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Generative Model for Conceptual Design of Defence Equipment

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ABSTRACT

Requirement study and analysis forms a key component in conceptual design of new products and systems. For complex systems like defence equipment, concept design is very important and should primarily satisfy all user requirements. The paper brings out a new generative model for concept design of defence systems using principles of systems engineering. A structured model and methodology is presented starting from capturing the user requirements, developing multiple solutions, short listing the candidate solutions and finally selecting one or two feasible designs. The model and process is illustrated with the help of a case study on the development of a torpedo defence system for naval ships.

Keywords: Systems engineering, concept design, requirements analysis, system abstraction, sonar, torpedo detection

1. INTRODUCTION

A successfully designed product is one that meets the user requirements completely. With shrinking timelines, selection and approval of concept design becomes very important. Significant challenges in capturing user requirements, design and development, evaluation and validation, production, maintenance, classified nature of information exist for defence system projects. A new generative model to capture the operational, functional and physical requirements of defence equipment for the concept design of new equipment from user requirements is introduced. Design of an engineering system consists of three distinct phases namely preliminary design, embodiment design and detailed design[1]. Concept design starts from the user requirements gathering, its analysis and study. Systems thinking and systems engineering principles[2,3] are used for requirements analysis and study and forms the basis for this new model. The new model is explained in detail with a case study on `Torpedo defence system'.

2. EXISTING MODELS

There are several existing models in practise for the requirements gathering to concept design approaches. The typical approach is to go by the functional design wherein focus is placed on the operational and functional requirements as desired by the user and methods are devised to achieve the functions from the inputs fed into the system. Ways of presenting the system outputs to meet stated objectives and performance parameters are also designed keeping in mind the physical configuration, space availability and other form and fit requirements[4].

A classical approach available in literature[5] consists of five phases namely concept development, system level design, detailed design, testing and refinement and production ramp up. Another method[6] is widely used by the industry is stage-gate model. The gates decide whether to go ahead with the project or terminate. A generic model[7] for new product design and development that includes three parts, pre-design/development, design and development process and post-design development. This model is different since it links post development design stronger into product development process. A holistic view on product development and life cycle management is missing in all these approaches and the attempt in this paper is to introduce systems approach in preliminary design of defence systems.

The typical system engineering model for design of a new product or system is the V model as exemplified by the International Council on Systems Engineering (INCOSE). The complete problem, according to the INCOSE definition[8], includes design, operations, performance, test, manufacturing, cost and schedule, training and support, and disposal. Most common system engineering approaches involve using a hierarchical decomposition or the V diagram[9] as shown in Fig. 1. The new model focuses on the pre engineering activities and emphasise the importance of concept of operations, requirements study and analysis for the preliminary design of new defence equipment.

3. THE NEW CONCEPT DESIGN GENERATIVE MODEL

A generative model is proposed in this paper which takes a structured approach to reach the concept design from the

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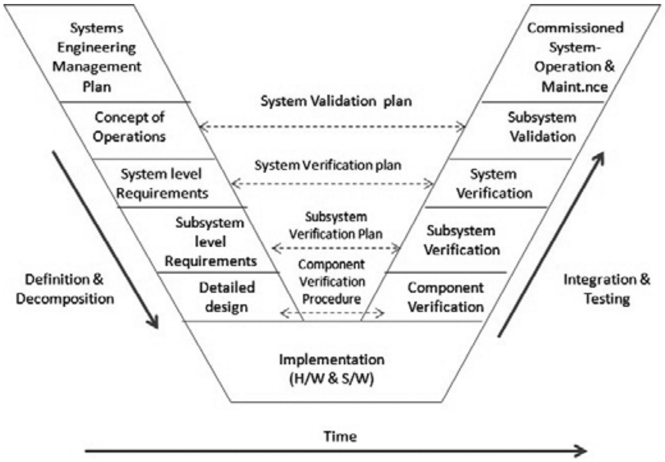


Figure 1. The V diagram in systems engineering.

requirement specifications. This approach takes the systems view and uses system engineering principles to converge to the optimum concept design. There are two decision gates for proceeding with the model. They are,

(a) decision gate meeting customer requirements
(b) decision gate on solution feasibility

At these two decision gates, objective evaluation is done with respect to the desired performance parameters and design outcomes and if not satisfied, the process is analysed once again so as to meet the desired objectives and only successful concepts are passed through. The new generative model flow chart is given in Fig. 2.

3.1 Requirements Study and Analysis

A context diagram for a new design is used to capture the user requirements. The objective of the context diagram is to focus attention on external factors that affect the designed system and identify the events that should be considered for developing the complete set of systems requirements and constraints. The boundaries and interfaces act as controls or enablers for the system of interest. Reference scenarios[10] also help in understanding user requirements.

3.2 Generation of Performance Specifications or System Design Parameters

Quality function deployment (QFD) technique like `House of quality matrix[11] is used for this. It utilises data for bench marking and allotting numerical values for various parameters. These benchmarked figures are used to derive target values for specifications/system parameters in the new design satisfying the voice of customer (VOC). In the case of naval systems, statistical data are collected from naval agencies like Anti-Submarine Warfare school, Naval Operations Analysis and Data Centre (NODPAC) and also through interactions with user group during `Underwater steering committee' meetings.

3.3 Decision Gate I – User Requirements Compliance Check

The performance based specifications are compared with the end user requirements in `Decision Gate I'. If new variables are needed, the requirements study process is redone till a

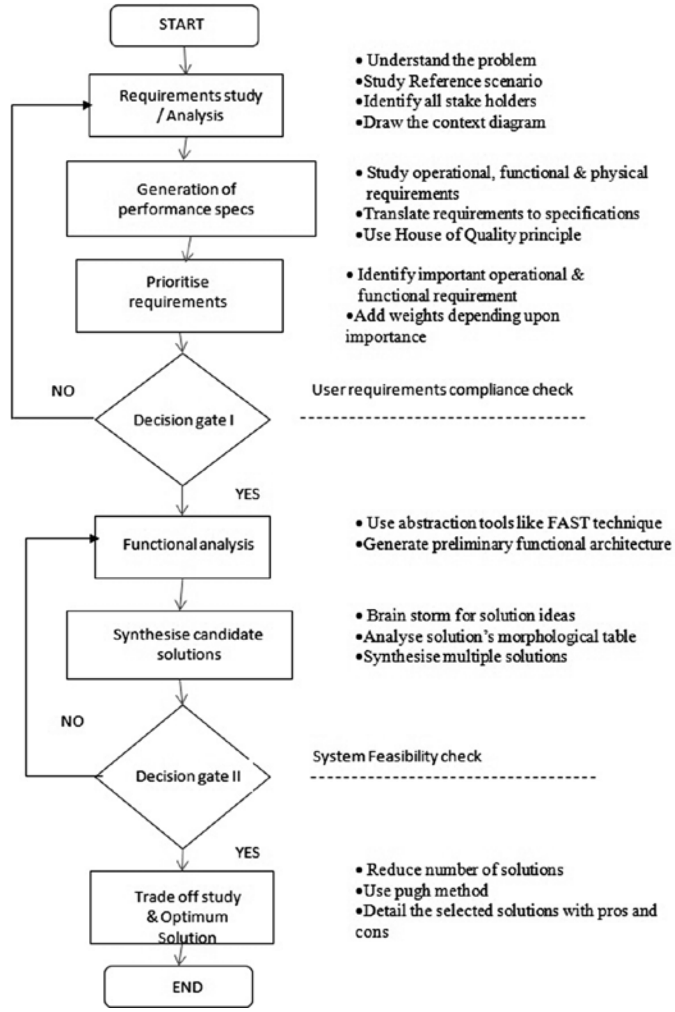


Figure 2. Proposed generative model process flowchart.

mutually acceptable set of system parameters are generated which completely captures the user requirements (VOC). Thus a compliance check w.r.t all user requirements is conducted at this stage.

3.4 Functional Analysis

Functional analysis helps to derive the functional architecture required for meeting the system parameters. Functional analysis helps to identify the basic functions and supporting functions for each of the tasks. Each primary function is further decomposed to secondary functions and so on.

3.5 Synthesise Candidate Solutions for Concept Design

After completing the functional task analysis, the solution principles for each of the system parameters are generated. Brainstorming techniques are employed to collect maximum number of varied solutions to address the tasks identified. Both converging and diverging ideas are collated prior to synthesising the feasible solutions. Both performance and the corresponding risks are graded for each of the solutions. For example, performance parameter (P) is graded from 5 to 1 where 5 indicates excellent and 1 indicates poor performance. Similarly risks (R) are also graded from 5 to 1 where 5 indicate very low risk and 1 corresponds to high risk. The cumulative grades ie sum of performance and risk grades are used for selecting solutions.

3.6 Identify Possible Solutions

A morphological Table[12] details all the functional tasks and available solutions for each function. The multiple solutions are sometimes known as means[13], design parameters[14], etc. The typical format of generic morphological table is given below (Table 1). In this morphological table, each of the functions are designated as $function_1$, $function_2$, etc. Each of the multiple solutions is represented by the term $S_{n,\ m}$.

3.7 Decision Gate II – System Feasibility Check

The second decision gate is to ensure that the connected solutions generated out of the morphological table are technically feasible. Technical and manufacturing feasibility, resource availability etc are all verified to see that the system can be developed successfully.

3.8 Selection of the Optimum Design by Trade off Study

The `Pugh' method[15] is used for identifying the optimum design. In this method performance weights are also considered. Each concept solution is compared to a bench marked reference and given a rating. The ratings are -1 (Inferior), 0 (Similar) and 1 (Superior). Using performance weights and ratings, the optimum design is identified.

4. EXAMPLE RESULTS – CASE STUDY

The generative model is explained with a case study on conceptual design of a system for Torpedo detection and countermeasure for a naval ship. The parameters / specifications listed and the numerical values specified in the tables / figures of the case study are meant for explaining the model and for illustrative purpose only. Actual values and specifications are omitted due to the classified nature of information.

4.1 Generating Performance Based Specifications

The context diagram for `Torpedo defence system' is given in Fig. 3. Being a tactical system, the two primary factors considered are functional efficacy and reliability. Escape probability of a ship is dependent upon early detection of torpedo and counter measure actions. Typically passive sonars[16,17] with long range detection capability are used for detection purpose. Literature suggest that frequency ranges of the order of 1.5 kHz - 3 kHz to be optimum[18] for detection sonar performance. From reference scenario, both operational and maintenance requirements are captured. Thereafter the performance based specifications as shown in Table 2 are derived from house of quality (Fig. 4). The main body of the matrix is filled with values 0, 1, 2 and 3. Number `0' indicates that the voice of customer (VOC) has no linkage to the particular system parameters (Top row) whereas `3' indicates VOC has heavy dependency.

The voice of the customer (VOC) is indicated in the first column. The up and down arrows in the second row indicates trends to be followed for the solutions. For example, it is preferred to have `MORE' targets for simultaneous detection and use `LESS' number of decoys.

4.2 Decision Gate I

A compliance check is carried out to see whether all the user requirements have been captured or not. The system parameters are prioritised by allotting performance weights. A higher value for the weight indicates that the particular parameter is important for overall success and performance of the system. The model suggests rework on system parameters (Table 2) if the compliance check fails w.r.t user requirements.

Table 1. Generic format of the morphological table

		Available solutions					
System requirement (design problem)	$Function_1$	$S_{1,1}$	$S_{1,2}$	$S_{1,3}$			$S_{1,m}$
	$Function_2$	$S_{2,1}$	$S_{2,2}$	$S_{2,3}$	-	-	$S_{2,m}$
	$Function_3$	$S_{3,1}$	$S_{3,2}$	$S_{3,3}$	-	-	$S_{3,m}$
	-	-	-	-	-	-	-
	-	-	-	-	-	-	-
	$Function_n$	$S_{n,1}$	$S_{n,2}$	$S_{n,3}$	-	-	$S_{n,m}$

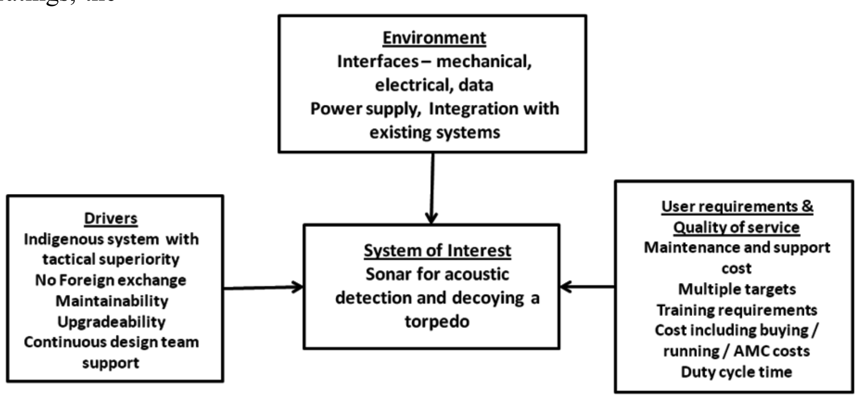


Figure 3. Context diagram for a torpedo defence system.

Table 2. Typical system parameters and weights

System parameters meeting the VOC	Performance weights
Automatic alert and decoying	20
Use of multiple sonars for detection.	12
Compact system with less inventory and cost	12
The running cost to be minimum.	10
Decoying using minimum number of decoys	9
Time to launch < 10 minutes	9
Weight < 5 tons and Overall dimensions within 2 cubic meter	8
Automatic operation	8
Redundant data telemetry tracks	8
Simultaneously detect and track 5 targets	4
Total weight	100

VOC	Number of targets	Auto alert	Number of decoys	Sonars	System launch time(s)	Weight / size	Automation	Telemetry routes	Production cost	Maintenance cost	W
Automatic alert and decoying	0	3	3	3	0	2	0	0	2	1	30
Panoramic detection	0	3	0	1	3	0	2	3	2	1	20
Multi mode decoying	3	3	3	1	2	1	2	0	0	0	10
Quick launch and recovery	0	3	0	2	2	0	1	2	1	3	10
Automatic operation	3	2	0	1	0	3	2	0	1	1	5
Standard interfaces	2	3	1	3	2	0	2	2	1	3	5
Reliable operation	1	3	1	2	0	1	1	1	2	2	5
Compact size and weight	2	3	1	0	0	2	2	2	3	2	5
Upgrades	0	3	0	0	2	2	2	2	2	2	5
Modular design	0	2	0	2	1	2	0	0	3	2	5
Total importance	70	290	135	180	125	120	115	115	170	140	
Relative importance	4	20	9	12	9	8	8	8	12	10	
Status NOW	Less	NIL	More	One	More	More	NIL	One	Ok	Ok	

Figure 4. The house of quality for advanced torpedo defence system (ATDS).

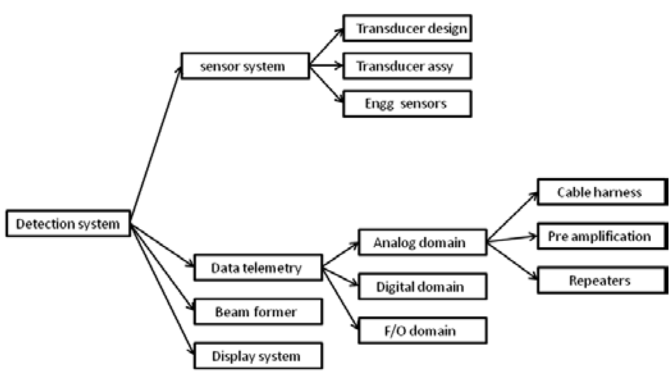


Figure 5. Example of functional analysis carried out for 'detection' parameter.

4.3 Functional Analysis of all Identified System Parameters

The functional analysis of system parameters help us to identify the basic functions and supporting functions required. The functional analysis for one of the parameter namely 'Use of multiple sonars for detection' as shown in Table 2 is illustrated in Fig. 5.

4.4 Synthesis of Conceptual Designs

Conceptual designs are synthesised for each of the basic tasks and supporting tasks identified during the functional analysis. Brain storming is done for generating multiple solutions for each of these tasks. For example, Table 3 gives a list of options for the data telemetry task. Each of these options have got both performance advantages and also risks. These performance and risks features are graded in Table 3. Performance grades are given from 1 to 5 where 1 indicates poor and 5 indicates excellent performance. Risks are graded from 1 to 5 where 1 indicates high risks whereas 5 indicate very low risk. Sum of Performance and Risk grades is computed. Higher the Sum, better the solution and vice versa. Similar procedure

Table 3. Brain storming – convergence and divergence grades for performance and risks

Solutions for data telemetry	Performance grades (P)	Risk grades (R)	P + R
Data send as digital signals	5	1	6
Data send as analog signals	4	1	5
Convert and send optically	5	2	7
Optical telemetry only	2	2	4
Analog / digital conversion	4	5	9
Data send as visual light signals	2	1	3
Telemetry using acoustics	2	1	3

Table 4. Morphological table for solution sets of ATDS

Morphological table			Multiple solutions			
			1	2	3	4
Functions / Tasks	Auto detection and Alert	1	Use dunking sonar [7]	Towed array and hull sonar [9]	Use towed array sonar and manoeuvre [8]	Non acoustic methods [6]
	Auto classification	2	Use magnetic signature [7]	Use spectral data for classification [9]	Use satellite data to process movement underwater [6]	Use target parameters [8]
	Counter measure	3	Acoustic countermeasure [9]	Silence own machinery [6]	Use acoustic false target [7]	Use noise makers [8]
	Escape measures	4	Move at flank speeds [8]	Escape geometry to be worked out [9]	Use a second platform to confuse [6]	Silence own ship completely [5]

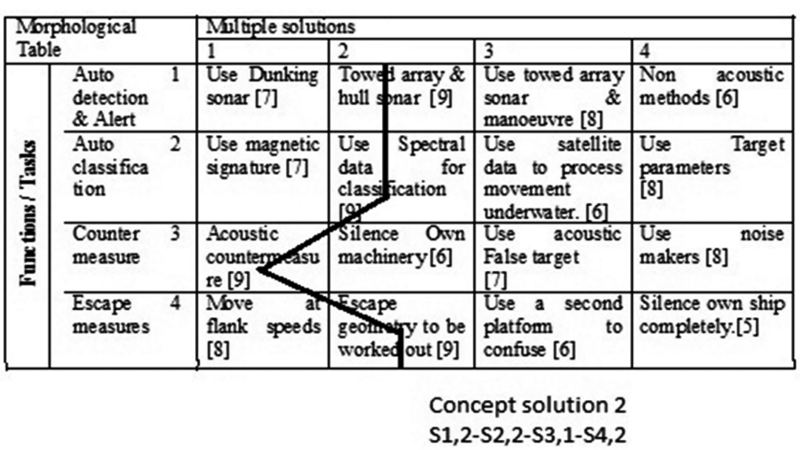
is followed for all other tasks like Automatic torpedo alert and auto decoying etc.

4.5 System Design Options from the Morphological Table

The total system design options are identified by combining solutions having higher summative grades of performance and risks. Table 4 shows the morphological table for some of the major customer requirements in ATDS. The numerals indicated the sum of performance and risk grades calculated for each solution. For example the sum of performance and risk grades in the case of using dunking sonar(Solution 1 for task 1)for auto detection and alert is 7. Dunking sonar performance grade is relatively high since it is detached from the platform but the risk factor is also equally high since it has to be suspended from an aircraft. In solution 2, towed array and hull mounted sonars are used which are good in performance and also the risks are comparatively less. Hence the summative grade in this case is 9 which is more than solution 1.

The feasible set of solution alternatives are listed below as possible design choices. There can be more number of solutions also. A pictorial representation for concept solution 2 is also given in Fig. 6 for illustrative purpose only.

(i) Concept solution 1: $S_{1,1}$ - $S_{2,1}$ - $S_{3,3}$ - $S_{4,1}$
(ii) Concept solution 2: $S_{1,2}$ - $S_{2,2}$ - $S_{3,1}$ - $S_{4,2}$
(iii) Concept solution 3: $S_{1,2}$ - $S_{2,4}$ - $S_{3,4}$ - $S_{4,1}$
(iv) Concept solution 4: $S_{1,4}$ - $S_{2,2}$ - $S_{3,4}$ - $S_{4,1}$



Morphological Table			Multiple solutions			
			1	2	3	4
Functions / Tasks	Auto detection & Alert	1	Use Dunking sonar [7]	Towed array & hull sonar [9]	Use towed array sonar & manoeuvre [8]	Non acoustic methods [6]
	Auto classifica tion	2	Use magnetic signature [7]	Use Spectral data for classification [9]	Use satellite data to process movement underwater. [6]	Use Target parameters [8]
	Counter measure	3	Acoustic countermeasu re [9]	Silence Own machinery [6]	Use acoustic False target [7]	Use noise makers [8]
	Escape measures	4	Move at flank speeds [8]	Escape geometry to be worked out [9]	Use a second platform to confuse [6]	Silence own ship completely.[5]

Figure 6. Pictorial representation of concept solution 2.

Table 5. Application of pugh method to find the optimum design

Operational requirements	Weights	Reference (Existing system)	Concept solution Number #			
			1	2	3	4
Automatic alert and decoying	20	L	+1	+1	+1	+1
Use of sonars for detection	12	L	+1	+1	+1	-1
Compact system with less inventory	12	L	0	+1	+1	-1
Running cost (operation and maintenance)	10	M	-1	+1	-1	-1
Number of decoys	9	L	0	+1	+1	+1
Launch and recovery time < 30 minutes	9	H	0	+1	+1	+1
Total weight and dimensions	8	L	0	+1	+1	+1
Automatic operation	8	M	+1	+1	+1	+1
Redundant data telemetry	8	M	+1	-1	-1	-1
Simultaneous detection and tracking of 5 targets	4	L	+1	-1	-1	-1
	100		42	76	56	36

4.6 Decision Gate II Feasibility Check

There are always multiple solutions for every major tasks. Each of these solutions are analysed for their technical feasibility. For example, the performance of the Torpedo Defence system is achieved in concept solution 2 as follows (Refer Fig.6). Concept solution 2 employs both towed array sonar and hull mounted sonars for panoramic detection of torpedo. Spectral analysis of acoustic data received on these sonars is used for auto alert and classification. Countermeasures are employed to decoy the torpedo attack and escape geometry is worked out. The same procedure is followed for all solutions. If not technically feasible, the solution is reworked at this stage.

4.7 Selection of Optimum Design by Trade-off Studies

The solution options which are short listed from the morphological table are further evaluated to identify the best design outcome. The Pugh method is quite advantageous for defence projects since subjective opinions can be addressed with objective reasoning in most of the cases. Each of the concept solutions is compared with an existing benchmarked system and given a rating for individual functional capabilities ie. +1, 0 or -1. These values indicate that the proposed solution is superior, similar or inferior to the bench marked system respectively. Corresponding performance weights are computed for each solution. The letters L, M and H refers to low, medium and high status ratings of existing reference system.

The two emerging solutions from Table 5 are concept solutions 2 and 3 (Having high cumulative performance weights). These candidate design solutions are critically analysed along with the users with the following metrics in mind.

(a) Specific core advantages and disadvantages of individual designs
(b) Compliance coverage of at least 95 per cent of all user requirements.

5. CONCLUSION

The paper proposed a new generative model and methodology for concept design selection process for defence system design using principles of systems engineering. Selection is done by accepted level of consensus in final ratings. Primary selection is done during the conceptual design stage whereas final selection is carried out during preliminary design stage. System specific parameters and values have been omitted from case study due to classified nature and for reasons of brevity. The new method helps in continuous improvements in all shortlisted solutions since design synthesis is possible with information gathered from alternate concepts and ideas.

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In this study : Introduction of systems engineering concepts in front end planning of a project / system. Developed the generative model (flow chart) for design of a new defence system. Developed the case study for explaining the new generative model. Process of project acceptance by compliance analysis with the Quality requirements was introduced in the model.

Dr M. Saravanakumar holds three post graduate degrees in Business Administration, Commerce and Information Technology and also PhD in Business Administration. His chosen areas of specialisation are strategic management, financial management and technology management.
In this study : Development of the research problem and contributed to the preparation of frame work. Project life cycle analysis and project success factors were introduced as part of the voice of customer for House of quality analysis. Concept of relative importance was introduced in the model.

Mr Jojish Joseph received his BTech (Electronics and Communication Engineering) from National Institute of Technology (NIT), Kozhikode and MTech (Electronic Design and Technology) from Indian Institute of Science, (IISc) Bangalore. He is working as Scientist- E at Naval Physical and Oceanographic Laboratory (NPOL), DRDO, Kochi. His research interests include: Sonar system design, sonar signal processing and towed array sonar systems.
In this study : Technology solutions for key performance functions were suggested for the case study analysis. Feasible solutions by combining appropriate solutions for each of the functions were suggested after careful analysis.

Dr Hareesh N Ramanathan after his post-graduation in Business Administration secured MPhil – Management from Bharathiar University and PhD in management from Alagappa University. He is presently working as Head of the Department in the Department of Management Studies at the Toch Institute of Science and Technology, Arakunnam, Kochi, Kerala. His chosen areas of interest are research methodology, marketing research and Research analytics.
In this study : Introduction of weights for core functions and its effect on the final concept design. Comparison of feasible solutions with the bench marked technology and systems. Need for a numerical matric for selection of feasible solution.