirements for other parts of the system.

4.4. Reducing Cost and Schedule Overruns

Combined with the disciplined project controls that form part of the systems engineering approach, the rigorous tracking of requirements helps reduce the risk of schedule delays and cost overruns.

5. Practical Study and Statistical Analysis

There is a need for understanding all criteria and sub-criteria that used in the implementation of sustainable infrastructure projects. This will support and develop managing sustainable projects. For implementing sustainable infrastructure it will be necessary to study criteria and sub-criteria to achieve major components of sustainability. the statistical study aims to know the most important factors that affect in implementation of sustainable infrastructure. For identifying criteria and sub-criteria for sustainable infrastructure the questionnaire has been developed to reach to the opinion of the experts through surveying. The questionnaire contains a list of criteria for sustainable infrastructure. In this study, a systematic approach has been taken to identify and analyze the criteria to implement sustainable infrastructure through literature review and interviews with experts and questionnaires.

The respondents were requested to rank these criteria and sub-criteria according to Likert scale that is the most well-known used approach to scaling responses in the research survey. In Likert scale, the (1= Does not affect and 5 = Very effect) The analysis of obtained data was done by using the Relative Importance Index (RII) method. The researcher was distributing 40 questionnaire forms and 30 forms were returned. The quantitative data collected was analyzed using (SPSS) a statistics program. 32 factors were considered to rank by the Relative Importance Index (RII) method. These factors are a category in seven components namely (Environmental side, Economic side, Social side, Importance of site selection, Energy efficiency, Water consumption efficiency, and Sustainable materials used). the rating of criteria and sub-criteria are taken out for all seven components deduced from the questionnaire [9-11].

5.1. Mean Score Ranking Technique

The responses of some collected data were analyzed by using the mean score ranking technique. The results are shown in Table 1, the rank options in descending order and it was calculated by using the formula below for mean score (MS):

$$MS = \frac{\sum_{i=1}^{n} X_i \times S_i + X_2 \times S_2 + \ldots + X_n \times S_n}{N}$$  \hspace{1cm} (1)$$

5.2. Standard Deviation Technique

The Standard Deviation (SD) Measures the dispersion of the average. If the standard deviation is small, it indicates that it is close to the average, whereas if the standard deviation is large, it indicates that the answers were wide and not convergent. The results are shown in Table 1. The standard deviation was calculated according to the equation shown:

$$\sigma = \frac{\sqrt{\sum_{i=1}^{n} (x_i - \bar{x})^2}}{N}$$  \hspace{1cm} (2)$$

Where $\sigma$ = standard deviation; $x$ = mean score; $x_i$ = degree of importance; and $N$= total number of responses

6. Relative Importance Index (RII) Method

Through the questionnaire, the concept of importance is explained in a general way and it was comparable in preference and the definition of all factors was provided in the questionnaire. the questionnaire is designed in a way that will support in keeping of integrity and consistency in data. To ensure that the data were good in quality, a summary of the subject was written and the methodology of the research was explained to each respondent on the questionnaire. The results are shown in Table.1. The analysis of the data obtained was done by using the RII method by using the equation below:
RII = \sum_1^n (X1 \times S1 + X2 \times S2 + \cdots + Xn \times Sn)/(A \times N) \quad (3)

Where RII = the Relative Importance Index; S = weights of factors; X = frequency of each factor; N = total number of respondents for each factor; and A = highest weight.

**Table 1. The results of the questionnaire.**

| No. | Criteria                                                                                                                                                                                                 | MS   | SD    | RII  | Rank |
|-----|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------|-------|------|------|
|     | Environment side                                                                                                                                                                                          |      |       |      |      |
| 1   | The importance of environmental standards to be considered in the design of sustainable infrastructure                                      | 4.17 | 0.648 | 0.83 | 2    |
| 2   | Considerations of the sustainable impact of the project on safety and public health                                                      | 4.27 | 0.691 | 0.85 | 1    |
|     | Economic side                                                                                                                                                                                             |      |       |      |      |
| 1   | the impact of sustainable designs on reducing costs at all stages of the project life cycle                                                   | 3.97 | 1.129 | 0.79 | 1    |
| 2   | Appropriate economic systems and the encouragement of the State for such projects                                                         | 3.90 | 0.995 | 0.78 | 2    |
| 3   | the impact of sustainable project implementation on increasing costs                                                                        | 3.60 | 1.133 | 0.72 | 6    |
| 4   | Take the cost of disposal of materials at the end of the service period in consideration                                                   | 3.63 | 1.159 | 0.72 | 4    |
| 5   | Sufficient profits through the operation of sustainable project                                                                       | 3.60 | 0.968 | 0.72 | 5    |
| 6   | Capital recoverability during the operating period                                                                                           | 3.60 | 1.221 | 0.72 | 7    |
| 7   | the amount of the price or fees for the service or product provided by the sustainable project                                              | 3.90 | 0.995 | 0.78 | 3    |
|     | Social side                                                                                                                                                                                              |      |       |      |      |
| 1   | the social impact on the formation of building designs for the community                                                                 | 3.43 | 1.073 | 0.68 | 4    |
| 2   | security, social and political stability of the country                                                                                      | 3.60 | 1.163 | 0.72 | 3    |
| 3   | Understand and accept sustainable infrastructure ideas by society                                                                          | 3.63 | 1.098 | 0.72 | 2    |
| 4   | Establish a reasonable and logical legal framework to accommodate the concept of sustainable infrastructure projects and ensure the rights of all parties involved in the project | 3.67 | 1.028 | 0.73 | 1    |
|     | Importance of site selection                                                                                                                                                                           |      |       |      |      |
| 1   | Ease of linking infrastructure with existing infrastructure                                                                                 | 4.07 | 0.828 | 0.81 | 1    |
| 2   | Near the site of the main transport routes                                                                                                   | 4.03 | 0.718 | 0.80 | 3    |
| 3   | Provide close transportation                                                                                                                | 3.93 | 0.980 | 0.78 | 4    |
| 4   | The impact of location on ecosystems                                                                                                         | 4.07 | 0.944 | 0.81 | 2    |
|     | Energy efficiency                                                                                                                            |      |       |      |      |
| 1   | The use of alternative and renewable energies in energy generation                                                                         | 4.17 | 0.592 | 0.83 | 1    |
| 2   | The importance of using solar energy                                                                                                         | 4.10 | 0.759 | 0.82 | 2    |
| 3   | Environmental techniques for cooling and heating                                                                                              | 4.03 | 0.809 | 0.80 | 3    |
|     | Water consumption efficiency                                                                                                                |      |       |      |      |
| 1   | Low water consumption                                                                                                                        | 4.10 | 1.029 | 0.82 | 1    |
| 2   | Gray water recycling for watering gardens                                                                                                    | 3.90 | 1.062 | 0.78 | 3    |
| 3   | Use of water from cooling and heating                                                                                                         | 3.63 | 1.326 | 0.72 | 6    |
| 4   | Use of counters                                                                                                                             | 3.67 | 1.093 | 0.73 | 5    |
| 5   | Rainwater harvesting                                                                                                                         | 3.40 | 1.163 | 0.68 | 7    |
| 6   | The use of special techniques to determine if there are leaks in the water system                                                           | 3.77 | 1.165 | 0.75 | 4    |
| 7   | Develop designs that contribute to reducing water consumption                                                                               | 4.07 | 1.112 | 0.81 | 2    |
|     | Sustainable materials used                                                                                                                  |      |       |      |      |
| 1   | Use of substances with little environmental impact                                                                                             | 3.77 | 1.104 | 0.75 | 4    |
| 2   | Use materials that can be recycled or used                                                                                                   | 4.00 | 1.017 | 0.80 | 1    |
| 3   | The use of materials of high sustainability                                                                                                  | 3.90 | 1.029 | 0.78 | 2    |
| 4   | Availability of sustainable resources                                                                                                         | 3.60 | 1.163 | 0.72 | 5    |
| 5   | Consider the possibility of disposal of material after the end of service (reuse or recycling) taking into account the functional performance | 3.80 | 1.186 | 0.76 | 3    |
From the results in Table 1, the following conclusions are drawn. Decision-makers should know the direct impact of sustainable management practices and spread awareness of sustainability, and the important impact of it is that the environmental factor is the most influential. This indicates that implementing sustainable management depends mainly on the desires of the shareholders themselves. Since the primary purpose of the project is to earn profits, the organization must realize that sustainable management will inevitably bring huge benefits to the organization, any organization can implement engineering systems that depend on sustainability and consider all criteria (environmental, social, economic, site selection, water efficiency, Energy efficiency and the use of sustainable materials) are all important factors that should not be overlooked. To enhance the implementation of sustainable management in institutions, it is necessary to enhance the administrative awareness of basic institutions in introducing engineering systems that depend on the application of sustainability in infrastructure.

7. Conclusion

Infrastructure projects are constantly evolving. The purpose of this paper is to introduce modern engineering systems that bring together relevant factors and project management with engineering systems covering all of the project life cycle to reduce delays or increase costs since all risks that affect the project are taken. Therefore, several major and sub-criteria have been defined which will greatly assist project managers in covering all factors, taking them into consideration, understanding infrastructure and engineering systems greatly, and knowing the sustainable factors that have a great link to sustainable infrastructure. Engineering systems help stakeholders monitor the project as a whole, even if there are secondary contracts to make paragraphs of the project. This paper is an important addition in the world of knowledge, which aims to improve project monitoring and increase confidence in expectations that have been calculated throughout the project life cycle.

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