Tradespace Exploration for Decision Making in Conceptual Design of Complex Systems

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Dedication

I dedicate this thesis to my class MS-SYSE-04 for being the most supportive and fun group of people I have come across; my teachers who put in the effort to make the concepts interesting; and to Beude and Alexander, the author of System Engineering books for writing such books which made comprehension of the subject easier and inspired me to pursue research in this domain. Also, to Game of Thrones, for being the best TV show ever.

STATEMENT OF ORIGINALITY

I hereby certify that the work embodied in this thesis is the result of original research and has not been submitted for a higher degree to any other University or Institution.

_______________ Date

_________________________ Sundas Rafat Mulkana

Declaration

I hereby declare that the work presented in the following thesis titled as "*Tradespace Exploration for Decision Making in Conceptual Design of Complex Systems"* is my own effort, except where otherwise acknowledged, and that the thesis is my own composition. All the secondary data has been cited properly in dissertation report and accordingly sources have been mentioned in references.

Sundas Rafat Mulkana

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List of Abbreviations

TE	Tradespace Exploration
MAV	Micro Aerial Vehicle
IP	Insulin Pump
SDLC	System Development Life Cycle
PDR	Preliminary Design Review
MATE	Method of Tradespace Exploration
MATE-CON	Method of Tradespace Exploration for Concurrent Engineering
WSM	Weighted Sum Model
CIR	Customer Importance Rating
IW	Importance Weightages
VNM	Von Newman Morgenstern
m	Meters
kg	Kilograms
RT	Risk Tolerance
A	Coefficient a
B	Coefficient b
LEP	Lottery Equivalent Probability
CE	Certainty Equivalent
NPO	Non-Profit Organization
DSM	Design Structure Matrix
QFD	Quality Function Deployment

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Abstract

Industries have adopted the practice of using Tradespace Exploration (TE) to investigate cost and performance of various designs for a product. Due to added complexity new tools are required beyond conventional System Engineering methods. Organizations require methodologies to quickly explore many concepts and easily determine those designs which will provide the highest value or utility to the stakeholders of the system. TE is a technique which is used during Concept Exploration phase, which is the first phase of the System Development Life Cycle, to weigh the utility of potential design combinations against the attributes which are deemed important by the system stakeholders. This enables the comparison of multiple potential architectures for a product and a more thorough exploration of the design space. TE leads to cost effectiveness and simplifies rework in Engineering Development phase. This research aims at studying prior models which have been developed for carrying out TE and taking inspiration from them develop a cross-disciplinary framework which explores potential design options for two different case studies: Automated Insulin Pump and a Micro Aerial Vehicle.

The stakeholder requirements were translated to a Quality Function Deployment (QFD) to derive significant requirements. A system breakdown hierarchy was formulated to identify the components, the variants for which were enumerated using a Morphological box. A Design Structure Matrix was used to highlight the relationship between design components. The major concerns of this thesis were to formulate the utility functions, generate the design space, transform it into tradespace and discover Pareto optimal architectures. A survey questionnaire was distributed amongst type 1 diabetes patients to find the customer preference for various design components of an Insulin Pump. These preferences are unit normalized so that their value lies between 0 and 1. ASSESS, an interactive tool for conducting stakeholder interview was used to find utilities for Micro Aerial Vehicle (MAV). Architecture enumeration lead to the generation of a design space which was translated into a tradespace. Non-dominated architectures were identified in order to plot the Pareto frontier, which was plotted using regression analysis. The architectures which lie on the Pareto frontier are optimum architectures and these need to be explored further by the decision makers.

Chapter 1

INTRODUCTION

1.1 Background

Designing a complex system involves consideration of multiple factors, from design decisions to maintenance and support decisions, which makes it a complicated endeavor. A complex system is an engineered system comprising of a set of interrelated components working towards a common objective. It is also known as the multiplicity of interrelated parts that collectively perform a significant function and have an intricate relationship with one another [1]. Prodigious engineering resources are devoted to the first phase of the System Development Life Cycle (SDLC) called concept development phase. Which means a wrong design chosen in the conceptual development phase can end up costing the project both time and resources. Moreover, a major challenge in the engineering development phase which is the second phase of SDLC is the reversal of decisions made in concept development phase [2]. Once a system enters "engineering development phase" rework due to a change in requirements or the addition/removal of a component can prove to be an expensive task. A traditional approach suggests to make decisions which are valuable throughout the operational lifetime of the system. An alternative approach to this is to make the architecture flexible enough to thwart exogenous system disturbances [3].

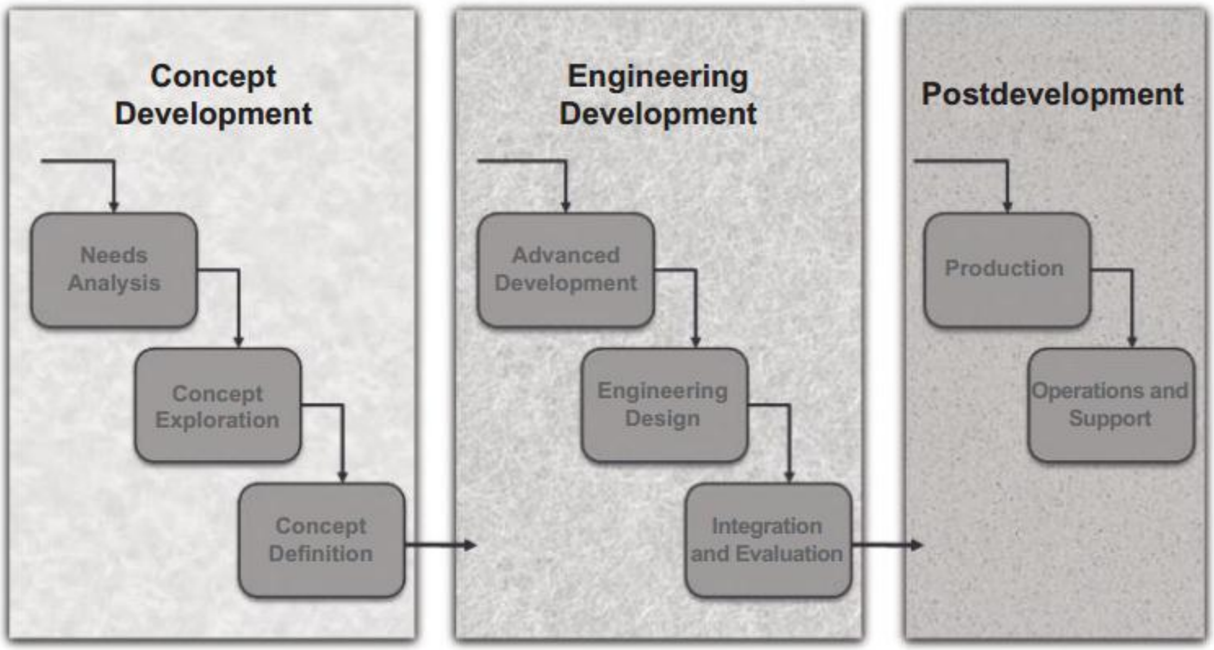


Figure 1. System Development Life Cycle (*Source: Alexander Kossiakoff, Systems Engineering Principles and Practices, 2nd Edition*)

In order to make valuable design decisions, the opinion of multiple stakeholders of the system need to be taken into consideration. Often, the most optimum design presented by the designer is rejected because of cost constraints. At times, the least expensive design is not a viable solution either because the end users, people who will ultimately have to use the product, do not favor it. Alternatively, the design which provides the highest utility to the user is often not feasible in terms of an engineering or business perspective.

Henceforth, the system developers require a method by which they can evaluate all possible design combinations against certain criteria set by each stakeholder. This will in turn lead to discovering a design which not only meets the objectives, for example cost, user friendliness, size etc. - but additionally, satisfy the stakeholders' needs. When it comes to design decisions, there are different schools of thought. One school of thought suggests to choose the most optimum design. This is considered the traditional approach. Another school of thought suggests using a technique called Tradespace Exploration in order to find all possible design combinations, i.e. architectures and then allows the supra decision maker to choose the most optimum architectures for their purpose form the design space. Supra decision maker is the supreme decision maker or in other words called the dictator, usually the company owner who has control over the ultimate decisions. This new approach, the "Tradespace Exploration paradigm" was depicted in contrast to the "classical paradigm" in that it sought to minimize the premature application of constraints, both on the potential solution systems and on the potential expectations of stakeholders [4].

The nature of the relationship between components of a system is often interdependent and integration of these components involves certain complexities. Complex systems development spans decades at times. During that time, often the management, people involved and higher authorities change. Often political instability vicissitudes the primary stakeholders, which can lead to a change in requirements; hence, altering the scope of the project. Pecuniary concerns are foremost when designing any system, especially systems which require immense resources. The purpose of concept exploration phase is to capture stakeholder preferences and translate them to design decisions.

When design decisions are to be made, there are a variety of options to choose from. The traditional approach of optimizing the design leads to limiting these options. The best system is not necessarily the combination of best sub-systems. Hence, Tradespace Exploration, a method by which we can explore all potential design architectures and evaluate them on the basis of set criteria is a superior option.

1.2 Research Scope

This research project aims to develop and validate a framework for decision making in complex systems using a technique known as Tradespace Exploration. This study is projected by application to two case studies, an automated Insulin Pump and a Micro Aerial Vehicle (MAV). The reason for choosing two diverse application areas is to check whether or not this framework can be applied across disciplines and can be used for a non-aerospace domain as well.

The major concerns of this thesis were to determine how utility functions are formulated; to generate a design space; and to find the Pareto optimal architectures. Prior to conducting the research critical research questions were identified in order to layout the purpose for conducting this research. During the course of the research these questions were answered by studying the existing frameworks for Tradespace Exploration extensively and developing a framework which was most suitable for the two case studies undertaken. This study addresses the following questions:

1. *How do stakeholder preferences influence component selection and design decisions?*
2. *How are stakeholder preferences cumulatively evaluated on a single platform?*
3. *Can Tradespace Exploration be accurately applied on non-Aerospace applications?*
4. *How to find non-dominated architectures from a tradespace and subsequently plot a Pareto frontier?*

The scope of this thesis involves the identification of processes used for Tradespace Exploration, the development of a framework which suits the chosen application areas and exploration of the techniques involved in execution of the framework. The purpose is to develop a quantitative framework based on qualitative assessment.

The Insulin Pump case study was taken from an ongoing project being undertaken by an NPO in Pakistan called Meethi Zindagi (Sweet Life) which is aimed at providing cost effective treatment solutions to Type-1 diabetics. Their current endeavors involve the development and distribution of a low cost automated Insulin Pump amongst the under-privileged population of the country.

The second case study on Micro Aerial Vehicle development takes inspiration from the research being carried out at the Mechanics Interdisciplinary Group (MIG) with regards to the design and development of low cost Micro Aerial Vehicle development setup. The data is mostly acquired from the available literature [5].

1.3 Research Relevance

A Preliminary Design Review (PDR) is undertaken during the concept development phase of SDLC. The purpose of PDR is to explain which concepts and system architectures are further chosen for review, to elucidate the reason behind choosing the particular architecture and to approve it as the design baseline. Subsequently, it's purpose is to compare the chosen architecture with the rejected architectures. It provides a quantitative analysis that gives confidence that the requirements as stated in the System Requirement Review (SRR) and derived since then can be met and describe the results of any risk reduction experiments or prototype.

During concept design, alternatives are generated using Pugh Matrix or Morphological box or similar alternative generation techniques. This is the stage when detailed mathematical models are not available but a vague qualitative understanding exists [1]. During the PDR, utility analysis is undertaken to find the alternatives which the stakeholder prefers. Subsequently, non-dominance is used to generate multiple designs for each concept and a Pareto filter is applied. The PDR demonstrates that the preliminary design meets all system requirements with acceptable risk and within the cost and schedule constraints and establishes the basis for proceeding with the detailed design. It will show that the correct options have been selected, interfaces have been identified, approximately 10% of engineering drawings have been created, and verification method have been described [6].

In the PDR, concept selection techniques should be flexible so that if the wrong concept is selected or some very important detail has been overlooked, the decision can be reverted without very heavy consequences. According to an email exchange with Dr. Mike Ryan from UNSW Canberra, an optimal system cannot be designed by combining a set of optimal system elements. We are interested in best combination of components rather than combination of best components in order to present the most desirable end product to the system's stakeholders. These stakeholders have utility for both utility of system elements, as well as utility of systems. In some products, we incorporate in the design system elements that have high subjective utility to stakeholder but little utility to the system design in order to achieved the prior mentioned objective.

1.4 Chapter Summaries

This thesis is divide into five chapters. Chapter one covers the background of the research topic, discusses the need for carrying out this research and addresses the questions which were raised at the beginning of the research.

Chapter two sheds light on the techniques which were used by previous researchers to resolve issues which were raised in chapter one. It further discusses the methods which have been derived and the short-comings of those methods when applied to the chosen case studies. Additionally, it informs the reader of the methodologies which exist in literature and the tools which have been developed by previous researchers to assist in the Tradespace Exploration effort.

Chapter three discusses the framework which has been developed and used during the course of this research. It further discusses the origination and the steps which are followed for carrying out Tradespace Exploration for the two case studies.

Chapter four demonstrates the implementation of the developed framework on the two case studies, an automated Insulin Pump and a Micro Aerial Vehicle. The results of the case studies are analyzed and a practical implementation of the developed framework is shown. Chapter four is divided into two parts- case study 1 focuses on the design of a Micro Aerial Vehicle and case study 2 which is based on the design of an automated Insulin Pump.

Chapter five concludes the research by providing answers to the questions which were raised in chapter one. Moreover, it elucidates upon the validity of using the suggested framework and the conditions under which it may be used.

Chapter 2

LITERATURE REVIEW

2.1 Tradespace Exploration

2.1.1 Introduction

After the generation of design alternatives, the ensuing task is to perform an attributes analysis and comparison between those design alternatives. This technique is commonly known as Tradespace Exploration. Tradespace Exploration is a model based high level assessment of system capability in which ideally multiple designs are assessed. A tradespace is an area of evaluation which is restricted by boundary constraints and aims to evaluate alternative options, choices and preferences to carry out a trade study investigation and analysis. It is a technique used to explore all possible architectures (design options) for a system, weigh them against a set criteria or attributes, identify the Pareto front and decide upon the best architecture to be used. This aids in effective decision making and risk assessment, especially when multiple stakeholders are involved. [7] The utility-cost plot has also been termed as tradespace [8]. The Pareto front are the set of points that are the best in a given metric with all other metrics held fixed [9].

Tradespace Exploration allows the quantitative comparison of a large number of designs on the same performance and cost basis early on in the design process therefore enabling designers to compare large number of system concepts before the allocation of a significant amount of design resources. Tradespace Exploration is applied to analyze the design space and hence, aids the decision maker in choosing the ‘good design’ alternatives from a large set. The advantage of a qualitative method is that it facilitates more complex exploration of a system design space and compares a large number of design options on the basis of similar criteria [10].

Tradespace ranking is the process of ranking architectures across multiple metrics. The goal of evaluation is to provide quantitative measures of metric to support subsequent down-selection of concepts and provide recommendations to decision makers. Metrics are used to evaluate architectures under different perspectives and are a measure of how good, expensive or risky the alternative architectures are.

What happens when requirements are changed? How do we make a system flexible and robust to these changes? Also, what are the policy effects on system cost and performance? The design choice space from which the concept is selected must be carefully considered in order to mitigate the risk of costly changes later on, and maximize the value created for the stakeholders of the system. Intentional or unintentional premature reduction of the design choice space may take away valuable information from the designer, thereby preventing realization of more robust and valuable systems [4].

Putting off focus on “point designs” this new paradigm sought to take a “value-centric” approach where alternatives are evaluated in terms of stakeholder-defined metrics, rather than designer determined metrics, thereby creating a proxy “voice” for the stakeholders during concept generation, evaluation, and ultimately, selection of alternatives [9].

The benefits acquired are that the designers get a better understanding of the end user’s desires and requirements for the system. IDEF0 diagrams are a complicated way to view the system and a tradespace provides a concise format in which the design space can be viewed and analyzed. Additionally, it provides the ability to optimize the system for initial evaluation. It provides a subsequent understanding of what will become optimal in evolutions and shortens the time required to redesign in case preferences change.

2.1.2 Frameworks for Tradespace Exploration

2.1.2.1 Method of Tradespace Exploration (MATE) by Adam Ross and Nathan Diller

Several researchers have introduced frameworks to carry out Tradespace Exploration. The first framework was introduced by MIT researchers Adam Ross and Nathan Diller [11]. Method of Tradespace Exploration (MATE), a method of developing models to simulate the product user's preferences for the attributes of a design helps in evolutionary acquisition. Once these preferences are well known, they can be used to guide the design choice. MATE allows the comparison of multiple concepts within the same Tradespace [9]. It places less emphasis on optimization because that limits the design space to one perfect solution, when in reality there can be a variety of optimum solutions which satisfy the stakeholder more than the optimized solution. Moreover, it provides high benefit versus cost solutions. Designers can observe changes in benefits and costs that occur when the dynamic system changes. The steps to be followed in MATE are to identify the mission concept, define the attributes, define the design vector and simultaneously calculate the utilities. Then develop system model and estimate the cost. Subsequently, enumerate the architecture Tradespace and evaluate it.

The methodology in MATE is as follows:

1. *Identify the key decision makers*
2. *Scope the enterprise boundary*
3. *Determine key context variables*
4. *Interview decision makers*
5. *Determine attributes*
6. *Determine design variables*
7. *Generate system model*
8. *Assess tradespace*

MATE is used because it is not limited to value focused thinking, which starts with a rationale that is value creation. It focuses on alternative thinking which starts with solutions and design options [12].

2.1.2.2 Multi-Attribute Tradespace Exploration with Concurrent Engineering (MATE-CON)

Multi-Attribute Tradespace Exploration with Concurrent engineering (MATE-CON) is a similar technique introduced by Dereleth [2] which captures the decision maker's preferences and generates and evaluates multiple space system designs to provide a common metric of evaluation. The Tradespace is quantitatively evaluated to consider technical, political, market and budgetary uncertainty, and provides the basis for rigorously developing techniques of improved conceptual design for manufacturability, logistics, reliability, maintainability, human factors, disposability, and in particular life-cycle affordability.

MATE-CON consists of two phases, an architectural level study followed by a preliminary design using concurrent engineering. In the architectural level study, engineers begin with the use of tools developed by social scientists to model the user's or customer's preferences. Through multiple iterations of the initial interview process, both the user and engineers involved gain substantial intuition about the project, allowing for the production of a better design. The user's preferences are then aggregated into a single utility function allowing for comparison of the utility of different systems. Engineers then build architectural-level parametric models of the system to simulate its performance, allowing the engineers to enumerate a tradespace of architectural designs. By using a parametric cost model, this tradespace can be graphed as a scatter plot with cost vs. utility on an xy-plane. A restricted, optimal set of concepts are considered by the user, and a single design chosen. The second phase of MATE-CON is concurrent engineering. Higher level tools and models are built by the engineers and used to produce a preliminary design and with the aid of built up intuition and through the use of further tools and their choices in these design sessions can be guided by the same utility function developed and verified initially. This grants the user a technical voice during the preliminary design process, helping to guide the design.

MATE-CON [7] is introduced to capture and assess the cumulative decision maker preferences for the formulation and evaluation of a plethora of system designs. It uses this technique to develop potential system design, subsequently employing Multi-Attribute Utility Theory to accumulate preferences for design evaluation.

It translates cost and utility preferences of the decision makers on a Tradespace. The major advantage is that if the stakeholders include an additional design variable during the design stage, translating the effect on the attribute can be done very quickly. What we can do is discover technical infeasibilities during the detailed design phase which can be mitigated by making appropriate design changes based on knowledge of the larger tradespace performed during MATE-CON [8].

MATE-CON process follows the following format:

1. *Need identification*
2. *Architecture solution exploration*
3. *Architecture evaluation*
4. *Design solution exploration*
5. *Design evaluation*

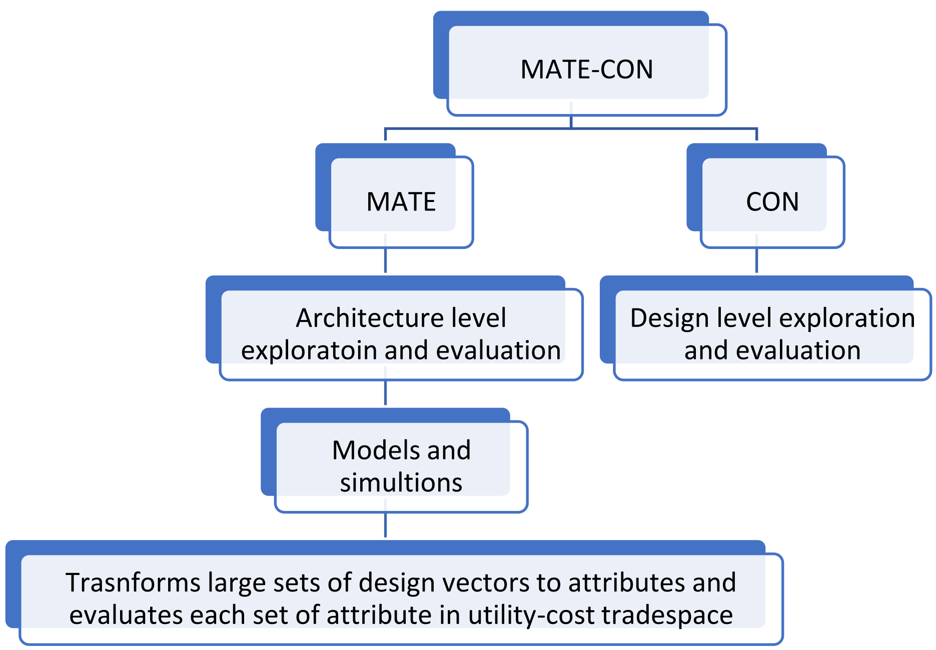


Figure 2. Method of Tradespace Exploration for Concurrent Engineering.

2.1.2.3 Implementation of MATE-CON by Chattopadhyay

Chattopadhyay [10] has addressed the issue of designing a quantitative method which allows decisions makers to compare diverse multi-concept System of System (SoS) designs on the same performance and cost basis in order to select value-robust designs during concept exploration phase as an extension of MATE. The method allows SoS designers to distinguish between component systems having high likelihood of participation in the SoS and those with lower likelihood of participation, based on the level of effective managerial authority that the SoS designer has over the component. Chattopadhyay has modeled two systems using MATE-CON process and Epoch Era Analysis, thus performing multi-attribute Tradespace Exploration for dynamic systems. The researcher considers varying stakeholder preferences with time. Multi-concept architectures are compared on same performance and cost basis allowing the designer to distinguish between the likelihood of participation of a system component, judging the impact on effective managerial authority.

2.1.2.4 System of System Tradespace Exploration Method

System of System Tradespace Exploration Method (SoSTEM) is used due to the addition of complexities when multiple systems merge to form a larger system called a System of System. The steps which are suggested by Chattopadhyay are as follows:

1. *Determine SoS mission*
2. *Generate list of component systems*
3. *Identify stakeholder and decision makers component system and for SoS*
4. *Classify component system according to managerial control and participation risk*
5. *Define SoS attribute and utility information through stakeholder interview*
6. *Define SoS context change*
7. *Model SoS preference and cost*
8. *Tradespace analysis*
9. *Epoch Era analysis*
10. *Select value robust SoS design*

This technique can be employed when a number of systems combine together to form a larger system where participation risk of elements and the effect of managerial authority on the overall system are also factors which need to be taken into consideration when designing the system.

2.1.2.5 Methods used by other Researchers

Li Qiao [13] has used data clustering algorithms with multi-dimensional scaling visualization. Using k-medoids clustering, similar designs are grouped, uncovering hidden patterns and features in the datasets. Principal component analysis allows users to visualize any design samples on 2-D scatter plots.

Smaling [14] has proposed a filtering scheme to reduce the set of solutions that include Pareto and near-Pareto points, by explicitly linking the objective space solutions to the originating design space. Ong [15] applies MATE and Epoch Era Analysis to generate alternatives and discover high value designs. Gary [8] has created a data visualization tool ‘Trade Space Visualizer’ in which you can compare the benefits of certain architectures, however, it does not cater to architecture evolution.

Davidson [8] explores architectural flexibility in the future evolution of long lifecycle systems. The researchers have introduced a method of shifting architectures; how to thwart exogenous system disturbances (e.g. budget reduction or changes in stakeholder requirements), failure to develop critical technologies, or planned evolution of the system over time which take a toll on resources, schedule and performance. The researchers have explored the relationship between architectures in Tradespace by exploring pathways to assess architecture selection decision and quantitatively compare architecture change decisions against one another by assigning architectures weights. Elemental commonality between architectures is assessed by asset portfolio of vertices (decisions), where edges represent the cost of corresponding architecture change. Sum of edge weights represents total development cost of architecture evolution. The study has proposed a method for cost savings if the need to shift from one architecture to the other arises. However, the scope of his study is limited and does not explore policy changes or other factors which are the root cause of the need to shift the architecture.

Design choice is guided by system level computer models that represent design choices available to the engineer. These choices are then varied systematically to create a “Tradespace” of possible designs. Each possible design choice is ranked in order of utility and cost and the result is graphically represented in the form of a tradespace [2]. Tradespace is the space which contains all possible design choices. The subsystem level vectors are varied and combined as they completely represent the system. Each unique combination of these design vectors is a system architecture. Using a high-level cost model, it is possible to assign a cost to each architecture.

2.1.3 Trade Space Visualization

A Trade Space Visualizer (ATSV) is a data visualization tool developed by researchers at the Applied Research Laboratory (ARL) in 2002 at Pennsylvania State University to visualize a multi-dimensional tradespace during concept design. Additionally, it is equipped with a feature finder tool. ATSV has the capability to calculate and display information about a selected point in the design space. It can display seven-dimensional information in a glyph plot by utilizing special position of an icon to denote the branched variables of one design with four other variables distinguished by size, color, orientation and transparency of the icon. It possesses the following capabilities: glyph plots, histogram plots, parallel coordinate plots, scatter matrices, brushing and linked views. It also includes the feature of preference shading and can display the Pareto frontier. This can aid the decision maker in the formulation of a preference structure [2]. Moreover, it's unique features include visual steering, brushing/linked views, preference shading and pareto frontiers. It also supports the mapping of continuous, discrete, categorical and datetime variables and can perform K-mean clustering and principal component analysis [16].

Visual steering aids the decision maker formulate partialities while conducting Tradespace Exploration. There are two distinct paths which may be followed; either the tradespace can be generated and then broadly explored or the knowledge gained during this exploration can be used to narrow down regions which need further attention [17].

Table 1. ATSV capabilities.

Samplers	Description
Basic Sampler	Samples the input space, defined by the upper and lower bounds on each input variable. Uses Monte Carlo simulation to perform wide search of tradespace. Inputs can have a uniform, normal or triangular distribution.
Attractor Sampler	Populated the new sampler at a point defined by the user in the tradespace.

	Evolutionary algorithm is used to guide sampling process at a user defined point. The fitness of the new points is judged by the Euclidian distance from the specified n-dimensional point attractor.
Pareto Sampler	During engineering design, the decision makers are faced with certain criteria which they would like to either minimize or maximize. Pareto sampler allows minimizing/maximizing preference on variable in Tradespace. Performs pareto search based on user specified directions of preference.

2.1.4 Methods for Carrying out Tradespace Exploration

There are three broadly defined ways of carrying out Tradespace exploration: shopping process, negotiated process and iterative process. These are dependent upon the preferences laid out by the stakeholders of the system.

1. ***Shopping process:*** The decision maker is already aware of their preferences and exactly looks for that particular preference. The methods which can be used in this scenario are
    a. The decision maker chooses form the values which lie on the Pareto Frontier
    b. The decision maker chooses a particular bracket
2. ***Negotiated process:*** Multiple decision makers are involved and they all have their own particular preferences and expertise.
3. ***Iterative process:*** First the Tradespace is generated and explored and then then the knowledge which is acquired during this process is used to narrow down areas of further search.

According to system engineering principles, the combination of the best subsystems is not necessarily the best system. Hence, optimization is not the ideal scenario in all cases. Tradespace Exploration allows us the flexibility to weigh different objectives and translate those to an efficient and stakeholder-oriented design.

2.1.5 Requirements Definition

Requirements are a set of goals in the design and objective space. Requirements can be classified into 'shall' requirements and 'should' requirements. 'Shall' requirements are must have requirements and help set constraints and define the boundary of the design space and objective space. 'Should' requirements are desirable requirements which set goals once shall requirements are satisfied.

After the requirements are elicited, there are two main spaces:

1. ***Design space:*** This is the space which is formed by the parameters which we decide as engineers.
2. ***Objective space:*** The are the parameters which the system or product must achieve and what the customer cares about.

Objective space is more flexible than design space, since design space is constraint by boundary conditions which are set by the designer. Whereas objective space is flexible with regards to customer desires.

Table 2. Difference between requirements and specifications.

REQUIREMENTS	SPECIFICATIONS
Specify what the product/system shall/should do:	***Describes how a system is built and works***
Functions it shall perform	The form the system is made of; materials used in the system, overall dimensions
How well should it perform these	Schematics, blueprints
Degree of automation of system	User interface
Input to design process	Output of design process

2.1.5.1 Types of Requirements:

Requirements can be divided into the following commonly acceptable types:

1. ***Functional requirements***: What functions need to be performed to accomplish the mission objectives.
2. ***Performance requirements:*** Define how well a system needs to perform the functions
3. *Constraints:* Requirements that cannot be traded off with respect to cost, schedule, performance.
4. ***Interface requirements:*** Requirements which define how the interfaces are to be integrated.
5. ***Environmental requirements:*** The requirements which define how the system will interact with the environment, e.g. medical device is going to be used in a hospital, insurance companies etc.
6. ***Others:*** Utilities requirements described in the system engineering handbook include human factors, reliability requirements and safety requirements.

2.1.5.2 Attributes of Acceptable Requirements:

Following are the commonly declared acceptable attributes of requirements:

1. Complete sentence with a single 'shall', numbered statement.
2. Characteristics for each requirement statement:
    a. Clear and consistent: readily understandable
    b. Correct: does not contain error of fact
    c. Feasible: can be satisfied within natural physical laws, state of the art technologies and other project constraints
3. Flexibility: not stated how it is to be satisfied
4. Without ambiguity: only one interpretation makes sense
5. Singular: one action/verb object requirement
6. Verify: can be proved at the level of architecture applicable.

There is a school of thought which suggests that expressing preferences before weighting options is not a good idea.

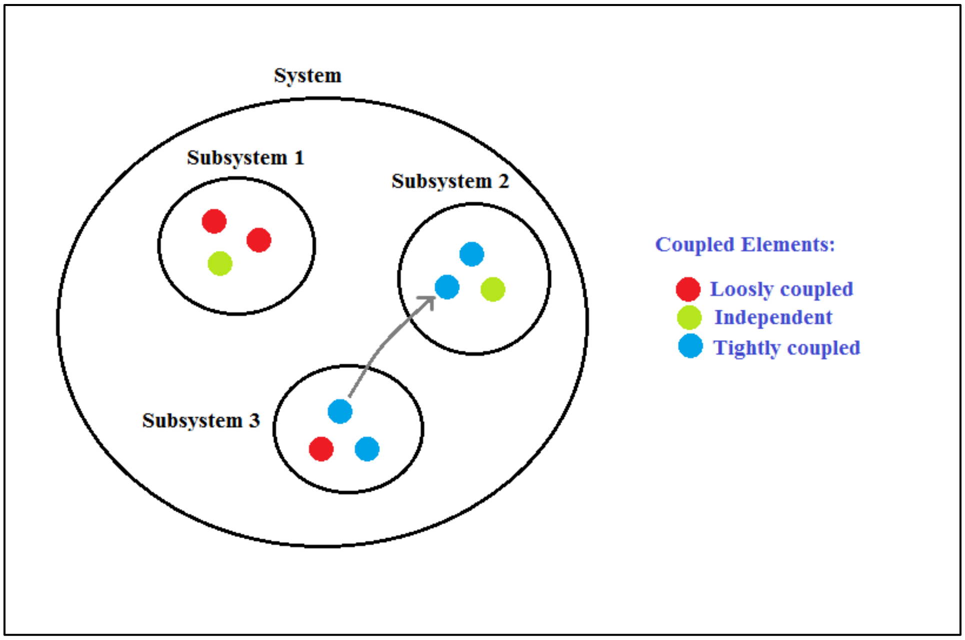


Figure 3. Interaction between components inside multiple subsystems in a system.

2.2 Multi-Criteria Decision Making

Objectives are provided by the decision makers and alternate options are available. The problem is to choose alternate course of action that best satisfies those objectives in some way. There are four types of decision making; decision under certainty, risk, imperfect information probability and conflict. Decision under certainty has only one outcome and deterministic theory is used. Risk has several outcomes and probability is known so is the state of nature. For imperfect information probability there are several outcomes for which probability is not given. Decision analysis models are used for both [18]. Game theory is used for decision which has conflict.

There are four categories of decision analysis [19]:

1. ***Under certainty:*** in this scenario an action leads to one certain outcome.
2. ***Under risk:*** in this scenario, an action can lead to several outcomes in which the state of nature has known probabilities.
3. ***Imperfect information probability (uncertainty):*** in this scenario an action can have several outcomes but the state of nature has unknown probabilities.
4. ***Under conflict:*** the nature is unknown but it is not necessary that the opponent is hostile.

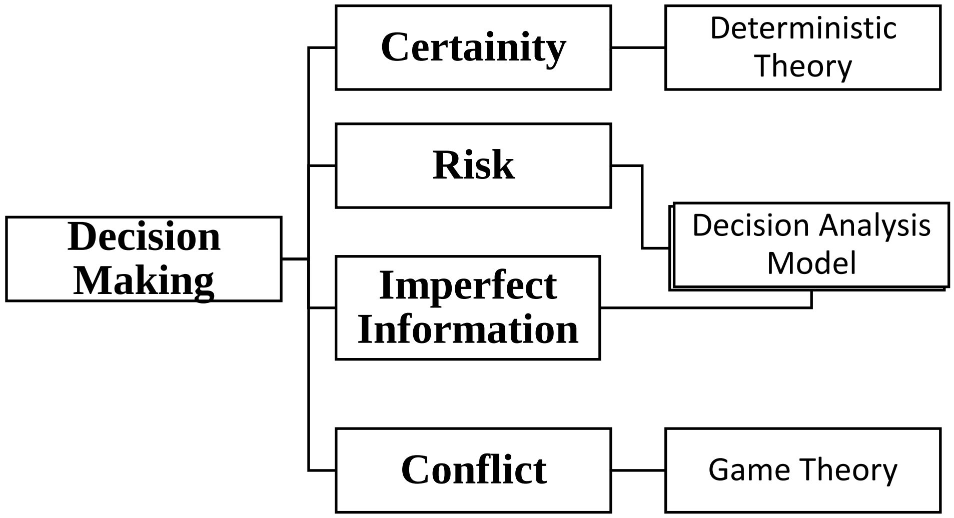


Figure 4. Decision making models.

For the first category deterministic decision theory is used because of the multi-attributed outcome situation. In the second and third category decision analysis models are used. For the fourth category game theoretic probabilities or conflict analysis is used. In the case of case study 1 MAV, we are assuming that the fourth category applies. To find the probability Bayes theorem is used which gives posteriori probabilities. Probability theory and utility functions combine together to form decision analysis [17].

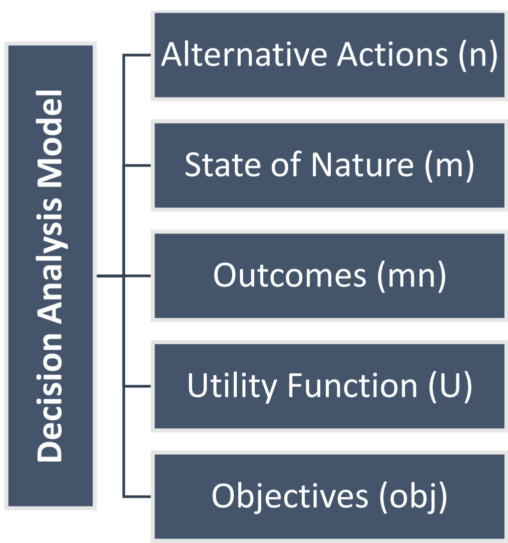


Figure 5. Decision analysis model.

Multi-criteria decision analysis is a technique which is employed when multiple conflicting objectives are involved. For example, when you want to reduce the price of an object, but simultaneously increase utility.

In designing complex systems, considerable resources are being expended for this effort which warrant a thorough evaluation before important design decisions are made. These decisions are based on multiple criteria. There are numerous stakeholders who are involved in the process, and how will that decision impact each stakeholder is also an important factor to take into consideration.

Better decisions can be made by developing well-structured complex problems and taking multiple criteria into consideration. There does not exist a unique optimal solution to these problems, hence, it is important to take into account stakeholder preferences to differentiate between solutions.

There solutions can be analyzed in a number of ways:

- Choosing the best alternative, the option most preferred by the decision maker, from a set of available alternatives
- Choose a set of preferred alternatives; find non-dominated alternatives

The problem now becomes complex because we are not taking only one criteria into account. Therefore, local optimization schemes cannot be followed. The most commonly used method in literature for Tradespace exploration is Multi-attribute utility theory. This implies multi-attribute utility or value functions are used to identify the most preferred alternatives and rank the alternatives. For this purpose, an intensive interview method is used for formulating additive utility functions and multiplicative nonlinear utility functions [20].

A parallel method to be used is Evolutionary Multi-objective Optimization. These take inspiration from the genetic theory in biology. In this technique an initial population is generated which is then restructured to get alternatives which are the fittest, where a 'survival of the fittest' phenomenon is applied. The goal of this scheme is to find non-dominated architectures which basically lie on the Pareto Frontier- hence, the goal is to identify the Pareto frontier [21]. However, there is a fundamental paradox which exists in decision making which is known as the decision-making paradox. The paradox is that different decision-making techniques yield different results of the same data and problem [22] .

In decision theory, the weighted sum model (WSM) is the most famous and easiest multi-criteria decision analysis method for evaluating a number of alternatives in terms of a number of decision criteria but it is only applicable when all the data is represented in the same units. The benefit criteria suggest the higher, the better.

$$A_i^{WSM\text{-}score} = \sum_{j=1}^{n} wiaij \; \dots (1)$$

Normalized swing weight:

$$w_j = \frac{wj}{\sum_{j=1}^{N} wj} \; \dots (2)$$

Table 3. Weightages alternatives with respect to objectives.

	Obj 1	**Obj 2**	**Obj 3**
weightage	w_1	w_2	w_3
A_1	a_{11}	a_{12}	a_{31}
A_2	a_{21}	a_{22}	a_{32}
A_3	a_{31}	a_{32}	a_{33}

where c_j is criteria, A_i is alternative, a_{ij} is performance, w_j is the relative weight of importance of criteria and n is the number of attributes. Objective is provided by the decision maker. The problem is to choose alternative course of action which best satisfies those objectives in some way.

Alternative actions (n):

$$A = \{a(1), a(2), \dots , a(n)\}$$

States of nature (m):

$$E = \{e(1), e(2), \ldots , e(n)\}$$

Outcomes (mn):

$$O = \{o(11), \ldots , o(ij), q(nm)\}$$

Utility functions:

$$: U = \{u(11), u(ij), \ldots , u(nm)\} = u_{ij}$$

$$u_{ij} = U(q(ij))$$

This is the decision maker’s utility (u) at having selected the alternative *i* and receiving state of nature *j* as a result [19].

2.3 Utility Theory

2.3.1 Utility

Utility is a measure of relative happiness or satisfaction gained by consuming different goods or services. Utility is a dimensionless parameter, generally mapped between a [0, 1] interval. A consumption set X has mutually exclusive alternatives. In decision theory, von Neumann-Morgenstern utility theorem states that a utility function exists when four axioms are satisfied by an individual’s preferences [23]. These axioms are, completeness, transitivity, continuity and Independence or Archimedean property.

Table 4. The four axioms of utility theory.

	Axioms	**Conditions**
Axiom 1	Completeness	When comparing two bundles of goods, prefer A or B, not both or neither Individual has well defined preferences. L<M, M<L or L~M (either M is preferred, L is preferred, or the

		individual is indifferent)
Axiom 2	Transitivity	Preferences are consistent across alternatives. $L \leq M$ and $M \leq N$, then $L \leq N$
Axiom 3	Continuity	If $L \leq M \leq N$, then there exists a probability p is a subset of [0,1] such that $pL+(1-p)N \sim M$
Axiom 4	Independence	If $L<M$, then for any N and p is a subset of [0,1] $pL+(1-p)N<pM+(1-p)N$

Utility values are taken between 0 and 1, where 0 is the worst outcome and 1 is the best outcome. The VNM utility functions translate the functional dependence of value on an attribute. The utility changes as the level of an attribute and the perceived value changes. Utility is the preference of the customer. Most researchers have measured it on a scale of 0 to 1, which is also called unit normalized. However, the concept of utility is still vague. It is measured on an ordinal scale and not a cardinal one which means that a utility of 0.4 is not twice that of 0.2. It is a concept derived from economics, which measures the relative happiness/ satisfaction gained by consuming different goods or services. The theoretical measure of utility is utils. Generally, the criterion is mapped onto a dimensional utility interval [0, 1]. Normally, we combine the utilities generated by criteria into overall utility. Every day when picking lunch, we are trying to maximize our utility.

2.3.2 Utility Classification

There are four types of utility shapes:

1. *Monotonic – increasing/decreasing*
2. *Strictly concave/convex*
3. *Concave/convex*
4. *Non-monotonic*

Utility functions come from interviews or surveys. Normally, we have three different customers for a system.

- ***Customer 1:*** needs particular level of minimum amount of preference, no satisfaction beyond that level
- ***Customer 2:*** gradual increase of utility
- ***Customer 3:*** no utility until reaches a particular value

We need to combine all these stakeholder utilities in order to judge the overall utility. The problem which arises is that how do we normalize the utility because we do not want the utility to exceed 1.

$$U(W)=1 \text{ and } U(L)=0$$

- U=0 no value delivered,
- U=1 value delivered to the stakeholder,

W is the most preferred alternative and L is the least preferred alternative. Utility theory is often use to define subjective metrics. In utility functions you prefer one thing over another. Utility functions are unit-normalized bounded functions describing value delivered to an individual stakeholder or a group of stakeholders as a function of the design vector.

2.3.3 Finding Utility

Utility is basically a function, which is plotted as discrete values when component utility is considered and as a continuous function when some attribute utility is considered as is the case in MAV design. To develop a utility function, an interview method can be used. User utility is determined in terms of satisfaction. Designer utility is identified in terms on compatibility of components and incompatibility. Hence, we have to do a component wise comparison. Utility is used in development of indifference curves which represent the combination of two products that a certain customer values equally and independently of price.

2.4 Multi-Attribute Utility Theory

In multi-attribute utility theory, single attributes are combined according to their relative weights into a multi-attribute utility value. The decision maker's needs and preferences are captured through multi-attribute utility analysis to form the preference space. The preferences are then translated to the Tradespace by formulating utility functions. These are continuous ranking functions. In the case of micro aerial vehicles, they are taken as continuous ranking functions and in the case of insulin pump these are taken as discrete values and the difference in the results is observed.

Adam Ross [24] in his thesis introduces the topic of Multi-attribute Utility Analysis taking inspiration from the Multi-attribute Utility Theory. It provides a systematic technique for assessing customer value in the form of preferences for attributes. Moreover, it also captures customers propensity towards risk. Most advantageously, it provides a mathematical representation which better captures the complex tradeoffs and interactions between different attributes. It strength lies in the fact that it can capture the decision makers preference for simultaneous different objectives. Utility scale is an ordered Metric scale. It does not have an absolute zero. Utility is defined in terms of uncertainty and this forms a relationship with a person's preference under uncertainty, displaying risk preference for an attribute. Attribute can be both concrete and a fuzzy concept [24].

Different techniques are applied for both the case studies to acquire utility equations owing to the diverse nature of both the projects. The reason two different utility functions are used for the two case studies is because of the nature of the design problem. In case study 1, micro aerial vehicles, the attributes were taken to be continuous values. Whereas in case study 2, the design vector consisted of components and the utility of components was taken into consideration hence that had to be a discrete value.

2.4.1 Multi-Attribute Utility Theory Calculation

Multi-attribute utility function for each decision maker:

$$\mathrm{KU(X)+1} = \prod_{i=1}^{N}[KkiUi(Xi) + 1] \ldots (3)$$

where K is the solution to:

$$K+1=\prod_{i=1}^{N}[Kki+1] \ldots (4)$$

$\sum_{i}^{N} ki < 1$	$K > 0$
$\sum_{i}^{N} ki > 1$	$-1 < K < 0$
$\sum_{i}^{N} ki = 0$	$K = 0$

$$U(X) = \sum_{i=1}^{N} kiUi(Xi) \ldots (5)$$

and K_i is the normalization constant.

Utility analysis is the investigation of how customers reach decisions to achieve utility maximization.

Table 5. Utility measurement scales.

Nominal	Within acceptable tolerances
Cardinal	Absolute value
Ordinal	Rank

2.4.2 Measurement of Utility

The two methods of measuring utility are Certainty Equivalence (CE) and Lottery Equivalent Probability (LEP) [18]. The general condition is:

$$U(Lottery)=\sum PiU(Xi) \ldots (6)$$

Utility of risky situations is equal to the sum of utility of each possible outcome times their probability of outcome. Finding utility functions is subject to the ways in which we can define the stimulus to the response. We keep the stimulus lottery constant and vary the outcome. Then we vary the probability and keep the outcome constant [25].

2.4.3 Multi Attribute Utility Analysis

In Multi-attribute Utility Analysis, the total utility becomes weighted sum of partial utilities. Single utilities are combined into an overall utility function.

$$U(J_1,J_2) = Kk_1k_2U(J_1)U(J_2) + k_1U(J_1) + k_2(J_2) \ldots (7)$$

where J is the attribute, K is the dependent scaling factor also known as the normalization constant, k is the weightage of the attribute and $U(J_i,J_j)$ is the combined utility of the attributes. There are several different techniques available in literature for determining k_i, the most common of which is to conduct interviews Another common method is to use Conjoint Analysis. However, that is an expensive and time-consuming method.

For two objectives the dependent scaling factor can be determined by using the following formula:

$$K = \frac{(1-k1-k2)}{k1k2} \ldots (8)$$

In order to carry out Multi-attribute Utility Analysis the following steps may be followed:

1. Identify critical objectives/alternatives
2. Develop interview questionnaire
3. Administer questionnaire
4. Develop aggregate utility function
5. Determine utility of alternatives
6. Analyze results.

Utility function can vary drastically depending on decision maker. It requires formulation of preference option. Utility is the non-linear combination of criteria J with no units. We need to obtain a mathematical representation for $U(J_i)$ for all *i* to include all components of utility. One of the recent concerns of the academic community is to develop a framework which ensures an architecture is robust to changing utility and decision maker change [26].

2.5 Morphological Box and Design Structure Matrix

2.5.1 Morphological Box

Morphological box or Zwicky's box is used for alternative generation. The basic idea behind a morphological box is to firstly, decompose the system into its functional subsystems. Secondly, the system engineer brainstorms alternatives that achieve the subsystem's function. Thirdly, the separate alternatives are combined in new ways, subsection by subsection. The infeasible combinations are identified and discarded. However, for the purpose of broad Tradespace exploration, the less favorable options are not discarded but instead are included in the evaluation space [24].

2.5.2 Design Structure Matrix

Design Structure Matrix (DSM) is a simple tool which allows modeling and visualization of the dependencies between different entities of a system. This system can be both product architecture and engineering design process. This is a two-dimensional matrix which represents the structural and functional interrelationship between objects, tasks or teams. In order to create a DSM, we identify the subsystems of a complex system [24].

2.6 Quality Function Deployment

Quality function deployment (QFD) is a matrix which represents the relationship between customer requirements and design requirements. QFD serves as a good measure of the customer requirements and design requirements and the inter relationship between each of their elements. It is a giant way of looking at what you as a designer want and what the customer wants. It helps clarify which aspects are lacking in your design and if you improve those aspects what other design aspects are you disturbing as a result. In the case the design aspect gets disturbed, what will be their significance [27]. The customer importance rating is determined by surveys and interview sessions. The percentage of the customer importance rating (CIR) is calculated by dividing the individual customer importance rating of the customer requirement with the sum of all the customer importance ratings for the complete set of customer requirements.

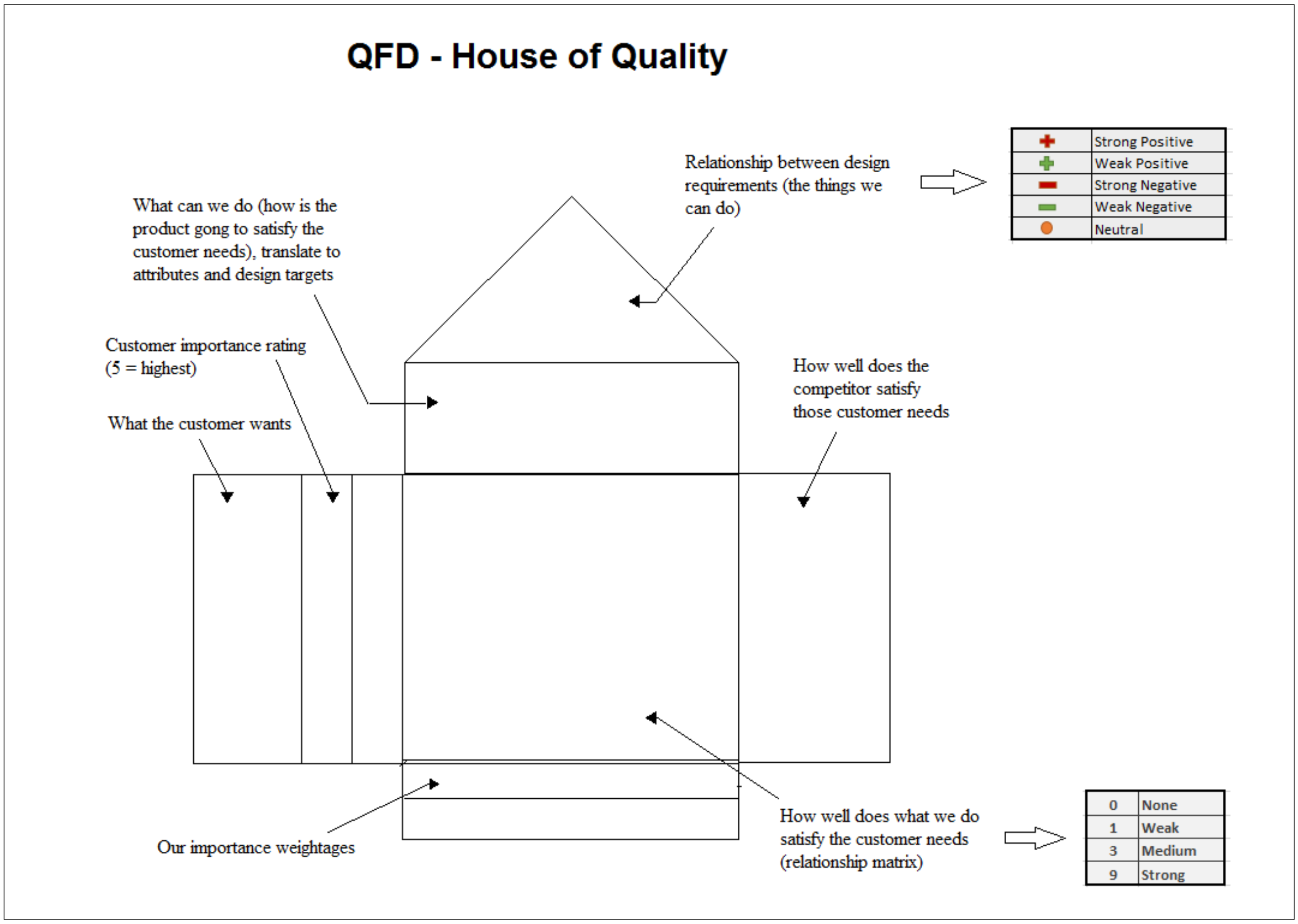


Figure 6. Description of House of Quality in Quality Function Deployment technique.

$$\%\text{ of CIR} = \frac{CIR}{\sum CIR} \text{ x } 100 \ldots (9)$$

The importance weightages (IW) are calculated by using the following formula:

$$\text{IW} = \sum_{i=1}^{n} CIRiXi \ldots (10)$$

$$\%\text{ of IW} = \frac{IW}{\sum IW} \text{ x } 100 \ldots (11)$$

N is the total number of customer requirements and X_i is the relationship between the customer requirements and the design requirements, with 0 meaning no relationship between them, 1 implies a weak relationship 3 signifies a medium relationship and 9 suggests a strong relationship. There are different scales which are used by different researchers, however, the 0, 1, 3, 9 scales perfectly elaborate the intervals between the preferences. The QFD should be upgraded as the project progresses.

2.7 Interview Platform - ASSESS

ASSESS an interactive interview platform was used to perform interview for the micro aerial vehicle. ASSESS has the option to perform analysis using three different techniques

1. Certainty equivalence method
2. Lottery equivalence method
3. Probability equivalence method

Probability in assessment lotteries is the probability of the most preferred outcome. After a number of choice iterations, the bracketing process will converge to a possible sense of indifference. The interviewee is required to enter the indifference point in the dialogue box. Entering an indifferent value completes the measurement of one point of the utility function. The interviewee may now choose to construct one more data point of the utility curve or stop the assessment interview by answering yes/no. the more points you assess, the better the definition of your utility will be. ASSESS will allow you to compare up to seven points for the utility function.

2.8 Regression Analysis

2.8.1 Methodology for Formulating a Relationship between a Dependent and an Independent Variable

Correlation tells you if a relationship exists between two variables. The strength of that relationship is depicted by the correlation coefficient which also provides the direction of relationship between the variables. However, to establish the relationship, a technique known as regression analysis is used.

In bivariate regression analysis, in which two variables are involved, the data of a dependent and an independent variable is represented by equation of a straight line. It estimates the relationship between two variables by estimating coefficients for an equation for a straight line. This can help in forecasting future trends from the previous trends.

However, in case there are more than one independent variables, bivariate regression analysis, which uses only a straight-line relationship cannot be used to accurately predict a relationship between the independent and dependent variables.

Previously, the information available for business decisions was discarded due to lack of storage spaces the because it was expensive to analyze that information and the benefits were not up to par with the cost associated with it. But since the advent of sophistical statistical analysis tools which are also cost effective, and new artificial intelligence techniques, including machine learning for example neural networking and genetic algorithms, the human learning approaches such as multiple regression, discriminant analysis and factor analysis have become easier.

In order to make accurate business decisions in today's increasingly complex environment, we must analyze intricate relationships with many intervening variables. Multivariate methods are powerful analytical techniques for addressing such issues.

Multi-variate analysis refers to a group of statistical procedures that simultaneously analyze multiple measurements on each individual or object being investigated. An individual's decision to buy a particular product is often based on different factors such as quality, variety and price. When corporations develop their database to better serve their customers, the database often includes a vast array of information, i.e. demographics, lifestyles, zip codes and purchasing behavior of each customer. [Marketing Analysis book]

2.8.2 Classification of Multivariate Methods

Multi-variate methods, that is, the equations which involve multiple variables, can be classified in the following methods:

1. ***Least square procedures:*** LSA is a regression approach that determines the best fitting line by minimizing the vertical distances of all the points from the line.

2. ***Unexplained variance:*** The amount of variance in the dependent variable that cannot be accounted for by the combination of independent variables.

3. ***Ordinary least squares:*** A statistical procedure that estimates regression equation coefficients that produce the lowest sum of squared differences between the actual and predicted values of dependent variable.

4. ***Regression coefficient:*** An indicator of the importance of an independent variable in predicting a dependent variable. Large coefficients are good predictors and small coefficients are weak predictors.

2.9 Pareto Frontier

The set of designs that give the best performance with respect to cost are the pareto efficient designs. For each Tradespace Pareto a set of designs are generated to obtain the optimal design choice for each stakeholder. Pareto frontier is the line on the Tradespace which gives non-dominated architectures. Pareto front is a set of non-dominated solutions, being chosen as optimal, if no objective can be improved without sacrificing at least one other objective. On the other hand, a solution x* is referred to as dominated by another solution x if, and only if, x is equally good or better than x* with respect to all objectives [28].

The purpose of finding pareto frontier is so that we can identify the architectures which are non-dominated. By non-dominated we mean that we are basically trying to solve a multi-objective problem in which we are trying to maximize one objective and minimize the other objective. The set of solutions which satisfy this multi-objective optimization problem are basically called pareto optimal solutions and lie on the pareto line.

All pareto optimal points are non-dominated. But not all non-dominated points are pareto optimal. It is easier to show dominated points than non-dominated points. Hence, we filter out dominated designs and concepts. We choose our end design according to our preferences, from amongst those designs which lie on the pareto frontier. [Olivier de Weck lecture]

1. The pareto optimality suggests that if everyone gets an equal share, resources have not been allocated optimally. You have to take from one group and give to the other.
2. Specify the objective function: S = f (Obj_1, Obj_2, ….)

Use expected value of objective function as a guide to identify best alternative according to the axioms of the utility theory by VNM. The objective is to choose alternative that maximizes utility.

Chapter 3

FRAMEWORK FORMULATION

3.1 Inspiration from Prior Studies

Several frameworks have been identified in literature for carrying out TE. However, during the course of the research it was discovered that a common framework cannot be applied to every case study. This thesis works as a framework to show how to develop a Tradespace by using two different methods. The strategies developed and suggested by previous researchers have been thoroughly studied carefully and taken as an inspiration to develop a framework which works well with the data available for the case study.

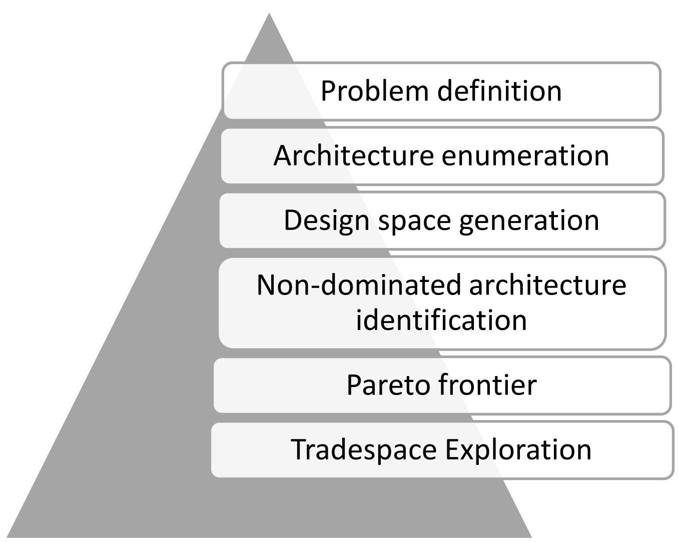


Figure 7. A general tradespace development strategy.

The attributes have some utility and the design variables have some cost associated with them. It allows the comparison of thousands of designs on a common, quantitative basis. Additionally, it maps the structure of stakeholder value onto the design space.

3.2 General Framework Development

During the course of the research, the author discovered that each case should be approached differently due to the diverse nature of the system and the data available. study begins with first defining the design problem. However, a similar general methodology was followed for the creation and exploration of tradespace. The methods presented by the previous researchers were used as an inspiration to formulate a framework which suits the needs of the researcher.

In the concept exploration phase of the System Engineering Life Cycle, there phases involved; mission definition, concept generation and design evaluation.

Figure 8. Tradespace process flow.

3.2.1 Phase 1 - Mission Definition

In this phase, the attributes are initially their associated utility curve and multiplicative weightage factors are elicited through formal utility interviews with decision makers. Single attribute utility curves are typically aggregated using a multiplicative utility function (that is dimensionless metric of user satisfaction ranging from zero, numerically acceptable to 1, highest of expectations).

The NGO Meethi Zindagi carried out Need Analysis and a mission statement was defined for the project. Next the stakeholders of the system were identified. Then a market survey is carried out in order to derive requirements for the system. These requirements are translated into a QFD by the System Analyst. The designer’s input is taken into consideration while developing the QFD.

Design Structure matrix was used to show the relationship between the components of the system and the significance of the relationship was displayed by the QFD in which the customer requirements were plotted against the design requirements. This enables system breakdown which identifies the components of the system.

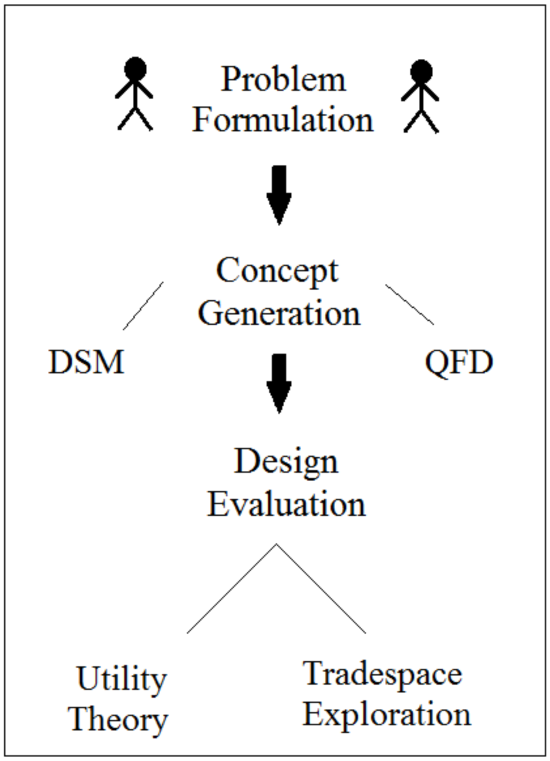


Figure 9. Tradespace exploration in complex systems (TECS) process.

3.2.2 Phase 2 - Concept Generation

In this phase, attributes are inspected and various design variables are proposed that drive performance in attributes. The variants of each component available are identified and are enumerated using a morphological box. The elicited requirements are used to create a design structure matrix which shows the relationship and interdependence of components. In order to limit the number of components taken in a tradespace a QFD is constructed. QFD tells the strength of relationship between a customer requirement and the corresponding design requirement which is needed to meet that customer requirement. The designer's input is taken to elaborate the House of Quality. Significant components are identified by this method and the rest are discarded from the design set. A set of important attributes is determined after a discussion with the stakeholders of the system. A stakeholder interview method is set up to determine the utilities of each component. Then data gathering is carried out to determine the value and constraints of the attributes.

3.2.3 Phase 3 - Concept Evaluation

This phase is used to develop models to evaluate attributes against utility for the design under consideration. To assess the sampling of the design space, parametric computer models can be used to transform each design vector into attribute values against which utility functions can be applied. A utility determination methodology is decided for each case study. This is generally an interview or a survey to gauge stakeholder preferences. Some researchers have used discrete values for determining utilities while others have developed utility functions.

A code is written in MATLAB to enumerate the architectures using the "combvec" tool. There architectures are further plotted against the attributes to judge the relationship and trend between the utility and the attribute for all architectures. Additionally, the relationship between the attributes is also graphically represented. The non-dominated points are taken to be the points which provide the highest utility in their attribute interval. Regression analysis employed to find the pareto frontier. A separate subset of the non-dominated architectures is created. A second-degree polynomial equation is made to pass through these non-dominated points on their utility vs. attribute graph. The points which lie on the Pareto frontier represent the most viable design solutions.

3.3 Framework for Case Study 1

Data for the Micro Aerial vehicle was gathered using the data provided by Jay Gundlach [5]. The requirements for the Micro Aerial Vehicle were additionally gathered from prior reports [29]. These requirements were used to formulate the DSM and the DSM helped to identified the requirements which were interlinked. Afterward, a QFD is created which links what the customers want out of the system with what the design requires. This is used to identify the important attributes to analyze.

Following these, the interactive interview platform ASSESS is used to determine the utility functions for the defined attributes. The reason for choosing utility functions instead of discrete utility values to expand the range of values which can be analyzed and also to use one other method used in literature to find utilities.

3.4 Framework for Case Study 2

Data for Insulin Pump was acquired by rigorous interview sessions with the designer, company owner and end-user designed survey to gauge customer preference of certain features of the product. A QFD was formulated which stated the customer requirements against the design requirements. System breakdown reveled the important components which were to be included in the design space. A discussion was carried out with the designer to eliminate the infeasible combinations. This way the design space was reduced before proceeding with the evaluation process. The critical components were determined in the meeting with the designers.

The attributes were decided by the primary decision maker. A morphological box was constructed to further enumerate the variants of each component. Since now the utility is for the component variants and not for the attributes a survey is designed to gauge the customer preference for each variant. This preference is translated into utility value. A Likert scale of 1-5 was used for the survey. An average of the customer responses is taken. The averages are further unit normalized to translate them into utility values between 0 and 1.

Similarly, discrete attribute value data is gathered unlike in the previous case study where the utility function is plotted by taking continuous attribute values. This is because in this case study, the design space is component based. The objective space is based on attributes. The utility values are plotted against the attribute values to formulate a tradespace. The non-dominated architectures are picked from the tradespace and a Pareto frontier was plotted using a second-degree polynomial equation through regression analysis.

Chapter 4

RESULTS AND DISCUSSION

4.1 Case Study 2: Insulin Pump

4.1.1 Introduction

Type 1 diabetes is caused by the malfunctioning or loss of cells called pancreatic beta cells which produce Insulin. Damage to beta cells brings about an absence or deficiency of insulin produced by the human body. Traditionally, diabetics used injections to get their required insulin dose. However, using injections is a tedious and inefficient process. The Insulin Pump acts as a substitute to pancreas and the reservoir provides insulin to the body, hence, subverting the need for injections; basal insulin which is given in small doses throughout the day and bolus insulin which is provided before and after meals [30].

Insulin Pump has three main components: firstly, a pump which contains the insulin reservoir, the batteries, a display screen and the controller; secondly, an infusion set which consists of a cannula, tubing that connects the pump and the cannula and a stick on; and thirdly, a continuous glucose monitor.

Insulin Pumps without tubing generally come with a hand-held device with can display the glucose levels and plot graphs. The major disadvantage of tubing is that it wastes insulin and insulin is expensive. Around 15 units of insulin is wasted when the reservoir is refilled and air bubbles have to be removed from the tubing before it can be attached again. Another disadvantage reported by users of tubing is that it gets stuck in clothes and there is a danger of tethering.

Insulin pump delivers insulin every few minutes in tiny amounts, 24 hours a day. It is usually the size of a deck of cards. Insulin flows through a cannula which sits in the subcutaneous tissue. The user changes the pump infusion set or cannula every few days. Insulin is of two types; basal and bolus. Basal insulin is background insulin which is programmed to meet the pump user's needs. Bolus insulin is delivered either with the touch of a button to be automatically injected after food consumption to bring down high blood glucose levels.

For people with type 1 diabetes, keeping blood glucose levels in the normal range is the best way to prevent or delay complications of type 1 diabetes which include coma and shock. However, tight control can increase the risk of hypoglycemia, whereas lose control can cause hyperglycemia, both of which are dangerous conditions [31].

The disadvantage of injections is that once long-acting insulin is injected, it cannot be turned off or slowed down, neither can it be tailored to the time varying needs of the user throughout the day. However, basal insulin delivered by a pump can be slowed down, stopped, increased for a few minutes or hours. Tiny doses of insulin are more easily absorbed then larger amounts from an injection. This way blood glucose levels are more stable and predictable. Also, Insulin pumps reduce the need for multiple daily injections and give users the ability to make smaller, more accurate adjustments to insulin delivery. They do not measure blood glucose levels but some pumps can read signal from separate glucose sensor.

The type of pump varies according to weight, unit of adjustment, tubing, battery life, life time, cost, ease of use and the simplicity of interface. The pump can we worn in a pocket or clipped to a belt. The major advantages of an Insulin Pump are the increased control the user gets over his diabetes, the flexibility to skip meal or eat late and the ability to manage dawn phenomenon. Moreover, needles need to be changed every 2 to 3 days which provides enhanced flexibility. This is especially useful for children and athletes.

4.1.2 Motivation for Selection

Relatively, a large percentage of world population is affected by diabetes mellitus. Approximately 5-10% of the persons with diabetes have type-1. Insulin administration is essential for type-1 person while it is required at advanced stages by the person of type-2 diabetes.

Current insulin delivery systems are available as transdermal injections which may be considered as invasive. Any new insulin delivery system requires health authorities' approval, to provide long term safety profile and ensuring person acceptance. Several non-invasive approaches for insulin delivery are being pursued by pharmaceutical companies to reduce: the pain associated with injection pricking; and hypoglycemic incidences associated with injections in order to improve person compliance.

This research idea was initiated by Meethi Zindagi (Sweet Life) an NPO working on providing cost effective solutions to people with type 1 diabetes in Pakistan. They are working on designing an automated Insulin Pump. This research focuses on improving the design on the basis of utility and cost effectiveness. The other two factors taken additionally into consideration are mass and user friendliness, in order to reduce the weight of the pump and enhance user satisfaction.

4.1.3 Competitor's Summary

The famous suppliers of Insulin Pump are Medtronic, OmniPod, Animas, Advanced Therapeutics, CellNovo and Roche. Most existing pump designs do not ensure discreteness of operation. For example, the pumps with tubing have a user interface on the pump. The pump is attached to the body with a 20"-60" long tube, and usually placed in pocket or hung with belts. When a user has to give an insulin bolus to himself before meals, he / she has to take the pump device out of pocket or detach it from the belt and program the bolus amount on the device's screen. This is not only inconvenient; it also attracts attention from onlookers. Many pump users find this attention very

. The pump under development's body mounted part, apart from being tubeless and lightweight, will not require onboard user interface. Instead, the user interface will be provided on a handheld, wireless device which will provide a communication link to control the pumping action of the body mounted part. The interface on the handheld device will be user friendly for easier operation, just like a simple mobile phone application.

This is similar to an existing pump design (OmniPod). However, OmniPod is designed as a disposable pump. After every 3 days, the pump has to be disposed of, and a new one is used in its place, increasing the costs manifold. The aim is to expand the life of the pump, crease a reusable device, using some engineering design modifications.

The pump will have a CGM sensor augmentation option for users wishing to use Continuous Glucose Monitoring Sensors for micromanagement of blood glucose levels. Lublin will be compatible with existing CGM sensors. CGM sensors require a lot of research work and additional budget, because of lack of open research on the topic and monopoly.

The only company marketing pumps in Pakistan is doing it using a Business-to-Consumer model. Since only a very small percentage of Pakistani consumer market can afford the high cost pump, The pump once fully developed and produced in large scale, will not only be significantly lower in cost and easier to use, it will use both Business-to-Business and Business-to-Consumer business models for approaching a larger market. This will greatly enhance the accessibility of people with diabetes treated with insulin to this new technology that can improve their blood sugar level control, as well as introduced flexibility in their diet and lifestyles.

4.1.4 System Analysis

Problem Statement: In type 1 diabetics, the body does not produce insulin. Human body requires insulin to break down glucose and release energy. Traditionally insulin injections were used; however they are cumbersome and require repeated application. Currently, insulin pumps are in use. However, they are too expensive for most people to purchase. Also, they have some issues, e.g. the tubing is irksome, insulin which is expensive, is wasted while refilling.

Purpose: Design and develop a low cost, longer life time product for a not for profit organization, aiming to provide insulin pumps to diabetics. A product which has low cost, weighs less and is user friendly.

4.1.5 Concept of Operation

Operational Concept is a vision for what the system is. It is a statement of mission requirements and a description of how that system will be used. It is a set of scenarios describing how the system will be used.

4.1.5.1 Operational Concept for Insulin Pump:

Following is the operational concept for Insulin Pump:

- Using readings from an embedded sensor, the system automatically measures the level of glucose in the sufferer's body
- Consecutive readings are compared and, if they indicate that the level of glucose is high then insulin is injected to counteract this rise
- The ideal situation is a consistent level of sugar that is within some 'safe' band.

Table 6. Operational concept for Insulin Pump.

Sugar Level	
Unsafe	A very low level of sugar (arbitrarily, we will call this 3 units) is dangerous and can result in hypoglycemia which can result in a diabetic coma and ultimately death.
Safe	Between 3 units and about 7 units, the levels of sugar are 'safe' and are comparable to those in people without diabetes. This is the ideal band.
Undesirable	Above 7 units of sugar is undesirable but high levels are not dangerous in the short-term. Continuous high-levels however can result in long-term side-effects.
Injection Scenarios	
Level of sugar is in the unsafe band	○ Do not inject insulin; ○ Initiate warning for the sufferer.
Level of sugar is	○ Do not inject insulin if in safe band. Inject insulin

falling	if rate of change of level is decreasing.
Level of sugar is stable	○ Do not inject insulin if level is in the safe band; ○ Inject insulin if level is in the undesirable band to bring down glucose level; ○ Amount injected should be proportionate to the degree of undesirability i.e. inject more if level is 20 rather than 10.
Level of sugar is increasing	○ Reading in unsafe band ▪ No injection. ○ Reading in safe band ▪ Inject only if the rate of increase is constant or increasing. If constant, inject standard amount; if increasing, compute amount based on increase. ○ Reading in unsafe band ▪ Inject constant amount if rate of increase is constant or decreasing. ▪ Inject computed amount if rate of increase is increasing.

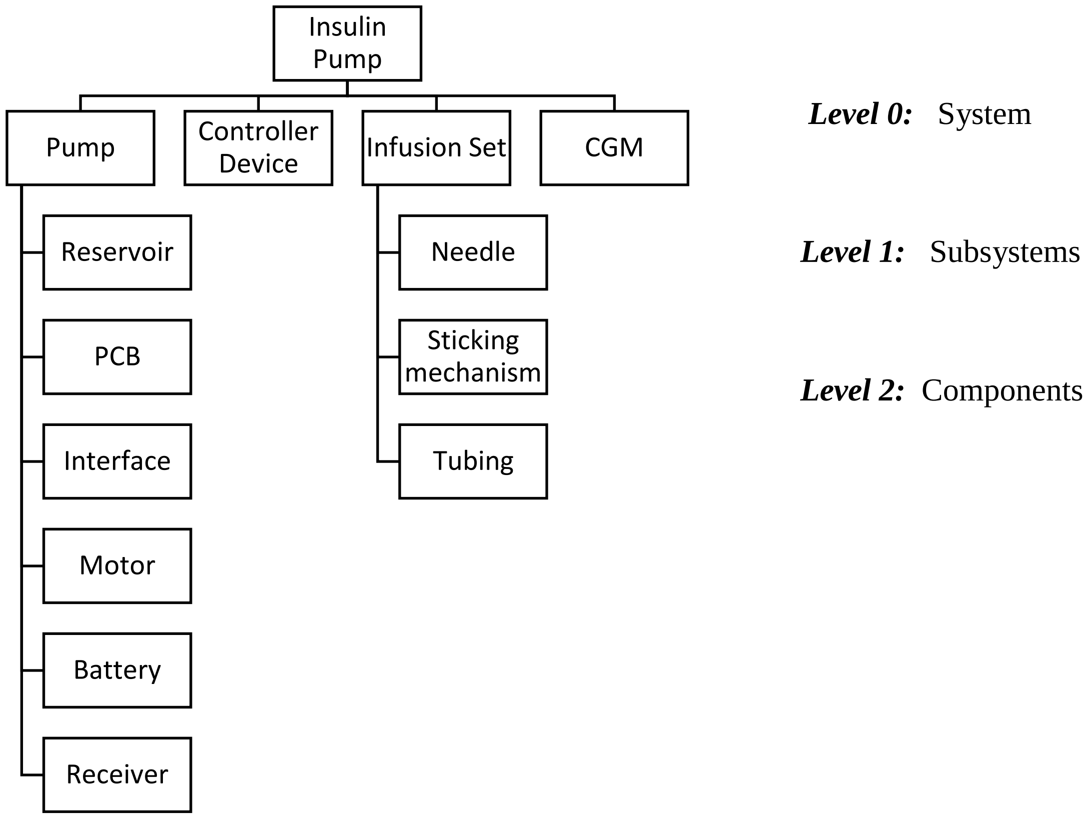


Figure 10. Insulin Pump system breakdown.

The need is to communicate the impact of a decision across a system's life cycle. Concept of operations is the major outputs for capturing stakeholder expectations. It is the important component in capturing expectations, forming requirements and developing architecture of a project/system. Thinking though ConOps and use cases often reveals requirements and functions that might otherwise be overlooked.

Insulin pump can be decomposed into the pump, the infusion set and the Controller. The pump consists of the insulin reservoir, the pumping mechanism, battery, computer chip and screen. The infusion set consists of the connector which allows insulin to flow from pump to skin, and is placed under the side of infusion set, a short fine cannula that passes through the skin and rests in the subcutaneous fatty tissue. The tubing brings the insulin from the pump (insulin reservoir) to the infusion set.

Table 7. Stakeholders for Insulin Pump.

System Stakeholders	
1.	Designers
2.	NGO owners
3.	DRAP
4.	Distributers
5.	Manufacturers
6.	System Engineers
7.	Users a. Direct operators: patients b. Indirect operators: parents etc
7.	Health practitioners a. Maintainers b. Trainers

The advantage of insulin pump is decreased risk of severe hypoglycemia, safety and effectiveness. In the existing designs there were a number of problems related to mechanical parts, e.g. air bubbles can form kinked infusion set, dislodged tubing. This can cause lack of expected Insulin delivery. The project objective was to reduce cost and to reduce the risk of complications.

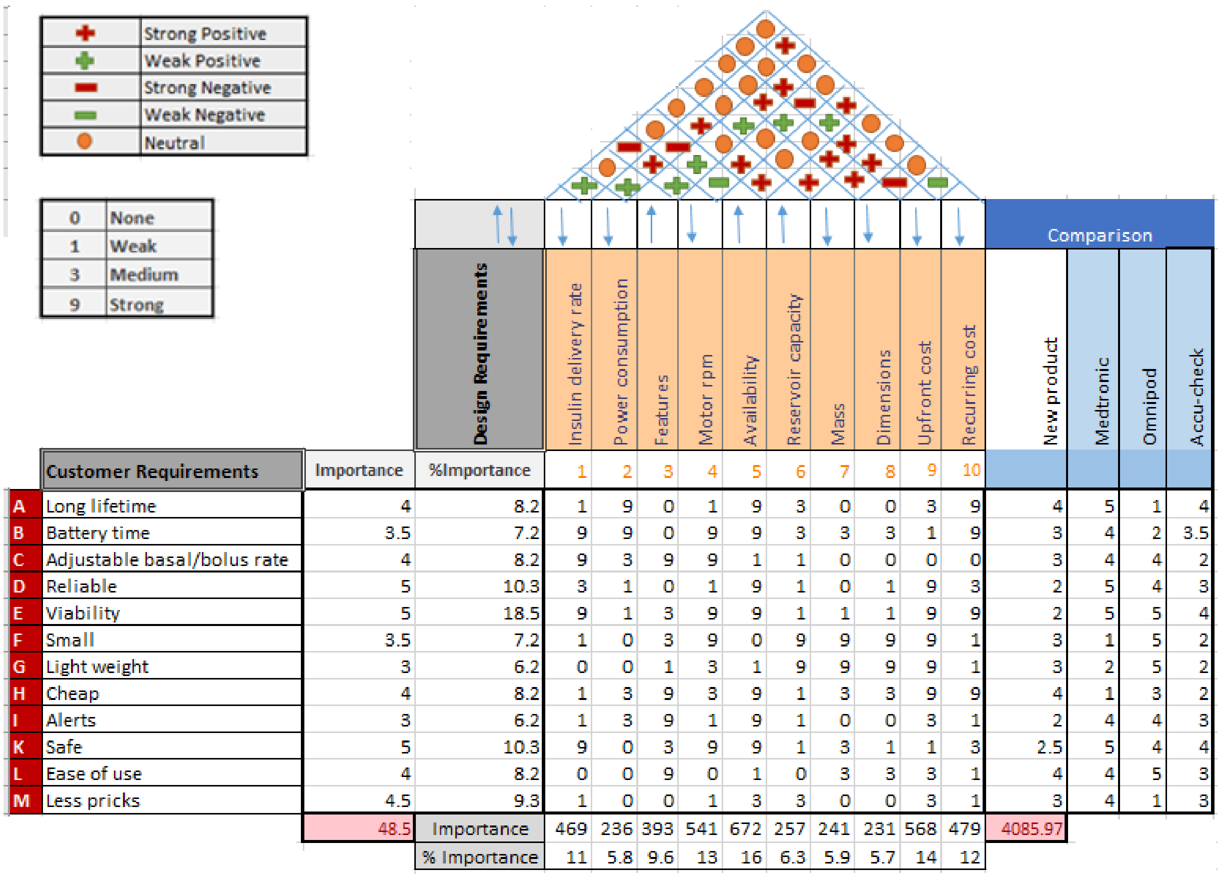
The components were identified after carrying out a market survey and narrowing down the important requirements after a meeting with the company owner and the designers. An initial meeting was set up with the designers who identified the design variables which affected the identified attributes. These were narrowed down to the essential components which derive customer utility. A survey questionnaire was formed based on the identified components, which was distributed amongst Type 1 diabetic patients. Hence, the customer utility for the design options was calculated from the survey questionnaire.

Table 8. Stakeholder division and analysis.

Relation to organization	Stakeholders	Typical expectation
External	User FDA Health Practitioners	Cost, weight, user friendliness, reliability, meet regulations and medical standards, on time service.
Internal	SE Designers NGO	Development and production cost, resources, components availability, design complexity.

DSM		A Insulin reservoir	B Reservoir capacity	C Battery	D Adhesive material	E Basal/bolus rates	F Motor	G Tubing	H Controller	I Display	J Dose precision	K Control system	L Insulin delivery rate	N Infusion set
A	Insulin housing	A												
B	Reservoir capacity	X	B											
C	Battery	X	X	C										
D	Adhesive material		X	X	D									
E	Basal/bolus rates	X		X		E								
F	Motor	X	X	X	X	X	F							
G	Tubing				X	X		G						
H	Controller			X		X			H					
I	Display				X				X	I				
J	Dose precision	X	X	X		X	X	X		X	J			
K	Control system	X	X	X		X	X		X	X	X	K		
L	Insulin delivery rate	X	X	X	X	X	X	X	X	X	X	X	L	
N	Infusion set				X	X		X		X	X	X	X	N

Figure 11. DSM for Insulin Pump.



	Customer Requirements	Importance	%Importance	Insulin delivery rate (1) ↓	Power consumption (2) ↓	Features (3) ↑	Motor rpm (4) ↓	Availability (5) ↑	Reservoir capacity (6) ↑	Mass (7) ↓	Dimensions (8) ↓	Upfront cost (9) ↓	Recurring cost (10) ↓	New product	Medtronic	Omnipod	Accu-check
A	Long lifetime	4	8.2	1	9	0	1	9	3	0	0	3	9	4	5	1	4
B	Battery time	3.5	7.2	9	9	0	9	9	3	3	3	1	9	3	4	2	3.5
C	Adjustable basal/bolus rate	4	8.2	9	3	9	9	1	1	0	0	0	0	3	4	4	2
D	Reliable	5	10.3	3	1	0	1	9	1	0	1	9	3	2	5	4	3
E	Viability	5	18.5	9	1	3	9	9	1	1	1	9	9	2	5	5	4
F	Small	3.5	7.2	1	0	3	9	0	9	9	9	9	1	3	1	5	2
G	Light weight	3	6.2	0	0	1	3	1	9	9	9	9	1	3	2	5	2
H	Cheap	4	8.2	1	3	9	3	9	1	3	3	9	9	4	1	3	2
I	Alerts	3	6.2	1	3	9	1	9	1	0	0	3	1	2	4	4	3
K	Safe	5	10.3	9	0	3	9	9	1	3	1	1	3	2.5	5	4	4
L	Ease of use	4	8.2	0	0	9	0	1	0	3	3	3	1	4	4	5	3
M	Less pricks	4.5	9.3	1	0	0	1	3	3	0	0	3	1	3	4	1	3
		48.5	Importance	469	236	393	541	672	257	241	231	568	479	4085.97			
			% Importance	11	5.8	9.6	13	16	6.3	5.9	5.7	14	12				

Figure 12. QFD for Insulin Pump.

4.2.6 Morphological box for Insulin Pump

Morphological box represents the different options which are available for the components of the system. Table 9 enumerates the options available for the components which influence customer's utility. Table 10 enlists the components on which the designer's utility depends and the design options which are available for them.

The total number of architectures based on the design options for components on which the customer's utility depends are 36. The component variants for the designers are not taken under consideration in this study. The options are selected based on an interview with the designers and the primary stakeholder, i.e. the company owner.

4.2.6.1 Stakeholder 1: Customer

Table 9. Morphological box for Insulin Pump (customer).

Subsystems	Variants			
Battery	Rechargeable	Disposable		
Tubing	Tubing	No tubing		
Controller	Mobile phone and smart watch	Hand held device	On pump	
Insulin dosage calculation features	Manual	Semi-automatic	automatic	

Total architectures = 2 x 2 x 3 x 3 = 36

4.2.6.2 Stakeholder 2: Designers

Table 10. Morphological box for Insulin Pump (designer).

Subsystems	Variants			
Reservoir capacity	150mL	180mL	300mL	
Communication link	Bluetooth	Energy	Radio	ZigBee
Motion mechanism	Stepper Motor	DC motor/actuator	Controlled suction pump	
Dose precision	Encoder based	With secondary mechanism		

4.2.7 Data Collection for Insulin Pump

The data for the Insulin Pump was gathered by expensive interview with the product owner. In case of no tubing, the cost is due to complex engineering design, does not include cost of other design variables. The recurring cost is that of cannula and tubing. 220 g is the baseline mass of the pump with tubed architecture, whereas, 100g is the baseline mass of the pump with tubeless architecture. The cost is recurring per annum for a period of four years.

Table 11. Component wise data for Insulin Pump.

Subsystem	Variables	*Obj 1*	*Obj 2*		*Obj 3*	*Obj 4*
			Cost (pkr)			
		Utility	**Upfront**	**Recurring**	**Mass (g)**	**UF**
1. Battery	1.1 Rechargeable battery	0.9	2300	650	12	8
	1.2 Disposable battery	0.4	0	5214	12	6
2. Tubing	2.1 Tubing	0.3	50000	6000	240	5.5
	2.2 No tubing	0.7	100000	5000	115	8.5
3. Controller	3.1 Mobile phone and smart watch	0.8	2500	0	0	8
	3.2 Hand held device	0.6	5000	0	0	6
	3.3 On pump	0.5	1000	0	50	4
4. Insulin dosage calculation features	4.1 Manual	0.6	0	0	0	4
	4.2 Semi-automatic	0.7	5000	0	0	8
	4.3 Automatic	0.8	15000	0	0	9

4.2.8 Utility Calculation for Insulin Pump

The utilities for the attributes defined for the Insulin Pump were calculated using the following steps:

- Interview designers and determine constraint.
- From the design envelope which excludes infeasible options, formulate a questionnaire to find out user preferences for a list of components and features.
- Formulate a vector component consisting of mass, cost, reliability and user-friendliness.
- Formulate design vectors and architectures.
- Plot those architectures on utility versus cost plot.

4.2.8.1 Interview Questionnaire

A survey was designed in order to determine the utilities for the selected design components of an Insulin Pump. The survey was distributed in Type 1 diabetics, a minority of whom were Insulin Pump users and majority were not. A video was made to elucidate the potential users about each design component.

A Likert type scale of 1-5 was used to gauge the customer response for four components. 83 diabetes patients were asked to fill a survey form. The data was collected from 32 females and 51 males. Two components had two variants and the other two components had three variants. The potential Insulin pump users were asked to state their preference for each by choosing a value on the Likert scale. The patients belonged to Islamabad, Karachi, Lahore, Peshawar, Rawalpindi, Multan, Hyderabad, Wah Cantt, Sioux Falls, Attock, Gujranwala, Khairpur Mir's, Rahim Yar Khan, Sadiq Abad and Jhelum. Only 14% of the survey respondents had used an Insulin Pump, and out of the total respondent's only 9.6% were satisfied with their Pump.

The survey respondents were asked to fill an online survey form. Prior to filling the form, a video was uploaded which informed the respondent about the particulars of an Insulim Punp. This ensured that all respondents were on the same knowledge level when filing the survey form.

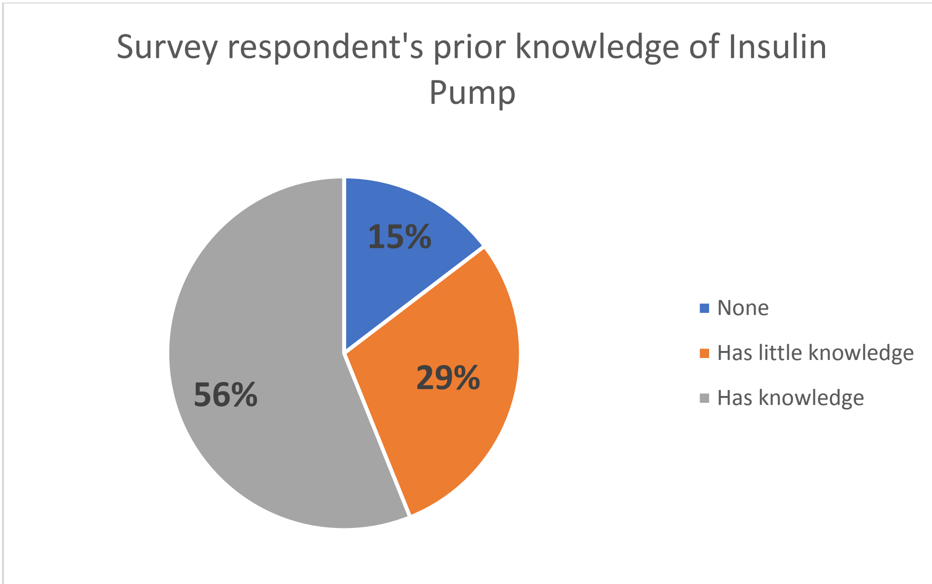


Figure 13. Pie chart for the survey respondent's prior knowledge of Insulin Pump.

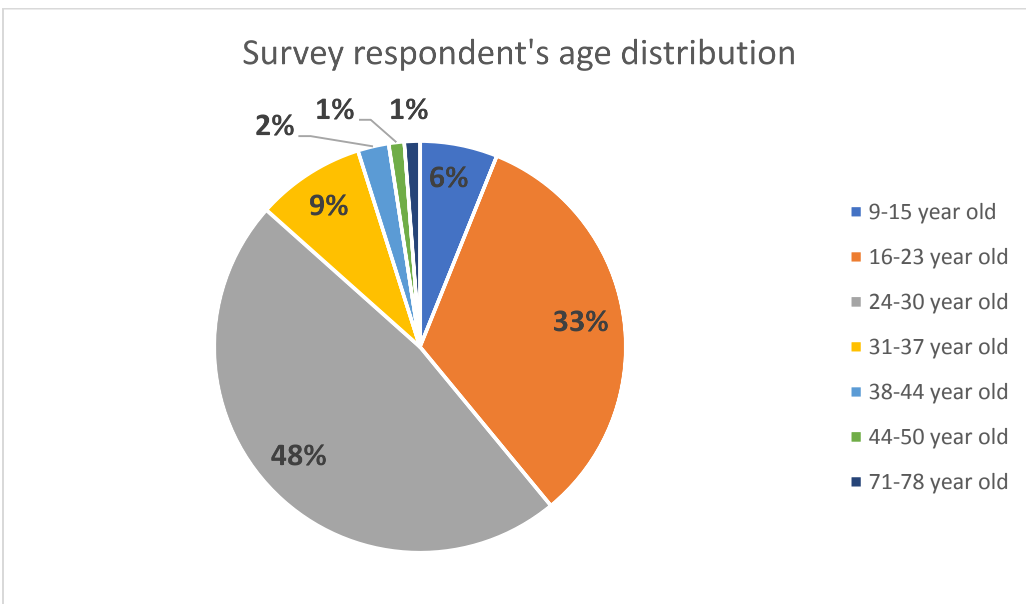


Figure 14. Pie chart for the survey respondent's age distribution.

Table 12. Insulin Pump survey respondent's information.

Gender Division	
Male	**Female**
51	32
Demographical Information	
Abbottabad	1
Attock	1
Gujranwala	2
Islamabad	11
Lahore	12
Karachi	18
Wah Cantt	2
Rahim Yar Khan	3
Sadiq Abad	1
Jhelum	2
Peshawar	6
Khairpur Mir’s	2
Multan	5
Rawalpindi	10
Quetta	1
Suiox Falls	2
Hyderabad	2

4.2.8.2 Customer Survey Results

The respondents rated their preferences on a Likert scale of 1-5. An average of these responses for each component was taken and represented in Table 18. The standard deviation and the variance are also presented which show how much the responses varied from the mean response.

Table 13. Results for the customer-oriented survey for Insulin Pump components.

Insulin Pump Survey Results				
		Mean	**Sd**	**Variance**
1	**1.1**	4.23	1.18	1.39
	1.2	2.32	1.34	1.78
2	**2.1**	2.16	1.33	1.76
	2.2	3.86	1.35	1.81
3	**3.1**	4.02	1.21	1.47
	3.2	2.97	1.45	2.10
	3.3	2.75	1.35	1.81
4	**4.1**	2.91	1.43	2.05
	4.2	3.63	1.34	1.80
	4.3	4.21	1.09	1.18

4.2.9 Design Space Generation for Insulin Pump

4.2.9.1 Objectives Breakdown

The system analysts initially determined the objectives of the system which are presented in table 19. The upper and the lower limits of the utility of the system were set to be between 0 and 1. Scaling the utility values between these limits allows the data to be evaluated with ease.

Table 14. Insulin pump problem definition.

Model Inputs		
Variables	Lower Bound	Upper Bound
A	0	1
B	0	1
C	0	1
D	0	1
E	0	1
Model Outputs		
Obj 1	Cost	Smaller is better
Obj 2	Mass	Smaller is better
Obj 3	Reliability	Larger is better
Obj 4	User Friendliness	Larger is better
Obj 5	Size	Smaller is better

a. Objective 1: Obj_1 = Minimize the development cost
b. Objective 2: Obj_2 = Maximize user utility
c. Objective 3: Obj_3 = Minimize the mass of the pump
d. Objective 4: Obj_4 = Maximize the user friendliness
e. Objective 5: Obj_5 = Maximize the reliability

Objective Space = {Obj_1, Obj_2, Obj_3, Obj_4, Obj_5}

This objective space is further reduced after consultation with the designers and the objectives which are further analyzed are cost, mass and user friendliness.

Reduced objective space = {Obj_1, Obj_2, Obj_4}

4.2.9.2 Cost vs. Utility plot for Insulin Pump

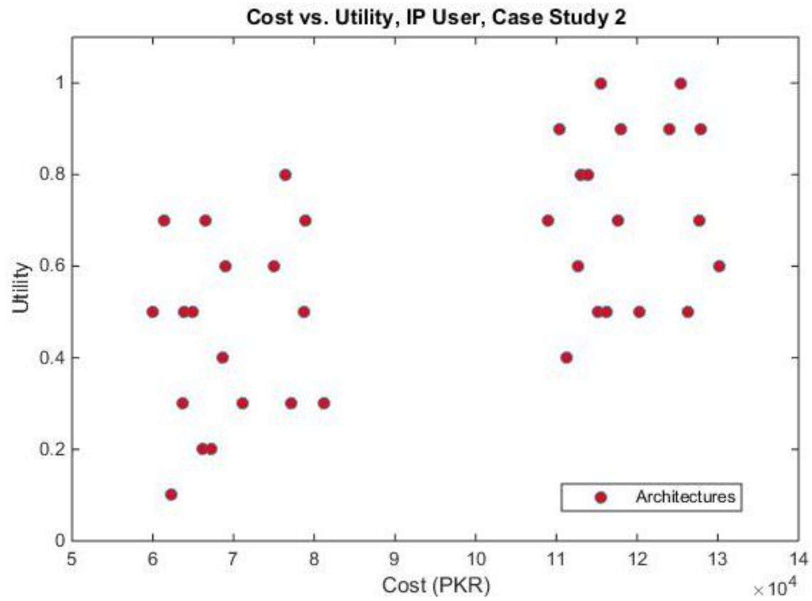


Figure 15. Cost vs. utility plot for potential Insulin Pump user.

4.2.9.3 Mass vs. Utility plot for Insulin Pump

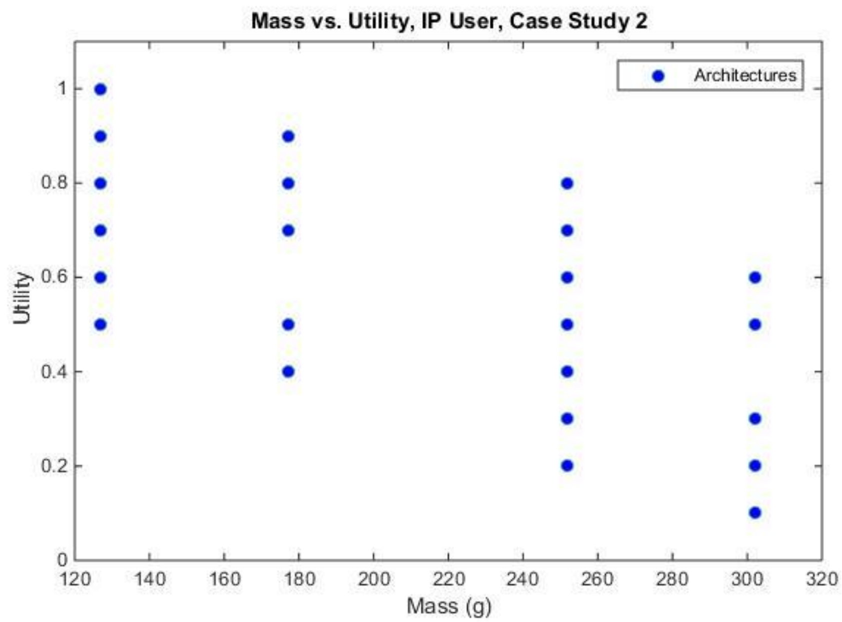


Figure 16. Mass vs. utility plot for potential Insulin Pump user.

4.2.9.4 User Friendliness vs. Utility plot for Insulin Pump

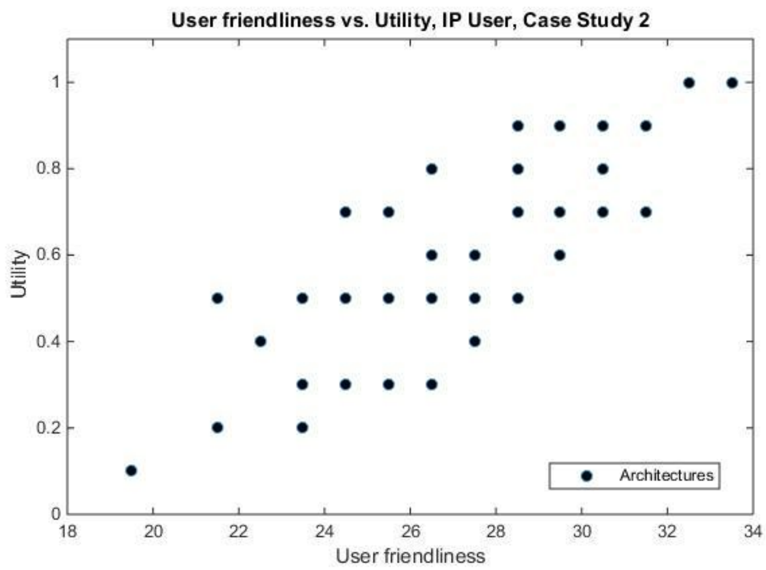


Figure 17. User friendliness vs. utility plot for potential Insulin Pump user.

4.2.9.5 Cost vs. Mass plot for Insulin Pump

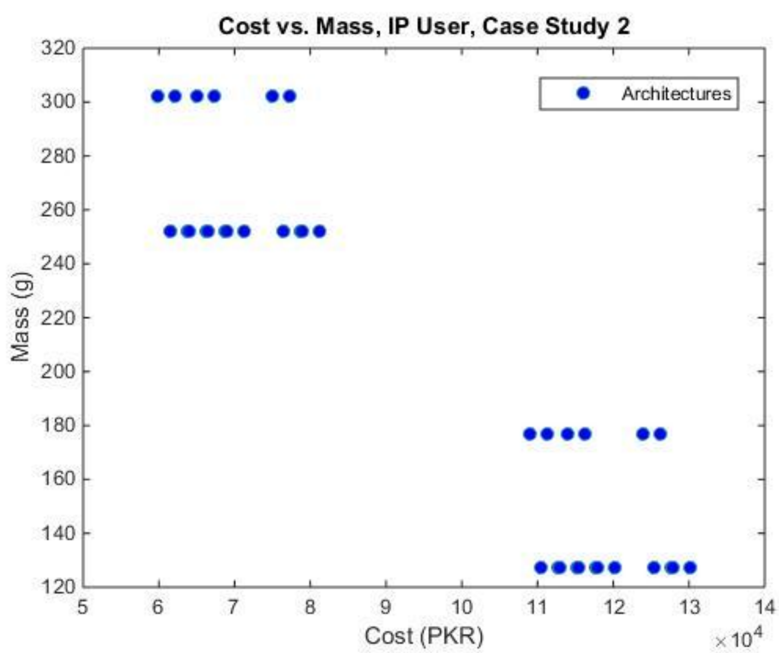


Figure 18. Cost vs. mass plot for potential Insulin Pump user.

4.2.9.6 Cost vs. User friendliness plot for Insulin Pump

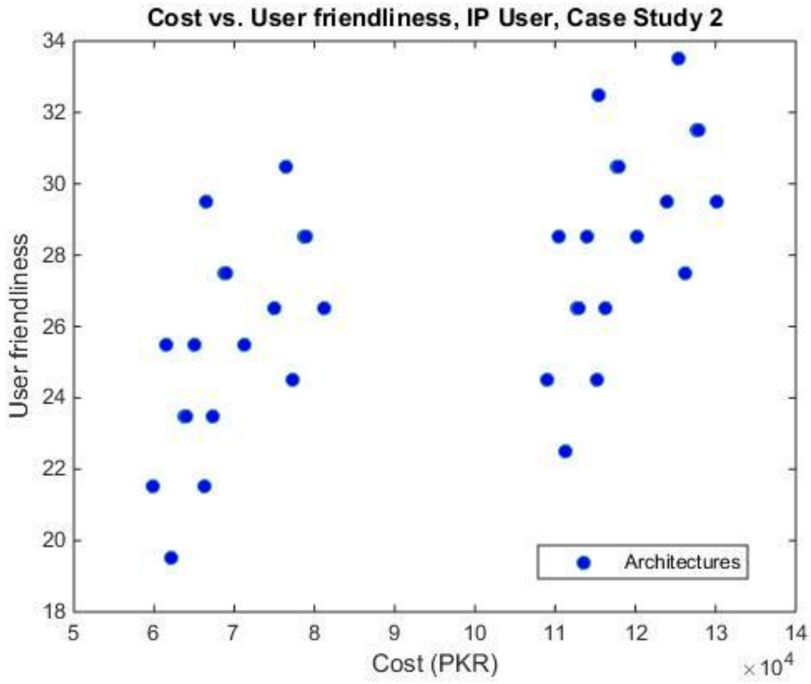


Figure 19. Cost vs. user friendliness plot for potential Insulin Pump user.

4.2.9.7 Mass vs. User friendliness plot for Insulin Pump

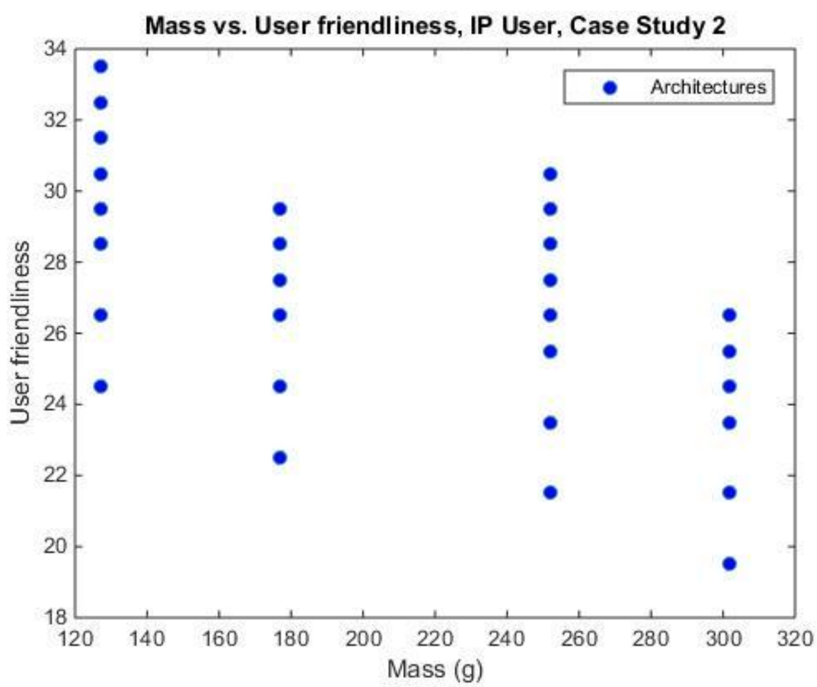


Figure 20. Mass vs. user friendliness plot for potential Insulin Pump user.

4.2.10 Tradespace Exploration for Insulin Pump

4.2.10.1 Tradespace Exploration for Cost vs. Utility

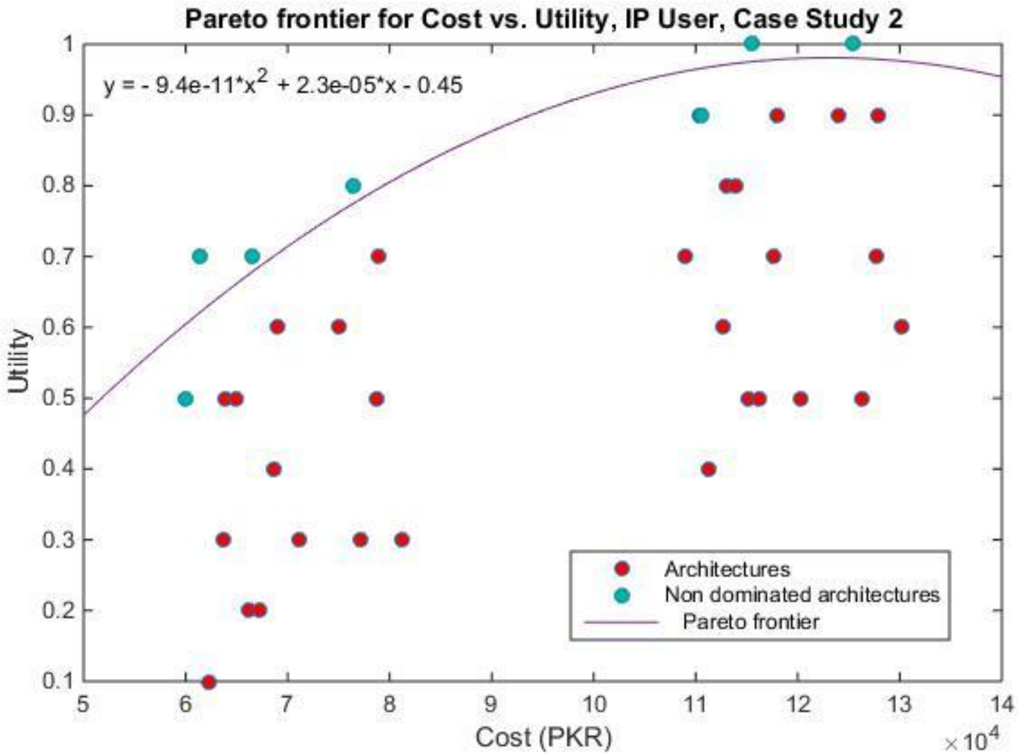


Figure 21. Cost vs. utility tradespace.

Table 15. Non-dominated architectures in terms of cost.

No.	Arch. No	Architecture	Cost (PKR)	Utility
1	9	{Rechargeable, tubing, on pump, manual}	59950	0.5
2	1	{Rechargeable, tubing, mobile and smart watch, manual}	61450	0.7
3	13	{Rechargeable, tubing, mobile and smart watch, semi-automatic}	66450	0.7
4	25	{Rechargeable, tubing, mobile and smart watch,	76450	0.8

		automatic}		
5	3	{Rechargeable, no tubing, mobile and smart watch, manual}	110450	0.9
6	15	{Rechargeable, no tubing, mobile and smart watch, semi-automatic}	115450	1
7	27	{Rechargeable, no tubing, mobile and smart watch, automatic}	125450	1

4.2.10.2 Tradespace Exploration for Mass vs. Utility

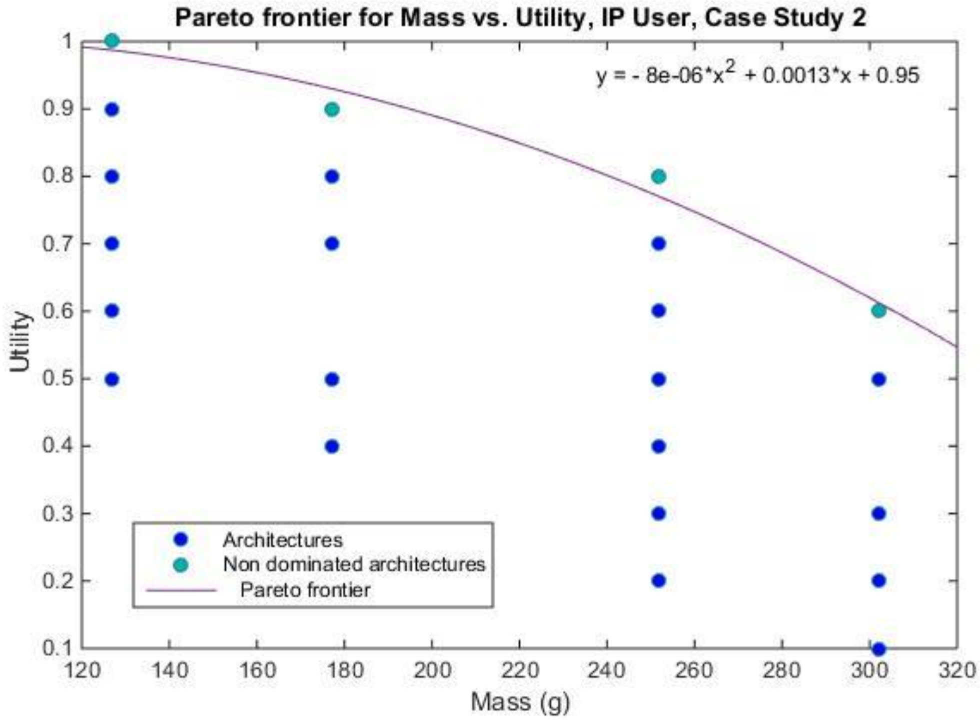


Figure 22. Mass vs. utility tradespace.

Table 16. Non-dominated architectures in terms of mass.

Sr. No.	Arch. No.	Architecture	Mass (g)	Utility
1.	15	{Rechargeable, no tubing, mobile and smart watch, semi-automatic}	127	1
2.	27	{Rechargeable, no tubing, mobile and smart watch, automatic}	127	1
3.	35	{Rechargeable, no tubing, on pump, automatic}	177	0.9
4.	25	{Rechargeable, tubing, mobile and smart watch, automatic}	252	0.8
5.	33	{Rechargeable, tubing, on pump, automatic}	302	0.6

4.2.10.3 Tradespace Exploration for User friendliness vs. Utility

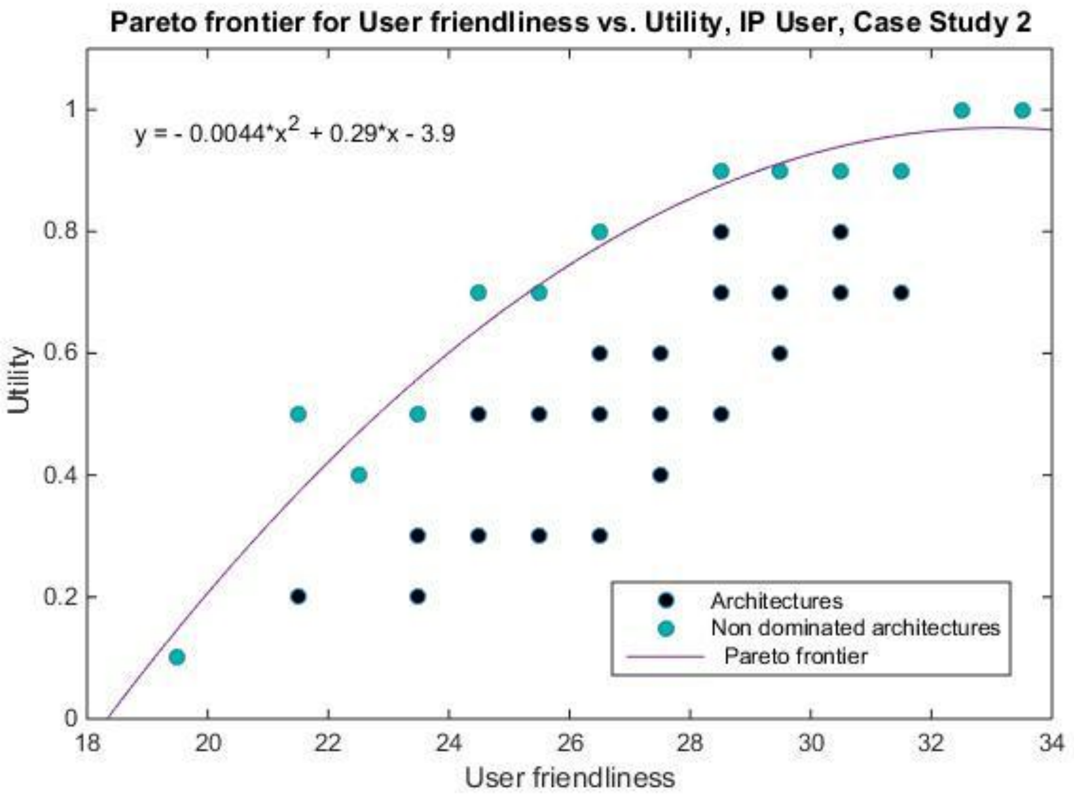


Figure 23. User friendliness vs. utility tradespace.

Table 17. Non-dominated architectures in terms of user friendliness.

Sr. No.	Arch. No.	Architecture	User friendliness	Utility
1.	9	{Rechargeable, tubing, on pump, manual}	21.5	0.5
2.	12	{Disposable, no tubing, on pump, manual}	22.5	0.4
3.	5	{Rechargeable, tubing, hand-held device, manual}	23.5	0.5
4.	11	{Rechargeable, no tubing, on pump, manual}	24.5	0.7
5.	1	{Rechargeable, tubing, mobile and smart watch,	25.5	0.7

		manual}		
6.	7	{Rechargeable, no tubing, hand-held device, manual}	26.5	0.8
7.	3	{Rechargeable, no tubing, mobile and smart watch, manual}	28.5	0.9
8.	35	{Rechargeable, no tubing, on pump, automatic}	29.5	0.9
9.	19	{Rechargeable, no tubing, hand-held device, semi-automatic}	30.5	0.9
10.	31	{Rechargeable, no tubing, hand-held device, automatic}	31.5	0.9
11.	15	{Rechargeable, no tubing, mobile and smart watch, semi-automatic}	32.5	1
12.	27	{Disposable, no tubing, mobile and smart watch, automatic}	33.5	1

4.2 Case Study 1: Micro Aerial Vehicles

4.1.1 Introduction

Micro Aerial Vehicle (MAV) is an autonomous flying craft that takes advantage of increasingly miniaturized electromechanical technology having a small size of less than 15cm and weigh less than 200g. MAVs have numerous promising civil and military applications. In accordance with the mission, size and type of equipment installed the category of MAVs differ. They can be employed for rigorous inspection of buildings, silent and inconspicuous surveillance and can be equipped with various micro-sensors, multiple micro-phones, cameras and gas detectors. Nature i.e. bird flight, has provided the inspiration for flapping wing MAV design. However, research carried out in MAV realm reveals a larger number of complexities present in designing flapping wing MAV as compared to fixed and rotary wing MAV due to their complex aerodynamics. To counteract the decreasing aerodynamic efficiency, high frequency flapping is required which demands an increase in the power to weight ratio. Also, manufacturing and assembly techniques become challenging for small size. By discovering the trends in a bird's flight, we can formulate empirical relationships using geometric parameters to assist in effective and efficient design. [32]

1.1.1 Reason for Selection

Mechanics Interdisciplinary Group at Research Centre for Modeling and Simulation at the National University of Science and Technology is working on nature inspired scalable design trends for MAV development.

The interactive platform ASSESS is used to determine the utility function of the attributes by using Lottery Equivalent Probability method. The customer requirements are selected from the QFD which are considered the most important requirements which will have an impact on the design requirements. The design requirements which are the most important for the fulfillment of customer requirements are chosen using QFD. Those requirements are translated into functions which will fulfill those requirements.

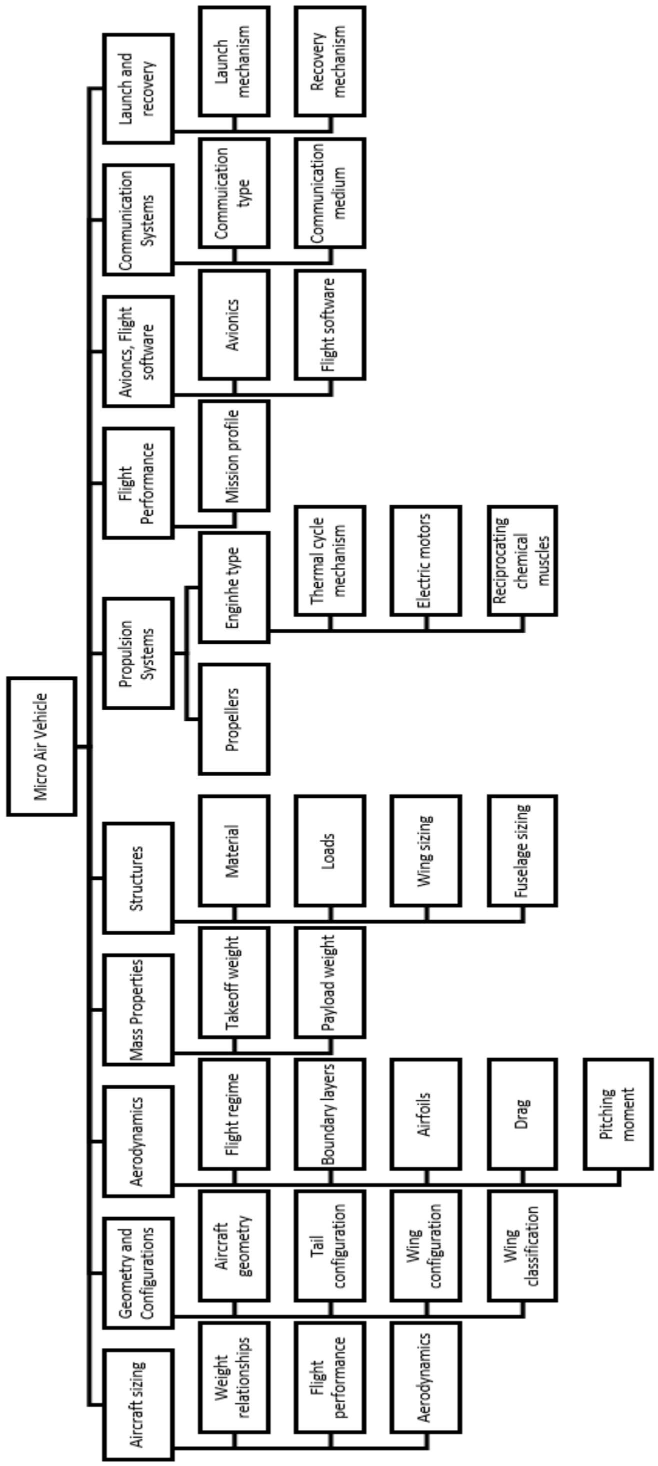


Figure 24. Micro Aerial Vehicle system breakdown.

Table 18. Morphological box for Micro Aerial Vehicle.

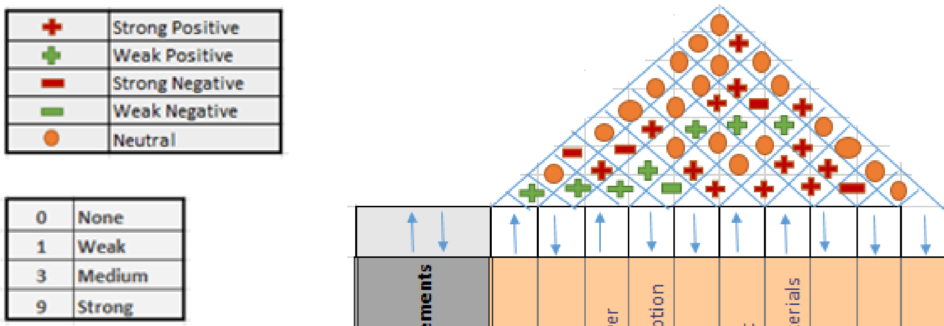
Wing classification	Tandem	Biplane	Single wing		
Wing Category	Fixed	Rotary	Flapping		
Wing Shape	Rectangular	Elliptical	Zimmerman	Inverse Zimmerman	
Guidance and Navigation	LOS	Autonomous			
Airframe Material	Metal	Ceramic	Composite	Wood	
Propulsion System	Thermal cycle machines	Electric motors	Reciprocating chemical muscle		
Actuators	Micro-motors	Piezo-electric devices	Electrostatics	Electromagnetic	Magneto-elastic Ribbon

DSM		A Wing shape	B Wing classification	C Wing span	D Fuselage length	E Maximum takeoff weight	F Payload weight	G Propulsion system	H Controller	I Landing mechanism	J Actuators	K Guidance and navigation
A	Wing shape	A										
B	Wing classificatoin	X	B									
C	Wing span	X	X	C								
D	Fuselage length	X	X	X	D							
E	Maximum takeoff weight		X	X	X	E						
F	Payload weight			X	X	X	F					
G	Propulsion system	X	X	X	X	X	X	G				
H	Controller		X	X	X	X	X		H			
I	Landing mechanism				X	X	X	X	X	I		
J	Actuators		X						X	X	J	
K	Guidance and navigation								X		X	K

Figure 25. Morphological box for Micro Aerial Vehicle.

The purpose of DSM is that if requirements are changed at some point, or if a certain component needs to be changed, we can clearly see which other components are going to be affected by that change. Figure 25 enlists the significant design attributes in the development of a MAV and represents whether a relationship exists between those attributes.

Figure 26 represents the relationship between the requirements which are important for the design of the MAV (horizontal) and the requirements which are important to the customer (vertical). The triangle or House of Quality represents the strength of the relationship between the different design requirements, so that if a design requirement is increased or decreased in capacity, the effect on other requirements can be easily gauged. This HOQ was filled after interviewing various industry experts in the field of UAV development.



	Customer Requirements	Importance	% Importance	L/D ratio (1)	Airfoil shape (2)	Propulsive power (3)	Power consumption (4)	Total Weight (5)	Payload Weight (6)	Strength of materials (7)	Controls (8)	Autonomy (9)	Dimensions (10)	Comparison	Fixed Wing	Rotary Wing	Flapping Wing
Design Requirements				↑	↓	↑	↓	↓	↑	↑	↓	↓	↓				
A	Small	5	9.9	3	0	9	3	9	9	0	0	0	9				
B	Carry payload	4	7.9	0	0	3	3	9	9	9	1	0	9				
C	Higher strength	5	9.9	1	0	3	1	9	1	9	1	0	1				
D	Weigh less	3	5.9	3	0	3	3	9	9	1	3	0	3				
E	Perform mission	5	9.9	3	1	9	9	3	9	3	9	3	1				
F	Controllable	4	7.9	3	3	3	1	9	3	3	9	9	3				
G	Communicate	5	9.9	1	0	1	3	1	0	1	9	9	1				
H	Perch and stare	4	7.9	9	3	3	3	3	1	1	3	1	3				
I	Less power	3.5	6.9	3	3	9	9	9	3	3	1	1	1				
J	Manuever	3.5	6.9	9	9	3	3	9	3	3	9	9	3				
K	Navigate	3	5.9	1	1	0	0	3	1	0	9	9	1				
L	Ceiling	2.5	5.0	9	9	9	9	9	3	3	1	1	1				
M	Low production cost	3	5.9	0	1	3	1	3	1	3	3	1	9				
		50.5	Importance	326	197	452	365	643	413	312	454	332	348	3841.58			
			% Importance	8.5	5.1	12	9.5	17	11	8.1	12	8.6	9				

Figure 26. Morphological box for Micro Aerial Vehicle.

1.1.2 Interviews for MAV- Utilities

The interview was conducted using the interactive stakeholder interview platform, ASSESS developed by researchers at Caltech. ASSESS is an interactive computer program for measuring utility. Due to an absence of a stakeholder, the researcher translated the requirements [29] as the criteria on which the interview was based. These were taken to be the design requirements. The purpose was to determine the utilities for each attribute. The attributes under consideration were cost, endurance, range and mass.

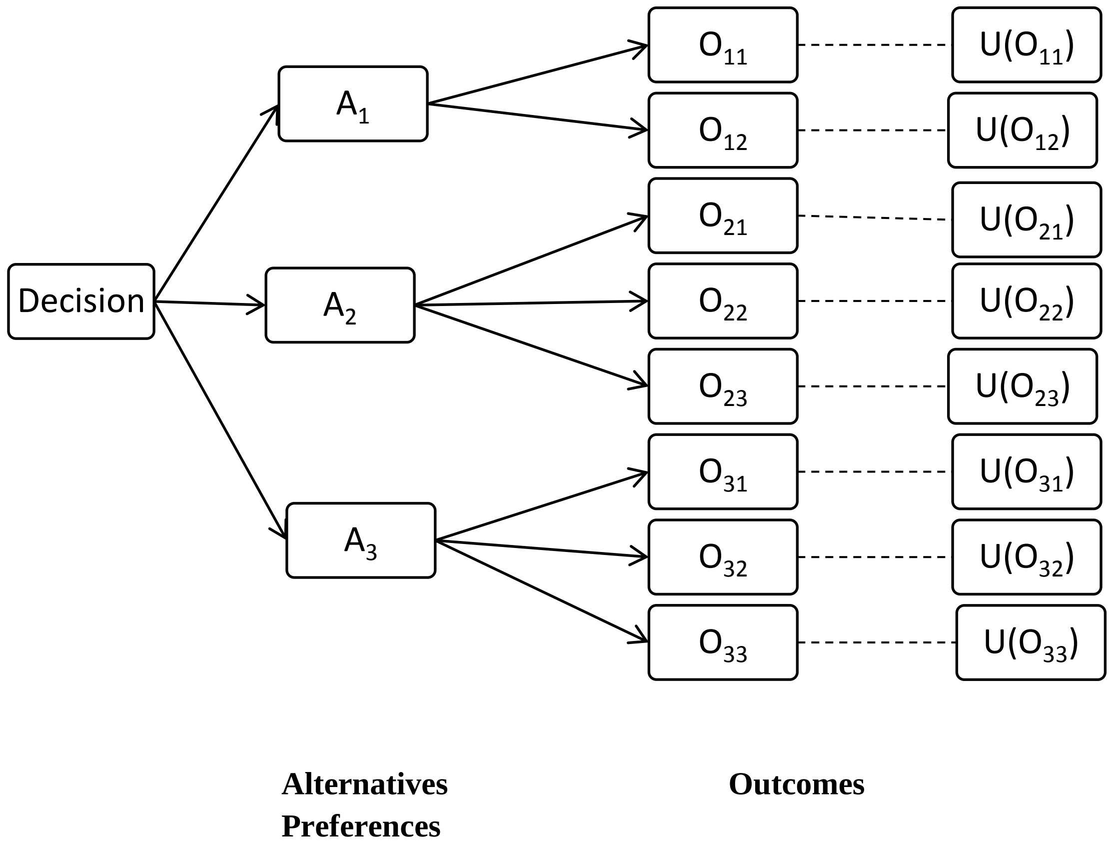


Figure 27. Decision tree.

1.1.3 Problem statement

If appropriate utility is assigned to each possible consequence and the expected utility of each alternative is calculated, the best course of action is the alternative with the highest expected utility. The software used (ASSESS) for conducting stakeholder interview for MAV works on the following principle:

- Choose amongst alternative A1, A2, …, A_m, such that each will eventually result in a consequence described by one attribute X.
- Decision maker does not know what consequence will result from each alternative.
- However, the decision maker can assign probability to the various consequences that might result from any alternative.

Assume 'n' consequences labeled x_i, x_2, …, x_n such that x_i is less preferred than x_{i+1}. Decision maker is asked to state preference about two alternative acts a' and a'' such that:

1. Act a' will result in consequence x_i with probability p_i' for i = 1…, n
2. Act a'' will result in consequence x_i with probability p_i'' for i = 1…, n

Assume that for each i, the decision maker is indifferent between the following options

1. Certainty option: receive x_i
2. Risky option: receive x_n with probability P_i and x_1 with probability $(1-P_i)$

This option is denoted as (x_n, P_i, x_1). Clearly, if P = 0 and $P_n = 1$, then, $P_1 < P_2 < P_3 < \ldots < P_n$. The assessment method for all of these is Lottery Equivalence Method and the probability of occurrence is taken to be 0.5 for all the attributes.

1.1.4 Utility for Attributes

4.1.5.1 Cost:

The cost taken under consideration is the development cost of the MAV. The cost constraints were taken from literature [29]. The System Analyst acted as a substitute to the stakeholder to be interviewed and self-performed the interview on ASSESS. As the production cost increases the stakeholder utility subsequently decreases. A fluctuating trend for cost is observed in table 7. This is owing to the way the interview was conducted and the selection of an erroneous value.

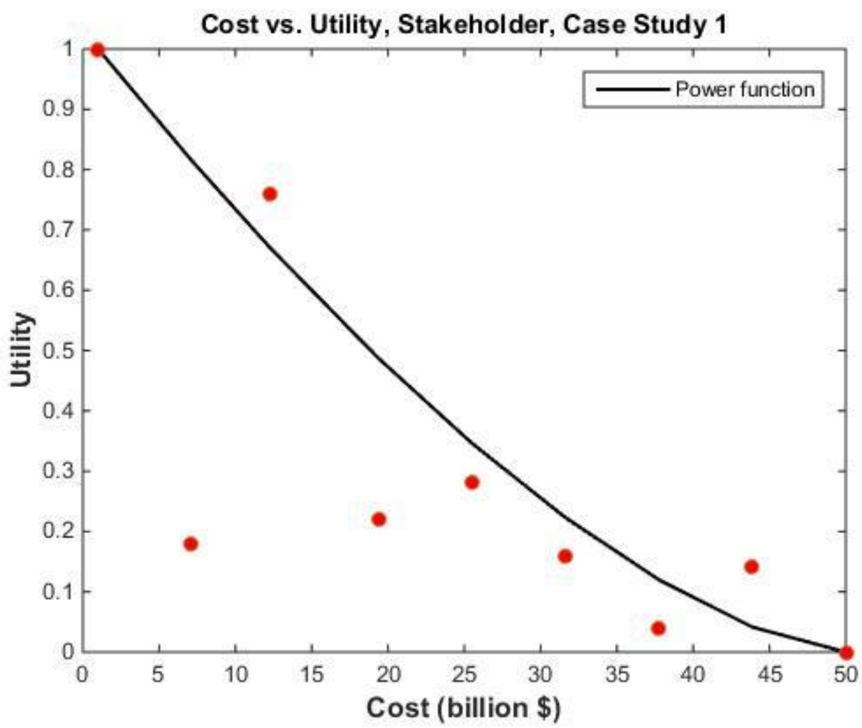


Figure 28. Cost vs utility plot for customer utility for a Micro Aerial Vehicle.

The best fitting exponential function:

$$U(X)= -0.0504+1.1176e^{\left(-\frac{X}{16.13}\right)} \quad \dots (12.a)$$

Risk Tolerance Level: RT= -16.12 (in Millions)

This represents a risk seeking behavior. This indicates that the stakeholders are ready to expend vast resources in the development process of an MAV.

Function Parameters		
A	**B**	**RT**
-0.05039	1.117557	16.13387

Best fitting power function:

$$U(X)=[\frac{50-X}{49}]^{1.53} \quad \dots (12.b)$$

Where U(X) is the utility of the attribute X which in this case is cost.

Table 19. Utility for attribute 1: cost.

Cost (Millions)	Utility
1	1
7.13	0.18
12.25	0.76
19.38	0.22
25.5	0.28
31.63	0.16
37.75	0.04
43.88	0.14
50	0

4.1.5.2 Endurance

Endurance is the time for which a flying craft can stay airborne. To increase the endurance of the MAV a propulsion system which can power it for an enhanced amount of time needs to be integrated in the system. Developing a miniaturized propulsion system can be a challenge. The stakeholders have a high utility for increased endurance, however, once it reaches a certain limit, the user no longer can a proportional increased utility for a further increase in endurance.

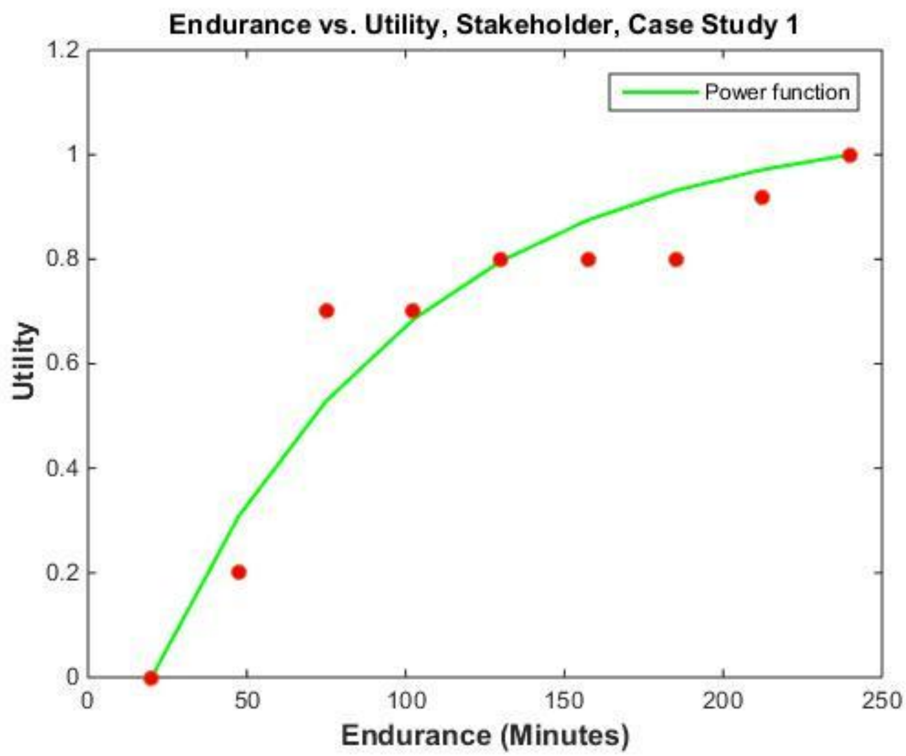


Figure 29. Endurance vs utility plot for customer utility for a Micro Aerial Vehicle.

Best fitting exponential function:

$$U(X)= 1.0701-1.371e^{\frac{-X}{80.7}} \ldots (13)$$

Risk Tolerance Level: RT=81 (in Minutes)

This represents a risk averse behavior. This implies that when it comes to endurance dropping below the preferred limit is not desirable to the stakeholder.

Function Parameters		
A	**B**	**RT**
1.070071	-1.371	80.70511

Table 20. Utility for attribute 2: endurance.

Endurance (Minutes)	**Utility**
20	0
47.5	0.2
75	0.7
102.5	0.7
130	0.8
157.5	0.8
185	0.8
212.5	0.92
240	1

4.1.5.3 Range

Range is the distance which the flying craft can travel. As the range increases the customer's utility for the MAV increases.

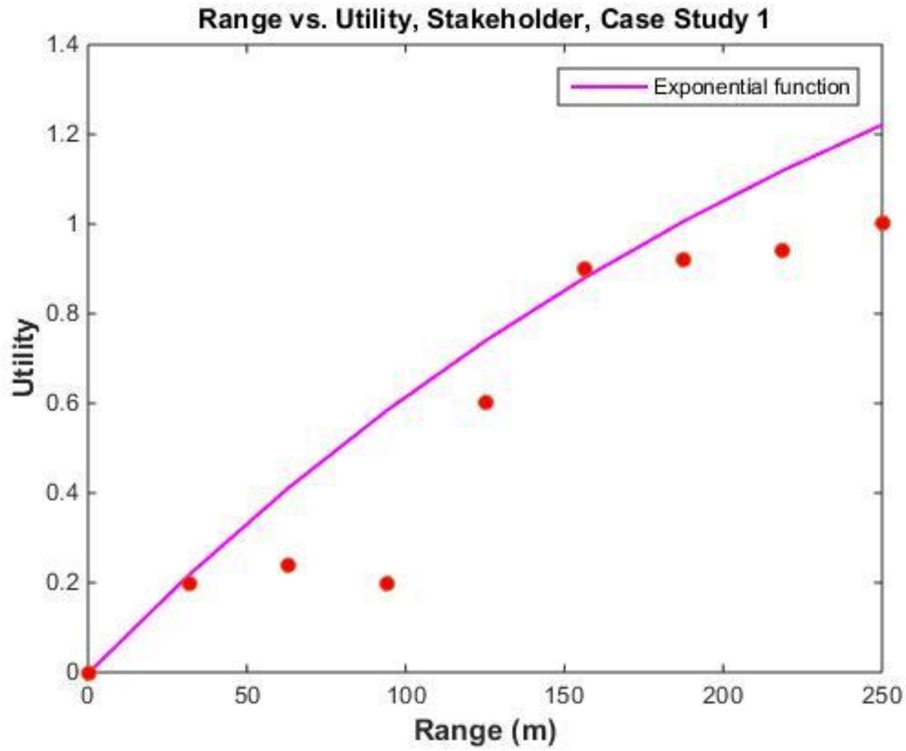


Figure 30. Range vs. utility plot for customer utility for a Micro Aerial Vehicle.

Best fitting exponential function:

$$U(X)=2.118 - 2.1207e^{\frac{-X}{390.5}} \ldots (14)$$

Function Parameters		
A	**B**	**RT**
2.117963	-2.12068	390.4866

Risk Tolerance Level: RT = 390 (in Meters)

The behavior is risk averse. This means that the stakeholder is cautious towards taking risky decisions when range is compromised.

Table 21. Utilities for attribute 3: range.

Range (m)	**Utility**
0.5	0
31.69	0.2
62.88	0.24
94.06	0.2
125.25	0.6
156.44	0.9
187.63	0.92
218.81	0.94
250	1

4.1.5.4 Mass

Mass of the MAV is the total mass of the structure and the payload. As the mass increases the customer's utility for the MAV decreases.

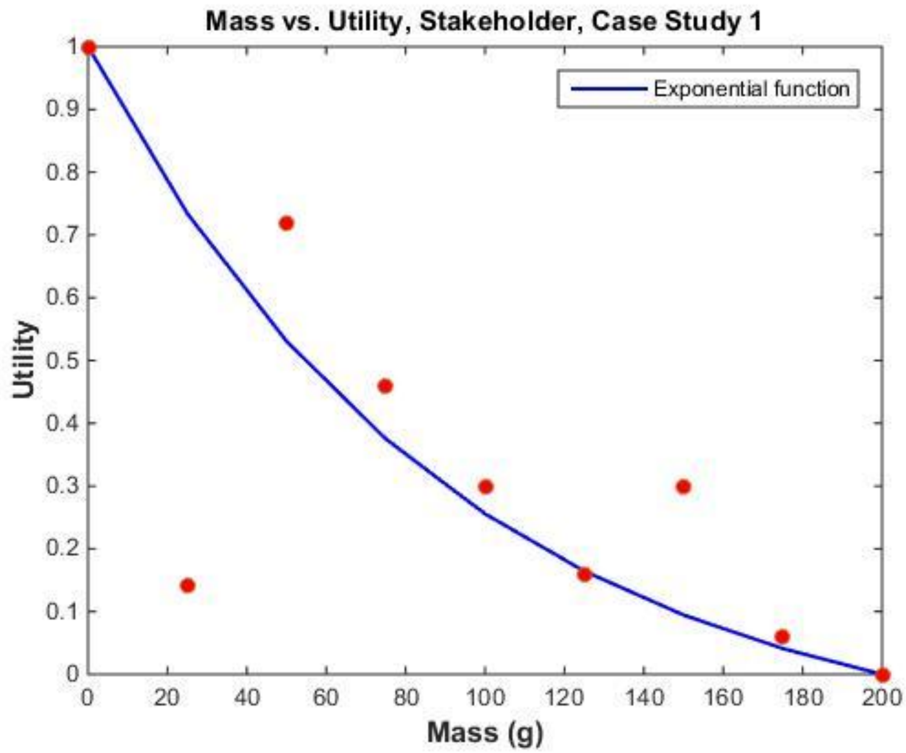


Figure 31. Mass vs. utility plot for customer utility for a Micro Aerial Vehicle.

Best fitting exponential function:

$$U(X) = -0.1337 + 1.1338e^{\frac{-x}{93.56}} \ldots (15)$$

Function Parameters		
A	**B**	**RT**
-0.1337	1.133819	93.55576

Risk Tolerance Level: RT= -94 (in grams)

The behavior is risk seeking.

Table 22. Utilities for attribute 5: mass.

Mass (kg)	Utility
0.01	1
25.01	0.14
50.01	0.72
75.01	0.46
100	0.3
125	0.16
150	0.3
175	0.06
200	0

4.1.6. Tradespace Exploration for MAV

Due to a lack of present stakeholder data available for the MAV, the tradesapace could not be formulated. However, table 23 elucidates the division of the components into variants and the acquired data can be used to plot the tradespace.

Total Architectures = 3 x 3 x 4 x 2 x 4 x 3 x 5 = 4,320

The total number of architectures which can be taken under consideration for the Micro Aerial Case Study are 4320. The data can be inserted in Table 23 and architecture evaluation can be carried in a manner similar to the one followed in Case Study 1.

Table 23. Component wise data for Micro Aerial Vehicle.

Subsystem	Variables	*Obj 1* Utility	*Obj 2* Cost ($)	*Obj 3* Endurance (Minutes)	*Obj 4* Range (km)	*Obj 5* Mass (kg)
1. Wing Classification	1.1 Tandem		-	-	-	-
	1.2 Biplane		-	-	-	-
	1.3 Single wing		-	-	-	-
2. Wing category	2.1 Fixed		-	-	-	-
	2.2 Rotary		-	-	-	-
	2.3 Flapping		-	-	-	-
3. Wing shape	3.1 Rectangular		-	-	-	-
	3.2 Elliptical		-	-	-	-
	3.3 Zimmerman		-	-	-	-
	3.4 Inverse Zimmerman		-	-	-	-
4. Guidance and navigation	4.1 LOS		-	-	-	-
	4.2 Autonomous		-	-	-	-
2. Airframe material	5.1 Metal		-	-	-	-
	5.2 Ceramics		-	-	-	-
	5.3 Composites		-	-	-	-
	5.4 Wood		-	-	-	-
3. Propulsion system	6.1 Thermal cycle machines		-	-	-	-
	6.2 Electric motors		-	-	-	-
	6.3 Reciprocating chemical muscle		-	-	-	-
4. Actuators	7.1 Micro-motors		-	-	-	-
	7.2 Piezo-electric actuators		-	-	-	-
	7.3 Electrostatics		-	-	-	-
	7.4 Electromagnetic		-	-	-	-
	7.5 Magneto-elastic ribbon		-	-	-	-

Chapter 5

CONCLUSION and FUTURE RECOMMENDATIONS

The tradespace generation process allows the evaluation of multiple design concepts on a common, quantitative basis and it provides the decision maker a perceived framework for selecting designs to carry forward more detailed analysis. This research has established and practically implemented cross-disciplinary frameworks for TE. It has also validated TE as a very useful technique to be used during concept exploration phase to determine the design which is most preferable to the stakeholder. However, the researcher has concluded, contrary to popular opinion, that tradespace exploration is a tricky process to be applied and it is to be used with caution because erroneous data can lead to impractical solutions. An easier methodology needs to be determined to generate potential design concepts. Nonetheless, tradespace exploration has proved its merit in assisting the system designers to choose a cost efficient and user-friendly product design. Also, this process leads to an increase in the product's utility and saves rework in the engineering design phase.

The questions which were raised at the start of the thesis were duly answered during the course of the research as follows:

1. ***How do stakeholder preferences influence component selection and design decisions?***

Customers are the main drivers of a product's utility which is greatly dependent on the designer's choice of how to develop the system. A design component which is of no importance to the customer can prove to be an expensive addition on the designer's part. Pecuniary concerns are foremost to the company owner. This triad (cost, schedule, performance) needs to be carefully evaluated in order to reach a consensus on the best designs to be selected.

In the automated Insulin Pump case study, the designers were interviewed to reduce the components of the initially constructed morphological box. This was done in order to reduce the design space for ease of determining utilities for the components. This simplified the process of gathering data from the survey questionnaire. The System Designer can also use Conjoint Analysis to evaluate the stakeholder utilities if the resources permit instead of using a survey methodology.

2. ***How are stakeholder preferences cumulatively evaluated on a single platform?***

Stakeholder preferences can be successfully evaluated on a single platform by using multi-attribute utility theory. Each individual stakeholder utility is evaluated on a single platform. However, for this thesis a different methodology has been adopted. The stakeholders were divided into different groups, starting with the company owner the initial attributes were derived and design variables were enumerated. An interview session with the designers was held in which the range of the attributes was determined and the infeasible design options were eliminated. After reducing the initial design space, with the consensus of the system architect and the system designers, the utility interview methodology was decided for the users of the system. Subsequently, the design space was formulated and TE was carried out.

3. ***Can Tradespace Exploration be accurately applied on non-Aerospace applications?***

Tradespace Exploration can be applied to both small and large systems. However, one common framework cannot be followed for all systems. The system designer needs to determine the scope of the system and the attributes which he needs to include in consideration of the design space. This includes determining whether the architectures are going to be comprised of component dependent design variables or attribute dependent design variables. The process of TE exploration is tedious, hence, the system analyst needs to evaluate whether consideration of tradeoffs is worth the time and effort spent in performing TE, in case where the cost or attribute variations are not significant.

4. ***How to find non-dominated architectures from a Tradespace and subsequently plot a Pareto frontier?***

Utility functions were derived from user interviews using the tool ASSESS for Case Study 2: Micro Aerial Vehicle. This was because the attributes were taken to be continuous values. However, for Case Study 1: Insulin Pump, a survey methodology had to be followed since the design variables were discrete values. Hence, for Case Study 1 a component-based interview methodology was adopted. A Likert scale of 1-5 was used and the user ratings for various options for components of the system were transformed into discrete utility values through unit normalization. The component variants were represented using a morphological box and were combined to form architectures. The attributes of these architectures were plotted against each other to form the design space. This design space was further evaluated to find the non-dominated architectures and Pareto frontier was found by plotting a best fit second degree polynomial function from the non-dominated architectures. The architectures which lie on the Pareto frontier were presented to the primary stakeholder (the Insulin Pump company owner) and were asked to further select the architectures which suited their preferences.

The case studies were used in order to develop and validate a framework for carrying out Tradespace Exploration. If the data changes, the system analyst will need to rethink which framework is to be applied. The researcher has reached a conclusion that the same strategy cannot be applied for every project. The Systems Engineer or System Architect needs to decide what works best for their project.

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Appendix A

```
%Written by Sundas Rafat Mulkana
%MS-SYSE-04, RCMS, 14thJune2018
clc
clear all
%%
%Data for Insulin Pump
Arch={[1 2], [3 4], [5 6 7], [8 9 10], [11 12 13],...
    [14 15 16], [17 18], [19 20 21 22]}; %Data enumeration
Ut = {[0.9 0.4],[0.3 0.7],[0.8 0.6 0.5],[0.6 0.7 0.8]};%component utilities
C = {[2950 5214],[56000 105000],[2500 5000 1000],[0 5000 15000]}; %cost
utilities
M = {[12 12],[240 115],[0 0 50],[0 0 0]};
UF={[8 6], [5.5 8.5], [8 6 4], [4 8 9]};
%%
%Architecture Enumeration
X_Arch = combvec(Arch{:}); %Enumerate architectures
%Utility
X_U = combvec(Ut{:}); %Utilitiy of all components stored in single vector
Util = sum(X_U,1); %utility of architectures
Util = Util.';
%Cost
X_C = combvec(C{:}); %cost of all components stored in one vector
Cost= sum(X_C,1); %cost of architectures
Cost = Cost.';
%Mass
X_M = combvec(M{:}); %mass of components stored in a vector
Mass = sum(X_M,1); %mass of architectures
mass = Mass.';
%User friendliness
X_UF = combvec(UF{:}); %mass of components stored in a vector
U_F = sum(X_UF,1); %mass of architectures
U_F = U_F.';

%Unit normalization; bringing utility values between 0 and 1
Unit_normalize(util, Sub, V)

%Plotting
IP_plot(Util, Cost, mass, U_F)
```

```
function Unit_normalize(Util, Sub, V)

% %Unit normalizing utility
x=min(Util);%Minimum value
y=max(Util);%Maximum value
T=numel(Util);%Total values
I=T-1;%Interval
z=y-x;%difference between maximum and minimum value
Z=z/I;%width of interval
Sub=[x:Z:y]';%dummy set for range
```

```
V=[0.1:0.1:1]';%normalized set
U=Util;

for i=1:1:T
%Compare utility value with range value and replace with utility set value
if U(i)<=Sub(1)
    X(i)=V(1);
else if Sub(1)<U(i)<=Sub(2)
        X(i)=V(2);
   else if Sub(2)<U(i)<=Sub(3)
        X(i)=V(3);
        else if Sub(3)<U(i)<=Sub(4)
        X(i)=V(4);
        else if Sub(4)<U(i)<=Sub(5)
        X(i)=V(5);
        else if Sub(5)<U(i)<=Sub(6)
        X(i)=V(6);
        else if Sub(6)<U(i)<=Sub(7)
        X(i)=V(7);
        else if Sub(7)<U(i)<=Sub(8)
        X(i)=V(8);
        else if Sub(8)<U(i)<=Sub(9)
        X(i)=V(9);
        else if Sub(9)<U(i)<=Sub(10)
        X(i)=V(10);
            end
            end
            end
            end
            end
            end
            end
       end
    end
end
New(i)=X(i);
end
end
New
```

```
function IP_plot(Util, Cost, mass, U_F)

%plot cost vs. utility
figure(1)
scatter(Cost,Util, 'o', 'MarkerFaceColor','r') %Plotting cost vs. utility
xlabel('Cost (pkr)')
ylabel('Utility')
title('Cost vs. Utility, IP User, Case Study 2')
box on
%plot mass vs. utility
figure(2)
scatter(mass,Util, 'o', 'MarkerFaceColor','b') %Plotting mass vs. utility
xlabel('Mass (g)')
ylabel('Utility')
```

```
title('Mass vs. Utility, IP User, Case Study 2')
box on
%plot user friendliness vs. utility
figure(3)
scatter(U_F,Util, 'o', 'MarkerFaceColor','k') %Plotting user friendliness vs.
utility
xlabel('User friendliness')
ylabel('Utility')
title('User friendliness vs. Utility, IP User, Case Study 2')
box on
%plot cost vs. mass
figure(4)
scatter(Cost, mass, 'o', 'MarkerFaceColor','b')
xlabel('Cost (pkr)')
ylabel('Mass (g)')
title('Cost vs. Mass, IP User, Case Study 2')
box on
%plot cost vs. user friendliness
figure(5)
scatter(Cost, U_F, 'o', 'MarkerFaceColor','b')
xlabel('Cost (pkr)')
ylabel('User friendliness')
title('Cost vs. user friendliness, IP User, Case Study 2')
box on
%plot user friendliness vs. mass
figure(6)
scatter(mass, U_F, 'o', 'MarkerFaceColor','b')
xlabel('Mass (g)')
ylabel('User friendliness')
title('Mass vs. user friendliness, IP User, Case Study 2')
box on

end
```

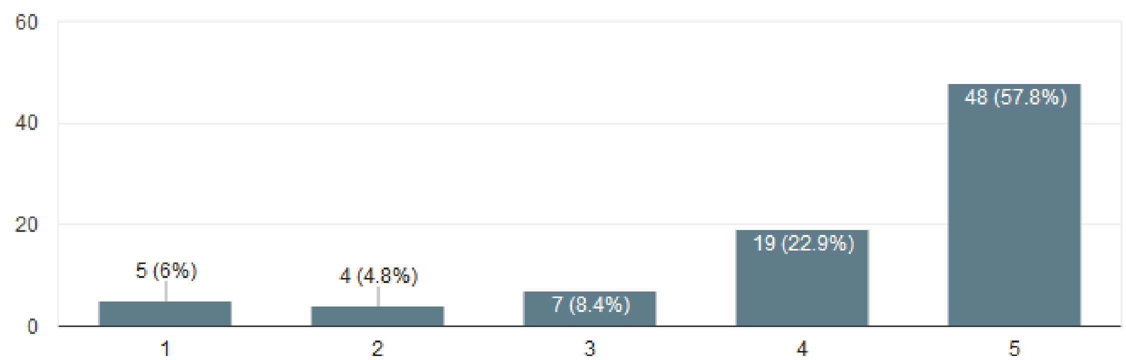
Appendix B

Case Study 2: Insulin Pump Survey Questionnaire

1.1 Battery

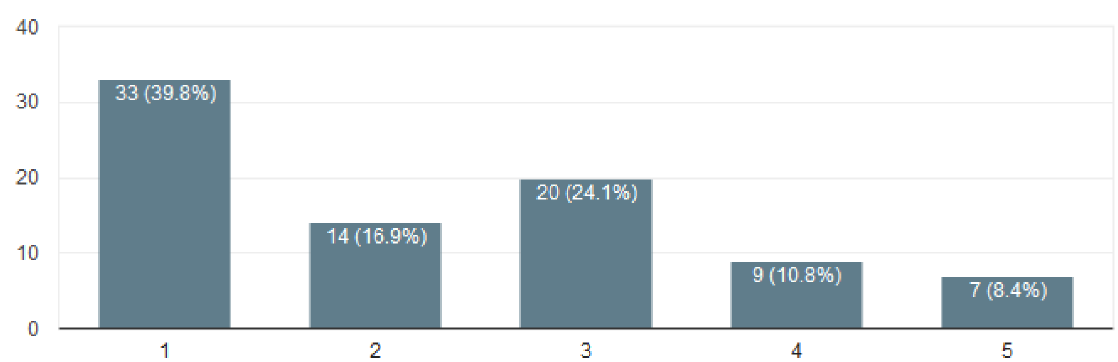
1.You prefer a rechargeable battery for the pump.

83 responses



2. You prefer a disposable battery for the pump.

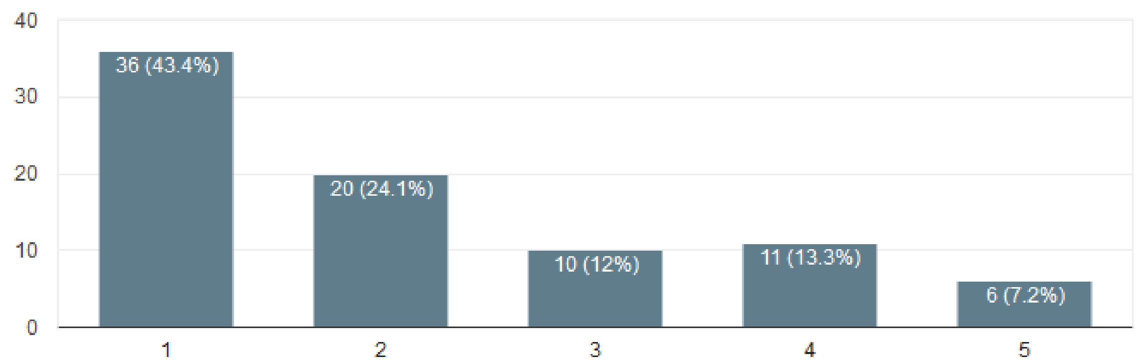
83 responses



1.2 Tubing Options

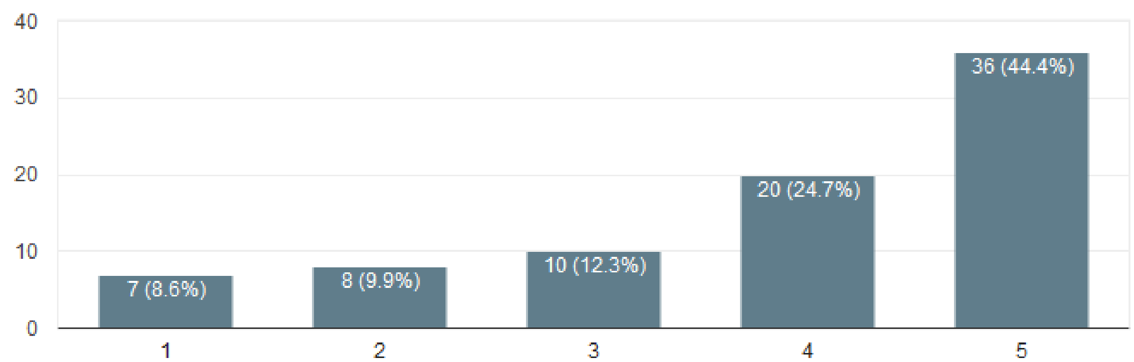
1. You prefer the pump which has a tube connecting the pump to the infusion set (as shown in figure. 1 in the table).

83 responses



2. You prefer a pump which is attached to your body (as shown in figure. 2 in the table).

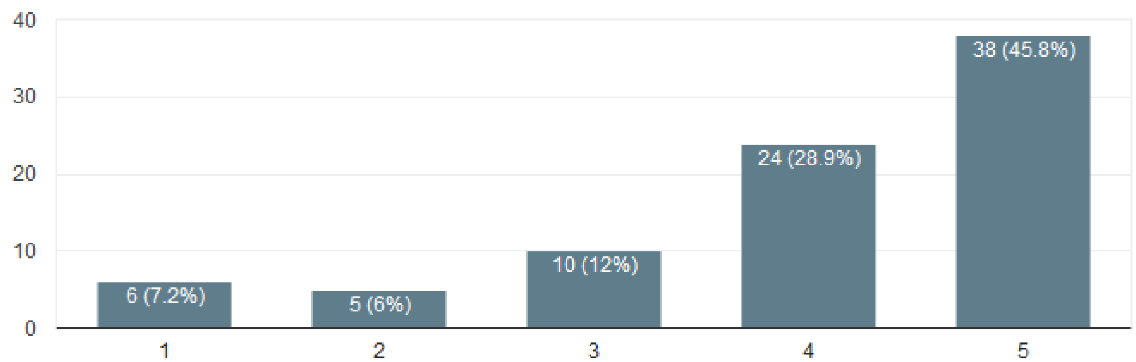
81 responses



1.3 Controller Options

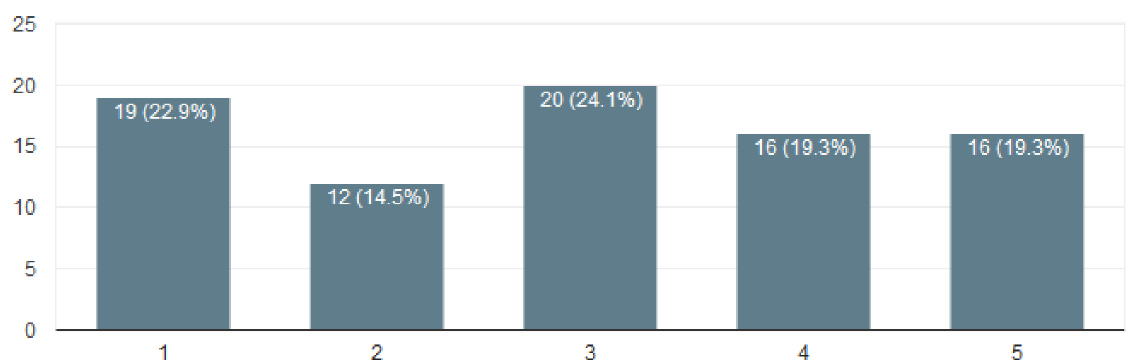
1. You prefer all features and control options to be on a mobile phone and a smart watch (figure on the left).

83 responses



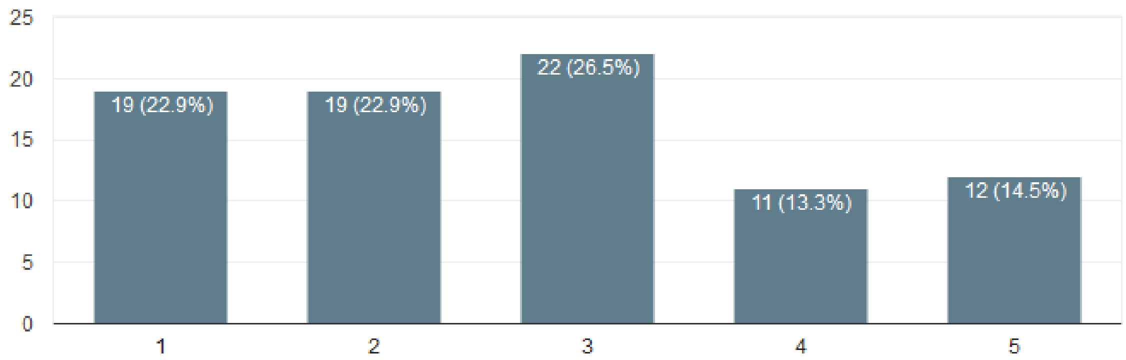
2. You prefer all functions and control options to be on a hand held device (figure in the middle).

83 responses



3. You prefer all functions and control options to be on the pump (figure on the right).

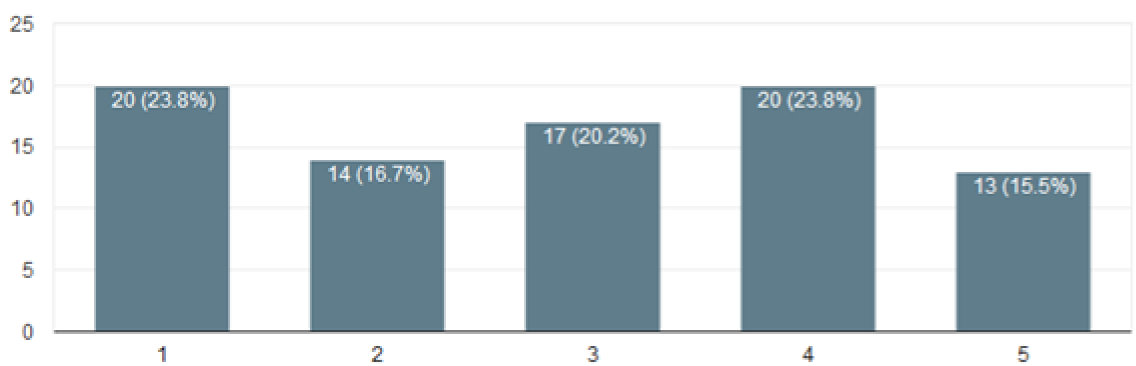
83 responses



1.4 Insulin Dosage Calculation Features

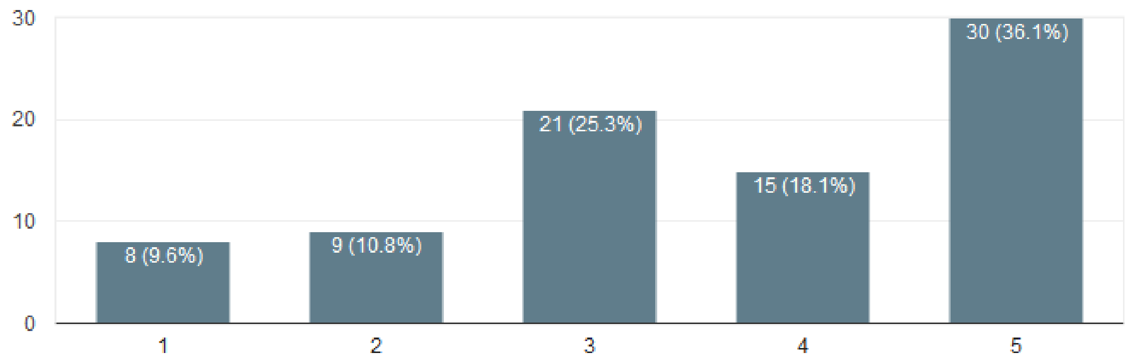
1. You prefer to input your bolus/basal dosage in the pump yourself.

83 responses



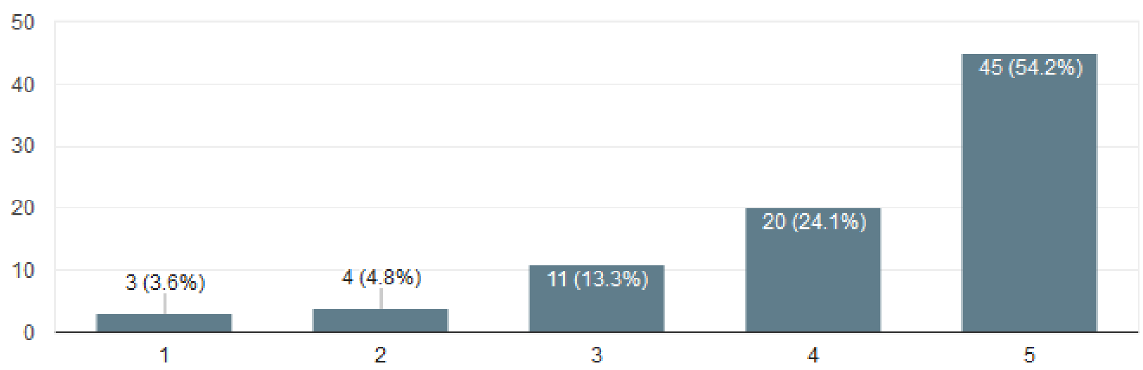
2. You prefer the pump to calculate the basal/bolus dose itself and automatically inject.

83 responses



3. You prefer the pump to calculate the basal/bolus dose itself but ask you to approve before it injects.

83 responses



Appendix C

Operational Scenario for Insulin Pump

User Scenarios

1. User programs the insulin pump
   a. User turns on the insulin pump
   b. Pump displays the selection of items
   c. User enters the basal and bolus rate
   d. Pump stores the information
2. User inserts the pump and CGM into subcutaneous tissue
   a. User selects a location on the body to insert the pump
   b. User holds the pump at x degree angle and inserts it inside the skin
   c. User applies pressure on the pump to stick
   d. Pump supplies 24-hour basal insulin and bolus insulin before meals
   e. CGM does continuous glucose monitoring and sends the data to the pump
   f. The pump computes the average glucose level over a period of three reading
   g. If the glucose level falls below the threshold set, pump notifies the user through an alarm to prevent hypoglycemia
3. User monitors blood glucose level
   a. User checks the blood glucose level on the hand-held device
   b. Pump signals the user by means of an alarm when the sugar level falls below the minimum level.
4. User charges the pump
   a. Pump signals when the battery is low
   b. User de-attaches the pump from the body
   c. User removes the battery from the pump
   d. User replaces the battery in the pump with an already charged spare battery
   e. User charges the battery
   f. When battery is charged, user re-inserts the battery back into the pump
5. User refills insulin in the insulin reservoir

a. User removes the pump from the body
b. User removes the insulin reservoir
c. User refills the insulin in the reservoir
d. User re-assembles the pump
e. User re-attaches the pump to the body

Health-practitioner’s scenario

a. Data is recorded in the insulin pump
b. Doctor extracts the data from the pump using a USB
c. Doctor analysis the patient’s data and suggests changes in the programming of the pre-set insulin dosage to patient