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System Engineering Implementation Process for Super-Systems

Saeid Azad[1], Mehdy Morady Gohareh[2*]
[1]Department of Industrial Engineering, Najafabad Branch, Islamic Azad University, Isfahan, Iran
[2]Department of Industrial Engineering, Faculty of Engineering, Arak University, Arak, Iran
[*]Email of Corresponding Author: m-moradygohareh@araku.ac.ir
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Abstract
System engineering is one of the most powerful tools for comprehensive project management and control. This tool emphasized the life cycle of the projects, manages every single activity and helps manage the main elements of the project through a set of management and engineering processes. The goal of the current study is to use a system engineering approach in design phase in order or to meet operational needs. This study proposes a conceptual design process with system engineering approach which institutionalizes configuration management, risk management, change management, requirements management and integration during the entire design process. The results indicate a significant increase in meeting customer requirements and a positive increase in project quality. Finally, the indicators of design documents created using this approach are provided as an example.

Keywords
System engineering, Requirement management, Integration, Product design and implementation process, Parametric design

1. Introduction

Today, advances in technology, the variety in customer needs has led to sensitivity of design for complex products. Due to importance of competitiveness and cost and time effectiveness as well as parameters such as performance and effectiveness for complex and military products, the importance of design method in creation of complex products has increased. A design method should answer several questions. Questions such as how a product can meet the needs of customers based on its complexity and time necessary for its production; how a product can produce an integrated system; what the nature of parametric design process in creation of complex products is; what the necessities of system engineering are and how these factors can grantee an integrated product system; are among those considered in modern design questions [1].

Generally, literature and publications mention the general ideas while considering the details of design process to be confidential. These details can differ based on the product, organization and industrial field and must be localized [2].

Therefore, given the nature and numerous parameters in design of highly complex products, implementation methods are of great importance. Today, experts believe integrated design method to be the most suitable design method which can meet all product conditions based on limits, parameters and design factors. These parameters include risk, performance, cost and time which are a necessary part of system engineering [3].

This means that we must know what structures, processes, approaches and software are necessary for creating a product and how these parameters can interact with each other in order to ensure a successful product design.

The main goal of the current study is to emphasize on necessary levels for design in the first design phase of a complex product. The first design phase for complex precuts is the feasibility phase which is very important. On the other hand, given the number and variety of design parameters in feasibility phase, parametric design can lead to saving time and cost reduction of the process. This means that implementation of system engineering in parametric design during feasibility phase can grantee a strong design process for complex products [4].

In order to expand this concept and propose a model regarding this design method, first it is necessary to understand the expansive literature available on this topic. This literature includes topics such as system engineering processes in feasibility phase, and conceptual design using parametric design and focus on requirement integration in design of complex products. The example of a complex system used in the current study is a super system float with the ability to submerge under water with minimum amount of noise and maximum submersion time which can be used for scouting and espionage operations. Therefore, the current study aims to cover the existing gaps in order to expand the concepts and model necessary for increasing design maturity based on system engineering requirements in feasibility phase and conceptual design of complex products. In the following sections, first a review of literature on system engineering and its various models and also different design models is provided. Then, a suitable model is proposed by combining these models. Afterwards, an example of designed process is introduced and some suggestions are provided [5].

2. Literature Review

2.1 Combining Design Steps using v Logic

One of the advanced approaches which have gained increased attention for defining design steps is the use of v logic. Using this logic makes it possible to achieve the following concepts:

- Verification and validation based on testing
- Using a hierarchical approach in implementation of design steps
- Implementation of project design with a nucleus and central approach

The following section explains design staging based on the abovementioned three concepts of v logic [6].

The aforementioned steps can be summarized as the v model shown in Figure 1. This v model is divided into two main sides. The left side from top to bottom is in the patch of system deconstruction and is called design branch. The right side which shows the construction patch of the system is the prototyping or verification branch. This means that the main design and prototyping stages can be combined as the following four steps:

- Conceptual design and technical feasibility study
- Initial and final design and proof of technology
- Expanded design, prototyping and testing of subsystems

- Setup, assembly and testing of the system [5].

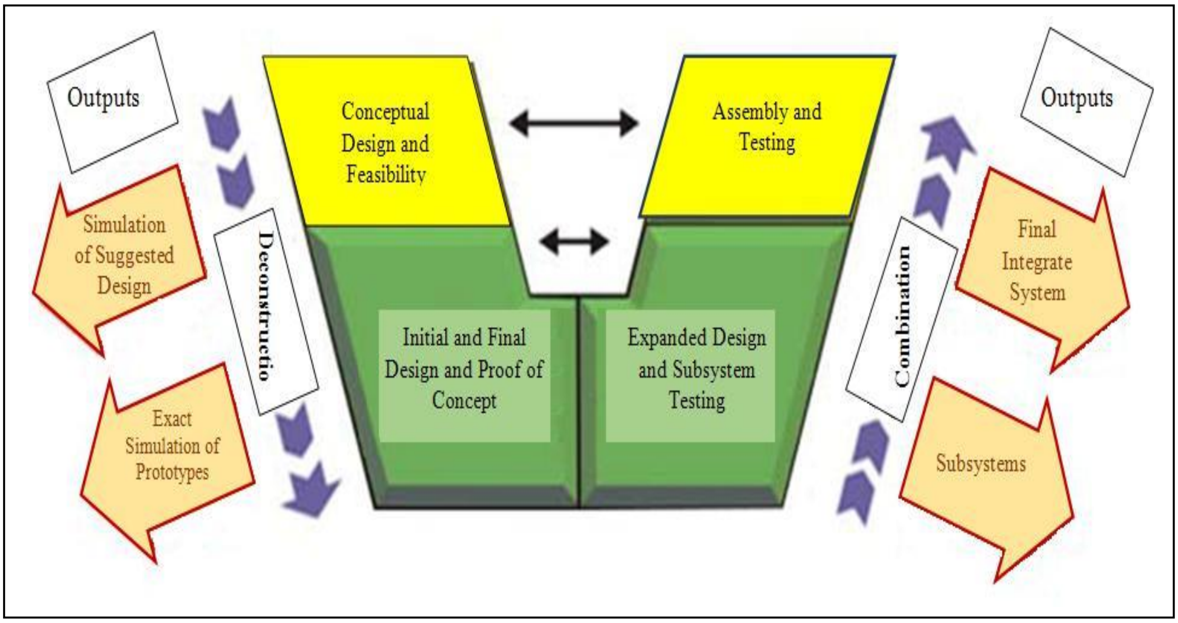

Figure1.V model in system engineering for defining design steps [1]

In each of the steps of design branch (top to bottom path) the requirements of a higher-level employer which are defined as input requirements turn into requirements of one step lower due to design process. In other words, the requirements of one level of the system during each design steps are turned into requirements of one step lower and this deconstruction path continues until the lowest necessary level [6].

In the prototyping branch (upward path), product system leaves the conceptual and virtual world and enters the real and physical realm. In each of these steps, system levels are constructed and tested based on the designs carried out in the design branch. If the test results are satisfactory, the product is sent to a higher-level design office which assemblies are parts arriving from lower levels of the system hierarchy to produce a higher-level product [6].

By using v model, in each project step, it is possible to determine the steps that are main focus in the hierarchical system and system requirements until the system level is extracted or verified. In this project, v model is defined in to layers (system and subsystem domains). As a result, layer 1 focuses on defining and meeting system characteristics by defining requirements for parts, outsourcing and delivery (including weapon system requirements) while layer 2 focuses on defining and meeting part characteristics by defining and meeting subsystem requirements (engine, propulsion, navigation, etc.). This hierarchical approach is also used in each part. This means that each part can be divided into two design layers during design and construction. In other words, contractors for each part can also play the role of level 1 employers for their own contractors [7].

The v approach makes it possible to implement the project with a systemic and hierarchical outlook to that design team at each level which is independent from its higher levels [7].

2.2 System Engineering and Its Models

System engineering is a set of activities which are used to create a product suitable to the needs of the customer using a systematic approach. The set of activities used in system engineering are introduced as different models and processes which have large similarities despite small differences. For example, U.S. Department of Defense, International Standard Organization, American National Institute for Standardization, the Association of Electrical and Electronics Engineers and the US Space Agency (NASA) each introduces a different model for describing system engineering processes which, despite general similarities, offers different levels of convergence between system engineering and life cycles. The following section offers a brief introduction of these models [8].

U.S. Department of Defense (DoD) was the first organization to officially codify a system engineering process. The system engineering process of this organization consists of 4 levels including requirement analysis, performance analysis, design and evaluation and system control. The system engineering model of the Association of Electrical and Electronics Engineers is an expanded version of the process introduced by Department of Defense, with only difference being the addition of two processes including performance verification and design verification. The system engineering process introduced by American National Institute for Standardization consists of 13 interconnected processes. These 13 processes are divided into 5 set of processes including technical management, supply and acquisition, system design, product realization and technical evaluation, the first and last of which (technical management and technical evaluation) are usually used continuously during the entire lifecycle of the system. As a result, planning, evaluation and control processes among technical management processes continue to be used after initial phase of system lifecycle while system analysis, requirement verification, system verification and final product verification processes also start before physical manufacturing of the products. NASA defines 17 processes for system engineering. These activities are divided into three main categories of system design, product realization and technical management and are shown in figure 2 as system engineering motor [1].

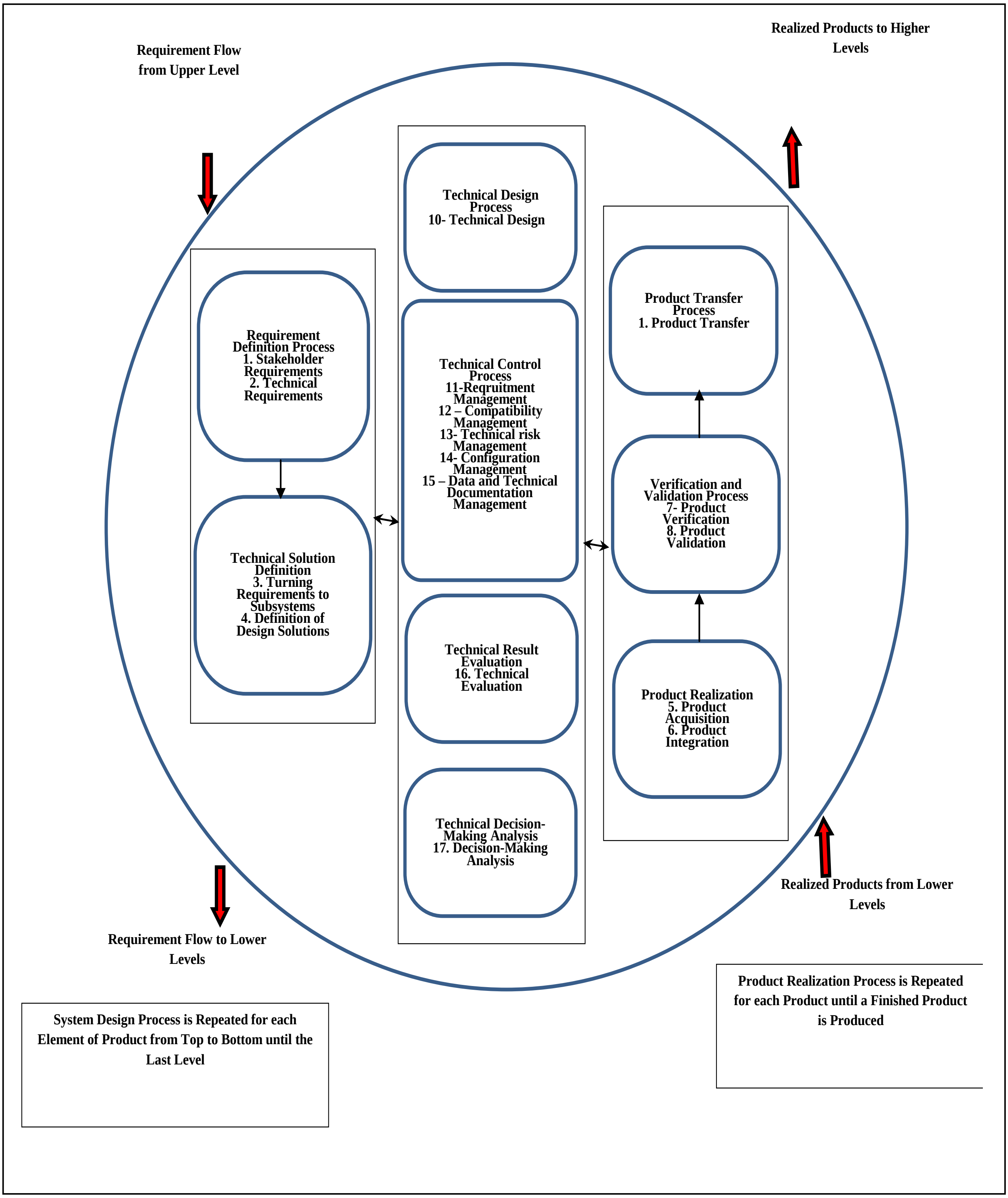

Figure2. NASA's system engineering motor [1]

In this Figure, the process flow is from top to bottom while the flow of realization processes is upward. System management processes are support processes which are used laterally through the entire system design and realization processes.

3. Study Method

The implemented algorithm in the current study is based on v design model. The conceptual model implemented in the current study based on v design model is seen in Figure 3.

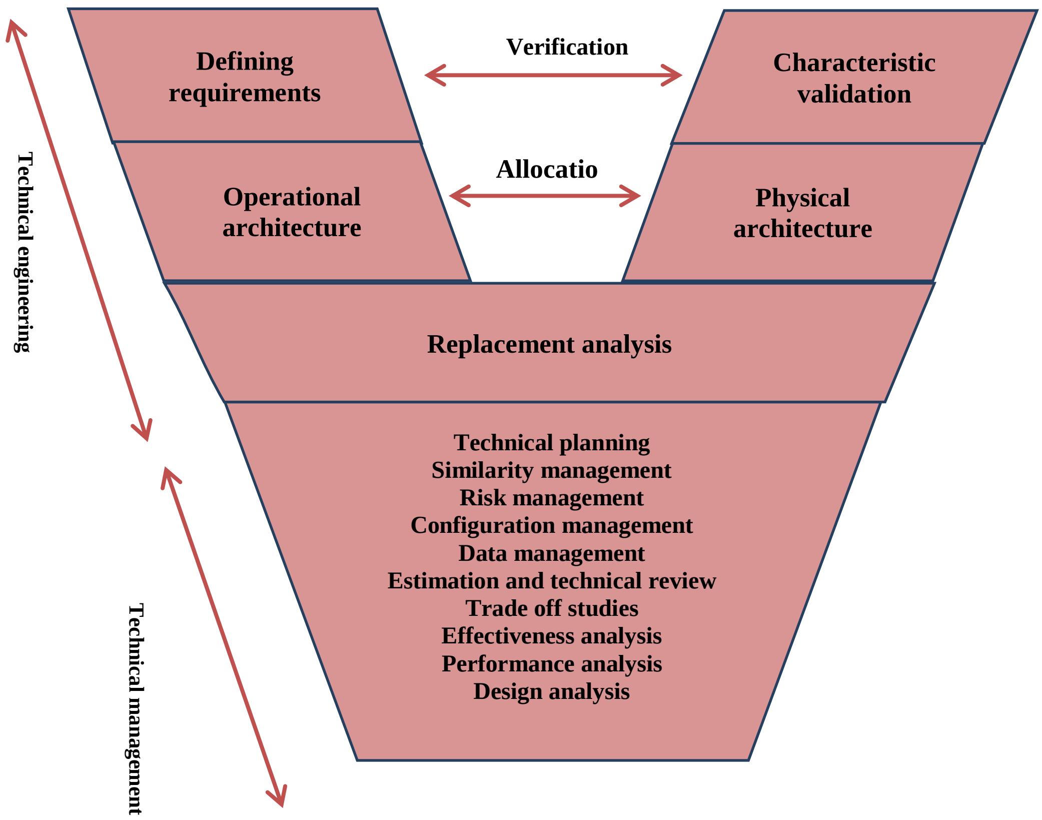

Figure3. Implemented algorithm in the current study based on v model

The following section explains each of the steps in system engineering process.

In any system problem, first it is necessary to clarify the problem itself. The "defining requirements" step is used to explain customer's needs (which is the highest level of system hierarchy). The first step in this patch is to determine the final goals of the system or operational requirements which should be met in the final product. System characteristics (performance, operational, configuration and technological) are directly related to system requirements. Therefore, defining operational requirements and estimation of possible threats is one of the first actions carried out in this phase.

After defining the operational requirements and estimation of threats, it is then necessary to analyze and develop these requirements. Analysis of technical – engineering requirements is carried out by design (technical – engineering) team and covers requirements related to operational, performance, technological and configurational parameters of the system. Requirement analyses of other areas (testing and evaluation, support, prototyping and manufacturing and electronic and computer resources) are also carried out by related branches. Finally, using the result of these analyses, system recruitments are extracted based on the needs of all different areas. In this step, management branch attempts to integrate and finalize the requirements of different areas.

After extracting system requirements based on customers' needs in different areas including functional (operational), engineering (performance, technology and configuration), simulation and analysis, testing and evaluation, support, electronic and computer resources and finally prototyping and manufacturing, it is possible to create the system's operational architecture.

In this step, first system characteristics necessary for meeting system requirements in different areas are defined. Then, based on similarities and functional relations, these functions are combined and an integrated system architecture is created. it's worth noting that system's functional architecture can help clarify previously hidden angles and update system requirements. Another important action carried out in this step is allocation of requirements to functions. After determining first level functions, it is then necessary to determine the functional (operational), engineering (performance, technology and configuration), simulation and analysis, testing and evaluation, support, electronic and computer resources and finally prototyping and manufacturing requirements which are met using these functions. Therefore, allocating requirements to functions makes it possible to identify physical replacements for different functions in order to carry out replacement analysis step.

After determining the functional architecture of the system, it is then necessary to determine a physical example for each of these functions. To this end, possible physical replacements for each function are identified, analyzed and compared. It is necessary to use a systematic approach during replacement analysis. This means that the necessary tools for replacement analysis are provided by statistical studies on similar systems and investigation of technical – engineering characteristics (function, performance, configuration and technology) as well as other system characteristics (testing and evaluation, support, etc.). These studies should be carried out in a way that makes it possible to determine the advantages and disadvantages of each option in areas such as technological availability, performance, cost effectiveness and time saving. Comparing necessary technical characteristics with existing statistics and analysis of current technologies can help create a more realistic outlook in designers regarding necessary technologies and time constraints. It is also necessary to determine the risks associated with each option as one of the main activities in this step and to consider this risk assessment in the final results.

Finalizing the replacement analysis from the previous step means that parts of the base system have been determined. System parts determined in the previous step are based on design structure matrix and system functions. The exchanges in design structure matrix lead to functional integration which means that functional integrity as well as parts of the physical integrity necessary for effective performance have been achieved. Since the effects of all physical characteristics on performance parameters are not known, it is necessary to investigate physical structural integrity separately. this is carried out in the physical architecture step and is recorded in system's physical architecture report. Furthermore, this step records system characteristics in different physical and functional dimensions (mechanical, electronic).

After determining the architecture of the base system, it is possible to extract the final summary of characteristics without any explanations or evaluations. After extracting system characteristics, it is necessary to use suitable technological analysis tools, simulation charts, numerical analyses and other similar methods to validate and verify system characteristics.

All of the abovementioned activities are those used in the technical – engineering domain in regards system design. Along with these activities, there are another set of activities in the technical – management domain which are carried out in all the aforementioned steps parallel with engineering activities.

The current study used the opinions of 8 experts and managers in system design domain which were gathered during brainstorming sessions.

4. Analysis

The current study localizes system engineering activities in order to meet customer requirements in large and complex projects (super-systems). This process defines the needs and requirements of stakeholders and turns them into technical system requirements in order to meet all these needs and requirements. This process also breaks down technical requirements into smaller parts at lower levels until an answer can be found for each small problem. These answers determine the last break down in requirements. System engineering uses the answers found by the previous processes for the lowest requirement level and integrates lower level products to create a higher-level product. This method manages requirements and turns the requirements and needs of customers and stakeholders to system requirements; then beaks down these requirements in a chain reaction until lowest level and manages any changes in requirements. Compatibility management controls and manages requirements created due to physical or functional links between parts, subsets, sets and subsystems. Configuration management identifies configuration parts including hardware, software, documents and technical data and controls their production, transfer and change. Technical risk management helps identify all risks with technical roots and categorizes them based on the probability of their occurrence. This management also helps in planning and implementation of plans in order to minimize the effects or these risks on project's success. Data and technical document management gathers, stores and retrieves technical data and documents related to the process and transfers them to those who need them in a timely fashion. In order to carry out its duties, system engineering requires certain tools and infrastructures. It also needs to carry out a systematic analysis of technical decisions regarding project's technical dimensions. The steps of systematic decision making include determination of subject area, determination of different options, determination of the method used to select the superior method, determination of evaluation criteria and selection of the superior solution based on evaluation criteria and documentation during work process.

Due to implementation of system engineering process for super-system, configuration indicators were extracted based on expert opinion from design office of the organization. An example of extracted indicators resulting from implementation of system engineering process in design of super-system products is shown in Table 1.

Table1. Extracted indicators for super-system product design with system engineering approach

<table>
<tr><th>No.</th><th colspan="2">Operational characteristics</th><th>Value</th></tr>
<tr><td>1</td><td colspan="3">Cyclogram requirements</td></tr>
<tr><td>1,1</td><td colspan="2">General snorkel range</td><td></td></tr>
<tr><td>1.2</td><td colspan="2">General snorkel speed</td><td></td></tr>
<tr><td>1.3</td><td colspan="2">Surface speed</td><td></td></tr>
<tr><td>1.4</td><td colspan="2">Charge speed</td><td></td></tr>
<tr><td>1.5</td><td colspan="2">Maximum underwater range</td><td></td></tr>
<tr><td>1.6</td><td colspan="2">Economic speed</td><td></td></tr>
<tr><td>1.7</td><td colspan="2">Maximum underwater speed</td><td></td></tr>
<tr><td>1.8</td><td colspan="2">Minimum (critical) speed</td><td></td></tr>
<tr><td>2</td><td colspan="3">Reliability and rescue</td></tr>
<tr><td>2.1</td><td colspan="2">Accessibility</td><td></td></tr>
<tr><td>2.2</td><td colspan="2">Reliability</td><td></td></tr>
<tr><td>2.3</td><td colspan="2">Maintenance capabilities</td><td></td></tr>
<tr><td>2.4</td><td colspan="2">Support capabilities</td><td></td></tr>
<tr><td>2.5</td><td colspan="2">Damage control and rescue capabilities</td><td></td></tr>
<tr><td>3</td><td colspan="3">Maneuverability characteristics</td></tr>
<tr><td>3.1</td><td colspan="2">Turn diameter</td><td></td></tr>
<tr><td>3.2</td><td colspan="2">Submersion time</td><td></td></tr>
<tr><td>3.3</td><td colspan="2">Stop distance</td><td></td></tr>
<tr><td>3.4</td><td colspan="2">Depth stability</td><td></td></tr>
<tr><td>4</td><td colspan="3">Environmental operation conditions</td></tr>
<tr><td>4.1</td><td colspan="2">Operation area</td><td></td></tr>
<tr><td>4.2</td><td rowspan="2">Sea force</td><td>Durability</td><td></td></tr>
<tr><td>4.3</td><td>Operation</td><td></td></tr>
<tr><td>4.4</td><td colspan="2">Environmental conditions</td><td></td></tr>
<tr><td>5</td><td colspan="3">Other requirements</td></tr>
<tr><td>5.1</td><td colspan="2">Dimensions</td><td></td></tr>
<tr><td>5.2</td><td colspan="2">Tonnage</td><td></td></tr>
<tr><td>5.3</td><td colspan="2">Floating reserve</td><td></td></tr>
<tr><td>5.4</td><td colspan="2">Maximum operational depth</td><td></td></tr>
<tr><td>5.5</td><td colspan="2">Testing depth</td><td></td></tr>
<tr><td>5.6</td><td colspan="2">Lifespan</td><td></td></tr>
<tr><td colspan="4">Functional requirements</td></tr>
<tr><td>No.</td><td colspan="2">Operational characteristics</td><td>Value</td></tr>
<tr><td>5.7</td><td colspan="2">Number of crew members</td><td></td></tr>
</table>

5. Conclusions

Needs or deficiencies in any system can occur due to various reasons including:

- Policies, doctrines and approaches
- Environmental threat analysis
- Ineffectiveness of current systems
- Operational designs

- Defensive and operational scenarios

Usually, when such a need is felt, it will be introduced as a system or equipment. However, when the need is expressed by customers, the solution isn't always a new system or equipment and sometimes creative shuffling and realignment of parts and elements can meet these new needs. It might also be possible to fix the system through changes in tactics, structure, better training or use of various systems and equipment. If these methods are unable to fix the problem, then a system or equipment solution for the problem is required. At this point, all system solutions need to be investigated and evaluated in order to determine the most suitable solution. Finding the suitable solution is carried out by combining the abilities and equipment's present in the system and can be helped with creativity and innovation.

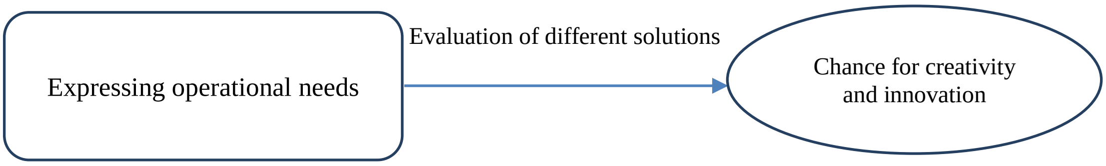

Figure4. The expressed need for innovation

There are some facts that should be taken into consideration when expressing needs including:

- At the beginning, the need should not be limited to a certain solution
- Limiting the solutions to a certain path at the beginning limits innovation
- Systems seen on the internet or other media are not always suitable solutions
- A new system might be unnecessary
- All systems proposed in other countries are not suitable solutions
- The need shouldn't be expressed along with a preconceived possible solution

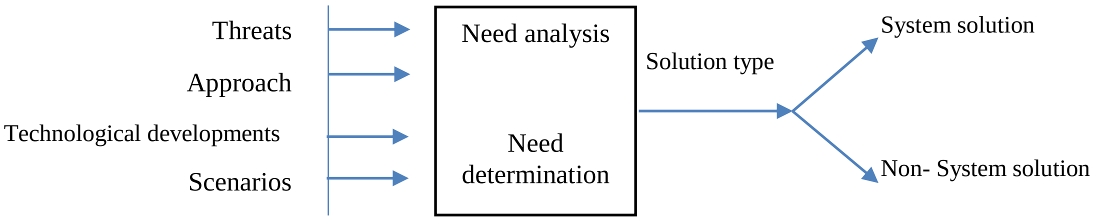

Figure5. The relation between need and solutions

When analyses show the need for a system solution, it is necessary to express the need for that system in a way that clearly defines the duties of this new system, especially in regards to filling current deficiencies.

This means that any need can have numerous solutions and attention to different solutions expresses creativity and innovation in order to use current capabilities to find the most suitable solution. It also must be noted that capabilities should be expressed separately from solutions. It is also best not to express a solution at the start or to assume that the expressed solution is the only possible one.

If needs assessment is correctly carried out, and different requirements and conditions are fully taken into consideration, a suitable solution can be selected.

Expressing needs and requirements is carried out in two steps:

- Expressing needs based on missions or duties
- Expressing characteristics and requirements for system or equipment in order to meet these needs

In the first step, we are looking for an expression of customers' needs based on their own vision. Customers feel certain needs based on duties or responsibilities which they need to carry out and express these needs as a system. They also mention the reasons behind these needs and express and document their macro expectations. In this step, we shouldn't think about a predetermined system but instead it is necessary to discuss needs and expectations, current deficiencies, required capabilities for fulfilling the assigned missions and answers to possible threats. These deficiencies are usually fixed through a system which provides us with necessary capabilities.

After expressing the functional needs of a system using a certain pattern called “functional need expression pattern” or “functional needs' statement”; it is necessary to seek solutions for these needs. There might be several possible methods for fulfilling these needs. Each of these solutions must be identified and analyzed in order to select the most suitable solution. Out criteria for identification and selection of solutions are current deficiencies and capabilities expected by the customer which are present in “functional needs' statement”.

In design of super-system projects, all operations including processes and change control, compatibility management, configuration management, and risk management require implementation of operational requirements. The current study attempted to implement these requirements by introducing a system engineering approach. Careful identification of customer requirements and turning them into technical and functional requirements in order to create a clear pattern for design and manufacturing are the aims of system engineering approach. Controlling numerous environmental changes and parameters affecting plans and projects due to technological advances, and monitoring and parametric management of data against changes using suitable configuration management are also among advantages of system engineering approach.

In order to fully realize this process and meet all necessary requirements, we suggest that special attention should be paid to step by step implementation and monitoring of tools and principles introduced in this study including identification and management of stakeholder needs, implementation of changes' management, implementation of configuration and data management and other similar concepts in order to help validate processes and determine the starting point and driving force of next project phase. Modeling and adaptive improvement of projects from developed countries regarding the design of recreational submarines which shows effective use and implementation of system engineering can also be used for improving design effectiveness and performance.

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