IMPROVING ACCESS TO MEDICAL CARE FOR PATIENTS IN NEED OF AUGMENTATIVE AND ALTERNATIVE COMMUNICATION USING SYSTEMS ENGINEERING AND OPTIMIZATION MODELS

by

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DEDICATION

To my family,

for their endless love and support

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ABSTRACT

Augmentative and Alternative Communication (AAC) is a set of tools and strategies used for the support or replacement of speech for people with complex communication needs. AAC devices have great potential to improve the quality of life for people with severe communication impairments by enhancing educational opportunities and facilitating independence and development of social relationships. Several barriers currently exist preventing access to AAC devices for individuals in need. AAC assessment is a complex process that involves many professionals to effectively serve patients with complex communication needs. There is a substantial gap between the need for and the provision of assistive technology assessment available. Selection of an unsuitable AAC device can result in abandonment of the device, which can lead to loss in revenue, time, and effort. Therefore, pairing the competencies of the AAC user with a fitting communication system and providing a method of access are crucial.

This thesis addresses two specific aims as a first step towards achieving the goal of improving access to AAC devices. The first thesis aim looks at developing optimization models and solution algorithms that can help in recommending the best-suited devices to consider for a patient based on a disability profile. The optimization model and algorithm developed in this thesis administer the decision-making process by matching the conforming attributes of the patient's diagnostic profile with the devices' attributes to select the devices with the highest fitting score to be recommended for the patient. The computational study in the thesis demonstrates that the overall device satisfaction score is

always equal for the optimization model and the algorithm. Several factors contribute to the overall device satisfaction score; the factors include ‘Patient condition’, ‘Number of devices available’, ‘Assessment weight distribution’ and ‘Minimum level of assessment satisfaction’.

The second thesis aim is to derive a healthcare mobile facility concept for patients needing AAC using the systems engineering life cycle model. The high-level conceptual design of the system was carried out in three phases of needs analysis, concept exploration, and concept definition. To fulfill the system requirements, the mobile assessment vehicle will have seven subsystems: the assessment vehicle, electrical system, network and audio-visual system, medical equipment, AAC devices, AAC device assignment tool, and human resource team. The design of an AAC mobile assessment vehicle can have a global impact and can revolutionize medical service delivery in different parts of the world.

1. INTRODUCTION

The World Health Organization (WHO) estimates that more than one billion people are in need of at least one type of assistive technology (AT); however, only one in ten people in need have access [1]. One of the significant challenges faced by patients in need of AT is access to services. Individuals in need of AT often need to attend multiple appointments at different locations with different health professionals to obtain a complete assessment of their condition. Multiple appointments are also needed to find the best AT fit for the patient's disability profile from a large pool of equipment options. The availability of medical services can vary greatly by geographic region. Access to health care is even more challenging for patients living outside urban areas in the US.

As a global commitment to improve access to assistive technology products, WHO established the Global Cooperation on Assistive Technology (GATE), which specifies fifty priority assistive products carefully selected on the basis of need and impact on an individual's life [2]. A significant portion of the prioritized list is dedicated to products that aid the communication needs of people with acquired or degenerative communication disorders. Assistive technology used for the support or replacement of speech of people with complex communication needs is known as Augmentative and Alternative Communication (AAC). There is a wide range of congenital and acquired health conditions that require the use of AAC devices for augmented communication. These conditions include but are not limited to autism, cerebral palsy, dual sensory impairments, genetic syndromes, intellectual disability, multiple disabilities, hearing impairment, disease, stroke, and head injury [3]. The process of selecting and fitting an AAC device proves to be particularly challenging when patients have decreased memory, distractibility, and lack of insight. To improve access to assistive technology, the GATE initiative hopes to develop innovative models of service provision that would enable individuals to access assistive products for all their functional needs from a single healthcare infrastructure.

The goal of this research is to improve the access to services for patients in need of AAC. This research addresses two specific aims as a first step towards achieving this goal. The first research aim looks at developing optimization models and solution algorithms that can help in recommending the best (top three) group of devices to consider for a patient based on a disability profile. Currently, there are multiple companies that offer many products/devices targeting patients in need of AAC. However, the decision-making process of what device to try on the patient is largely based on the health professional’s experience and familiarity with specific devices or companies. The developed models and algorithms stand to minimize patient discomfort and reduce device assessment time by recommending a limited list of devices that are likely to provide the best fit based on the patient’s disability profile.

The second research aim is to derive a healthcare mobile facility concept for patients needing AAC using the systems engineering life cycle model. The vehicle should facilitate the health care service delivery for patient condition assessment and AAC device evaluation. The evaluation of the individual’s ability for the use of AAC requires assessment of the user’s cognitive and linguistic skills, literacy skills, sensory skills, perception skills and motor capabilities. Therefore, the assessment requires the knowledge and skill sets of an array of medical professionals. In addition, fitting of an AAC device ideally demands a multi-disciplinary team of speech-language pathologists (SLP), a physician, an occupational therapist, vision specialist, a learning specialist, a social worker, and caregiver from the family. Given that this group of professionals is typically only available in large well-funded medical facilities and rehabilitation centers often located in large cities, adults with severe communication disorders who lack transportation, are poor, or live outside of large cities do not have access to the professionals they need. To reduce the burden, WHO wants individuals to be able to access all their Assistive Technology (AT) services, which includes AAC, at one location.

The contributions mentioned in the previous two paragraphs are significant because they address two critical barriers in the AAC field. The first barrier is the lack of standard methodologies for the selection of the most suitable AAC option according to each patient's case. Multiple appointments are needed to find the best AAC fit for the patient's disability profile from a large pool of equipment options. In addition, the selection of an unsuitable AAC device can lead to the abandonment of the device and can hinder the patient's ability to manage basic communication needs [4]. The second barrier is the lack of access to patient care. According to the International Classification of Functioning, Disability, and Health (ICF) framework [5], an all-inclusive patient evaluation is necessary to identify and describe strengths and weaknesses in verbal communication, co-morbid deficits, limitations in activity, and contextual factors that serve as barriers to functional communication and poor patient quality of life. Unless the patient lives in a large metropolitan area and has transportation, the patient will need to attend multiple appointments at different locations with different health professionals, to be fitted correctly for an AAC device.

This research is innovative because it presents a new and substantially different way of (1) systematically matching AAC devices to patients with complex communication impairments and (2) providing AAC services to patients who lack transportation, and/or live in rural areas. The results of this work are expected to have a positive impact in advancing the fields of AAC by creating an algorithm that systematically matches AAC devices with a patient's disability profile, a process that currently is based solely on the allied health professionals' judgement. This work will also have a positive impact on operations research and systems engineering by demonstrating how concepts and processes from these disciplines can be integrated to improve access to AAC services for patients in need. Furthermore, for patients who lack transportation and/or live in rural areas, the developed work will serve as a step forward for the development of a mobile clinic that will reduce the patient's current need of attending multiple appointments at different locations with different professionals, a behavior that creates both an economic burden and a caregiver burden.

1.1. Thesis Outline

The thesis document is organized as follows. Chapter 2 explores a detailed literature review addressing the research goals. It is structured as two sections; the first section explores previous work that considers optimization models for the assignment of resources and the second section surveys literature related to the use of systems engineering principles in developing a system concept. Chapter 3 recounts the development of the AAC device assignment tool. The computational study and the analysis of results obtained from the device assignment tool are also addressed in this section. Chapter 4 details the concept definition of the AAC assessment vehicle using the systems engineering principles. Finally, Chapter 5 summarizes the overall research contributions and possible future research directions.

2. LITERATURE REVIEW

The literature review is organized as two sections addressing each of the two specific aims in this research. Section 2.1 focuses on the aim of developing optimization models and solution algorithms to find the best-suited device for a patient with complex communication needs. Given that research in the context of allocation of Augmentative and Alternative Communication (AAC) medical devices to patients is nil, this section explores research papers that discuss some of the elements that are similar to the aforementioned aim. Section 2.2 addresses the aim of deriving a mobile AAC assessment vehicle concept using the systems engineering life cycle model. This section summarizes the literature concentrating on the challenges in the design of mobile health clinics and the design and control of novel systems using systems engineering principles.

2.1. AAC Device Assignment Tool

There are numerous applications that consider the use of optimization models for resource allocation; however, no research papers have considered the use of optimization techniques and solution algorithms to find the best AAC device fit for patients suffering from conditions associated with neurological disorders. The focus of this literature review is on applications that consider some of the elements associated with our problem. Patient-organ donation and allocation, selection of suppliers by organizations, assignment of stock-keeping units to optimal locations and assignment of projects to students are some of the applications that use optimization models for the allocation of resources. The following paragraphs in this section summarize the research papers that present the resource allocation approaches used in these applications. The allocation models discussed in these applications are mathematically similar to the problem addressed in the research work in the context of assigning the best-fit device for the utilization of an AAC user. However, none of these existing models can be used to address the unique issue of assigning the best-fit AAC device for an AAC user. In the following sections, (a) each of the aforementioned existing models is discussed, (b) reasons are given as to why the models are inadequate for an AAC allocation model, and (c) solutions are identified to create a new allocation model designed to assign the best-fit AAC device to an AAC user.

Given the enduring scarcity of donated organs for transplantation, several allocation models that use data mining techniques have been developed to identify patterns critical to assigning an organ to a patient in need of a transplant. Su and Zenios [6] presented a kidney allocation framework that captures the imbalance between patient choice and social welfare. The authors present a model in which candidates form different queues based on the type of kidney to be received. The problem is solved using a subjective partition policy by dividing the organ supply among the different queues to maximize social welfare. Later, Su and Zenios [7] developed a sequential stochastic assignment model taking into consideration the patients' choice on the allocation and acceptance of kidney. An incentive compatibility condition is derived by the authors to ensure that the offers made by the allocation policy are never declined. The algorithm presented in the paper suggested an optimal allocation policy that maximizes total expected reward for patients. Segev et al. [8] proposed a software based on the maximization of edge-weight matching of a kidney-patient pair. The algorithm determines the compatible patient-donor pairs and compares all the possible combinations to find the optimal pair. Biro and Cechlarova [9] framed the kidney assignment as a Game theory model in which the patient-donor pairs are assigned as the players. The Top Trading Cycles algorithm results in one core solution for assignment. Akan et al. [10] developed a dynamic fluid model for liver allocation maximizing the quality-adjusted life years of the patients. The system ranks the patients in different classes based on a trade-off between medical urgency and the impact of the transplant on the future well-being of the patient.

Koyuncugil and Ozgulbas, Bertsimas et al. and Ahmadvand and Pishavee [11-13] used data-driven methodologies for designing kidney allocation models. Koyuncugil and Ozgulbas [11] designed a system based on the A-priori algorithm that aims to find important factors to match the corresponding donors via a SQL query. Bertsimas et al. [12] proposed a mechanism of estimating weights of scoring rules for patients on the waiting list. The resulting scoring policy aimed to maximize the life years of the patients from the transplant. Ahmadvand and Pishavee [13] framed a data-envelopment analysis (DEA) model to augment the efficiency of organ allocation. This model assigns the candidate-organ pairs as decision-making units and minimizes the unit's deviation from its ideal efficiency score using fuzzy logic. The papers just reviewed as part of this section present examples of methodologies that exploit data mining techniques to discover patterns that aid in allocation. The next section shows how these methodologies can be applied to AAC equipment allocation.

The principles involved in organ allocation are substantially similar to those that are applied in AAC equipment allocation. The mathematical models discussed in the reviewed research papers consider patients' attributes such as blood group, tissue matching, the age of the patient, expected waiting time for transplant, and life years from transplant and the medical attributes of the organ. In the AAC allocation model studied in this thesis, the physical attributes affecting the patient include: cognition and communication abilities, the psychosocial competence of the patient, which is the ability to maintain a state of well-being and establish positive and adaptive behaviors, and the performance characteristics of the AAC devices. Kidney allocation models are derived as a sequential decision-making process and have the objective of maximizing the quality-adjusted life expectancy of the patients. Similar to the kidney allocation model, the thesis approach aims to maximize the utility for the patient by using discretized qualitative data. The model presented in this thesis considers factors like family support and willingness of the patient to use AAC devices, which are unique to the AAC device assignment model. In the circumstance of organ allocation, the demand for resources is hefty and the supply is limited due to the scarcity of organs. On the contrary, for AAC device allocation, the demand is from a single patient and the supply of AAC devices is plentiful. The Supplier selection optimization models, discussed next, offer model features that reflect the supply and demand relationship similar to the AAC device assignment.

Supplier selection optimization is the process by which a large number of suppliers' performances and abilities are studied to select the most appropriate supplier for the organization's project. Similar to the Supplier Selection models, the optimization model presented in this thesis examines the attributes of the devices to select the best-fitting AAC device for an individual in need. A wide range of practices and methodologies has been applied in supplier selection. In this review, a sample of supplier selection papers is chosen to summarize methods relevant to the AAC device assignment setting. Cao and Wang [14] formulated a combinatorial two-stage optimization model to help the clients find the best vendor match for an outsourced project. Due to the NP-hardness (non-deterministic polynomial-time hardness) of the problem, an exact optimal solution is not possible.

Nevertheless, the authors formulated a search procedure that always finds the optimal solution. Ebrahim et al. [15] formulated a multi-objective linear integer program for the assignment of suppliers. The model is solved using two sets of algorithms, namely, scatter search algorithm and branch and bound algorithm. Erdem and Gocen [16] and Ting and Cho [17] applied the analytical hierarchy process (AHP) to acquire a total weight for the contender suppliers. The hierarchical decision-making procedure is utilized to find a set of potential suppliers; however, due to the pair-wise comparison procedure, AHP can compare a minimal number of decision variables, usually not more than 15. Beauchamp et al. [18] modeled the supplier selection problem as a generalized assignment problem since there were capacity constraints for the suppliers. The authors developed three different optimization models to maximize the overall matching score between the requested services by the organization and the suppliers' advertisements. Most problems presented in the optimization of supplier selection is formulated for matching many suppliers to many projects, the decision making process in AAC device assignment is to find a group of devices best fit for one patient. Erdem and Gocen [16] and Ting and Cho [17] utilized AHP to identify a set of candidate suppliers for the project, whereas AAC device assignment is accomplished by integer programming.

The assignment of stock-keeping units to optimal storage locations [19] is also a problem with similarities to the problem studied in this thesis. Similar to the model presented in this thesis, the assignment of stock keeping units is executed by constructing mathematical programming models to optimize the resource (storage location) allocation. A few approaches in stock-keeping assignment introduce integer programs to maximize the overall fitness identical to the method in AAC device assignment. Some of the most relevant studies for this problem are discussed next.

Chen and Lu [20] proposed a mixed-integer programming model to solve the storage location assignment problem for outbound containers in maritime terminals. The assignment is solved by minimizing the number of re-handle operations during stacking. Pang and Chan [21] developed an algorithm for storage location assignment that minimizes the manual labor in the warehouse operations. The authors formulated an integer program with the objective function of maximization of fitness, which is determined using association strength in data mining. Bazzazi et al. [22] solved the storage space allocation problem using a meta-heuristic approach known as Genetic Algorithm. The resulting algorithm operates by exploring a population of solutions simultaneously to determine the fittest solution space. Analogous to the approaches presented in the context of storage allocation, this thesis constructs a mathematical framework incorporating optimization techniques for the AAC device allocation process. The characteristics considered for storage location allocation are the frequency of the order of the product, the turnover rate of the stock, correlation with the other products in the warehouse and the distance of the storage location from the input/output area. The model presented in this thesis considers the communication and cognition abilities of the patient and the performance attributes of the AAC device for allocation. The above-mentioned papers frame their assignment models to minimize the travel distance or the cost involved in the transfer of stock, while the model presented in this thesis aims to optimize the assignment by maximizing the utility of the device for the AAC patients. In the context of storage location allocation, multiple products are being optimally assigned to multiple locations whereas AAC device assignment deals with the allocation of the best-fit AAC device from multiple communication devices for the usage of a single AAC patient. Also, the models discussed in storage location assignment are associated with static systems. Conversely, the process of identifying the best-fit AAC device for an AAC user is associated with a dynamic system because the neurological conditions of AAC users vary greatly across users and often change within users, particularly for users with degenerative neurological disorders. So, an AAC allocation model requires the assignment of weights to maximize fitness. The Genetic Algorithm model, discussed next, includes weighted scores to maximize fitness.

Harper et al. [23] used the Genetic Algorithm for the allocation of projects to students based on their preferences. The model considers penalty weights by assigning scores to preferences to maximize the satisfaction of the students. Similar to the project assignment model, the model presented in this thesis intends to find an optimal assignment by maximizing the fitness. The project assignment is only based on the preferences specified by the students for the projects; however, for the allocation of an AAC device, numerous characteristics of the patients such as mobility and communication skills of the patients as well as performance attributes of the AAC device need to be considered.

In contrast to the above-referenced literature, the first goal of this thesis is to allocate the best-suited AAC device for a patient with complex communication needs, which has not been explored in any research papers. Critical features of the AAC allocation model created in this thesis include the supply and demand relationship and the use of deterministic score to translate qualitative results to quantifiable values. The allocation model matches the features of the communication device with the diagnostic profile of the patients to maximize the utility of the device. The literature addressing the second thesis aim of developing a concept definition for a mobile AAC assessment vehicle is discussed in the next section.

2.2. AAC Mobile Assessment Vehicle

The use of systems engineering life cycle model for the design of mobile healthcare vehicles has not been studied in any research work. Therefore, the focus of this section is to review a sample of papers on the design of mobile healthcare vehicles and the technical system design using the fundamental concepts and tools of systems engineering. Information gleaned from these papers will be used in this thesis to create an AAC mobile assessment vehicle.

Qualitative studies by Aung et. al [24] indicate that mobile clinics eliminate many logistical barriers to customary forms of healthcare, such as transportation, complications in appointments, long waiting times and complex administrative processes. Higier et. al [25] designed a renewable energy powered mobile medical clinic with an automated modular control system. The integration of the different renewable energy technologies was done by developing a unique control system which regulated battery charging. Ferreira and Hignett [26] examined the inadequacies of healthcare vehicles for clinical efficiency. The authors used link analysis to study the patient compartment layout with reference to the performance of tasks. The team fabricated an ideal layout allowing access to all necessary equipment for the paramedics to administer medical services from a safe working position. Hignett et. al [27] investigated the short and long-term requirements of future mobile healthcare services. The authors identified nine challenges with respect to the design of the vehicle: access of patients; space and layout design; securing patients and paraphernalia during transportation; communication; security; sanitation; equipment;

engineering of the vehicle; and patient experience. Chen et. al [28] studied a mobile mammography unit to determine the impact on service quality. It is noted that the use of portable machines resulted in an inferior intrinsic quality of imaging compared to traditional clinics, leading to client dissatisfaction. The proposed concept of the mobile AAC assessment vehicle aims to address the limitations presented in the aforementioned papers to reach its full potential in fitting AAC devices to patients with complex communication needs.

Systems engineering centers on the design, control, and instrumentation of system activities to meet performance requirements [29]. Calvano and John [30] studied the creation of Complex Engineered Systems (CESs) using the systems engineering approach and discussed the challenges faced due to complexity. The study focused on a systematic approach to understand the nature of systems and to recognize, characterize, and quantify the nature using systems engineering tools. Hanson et. al [31] developed and validated a medical system with capabilities for Mars transit using a Model-Based Systems Engineering (MBSE) approach. The MBSE approach uses Systems Modeling Language (SysML) to model the medical system functional needs, requirements, and architecture. The design of the system validated the central mission of streamlining future integration with a robust design to meet crew health needs during Mars transit. Hazare and Venhovens [32] used the system engineering method for the conceptual design of vehicle handling dynamics. The authors systematically derived vehicle, subsystem, and component-level specifications to meet the customer's requirements under realistic design constraints. Kopach-Konrad [33] presented important parallels between systems engineering and health services. The paper states that systems engineering is instrumental in making design and operational decisions for implementation and anticipation of success and in helping to re-engineer healthcare delivery. Researchers have explored systems engineering approaches along several dimensions; however, using systems engineering methods for the derivation of a mobile healthcare unit concept for fitting AAC devices to patients with complex communication needs makes the this research a novel project.

3. AAC DEVICE ASSIGNMENT OPTIMIZATION

The goal of this research is to improve the decision-making process for patients in need of AAC. As stated in Chapter 1, the first research aim is to develop optimization models and solution algorithms that can help in recommending the best (top three) group of devices to consider for a patient based on a disability profile. Currently, there are multiple companies that offer many products/devices targeting patients in need of AAC. However, the decision-making process of what device to try on the patient is primarily based on the health professional's experience and familiarity with specific devices or companies. The models discussed in this chapter will minimize patient discomfort and reduce device assessment time by recommending a limited list of devices that are guaranteed to provide the best fit based on the patient's disability profile.

3.1. Methodology

The methodology for selecting the best AAC device(s) uses the patient's disability profile to select AAC devices that are more likely to meet the patients' needs. A large variety of AAC devices are available for patients in need. The number of devices available is large because no single device can offer efficient and effective communication to all people with complex communication needs. Currently, the Texas Technology Access Program has about one-hundred devices listed on their website for patients in need of borrowing AAC devices. The role of the decision-making methodology is to provide a systematic process that matches a patient's disability profile to the attributes of the wide range of AAC devices available. Figure 1 depicts the decision-making framework for the selection of AAC devices.

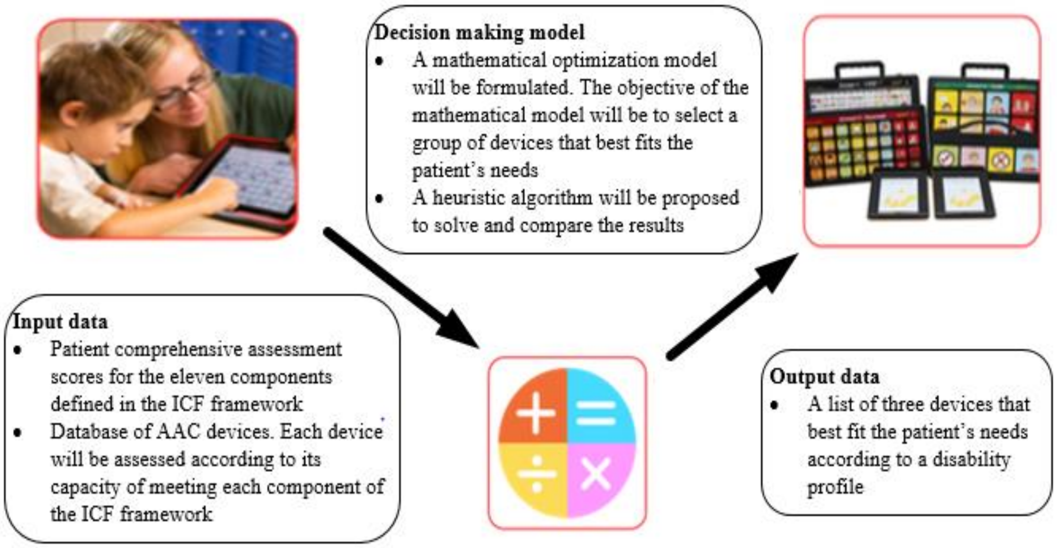

Figure 1: Decision-making framework for selecting AAC devices

The input component of the methodology includes two types of data. The first group of data comes from the patient and includes the comprehensive assessment scores for the thirteen components defined in the International Classification of Functioning, Disability, and Health (ICF) framework. The second group of data contains information about each AAC device considered as an option for the patient disability. Each device is assessed according to its capability of meeting each component of the ICF framework.

Both data groups are discretized using a deterministic selection score. For the patient data, the scores translate the qualitative results from the ICF framework assessments to quantifiable values. The evaluation score set for each ICF framework assessment is E =[1, 2, 3, 4], where 1 $=$ "$poor$", 2 $=$ "$fair$", 3 $=$ "$average$", and 4 $=$ "$good$". For the device data, the scores are used to characterize the competency of available devices to satisfy each component of the ICF framework. Each device $i \in I$ is evaluated using a set of relevant assessments $j \in J$ from the ICF framework. The device evaluation score for each device i and each ICF assessment j is denoted by $d_{ij} \in E$. The patient evaluation scores for each ICF assessment $j \in J$ are denoted by $s_j \in E$. The thirteen components of the ICF framework [5] are listed below:

1. *Sensory and Motor Status*: The sensory and motor status assessment includes vision test, sensation status and the integrated sensory system ability. Vision test mainly focuses on the ability of the patient to see the symbols or orthography on the AAC device. Sensation assessments include light touch and pressure test, proprioception test, temperature test and pain test. The integrated sensory assessment tests the patient's ability to regulate and ready the body for communication.
2. *Hearing Screening*: A pure-tone test is the most common hearing screening. It is an assessment to see how well the patient hears different sounds. Failing a hearing screening does not mean that the patient has a hearing loss. If the patient fails, he/she requires a complete hearing test by an audiologist to determine the degree of hearing loss.
3. *Speech-Sound Assessment*: Speech-sound assessment of a patient can help in the identification of factors that contribute to the speech-sound disorder and description of the characteristics and severity of the disorder. The severity of the patient case is often defined along a continuum from mild to profound.
4. *Spoken Language Assessment*: Standardized language screening is used to identify the broad characteristics of language functioning. A literacy assessment is included in the comprehensive assessment for language disorders because of the well-established connection between spoken and written language.
5. *Written Language Assessment*: Assessments of reading and writing skills must be linguistically appropriate, culturally relevant and functional. Screening can result

in the determination of premorbid and current literacy level of the patient with complex communication needs.

6. *Social Communication Assessment*: Social Communication screening includes the use of competency-based tools such as interviews and observations and self-report questionnaires. The assessment helps to identify underlying strengths and weaknesses in communication and communication-related areas and limitations in activity and participation, including functional communication and interpersonal interactions.
7. *Cognitive Communication Assessment*: Cognitive-Communication deficits result from underlying cognitive or thinking difficulties in attention, memory, organization, reasoning, executive functions, self-regulation, or decreased information processing. Cognitive communication screening helps in identifying cognitive and communication demands of relevant real-world contexts.
8. *Symbol Assessment*: Symbol assessment process involves the screening of patients in the identification and recognition of the type of symbols, symbol size, field size and organization of display.
9. *Feature Matching Assessment*: Feature Matching is a collective process which involves using criterion-based assessment plans to gather relevant information about an individual's communication. Feature matching allows identification of the most appropriate applications available in the AAC devices.
10. *Identification of Contextual Facilitators and Barriers*: Facilitator Screening identifies the ability and willingness of the patient to use AAC systems, family support and the patient's motivation to communicate. The barriers during the

assessments include cognitive deficits, visual and motor impairments, lack of acceptance of disability and/or AAC use, limitations of AAC system, seating and positioning limitations across environments.

11. *Case History*: Medical status and history, education, occupation, and cultural and linguistic backgrounds are considered a part of the patient's case history. Prognosis and the potential for disease progression are also deliberated in determining the best- suited device for the patient.
12. *Ecological Inventory*: Ecological inventory identifies the current communication skills in relation to similarly impaired peers. This assessment also considers the communication needs and potential AAC use of the patient.
13. *Self-report*: The languages preferences, social interactions and work activities of the AAC patient are assessed to gather the relevant information. Self-report also considers the functional communication difficulties of the AAC patient and the impact it poses on their family.

3.2. Mathematical Model

An Integer Programming (IP) model serves as the decision-making tool to find the best-fit AAC device for a patient. The objective function of the model is to maximize the patient-device fit. The model takes the input parameters discussed in Section 3.1 and finds n number of devices that are more appropriate for the patient given the patient's disability profile. Table 1 lists the sets, parameters, and decision variables used to formulate the model and Equations (1) to (7) provide the model equations. Equation (2) checks if the patient assessment score for assessment j is greater than or equal to device i score. Device i score for assessment j (d_{ij}) represents how well the device i meets the needs of assessment j. Equation (3) is used to check if device i overall evaluation with respect to the patient needs is greater than or equal to the required level of satisfaction. Equation (4) limits the number of devices to be selected to no more than n. Equation (5) is a selection constraint. Finally, Equations (6) and (7) limit the decision variables to assume binary values.

Table 1: Integer Programming (IP) model sets, parameters, and variables

Sets	
I	Set of AAC devices, with index $i \in I$ representing a particular device
J	Set of ICF assessments, with index $j \in J$ representing a particular assessment
E	Evaluation score set for each ICF framework assessment $j \in J$. $E = [1, 2, 3, 4]$.
Parameters	
d_{ij}	Device i evaluation score for ICF assessment j, $d_{ij} \subset E$.
s_j	Patient evaluation scores for ICF assessment j, $s_j \subset E$.
β	A percentage used to establish the minimum total number of ICF assessments that must be passed in order for the device to be consider a good fit for the patient.
n	Minimum number of AAC devices to be recommended for consideration given the patient disability.
w_j	Weight used to denote the importance of assessment j. High w_j's identifies patient priorities in terms of their disabilities as measured by the ICF assessments.
Decision Variables	
x_i	A binary variable that determines the devices selected for the patient. $x_i = 1$, if device i is recommended for the patient case and 0 otherwise.
y_{ij}	A binary variable that determines if device i satisfies patient assessment j. $y_{ij} = 1$, if device i passes assessment j and 0 otherwise.

$$\max \ z = \sum_{i \in I} \sum_{j \in J} w_j y_{ij} \qquad (1)$$

Subject to:

$$s_j \, y_{ij} - d_{ij} y_{ij} \geq 0, \qquad \forall \, i \in I, \ \forall \, j \in J \quad (2)$$

$$\sum_{j \in J} \frac{1}{|J|} y_{ij} \geq \beta x_i, \qquad \forall i \in I \qquad (3)$$

$$\sum_{i \in I} x_i \geq n, \qquad (4)$$

$$y_{ij} - x_i \leq 0, \qquad \forall\, i \in I, \forall j \in J \qquad (5)$$

$$x_i \in \{0,1\}, \qquad \forall\, i \in I \qquad (6)$$

$$y_{ij} \in \{0,1\}, \qquad \forall\, i \in I, \forall j \in J \qquad (7)$$

The percentage of satisfaction β and the minimum number of AAC devices n to be recommended for consideration can be varied given the patient disability. A patient with severe disabilities may secure low scores of 1 and 2 for most assessments whereas a patient with low disabilities obtains scores between 1 and 4 for the medical assessments. There are two sets of binary decision variables present in the model: decision variable y_{ij} determines if device i satisfies patient assessment j and decision variable x_i determines which devices are to be assigned to the patient. The goal of the objective function in the mathematical model is to maximize the device satisfaction for the patient by selecting the devices with the highest matching scores. The decision-making process matches the conforming scores of the patient's profile with the devices and selects the devices with the highest fitting score to be recommended for the patient. The number of decision variables and constraints for different instances are depicted in Table 2. Since the problem is an integer programming problem its complexity is considerable, and the number of decision variables and constraints increase linearly with the increase in the number of devices considered.

Table 2: Number of decision variables and constraints for the devices

Instance Number	**Number of devices**	**Decision variables**	**Constraints**
1	20	240	701
2	50	600	1751
3	100	1200	3501

3.3. Solution Method

The Integer Programming model is solved using the Microsoft Excel OpenSolver software. A solution algorithm is proposed to make the decision-making process more efficient in terms of a health professional using the tool to determine the best-suited device for an AAC patient with complex communication needs. The solution algorithm is easy to use and provides a solution without the need for sophisticated solvers. The solution algorithm is coded using PHP (Hypertext Preprocessor) [34] language and the database is managed using MySQL. The software tool phpMyAdmin is used to administer the algorithm over the Web. The Decision-Making Algorithm (DMA) for device assignment is described next.

Table *3* displays the definitions of the terms presented in the pseudocode of the algorithm. The input parameters for the model include patient evaluation scores for each assessment, device assessment score for each assessment, assessment weights, minimum number of assessments to be satisfied and the number of devices to be selected. Through lines 4 to 19 of the pseudocode, device assessment scores for each device are compared with the patient evaluation score for every assessment to determine the total match score and the device satisfaction score for each device. Lines 8 to 15 indicate that match score is determined to be one if the patient evaluation score for an assessment is greater than or equal to the device assessment score for the same assessment or else, it is directed to be zero. The total match score of a device is obtained by the sum of the all the assessment match scores for a device. The weighted satisfaction score is calculated by multiplying the match score of each assessment with the assessment weight for every device. The sum of the weighted satisfaction score for all the assessments provides the total device satisfaction score for the device. Device selection process is detailed in the lines 20 to 43 of the pseudocode. In the event that the total match score of the device is greater or equal to the number of assessments to be satisfied, the device is selected and arranged in descending order of the device satisfaction scores. The devices with highest device satisfaction scores are displayed as the output to be recommended to the patient.

Table 3: Definitions of terms used in the pseudocode

S. No	**Name**	**Type**	**Definition**
1.	da_scores[m,$n+1$]	Array	Contains the scores for assessment $j \in J$ for device $i \in I$ and device number in the first column.
2.	n	Integer	Number of assessments $\lvert J \rvert$
3.	m	Integer	Number of devices considered for the patient $\lvert I \rvert$
4.	p_scores[n]	Vector	Contains assessment $j \in J$ scores for the patient
5.	a_weights[n]	Vector	Contains assessment $j \in J$ benefit weights
6.	devices_selected	Integer	Minimum number of AAC devices $i \in I$ to be recommended for consideration given the patient disability.
7.	min_sum_assessments	Integer	An Integer used to establish the minimum total number of ICF assessments $j \in J$ that must be passed for the device $i \in I$ to be considered a good fit for the patient.
8.	sum_assessments[m]	Array	Sum of all the satisfied assessments $j \in J$ for each device $i \in I$.

Table 3 : Continued

9.	sum_a_weights[m]	Array	Sum of all the satisfied assessments $j \in J$ multiplied with the weight of the respective assessment for each device $i \in I$.
10.	device_weights[p,2]	Array	An array generated for all the devices $i \in I$ that satisfy the min_sum_assessments with two columns (da_scores[p,0], sum_a_weights[p]).
11.	p	Integer	Number of devices $i \in I$ that satisfy the min_sum_assessments.
12.	temp	Variable	A variable to store temporary values.
13.	count	Integer	Count of the number of devices selected to be displayed as the result.

1: READ array da_scores[m,$n+1$], array a_weights[n]

2: GET array p_scores[n], Integer devices_selected

3: SET Integer min_sum_assessments = 10

4: FOR ($i = 0$; $i \leq m$; i++){

5: Integer counter = 0

6: Integer weight = 0

```
        FOR (j = 1; j ≤ n + 1; j++) {
                IF (da_scores [i, j] ≤ p_scores [j − 1] {
                        counter = counter + 1
                        weight = weight + a_weights[j − 1]
                }
                ELSE{
                        counter = counter + 0
                        weight = weight + 0
                }
                sum_assessments[i]= counter
                sum_a_weights[i]= weight
        }
}
FOR (i = 0; i ≤ m; i++){
        IF( sum_assessments[i] ≥ min_sum_assessments){
                device_weights[i,0]= da_scores [i, 0]
                device_weights[i,1]= sum_a_weights[i]
        }
```

```
}
temp= 0
FOR(i = 0; i ≤ p; i++){
    IF(device_weights[i + 1,1])> device_weights[i,1]){
        temp = device_weights[i,1]
        device_weights[i,1] = device_weights[i + 1,1]
        device_weights[i + 1,1]= temp
    }
}
count = 0
IF (p > 0){
    FOR(i = 0; i ≤ p; i++){
        PRINT “Device No is: “device_weights[i,0]” and Total
        Weighted Device score is: “device_weights[i,1]”
    }
    count= count+1
}
ENDIF (count = devices_selected)
```

```
ELSE{
    PRINT “0 rows with min_sum_assessments satisfied"
}
```

3.4. Computational Study

This section investigates the effect of input parameters on the overall device satisfaction by conducting statistical experiments with the optimization model. A general factorial design was considered to conduct a total of 81 runs with no replications. The experiments consider four input factors with three levels each that contribute to the output response of overall device satisfaction for the patient. The four factors include ‘Patient condition’, ‘Number of devices available’, ‘Assessment weight distribution’ and ‘Minimum level of assessment satisfaction’. Figure 2 displays the input factors and the output responses of the experimental model.

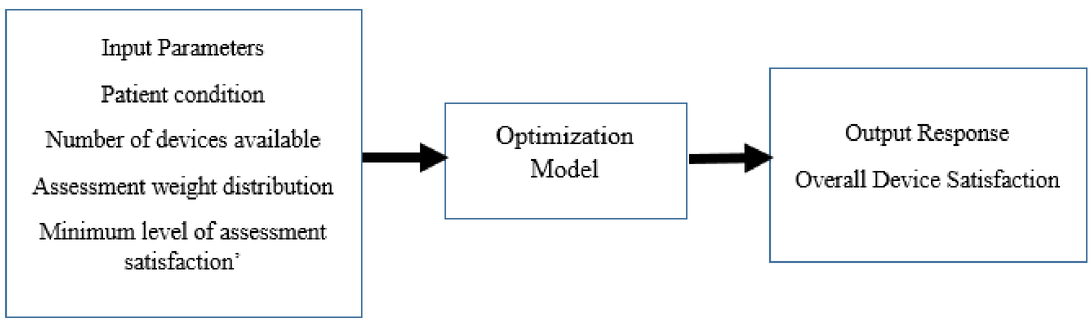

Figure 2: Factors and performance measurements in the study

The factor levels depicted in Table 4 are designed to incorporate variability in the statistical experiments. The factor ‘patient condition’ compares patients at three different levels of medical conditions namely minor, moderate and severe. Patient condition is determined based on the scores obtained by the patient for the medical assessments. The attainable scores span from 1 to 4 ranging from the lowest to the highest possible score. A patient with severe medical condition secures low scores of 1 and 2 for most assessments.

A moderate level patient often scores between 1 and 3 and a patient with minor medical condition receives scores between 1 and 4 for the medical assessments.

'Assessment weight distribution' denotes the importance of the assessments and helps to identify the patient priorities in terms of their disabilities. The levels categorize the factor to be equally weighted where the weights are distributed equally among the assessments, highly weighted on needs for which 80% of the weights are distributed among a few assessments which concentrate on medical needs and 20% of the weights distributed among the other assessments and randomly weighted where the weights are distributed randomly among the assessments.

The factor 'minimum level of assessment satisfaction' is a percentage used to establish the minimum number of assessments each device must satisfy for the device to be considered a good fit. The choice environments of 70%, 80% and 90% minimum assessment satisfaction are considered for experimental purposes. 'Number of devices available' addresses the size of the device pool accessible to the patients. The three levels considered for the factor are 20 devices, 50 devices and 100 devices.

Table 4: Experimental factors and corresponding levels

Factors	**Level**		
	Low(L)	*Medium (M)*	*High(H)*
Patient Condition	Minor UNIF(1,4)	Moderate UNIF(1,3)	Severe UNIF(1,2)
Number of devices available	20	50	100
Assessment weight distribution	Equally weighted	Highly weighted on needs	Randomly weighted
Minimum level of assessment satisfaction	70%	80%	90%

The goal of this computational analysis is to study the effects of the experimental factors on the overall device satisfaction for the patient. Table 5 displays the general factorial design of the four factors varying each of them at three levels to consider all possible combinations and the overall device satisfaction (i.e. value for the response variable) for each run. The table also shows the devices selected by the optimization model and the algorithm for each experimental combination. While some of the factors like patient condition are beyond control, factors like the level of satisfaction and assessment weight distribution can be controlled. The analysis of the results presented in Table 5 can help to identify the factors posing high influence on the overall device satisfaction.

Table 5: Experimental Results

Run No.	**Patient Condition**	**Devices Available**	**Weight Distribution**	**Assessment Satisfaction**	**Optimization Solution**	**Algorithm Solution**	**Device satisfaction**
1	Minor	20	Randomly	70%	6, 10, 11, 12, 13	6, 10, 9, 11, 12	4.85
2	Minor	20	Randomly	80%	6, 10, 11, 12, 13	6, 10, 9, 11, 12	4.85
3	Minor	20	Randomly	90%	6, 10, 11, 12, 13	6, 10, 9, 11, 12	4.85
4	Minor	20	Highly	70%	5, 6, 10, 17, 18	6, 10, 5, 8, 9	4.76
5	Minor	20	Highly	80%	5, 6, 10, 17, 18	6, 10, 5, 8, 9	4.76
6	Minor	20	Highly	90%	5, 6, 8, 10, 11	6, 10, 5, 8, 9	4.76
7	Minor	20	Equally	70%	6, 8, 10, 11,12	6, 10, 5, 8, 9	4.769
8	Minor	20	Equally	80%	5, 6, 8, 9, 10	6, 10, 5, 8, 9	4.769
9	Minor	20	Equally	90%	5, 6, 10, 17, 18	6, 10, 5, 8, 9	4.769
10	Minor	50	Randomly	70%	33, 40, 42, 48, 50	6, 10, 31, 33, 40	5
11	Minor	50	Randomly	80%	31, 40, 42, 48, 50	6, 10, 31, 33, 40	5
12	Minor	50	Randomly	90%	6, 31, 42, 48, 50	6, 10, 31, 33, 40	5
13	Minor	50	Highly	70%	33, 40, 42, 48, 50	6, 10, 31, 33, 40	5
14	Minor	50	Highly	80%	31, 40, 42, 48, 50	6, 10, 31, 33, 40	5
15	Minor	50	Highly	90%	6, 33, 40, 48, 50	6, 10, 31, 33, 40	5
16	Minor	50	Equally	70%	33, 40, 42, 48, 50	6, 10, 31, 33, 40	5
17	Minor	50	Equally	80%	33, 40, 42, 48, 50	6, 10, 31, 33, 40	5
18	Minor	50	Equally	90%	6, 10, 31, 42, 48	6, 10, 31, 33, 40	5
19	Minor	100	Randomly	70%	72, 75, 88, 91, 92	6, 10, 31, 33, 40	5
20	Minor	100	Randomly	80%	48, 75, 88, 91, 92	6, 10, 31, 33, 40	5
21	Minor	100	Randomly	90%	31, 33, 40, 72, 75	6, 10, 31, 33, 40	5
22	Minor	100	Highly	70%	48, 50, 72, 75, 88	6, 10, 31, 33, 40	5
23	Minor	100	Highly	80%	6, 50, 88, 91, 92	6, 10, 31, 33, 40	5
24	Minor	100	Highly	90%	50, 75, 88, 91, 92	6, 10, 31, 33, 40	5

Table 5 : Continued.

25	Minor	100	Equally	70%	72, 75, 88, 91, 92	6, 10, 31, 33, 40	5
26	Minor	100	Equally	80%	10, 75, 88, 91, 92	6, 10, 31, 33, 40	5
27	Minor	100	Equally	90%	31, 33, 40, 42, 72	6, 10, 31, 33, 40	5
28	Moderate	20	Randomly	70%	9, 11, 13, 17, 18	18, 9, 13, 17, 4	4.25
29	Moderate	20	Randomly	80%	9, 11, 13, 17, 18	18, 9, 13, 17, 4	4.25
30	Moderate	20	Randomly	90%	18	18	0.95
31	Moderate	20	Highly	70%	4, 10, 13, 17, 18	18, 4, 10, 13, 17	4.28
32	Moderate	20	Highly	80%	4, 10, 13, 17, 18	18, 4, 10, 13, 17	4.28
33	Moderate	20	Highly	90%	18	18	0.96
34	Moderate	20	Equally	70%	4, 9, 12, 13, 18	18, 4, 9, 10, 11	4.153
35	Moderate	20	Equally	80%	4, 9, 18	18, 4, 9	2.615
36	Moderate	20	Equally	90%	18	18	0.923
37	Moderate	50	Randomly	70%	18, 33, 48, 49, 50	33, 48, 18, 50, 21	4.775
38	Moderate	50	Randomly	80%	18, 33, 48, 49, 50	33, 48, 18, 50, 21	4.775
39	Moderate	50	Randomly	90%	18, 33, 48, 49, 50	33, 48, 18, 50, 21	4.775
40	Moderate	50	Highly	70%	18, 33, 48, 49, 50	33, 48, 18, 50, 4	4.78
41	Moderate	50	Highly	80%	18, 33, 48, 49, 50	33, 48, 18, 50, 4	4.78
42	Moderate	50	Highly	90%	18, 33, 48, 50	33, 48, 18, 50	3.92
43	Moderate	50	Equally	70%	18, 33, 48, 49, 50	33, 48, 18, 50, 4	4.692
44	Moderate	50	Equally	80%	18, 33, 48, 49, 50	33, 48, 18, 50, 4	4.692
45	Moderate	50	Equally	90%	18, 33, 48, 50	33, 48, 18, 50	3.846
46	Moderate	100	Randomly	70%	33, 48, 53,75, 77	33, 48, 77, 18, 52	4.85
47	Moderate	100	Randomly	80%	33, 48, 52, 53, 87	33, 48, 77, 18, 52	4.85
48	Moderate	100	Randomly	90%	33, 48, 52, 53, 77	33, 48, 77, 18, 52	4.85
49	Moderate	100	Highly	70%	18, 33, 48, 50, 75	33, 48, 18, 50, 75	4.88
50	Moderate	100	Highly	80%	18, 33, 48, 50, 75	33, 48, 18, 50, 75	4.88

Table 5 : Continued.

51	Moderate	100	Highly	90%	18, 33, 48, 50, 75	33, 48, 18, 50, 75	4.88
52	Moderate	100	Equally	70%	33, 48, 75, 76, 92	33, 48, 18, 50, 52	4.769
53	Moderate	100	Equally	80%	33, 48, 52, 53, 92	33, 48, 18, 50, 52	4.769
54	Moderate	100	Equally	90%	18, 33, 48, 87, 92	33, 48, 18, 50, 52	4.769
55	Severe	20	Randomly	70%	9, 12	9, 12	1.55
56	Severe	20	Randomly	80%	0	0	0
57	Severe	20	Randomly	90%	0	0	0
58	Severe	20	Highly	70%	9, 12, 13, 17, 18	12, 9, 11, 13, 17	1.58
59	Severe	20	Highly	80%	12	12	0.82
60	Severe	20	Highly	90%	0	0	0
61	Severe	20	Equally	70%	9, 12	9, 12	4.538
62	Severe	20	Equally	80%	0	0	0
63	Severe	20	Equally	90%	0	0	0
64	Severe	50	Randomly	70%	29, 33, 48, 49, 50	33, 48, 49, 28, 29	4.45
65	Severe	50	Randomly	80%	29, 33, 48, 49, 50	33, 48, 49, 28, 29	4.45
66	Severe	50	Randomly	90%	33, 48	33, 48	1.925
67	Severe	50	Highly	70%	29, 33, 48, 49, 50	33, 48, 49, 28, 29	4.6
68	Severe	50	Highly	80%	29, 33, 48, 49, 50	33, 48, 49, 28, 29	4.6
69	Severe	50	Highly	90%	33, 48, 49	33, 48, 49	2.88
70	Severe	50	Equally	70%	29, 33, 48, 49, 50	33, 48, 28, 29, 49	4.461
71	Severe	50	Equally	80%	29, 33, 48, 49, 50	33, 48, 28, 29, 49	4.461
72	Severe	50	Equally	90%	33, 48	33, 48	1.923
73	Severe	100	Randomly	70%	33, 48, 51, 75, 87	33, 48, 87, 51, 49	4.625
74	Severe	100	Randomly	80%	33, 48, 51, 75, 87	33, 48, 87, 51, 49	4.625
75	Severe	100	Randomly	90%	33, 48, 51, 87	33, 48, 87, 51	3.75
76	Severe	100	Highly	70%	33, 48, 73, 74, 87	33, 48, 87, 49, 73	4.76
77	Severe	100	Highly	80%	33, 48, 49, 75, 87	33, 48, 87, 49, 73	4.76

Table 5 : Continued.

78	Severe	100	Highly	90%	33, 48, 49, 75, 87	33, 48, 87, 49, 73	4.76
79	Severe	100	Equally	70%	33, 48, 73, 87, 89	33, 48, 87, 28, 29	4.56
80	Severe	100	Equally	80%	28, 29, 33, 48, 87	33, 48, 87, 28, 29	4.56
81	Severe	100	Equally	90%	33, 48, 87	33, 48, 87	2.846

By analyzing the results above, it can be seen that there are many runs in which the devices selected by the optimization model and the algorithm are not identical. This occurs when 2 or more devices with the same device satisfaction score for a patient are present. Table 6 illustrates an example of a run where two out of the five devices selected are different for the optimization model and the algorithm. The device satisfaction score for each device is depicted in Table 5. It is seen that the devices 8 and 9 selected in the place of Devices 17 and 18 have the same score of 0.9. The objective function of the model is to maximize the overall device satisfaction which is the sum of the device satisfaction scores for the devices selected. The overall device satisfaction score is always equal for the optimization model and the algorithm as the different devices selected are always of identical scores. Table 5

displays some runs where the overall device satisfaction score is 0 with no devices selected, this occurs when patients with severe medical conditions are paired with a small number of devices to be matched with.

Table 6: Results for run #5

Optimization Model						
Devices Selected	5	6	10	17	18	**Total**
Device Satisfaction	0.96	1	1	0.9	0.9	4.76

Algorithm						
Devices Selected	6	10	5	8	9	**Total**
Device Satisfaction	1	1	0.96	0.9	0.9	4.76

3.5. Discussion

The factorial analysis of variance conducted compares means across each of the factors to determine the **which** effects **(i.e. factors) and interactions are significant**. Figure 3 depicts the analysis of variance performed for the general factorial experiment shown in Table 5. A significance level of 0.05 is adopted to assess the experimental results.

General Linear Model: Overall Device Satisfaction Score versus Patient Condition, Number of Devices Available, Assessment Weight Distribution, Minimum Level of Assessment Satisfaction

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Assessment weight distribution	2	0.274	0.137	0.150	0.858
Patient Condition	2	49.780	24.890	27.980	0.000
Minimum level of assessment satisfaction	2	16.006	8.003	9.000	0.000
Number of devices available	2	52.241	26.120	29.360	0.000
Error	72	64.060	0.890		
Total	80	182.361			

Model Summary

S	R-sq	R-sq (adj)	R-sq (pred)
0.94325	64.87%	60.97%	55.54%

Figure 3: ANOVA Analysis

The *p*-values shown in the analysis of variance exhibits the strength of evidence for the significance of factors. The factors ‘patient condition’, ‘Number of devices available’, and ‘Minimum level of assessment satisfaction’ display a *p*-value less than 0.05 which indicates strong evidence of significance on the output model. *P*-value of 0.849 exhibited by the factor ‘Assessment weight distribution’ denotes very low significance on the overall device satisfaction. This is also validated by the low *F*-value of 0.15 for the factor demonstrating that the variation in assessment weight distribution does not have a high effect on the output response. The high *F*-values shown by the other factors confirm their significant effect on the overall device satisfaction.

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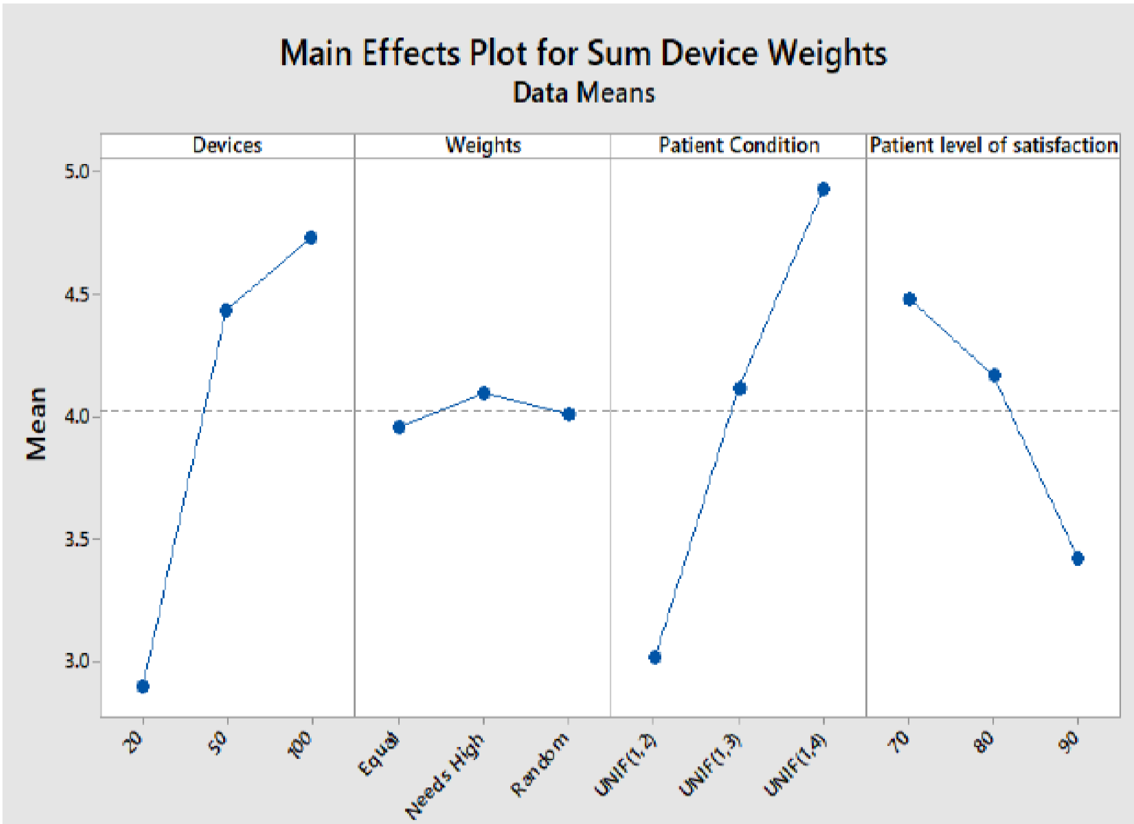

Figure 4: Main Effects Plot

Figure 4 depicts the main effects for each of the factors on the mean of the output response device score presented in Table 5. The main effect of a factor is independent of all other factors and therefore any possible interactions between the factors is disregarded. The mean device satisfaction sharply increases with the increase in the number of devices available. The chances of satisfying the patient needs are higher as choice of devices increases. The factor with the least effect on the output response is the assessment weight distribution which shows low variance in results for the three levels. This supports the evidence of low significance demonstrated by the p-value of 0.849 in the analysis of variance.

The main effects plot illustrates that the mean device satisfaction improves as the patient condition spans from severe to minor medical conditions. This indicates that the prospect of finding devices that satisfy the needs of a patient with severe medical conditions is lower compared to a patient with moderate or minor medical condition. Figure 4 shows that the mean device satisfaction reduces as the minimum level of assessment satisfaction increases. As the threshold level increases for the device to be considered a good fit, number of devices that satisfy the constraints degrade and hence the mean device satisfaction score reduces. It can be seen highest variation in means occur for the independent factors ‘patient condition’ and ‘number of devices available.

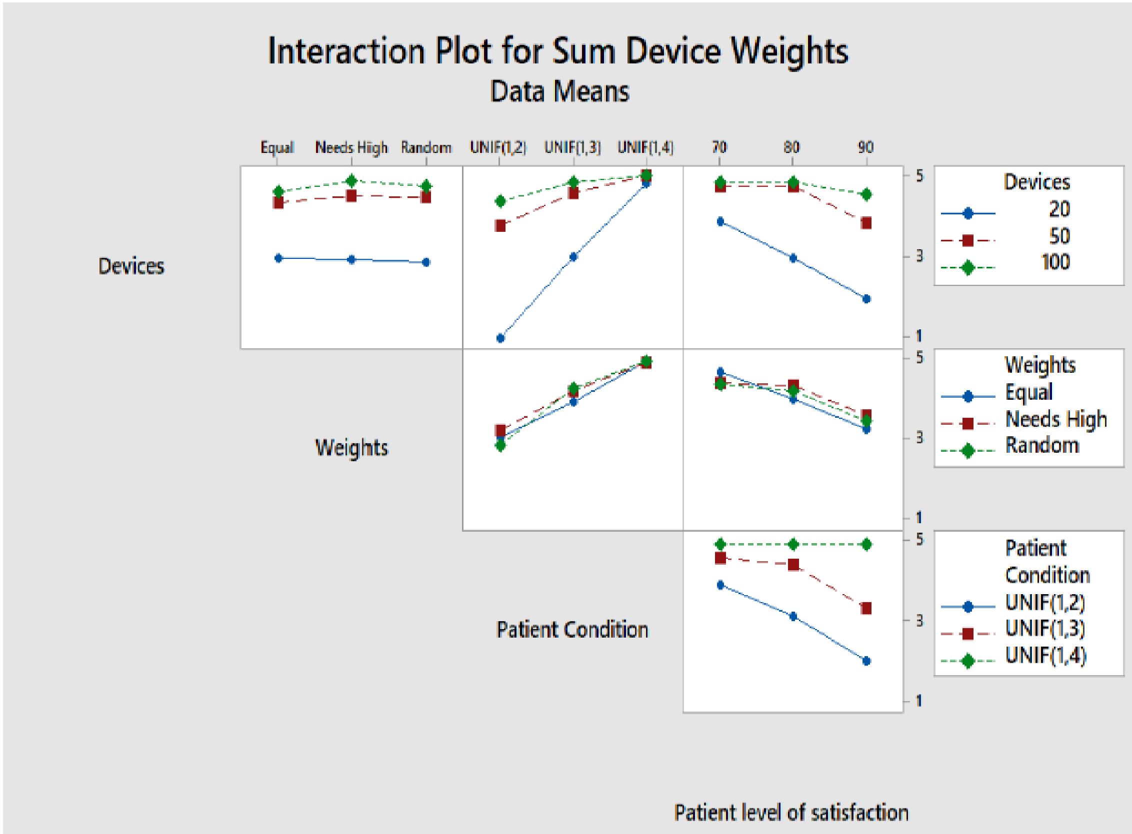

Figure 5: Two-Way Interaction Plot

Figure 5 analyzes possible 2-way-interactions whether the different levels for an independent variable produce results that differ depending on the level considered for the second independent variable. The 'Number of devices' vs 'weight distribution' graph shows that there is very low variance in the overall device satisfaction score when the assessment weight distributions are different. This demonstrates that the weight distribution can be varied without causing much difference on the overall device satisfaction score. From the 'patient interaction' vs 'level of satisfaction' interaction, it is inferred that when the patient condition is minor, the patient level of satisfaction does not have any effect on the output response. The overlapping of the output response for the 2-way interactions with the factor 'assessment weight distribution' confirms the low significance of the factor on the overall device satisfaction score. The two-way interactions of the factor 'level of satisfaction' illustrates that the overall device satisfaction reduces as the level of assessment satisfaction is higher. It is also seen that when the patient condition is minor, the level of satisfaction specified does not influence the response. This shows that there are high chances of finding the best set of devices when the patient condition is minor.

For all the 2-way interactions with the number of devices available, the overall device satisfaction score is much lower when a set of 20 devices is available compared to the occasions with 50 or 100 devices available. The graphs also indicate that there is high overall satisfaction when 100 devices are available regardless of the levels of the factors. There is a drastic reduction in the mean overall satisfaction score as the number of devices reduces. It is evident from the interactions plot that the 2-way interaction with the highest influence is the number of devices available vs patient condition. By studying Figure 4, the least overall device satisfaction occurs for a patient of ‘severe’ patient condition combined with number of available devices being ‘20’. This shows that it is challenging to find a fitting device for a ‘severe’ patient when only 20 devices are available. It is seen that the overall device satisfaction score can be high when only 20 devices are available, the level of satisfaction can be reduced to 70% to determine fitting devices.

4. AAC ASSESSMENT VEHICLE

The Global Cooperation on Assistive Technology (GATE) initiative by the World Health Organization (WHO) envisions a world where everyone in need has access to high-quality affordable Assistive Technology (AT) to lead a fulfilling life [35]. One of the significant challenges faced by patients in need of AT is access to services. Individuals in need of AT often need to attend multiple appointments at different locations with different health professionals to obtain a complete assessment of their condition. Multiple appointments are also needed to find the best AT fit for the patient's disability profile from a large pool of equipment options. The availability of medical services can vary significantly by geographic region [36]. Access to health care is even more challenging for patients living outside urban areas in the United States [37]. The second research aim of this thesis is to derive a healthcare mobile facility concept for patients needing AAC using the systems engineering life cycle model. The vehicle should facilitate the healthcare service delivery for patient condition assessment and AAC device evaluation. The evaluation of the individual's ability for the use of AAC requires evaluation of the user's cognitive and linguistic skills, literacy skills, sensory skills, perception skills, and motor capabilities [38]. The research presents a new and substantially different way of providing AAC services to patients who lack transportation, and/or live in rural areas. The work will also have a positive impact by demonstrating how concepts and processes from systems engineering can be integrated to improve access to AAC services for patients in need.

4.1. Research Methodology

The research aim is to derive a healthcare mobile facility concept for patients needing AAC using the systems engineering life cycle model. The vehicle facilitates healthcare service delivery for patient condition assessment and AAC device evaluation. The mobile AAC assessment vehicle is designed to support the primary goals of providing prime clinical and service quality for outreach and assessment. The challenges faced in the context of quality of portable equipment, ergonomic interior design, power and temperature control, storage and internet access is addressed in the concept definition for the assessment van to reach its full potential. The requirements and subsystems necessary to develop an AAC vehicle concept are defined following the Systems Engineering Life Cycle Model as defined by Kossiakoff et. al [29], as depicted in Figure 6. The concept development stage of the van consists of three phases: needs analysis, concept exploration, and concept definition. Figure 6 shows these phases, their principal activities, inputs, and outputs.

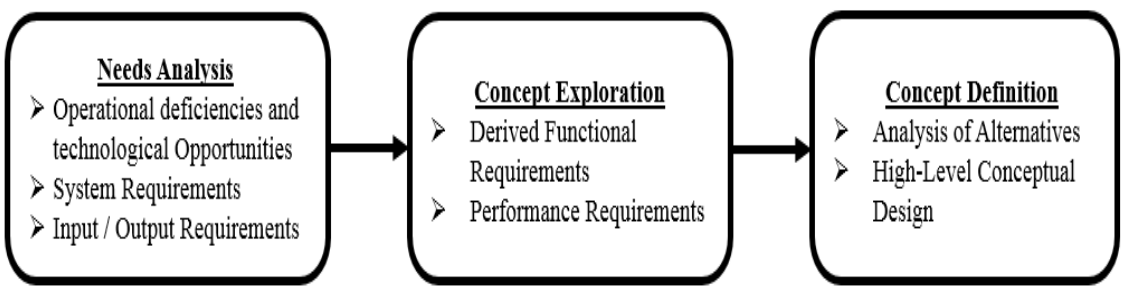

Figure 6: Concept development phases for the assessment van

Needs Analysis Phase

The primary objective of the needs analysis phase is to evaluate the needs or technological opportunities driving the origin of a new system. The inputs of this phase are the operational deficiencies and the technological opportunities for the AAC mobile assessment vehicle which produces persuasive arguments that support the need for the system [39]. The output of this phase is a description of the capabilities and operational effectiveness needed in the assessment van. The analysis refines and confirms the customer's needs and states them in terms of system requirements which is used to establish the functional, performance and design constraints of the assessment vehicle.

Concept Exploration Phase

This phase examines potential system concepts in answering the questions "What performance is required of the new system to meet the perceived need?" and "Is there at least one feasible approach to achieving such performance at an affordable cost?" Positive answers to these questions set a valid and achievable goal for the assessment van prior to expending a significant effort on its development. The output of this phase includes two sets of requirements, known as system functional requirements and system performance requirements. With the help of the initial sets of requirements, this phase produces a set of candidate system concepts. A variety of tools and techniques will be used in this phase and range from process methods (e.g., requirements analysis) to mathematically based (e.g., decision support methods) to expert judgment (e.g., brainstorming) [40].

Concept Definition Phase

The concept definition phase defines the framework conveying the clear description of the mobile AAC assessment vehicle. Alternative concepts will be considered, and their relative performance, operational utility, development risk, and the cost will be compared. The concept definition phase considers, refines, discards or adopts alternative concepts. The determined relative merits exposed by the analysis directs the early concept definition of the AAC mobile assessment vehicle.

4.2. Operational Deficiencies & Technological Opportunities

AAC devices are a solution for individuals with limited functional speech to express their needs and to experience a healthy and productive lifestyle. However, several barriers currently exist preventing access to assistive products for individuals in need. The availability of medical services varies greatly geographically. Even in developed countries, many residents need to travel great distances to access good quality healthcare system. The assessment of a patient requiring an AAC device requires the collaboration of Speech-Language Pathologists (SLP), Occupational Therapists (OT) and Physical Therapists (PT) for diagnosis and fitting the patient with the right device [41]. The availability of these health care providers is limited to the medical facilities in large cities. The difficulties of access to healthcare facilities reduce the likelihood of patients seeking follow up care and limiting family support. To address the deficiencies mentioned above, the research aims to develop a prototype definition of a mobile AAC assessment vehicle where individuals in need of AAC can be assessed, prescribed, fitted and given follow-up care. The mobile assessment vehicle provides an avenue for all the services to be accessible to patients at different locations. A predecessor system does not exist to consider operational deficiencies, but with the growing technological advancements, there exists a high scope for work collaboration among various medical professionals through remote and automated assessment administration.

WHO asserts that there is a lack of trained personnel in the field of assistive products to correctly prescribe and fit the right equipment for individuals in need of assistive technology [1]. AAC devices are of little use and are often abandoned if an unsuitable device is assigned to a patient. The proliferation of inexpensive gadgets and growth in technology has changed the landscape for individuals with communication difficulties as AAC devices are cheaper and more universally available. However; the absence of adequate skilled support to perform comprehensive decision-making process to identify appropriate communication systems for patients hampers the ability of AAC users to meet their daily functional communication needs. There exists an opportunity for automating the clinical decision-making process by developing a tool to systematically match the patient's disability profile with the device attributes to recommend the appropriate AAC device for the patient.

4.3. System Requirements

Systems requirements is a set of specifications at the system level that satisfy the stakeholder needs. It encompasses the set of operational, functional, physical or performance requirements necessary for the product accessibility [42]. The composed list of requirements forms the basis for the design, integration and validation activities. After the analysis of desired services and operational needs of the mobile AAC assessment vehicle, the set of systems requirements formulated for design and validation are given below:

1. The AAC assessment vehicle should include a multidisciplinary AAC assessment team to prescribe, fit and provide follow-up care for individuals with AAC needs.
2. The AAC assessment vehicle should include all the necessary medical equipment for the complete evaluation of the patient to be fitted with the appropriate AAC device.
3. The vehicle should be designed to conduct psycho-social, behavioral and neuropsychological evaluations of all ages.
4. The assessment vehicle should possess a built-in power source to supply constant electricity to all the equipment present.
5. The assessment vehicle should be equipped with audio-visual data capturing technology to allow remote assessment.
6. The assessment vehicle should be set up with wireless network for efficient communication, to collect and dispatch information and to complete electronic patient care reports.
7. The vehicle should include an AAC device assignment tool to aid the AAC assessment team in the decision-making process of finding a suitable AAC device for the patient.
8. The vehicle's interior should integrate an optimal environment for behavioral assessments with suitable and adjustable seating.
9. The vehicle should allow for easy access and egress of patients with mobility impairment.

10. The vehicle should be equipped with a range of low-tech devices for immediate communication assistance.

4.4. Input / Output Requirements

In order to fulfill the customer requirements and to improve access to AAC devices for those in need, the mobile AAC assessment van will have six subsystems:

1. Mobile Assessment Vehicle
2. Electrical System
3. Network and Audio-Visual System
4. Medical Equipment
5. Human Resource Team
6. AAC Device Assignment Tool

Mobile Assessment Vehicle

The mobile assessment vehicle subsystem shall provide space and transportation output for all the subsystems. The vehicle requires energy in the form of fuel, electricity or a combination of both to power its engine. The vehicle shall provide enough space to accommodate the necessary medical equipment and ergonomic interior for optimal assessment of the patient.

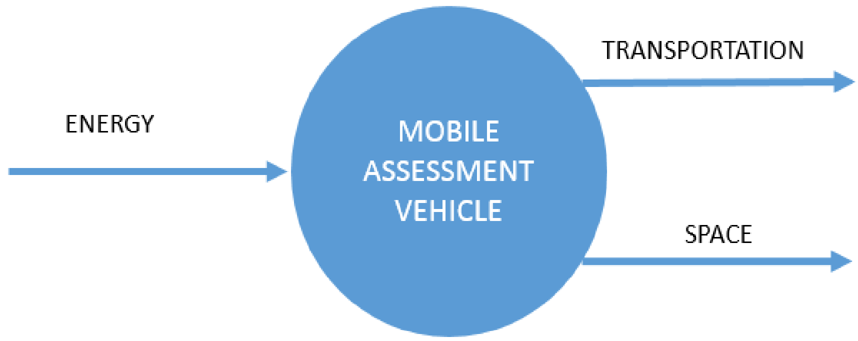

Figure 7: Input and output requirements for the mobile assessment vehicle

Electrical System

The electrical subsystem is responsible for providing power to the equipment, audio-visual data capturing subsystem, air conditioning, and lighting.

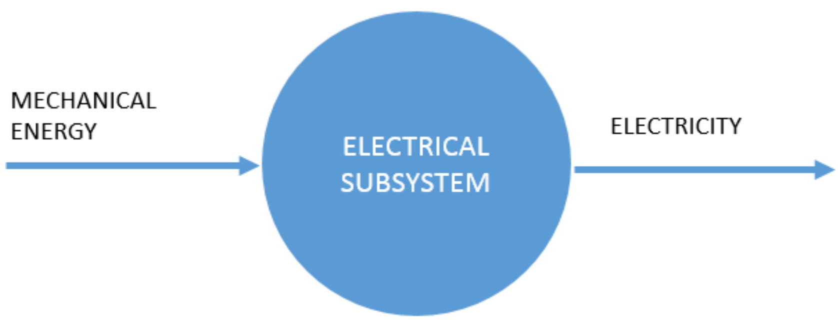

Figure 8: Input and output requirements for the electrical subsystem

Network and Audio-Visual System

The installation of wireless network system in the vehicle shall help in the transfer of vital data and remote assessment of patients by medical professionals at different locations. The network system uses electricity as an input to provide wireless communication for the system. The audio-visual data capturing subsystem with the help of electrical and network subsystems are used for remote or reviewed assessments of patients by medical professionals who cannot be present in the vehicle.

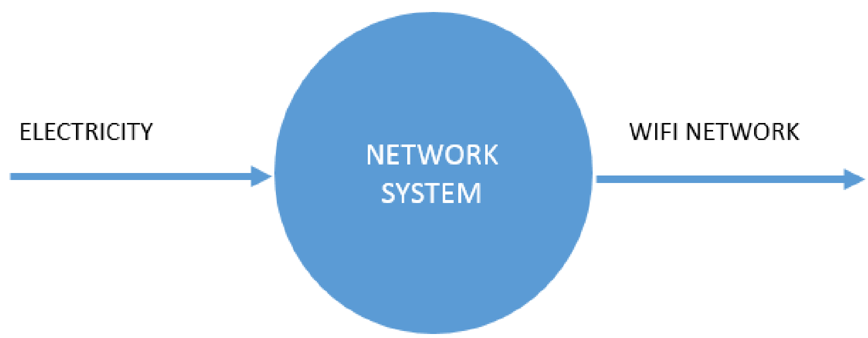

Figure 9: Input and output requirements for the network system

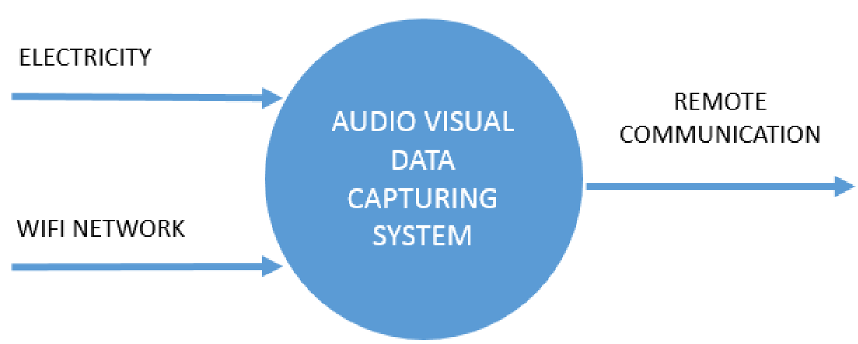

Figure 10: Input and output requirements for the audio-visual system

Medical Equipment

The medical equipment shall be powered by the electrical subsystem and shall be used by the AAC medical professionals for assessment of individuals in need of AAC to select a set of suitable devices for the AAC user.

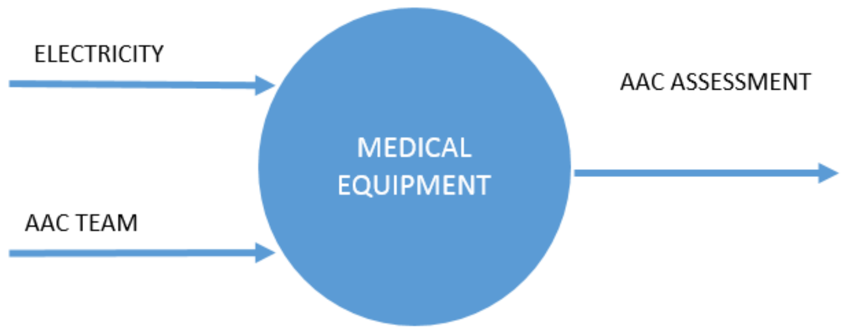

Figure 11: Input and output requirements for the medical subsystem

AAC Device Assignment Tool

The AAC device assignment tool improves the decision-making process by matching the disability profile of the patients with the attributes of the devices to select the best group of devices to be recommended to the patient.

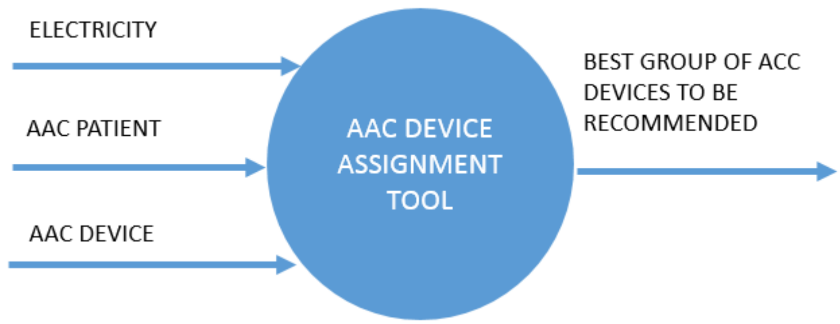

Figure 12: Input and output requirements for the AAC device assignment tool

Human Resource Team

The assessment process for determining a suitable AAC device often involves the collaboration of a wide range of healthcare professionals. The human resource team makes use of all the other subsystems to provide assessment for an individual in need of AAC.

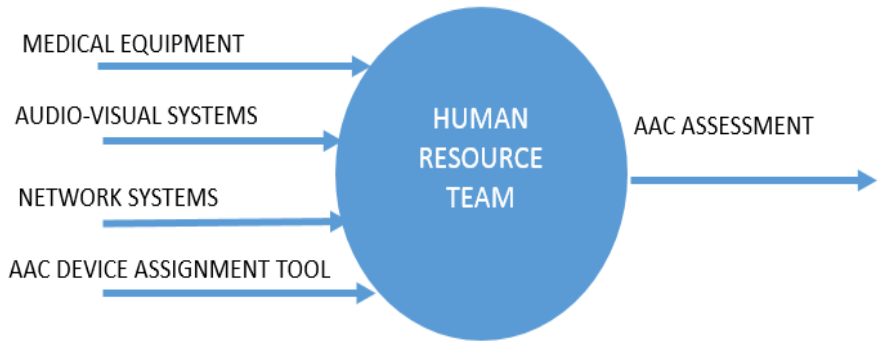

Figure 13: Input and output requirements for the human resource team

AAC User

AAC users are individuals who encounter difficulty in communication due to congenital or acquired disabilities. Selection of a suitable AAC system can increase the quality and quantity of their interactions with others [43]. The AAC assessment by various medical professionals aid in producing the output of finding the suitable device for the patient. Traumatic Brain Injury (TBI) accounts for a large portion of AAC patients [41]. Cerebral palsy, developmental disabilities, and individuals who have suffered stroke or spinal cord injury form a large group of AAC user among adults. A well-chosen AAC device incorporates the user's strengths such as their existing speech, vocalization, and gestures. Speech generation for individuals without the ability to use their hands can be done using eye-tracking, head-pointing, joystick or switches. The use of a suitable AAC device maximizes the AAC user's communication abilities effectively and efficiently.

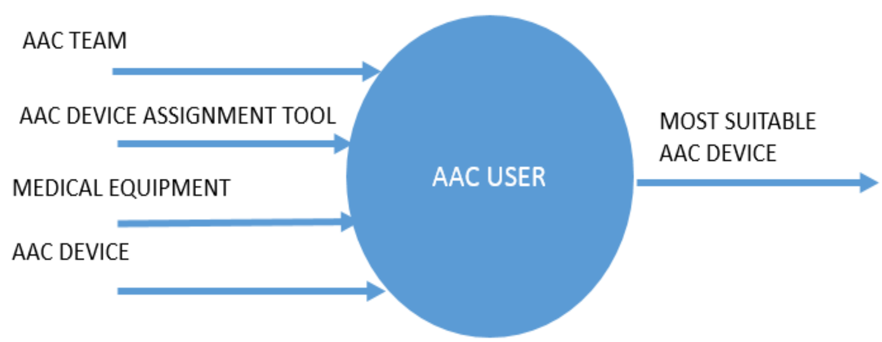

Figure 14: Input and output requirements for the AAC user

4.5. Derived Functional Requirements

The derived functional requirements describe the system functions and tasks to be performed qualitatively. They relate the functionality of the system with the customer requirements to form the basis for specified-solutions in the system design process.

Mobile Assessment Vehicle

There are several choices of vehicles to build a mobile assessment clinic. The expected size, feature and equipment requirements will determine the type of vehicle to be used. The functional requirements described in the section shall be used to identify potential vehicles that satisfy the system needs. The mobile assessment vehicle shall be flexible to be customized for AAC assessments and shall be large enough to accommodate the necessary equipment. The assessment van's interior shall be designed to house the following:

- Examination room
- Audiological booth
- Vision screening
- Waiting area
- Countertop and a sink
- Refrigerator for storage of biological specimens
- Storage space for the aac devices
- Wheelchair lift and ramp
- Fire extinguisher / safety alarms / first aid kit
- Driver's cabin

- Generator, batteries, and inverter

It shall also incorporate trauma lighting, air conditioning to provide an ambient atmosphere for assessment

Electrical System

The vehicle needs to provide sufficient power to operate the various specialized equipment during assessment and travel. Large vehicles that support numerous equipment usually have two electrical systems, a 12-volt system and a 120-volt system [44]. The 12-volt system powered by batteries helps to start the van and power some small loads. The 120-volt electrical system is powered by large generators or electrical hookup plugs which powers the electrical instruments installed in the van. Exceeding the available wattage can trip the electrical unit of the system. It is highly essential to install an inverter in the vehicle to ensure smooth operation.

Network and Audio-Visual System

Due to lack of availability of professionals specializing in AAC and the limited space available in the vehicle, some of the collaboration to determine the apt AAC device for the patient will require remote assessment using video conferencing. Internet access is essential for the remote diagnosis of the patient and for the communication of crucial information regarding the assessment with medical professionals who cannot be present in the vehicle. However, network is intermittent and exhibits slow speed while traveling to rural areas. In such cases, the video recorded during the assessment can be reviewed by professionals in later stages to suggest their recommendations. Compact cameras can be placed at various locations in the vehicle for video conferencing and to record the complete assessment for further evaluation by the AAC team.

Medical Equipment

AAC assessment and decision-making process is a complex process and limited guidelines exist for clinical practice. SLPs with varying level of experience approach the process with different strategies [41]. An adaptive seating and positioning chair shall be used to find the optimal seating for the patient. Diagnosis equipment shall be present for analyzing the sensory abilities of the AAC user. Audiological booths perform hearing tests without background noise interfering with audiometric testing. Compact and portable audiological booths are available to provide sound isolation with maximum flexibility in mobile clinics. Portable vision screening equipment can be used to identify the presence of a vision problem.

AAC Devices

An essential part of the evaluation process includes the trial of various AAC equipment and strategies to identify a suitable device for the individual in need [45]. AAC devices can be high-technology, mid-technology, or low-technology [43]. High-technology AAC devices are mostly personal computers or tablets, in the form of an app on a tablet or an eye gaze system running on a computer. Mid-technology AAC devices employ an electronic component like a button or grid of buttons that can be recorded with messages. A low-technology form of AAC employs non-electronic physical artifacts, like words and pictures. The vehicle shall carry a few of the devices from each category for the patient to try and choose based on their potential and need. The assessment vehicle shall also accommodate printers and laminators to produce low-tech communication binders for the immediate use of AAC patients.

AAC Device Assignment Tool

The AAC device assignment tool can help to improve the decision-making process for patients in need of AAC. The tool can be developed using optimization models and solution algorithms that can help in recommending the best (top three) group of devices to consider for a patient based on a disability profile. The number of devices available is large because no single device can offer efficient and effective communication to all people with complex communication needs. However, there is a substantial gap between the need for and the provision of assistive technology assessment available. The number of devices available is large because no single device can offer efficient and effective communication to all people with complex communication needs. The device assignment tool can help to improve the decision-making process for patients in need of AAC by matching the conforming attributes of the patient's diagnostic profile with the devices' attributes to select the devices with the highest fitting score to be recommended for the patient.

Human Resources Team

The AAC assessment process typically involves the collaboration of multiple healthcare providers at different points in the process. General practice SLPs are typically responsible for supervising AAC assessments. SLPs are professionals who focus in the area of communication but may not specialize in AAC. The SLPs who specialize in AAC and often work with AAC users for assessment and treatment processes are called AAC specialists. Occupational Therapists (OTs) and Physical Therapists (PTs) are two of the most critical collaborators involved in the assessment process. They assist in the process by dealing with the seating, positioning, and device access issues. Vision Specialists and audiologists provide critical information about the sensory diagnosis of the patients. A wide range of other medical and educational professionals like physicians, nursing assistants, special education teachers, etc. may be involved in the assessment process. However, the extent of their involvement varies drastically among AAC patients.

4.6. Performance Requirements

Performance requirements describe the specifications of a system to perform the derived functions, generally evaluated in terms of quantity, coverage, accuracy or timeliness [46]. The set of performance requirements can be traced back to the customer requirements and indicates the extent to which a task must be executed for the success of the system. The performance requirements of each system involved in the proposed model are discussed in terms of their figure of merit in this section.

Mobile Assessment Vehicle

Based on the functional requirements discussed in section 0, two types of vehicles are considered as candidates for the choice of the mobile assessment vehicle. The specifications for a diesel-engine heavy-duty vehicle and an all-electric battery powered heavy-duty vehicle are depicted in Table 7 and Table 8 respectively. The merits of each type of vehicle are further analyzed in section 4.7.

Table 7: Specifications for the diesel mobile assessment vehicle [47]

Attribute	**Specification**
Engine	Ford Engine: 6.8L Triton V10 Transmission
Horsepower	320 HP @ 3,900 RPM
Torque	460 lb.-ft. @ 3,000 RPM
Alternator	175 Amp
Fuel Capacity	100 Gallons
Cost	$114,000
Mileage	6 MPG - 11 MPG

Table 8: Specifications for the electric mobile assessment vehicle [48]

Attribute	**Specification**
Model	Tesla-Semi: All-electric battery powered
Powertrain	Four independent motors on rear axles
Energy Consumption	2 kWh per mile
Charger	Tesla Megacharger charging station
Cost	$180,000
Electric Range	500 miles

Electrical System

The electrical system of the mobile assessment vehicle shall comprise of a battery to power the light-duty appliances and a generator to power the larger appliances. The vehicle shall also be equipped with an inverter to turn DC power to AC power. The specifications for each electrical system are illustrated in Table 9.

Table 9: Specifications for the electrical system

Attribute	Specification
Generator [49]	
Model	12 HP 120/240 -Volt Diesel Motor
Running Wattage	8300 Watts
Runtime	8.5 hours
Inverter [50]	
Continuous Output Power	5000 Watts
Output Voltage	120Vac
Charger Rate	140Amp
Battery [51]	
Number of batteries	9
Capacity	126(Ah) Amp hours,
Reserve capacity	240 minutes

Network and Audio-Visual System

The main purpose of network and audio-visual system is to provide remote diagnosis of the patient. Personal computers are used for communication and storage purposes and their attributes are specified in Table 10. Internet access is provided with the help of Wi-Fi-routers detailed in Table 11.

Table 12 outlines the characteristics of the web-cameras to be used for remote visual communication and recording of assessments.

Table 10: Specifications for the personal computers [52]

Attribute	Specification
Model	Similar to: XPS Tower
Processor	8th Generation Intel® Core™ i7 Processor
Storage	1TB SSD
RAM	32Gb
Operating system	Windows 10

Table 11: Specifications for the Wi-Fi Network [53]

Attribute	Specification
Model	Similar to: Netgear R7000P
Speed	Up to 2300 Mbps
Port	Gigabit Ethernet ports (4 LAN & 1 WAN)
WIFI band	Simultaneous dual-band 2.4 & 5GHz
Security	Wi-Fi Protected Access® (WPA/WPA2—PSK) and WEP

Table 12: Specifications for the audio-visual system [54]

Attribute	Specification
Model	Similar to: Sarix® IMP Indoor and Environmental Mini Domes
Number of web-cameras	4
Resolution	Up to 5 megapixels
Frame rate	30 images/sec
Sensors	Motion detection and camera sabotage detection
Local Storage	Up to 64 GB on Micro SD

Medical Equipment

This section details the medical equipment used in the decision-making process of fitting an AAC device for an individual with communication impairments. Table 13 describes the function and features of the equipment to be included in the mobile AAC assessment vehicle.

Table 13: Specifications for the medical equipment

Function	Medical Equipment	Features
Vision Screening	Vision Screener [55]	• Automated vision screening device • Wireless easy export of data • lights and sounds to help engage children • minimal user training required
Hearing Test	Portable Audiology Booth [56]	• Shipped fully equipped and assembled • Noise-Lock magnetic-seal doors • Tranquil-Aire silent forced ventilation system • Casters for ready positioning or repositioning of the booth • Floor area is less than eight sq. ft.
Adjustable Seating	Reclining medical Treatment Chair [57]	• Fully automated adjustable comfort and client positioning • Extendable headrest and foot cushion • Remote controlled positioning • Swing-away arms for easy mounting and dismounting

AAC Devices

Table *14* presents an array of diverse AAC devices that shall be present in the vehicle for multiple device trials over an extended period of time. These trials help the specialists to collect data regarding the communication possibilities for the patient.

Table 14: Specifications for the AAC devices [58]

Nonelectronic All Devices	**Electronic (Direct) Devices**	**Electronic (Indirect) Devices**
Hand-held stylus	Light pointers	Pneumatic switch
Pointers (head, foot)	Infrared pointers	Rocking lever switch
Splints	Eye-gaze systems	Tread switch
Keyguards	Joysticks	
Mouthstick	Optical head pointers	

AAC Device Assignment Tool

The AAC device assignment can be executed using two different solution methods as mentioned in Chapter 3 of the thesis. The characteristics of the solution methods are mentioned in Table 15 and the merits of each of the solution methods are further analyzed in Table 18.

Table 15: Specifications for the AAC device assignment tool

Function	Specification
Solution Algorithm	
Coding Language	Hypertext Preprocessor (PHP)
Database Management	Structured Query Language
Software Tool	phpMyAdmin
Integer Programming Model	
Software Tool	Excel OpenSolver

Human Resource Team

The AAC team members provide an array of knowledge to generate the best possible solutions for individuals with complex communication needs. The AAC team typically involved in the assessment process is presented in Table 16.

Table 16: Specifications for the human resource team [36]

Function	Human Resource
AAC Evaluation	Speech-Language Pathologist
	AAC Specialist
Collaborating Professional	Physical Therapist
	Occupational Therapist
	Vision Specialist
	Learning Specialist
Support system for AAC user	Family Member / Caretaker
Vehicle Handling	Vehicle Driver

4.7. Analysis of Alternatives

The purpose of analysis of alternatives is to compare the overall effectiveness of alternate solutions available to satisfy system requirements. The operational and cost effectiveness of the alternate solutions are analyzed to select candidate solutions.

Mobile Assessment Vehicle

The vehicle should be capable of traveling great distances for the assessment of patients and needs to be large enough to accommodate the necessities for the assessment. With a wide array of choices for customizable vehicles, choosing a suitable one is essential because the assessment vehicle is a significant investment and it supports all the other subsystems during the entire process. Two different types of heavy-duty vehicles are considered for the choice of the mobile assessment vehicle, namely, a diesel-engine heavy-duty vehicle and an all-electric battery-powered heavy-duty vehicle. Table 17 illustrates and compares the attributes of the vehicles.

Table 17: Comparison of diesel engine vehicle and electric-powered vehicle for the mobile assessment vehicle [47, 48]

Diesel engine heavy-duty vehicle	**All-electric battery powered heavy-duty vehicle**
Medium-level safety features like anti-collision	Best safety features to ensure complete safety of the system
Availability of fuel even in remote areas	Supercharger stations are rare especially in rural areas
Fueled by diesel with 100 gallons capacity and 6-11 MPG	Electric powered and requires to be charged every 500 miles
Base Cost: $114,000	Base Cost: $180,000
High Diesel fuel costs	Low electric energy costs

The choice of the vehicle aims at maximizing operational effectiveness while reducing total cost of ownership. Although the safety features and the low total operational costs due to the low electric energy prices favor the choice of the all-electric battery-powered vehicle, the mobile assessment vehicle is required to go to rural areas for the assessment of Individuals in need of AAC devices. Most areas across the United States still does not have access to electric vehicle chargers. Until the technology advances enough to provide electric charging station in most rural areas in the country, the concept of using an all-electric vehicle for the design of an AAC mobile assessment vehicle is not feasible.

AAC Device Assignment Tool

The role of the AAC device assignment tool is to provide a systematic automated process of matching the patient's disability profile with the attributes of the devices to find the best suitable device for the patient. Two different solution methods namely, an Integer Programming approach and a solution algorithm approach. The comparison of the two different models are stated in Table 18.

Since both the integer programming model and the solution algorithm produce the same results, the process of selecting the tool to be used in the mobile AAC assessment vehicle is based on the ease of use of the tool. The device assignment tool is to be utilized by medical professionals with little to no experience with mathematical modeling and integer programming. It is evident from the comparison shown in Table 18 that the solution algorithm proves to be more efficient in terms of utilization by healthcare professional for the determination of the best-suited device for an AAC user.

Table 18: Comparison of the integer programming model and the solution algorithm for the AAC device assignment tool

Integer Programming Model	**Solution Algorithm**
Requires sophisticated optimization solvers	Uses easily available web-based software
Building the model is long and exhausting	Building the model is quick and simple
Requires knowledge of mathematical modeling to read and understand the model	Simple coding makes the model easy to understand
Significant changes to the model require the knowledge of Integer Programming	Significant changes to the algorithm can be made in simple steps and do not require in-depth knowledge of the coding language
Programming, database management, and execution can be performed in a single software tool.	Requires the use of several tools separately for programming, database management, and execution.

Do Nothing Alternative

The simplest alternative is always the 'do nothing' scenario. However, as stated in the needs analysis phase, there exists a grave deficiency in the access of assistive products for individuals in need to experience a productive lifestyle. The design of the mobile AAC assessment is part of a global commitment to improve access to assistive technology for people with acquired or degenerative communication disorders. With the increase in availability of inexpensive gadgets and growth in technology, there is high opportunity to advance the lives of individuals with limited functional speech [59]. The design of the mobile AAC assessment can have a high impact in improving medical care delivery around the world.

4.8. High-Level Conceptual Definition

High-Level Concept Definition (HLCD) is used for establishing a common framework in the early stage of the system development cycle. HLCD is constructed to lay the foundation for the definition of system requirements. It may be performed on an iterative basis throughout the life-cycle of the system development to identify candidate systems to satisfy user expectations [60].

Design Recommendation

The mobile AAC assessment vehicle concept is developed to facilitate AAC assessment service delivery available for individuals with complex communications needs. This section describes the candidate systems recommended to be further explored to meet the system expectations. A diesel-engine heavy-duty vehicle with a fuel capacity of 100 Gallons is considered for the assessment vehicle. The vehicle shall include ramps and winches to allow easy access of patients with low mobility. The electrical system of the vehicle shall be equipped with a battery and a generator to power the appliances as well as an inverter to convert DC power to AC. Remote assessment of AAC patients can be made available with Wi-Fi routers, personal computers and web-cameras installed in the AAC vehicle.

A multidisciplinary AAC team with medical and educational professional shall be present in the AAC vehicle to evaluate and fit the patients with the best-suited AAC device. The medical evaluation of the patient shall be conducted using a medical reclining chair and medical exam tables for adjustable positioning. Vision testing shall be conducted with the use of vision screeners that can easily export the data obtained over wireless network. A portable audiology booth shall be custom built into the assessment vehicle to allow for audiological testing. An array of low-, mid-, and high-technology AAC devices shall be carried in the AAC vehicle for trials by the patient to help the medical professional evaluate the possible device selections. The assessment vehicle shall include personal computers with the AAC device assignment solution algorithm to reduce the device assessment time by recommending a limited list of best-suited AAC devices based on the patient's disability profile. Figure 15 depicts the visual representation of the recommended design and the set of elements included in the vehicle to satisfy the system requirements.

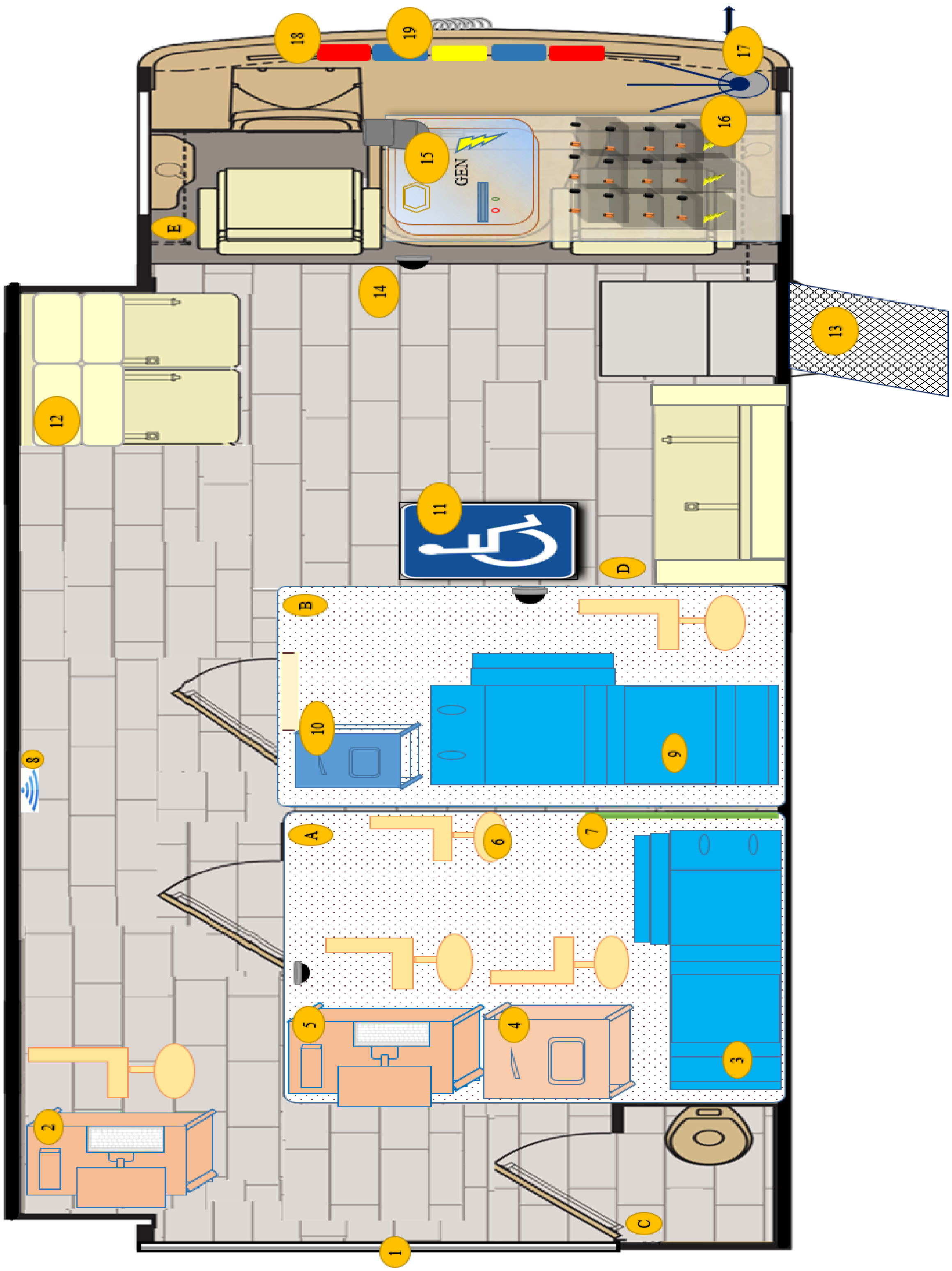

Figure 15: High-level system architecture of the mobile AAC assessment vehicle

Area:

A – Checkup booth

B – Audiological booth

C – Lavatory

D – Waiting area

E – Driver's cabin

1.Tail lift

2.Personal computer

- Printers
- Laminator
- Binder

3.Medical reclining chair

4.Medical Exam table

5.Personal computer

6.Doctors' chair

7.Vision screening

8.High-performance LTE-advanced vehicle router

9.Medical reclining chair

10. Medical Exam table

11. Wheelchairs

12. Waiting chairs

13. Ramp

14. Web-camera

15. Generator

16. Batteries & inverter

17. System Emergency Light

18. Winches

19. Fire extinguisher, safety alarm and first aid kit

Table 19 illustrates the set of actions used to check the compliance of the recommended system with the system requirements discussed in section 4.3. Validation of the system with the system requirements marks a milestone in the systems engineering process and it may be performed on an iterative basis throughout the development cycle of the system [61].

Table 19: Set of requirements that satisfy the system needs

System Requirements	Set of Elements that Satisfy the System Requirements
The AAC assessment vehicle shall include a multidisciplinary team to prescribe, fit and provide follow-up care for individuals with AAC needs.	The AAC multidisciplinary team shall use their expertise to identify a suitable device for the patient. The team includes: • Speech-Language Pathologist • AAC Specialist • Physical Therapist • Occupational Therapist • Vision Specialist • Audiologist • Learning Specialist
The assessment vehicle should possess a built-in power source to supply constant electricity to all the equipment present.	The electrical subsystem is designed to provide power constant power to other subsystems throughout the assessment and travel. It includes: • Generator • Battery • Inverter

Table 19 : Continued

The AAC assessment vehicle should include all the necessary medical equipment for the complete evaluation of the patient.	The medical equipment for analyzing the capabilities of the patient include: • Reclining Medical Treatment Chair • Portable Audiology Booth • Vision Screener
The assessment vehicle shall be equipped with audio-visual data capturing technology to allow remote assessment.	The audio-visual system for remote and reviewe assessment shall include: • Wi-Fi Routers • Personal computers • CCTV cameras
The assessment vehicle shall be set up with wireless network for efficient communication, to collect and dispatch information and to complete electronic patient care reports.	The wireless network system for the transfer of data shall be done using: • Dual-band Wi-Fi Routers • Personal Computers

Table 19 : Continued

	The design of the vehicle for patient evaluations shall include: • Reclining Medical Chair • Ramp • Tail Lift • Trauma Lighting
The vehicle shall include an AAC device assignment tool to aid the AAC assessment team in the decision-making process of finding a suitable AAC device for the patient.	The disability profile of the patient can be matched with the device attributes using: • AAC Assignment Optimization Tool • AAC Assignment Algorithm
The vehicle's interior should incorporate an optimal environment for behavioral assessments with appropriate and adjustable seating.	To provide an ambient environment for the diagnosis of the AAC users, the vehicle shall include: • Reclining Medical Treatment Chair • Exam Table • Trauma Lighting • Air Conditioning

Table 19 : Continued

The vehicle shall allow for easy access and egress of patients with mobility impairment.	The vehicle shall be customized with the following to allow easy access for patients: • Tail lift • Ramp • Winches
The vehicle shall be equipped with a range of low-tech devices for immediate communication assistance.	Communication charts for AAC users can be easily made available for immediate use by means of: • Printers • Laminator • Binder

5. CONCLUSION

AAC assessment is a complex process that involves many professionals to effectively serve patients with complex communication needs. There is a substantial gap between the need for and the provision of assistive technology assessment available. Selection of an unsuitable AAC device can result in abandonment of the device which can lead to loss in time and effort and reduce the likelihood of patients seeking follow up care for effective communication. Therefore, pairing the competencies of the AAC user with a fitting communication system, method of access and feedback techniques is crucial.

The model presented in this thesis, is solved by using both Integer programming and a solution algorithm. The solution algorithm is proposed for easier use without the need of sophisticated solvers. The optimization model and algorithm proposed in this research administer the decision-making process by matching the conforming attributes of the patient's diagnostic profile with the devices' attributes to select the devices with the highest fitting score to be recommended for the patient. The computational study in the paper demonstrates that the overall device satisfaction score is always equal for the optimization model and the algorithm.

Several factors contribute to the overall device satisfaction score; the factors include 'Patient condition', 'Number of devices available', 'Assessment weight distribution' and 'Minimum level of assessment satisfaction'. The effects of the factors on the overall device satisfaction are studied using ANOVA analysis and interaction plots in the computational study. The study demonstrates that 'Assessment weight distribution' has very low significance on the overall device satisfaction. It is observed that the factors with the highest influence on the overall device satisfaction score are 'the number of devices available’ and ‘patient condition’. It can be seen that finding a well-suited device can be challenging. The probability of finding devices that satisfy the needs of a patient with severe medical conditions is lower compared to a patient with moderate or minor medical condition when very few devices are available as choices. The probability of finding devices with a high level of satisfaction is higher for patients with minor medical conditions. When number of devices available is low, the level of assessment satisfaction can be reduced to find devices with matching attributes.

Researchers have expanded the allocation model along several dimensions; however, research in the context of assignment of AAC medical devices to patients is novel. The research aims to bridge the substantial gap between the need for and the provision of assistive technology assessment available around the world.

AAC devices have great potential to improve the quality of life for people of all ages with severe communication impairments. The devices enhance educational opportunities and facilitate independence and development of social relationships [4]. With technology advancements, the available options in high-tech AAC devices have rapidly increased over the years. AAC devices and strategies are tailored to the specific skills and needs of the individuals and there exists no standard protocol for assessments. Because of the various assessments requiring skills related to an array of medical and educational professionals, multiple appointments are often needed to find a suitable AAC device. The availability of the skilled professionals trained in AAC is often limited to the well-funded medical facilities in large cities. A large portion of people in need of AAC devices for communication has difficulty accessing these medical facilities. An AAC mobile assessment vehicle with the primary goals of assessing, prescribing and fitting AAC devices for individuals in need, aims at providing an avenue to improve access to AAC devices to improve the quality of life for those in need.

This research develops a concept definition of the mobile AAC assessment vehicle using the systems engineering life cycle model. The high-level conceptual design of the system is carried out in three phases of needs analysis, concept exploration and concept definition. The needs analysis phase addresses operational needs and the technological availability that drives the origin of the AAC mobile assessment vehicle. To fulfill the system requirements, the mobile assessment vehicle will have six subsystems, assessment vehicle, electrical system, network and audio-visual system, medical equipment, AAC devices, AAC device assignment tool, and human resource team.

The functional and performance requirements to meet the capabilities of the assessment vehicle are explored and stated in the concept exploration phase. The AAC assessment vehicle was chosen based on spatial requirements and the cost of operation of the vehicle. The mobile assessment vehicle is designed to be equipped with advanced wireless network routers and audio-visual equipment for the use of AAC specialist and the collaborating professionals for remote and reviewed assessment. The lack of adequate skilled support in the clinical decision-making process shall be addressed by the AAC device assignment tool developed in chapter 3. The device assignment tool using solution algorithms shall assist in the process of selecting the best fitting devices for the patients. The AAC mobile assessment vehicle reduces the patient's current need for attending multiple appointments at different locations with different professionals and encourages individuals in need to access AAC to improve their lives. The design of an AAC mobile assessment vehicle can have a global impact and can revolutionize medical service delivery in different parts of the world.

APPENDIX SECTION

APPENDIX A

<u>PHP program to generate the maximum weighted score devices</u>

```php
<?php

$minSumValue = 10;

//$pEvalScores stores the Patient Evaluation Score

$pEvalScores = array();



//$aWeights stores the Assessment Weights

$aWeights = array(0.1,0.05,0.1,0.1,0.05,0.025,0.2,0.025,0.1,0.025,0.05,0.1,0.075);



//$noOfDevices stores the Maximum Number of Devices

$noOfDevices = $_POST["devicesCount"];



$pEvalScores[] = $_POST["v1"];

$pEvalScores[] = $_POST["v2"];

$pEvalScores[] = $_POST["v3"];

$pEvalScores[] = $_POST["v4"];

$pEvalScores[] = $_POST["v5"];
```

```
$pEvalScores[] = $_POST["v6"];

$pEvalScores[] = $_POST["v7"];

$pEvalScores[] = $_POST["v8"];

$pEvalScores[] = $_POST["v9"];

$pEvalScores[] = $_POST["v10"];

$pEvalScores[] = $_POST["v11"];

$pEvalScores[] = $_POST["v12"];

$pEvalScores[] = $_POST["v13"];



/*

for($i=0;$i<count($pEvalScores);$i++){

	echo $pEvalScores[$i]." ";

}

*/



$servername = "localhost";

$username = "root";

$password = "";
```

```
$dbname = "assessment";


// Create connection
$conn = new mysqli($servername, $username, $password, $dbname);


// Check connection
if ($conn->connect_error) {
   die("Connection failed: " . $conn->connect_error);
}


$sql = "SELECT * from devices";
$result = $conn->query($sql);
if ($result->num_rows > 0) {
   while($row = $result->fetch_assoc()) {
          $dScores = array();
      $dScores[] = $row["dname"];
      $dScores[] = $row["d1"];
      $dScores[] = $row["d2"];
```

```
$dScores[] = $row["d3"];

$dScores[] = $row["d4"];

$dScores[] = $row["d5"];

$dScores[] = $row["d6"];

$dScores[] = $row["d7"];

$dScores[] = $row["d8"];

$dScores[] = $row["d9"];

$dScores[] = $row["d10"];

$dScores[] = $row["d11"];

$dScores[] = $row["d12"];

$dScores[] = $row["d13"];

$sum = 0;

$weight = 0.0;

for ($i=1; $i < count($dScores); $i++) {

   if($pEvalScores[$i-1] >= $dScores[$i]){

            $sum = $sum + 1;

            $weight = $weight + $aWeights[$i-1];

   }
```

```
        }
        if($sum >= $minSumValue){
                            $sql = "INSERT INTO dweights VALUES
('$dScores[0]','$weight')";
                            if (!($conn->query($sql) === TRUE)) {
                                echo "Error: " . $sql . "<br>" . $conn->error;
                            }
        }
    }
}
else
{
    echo "0 rows in devices table";
}
$sql = "SELECT * FROM dweights order by weight DESC";
$result = $conn->query($sql);
$count = 0;
if ($result ->num_rows > 0) {
    while($row = $result->fetch_assoc()) {
```

```
            echo "Device No is: ".$row["dname"]." and Total Weighted Device score is:
".$row["weight"];
            echo "<br>";
            $count = $count + 1;
            if($count == $noOfDevices){
                        break;
            }
    }
}
else{
            echo "0 rows with Total Match Score greater than or equal to $minSumValue";
            echo "<br>";
}
$sql4 = "DELETE FROM dweights";
$conn->query($sql4);
$conn->close();
?>
```

APPENDIX B

C++ Program to Create SQL Insert Statements

```
/*
A program that reads comma seperated values(integers or strings or characters) from the
input file (input.txt) and create a sql insert statement(s) and are stored in the output file
(ouput.txt).
*/
#include <iostream>
#include <vector>
#include <sstream>
using namespace std;
int main() {

  //The input file is specified in the next line
  freopen("input.txt","r",stdin);

  //The output is stored in the output.txt
  freopen("output.txt","w",stdout);

  string line;
  vector<string>values;
  string n;
  char ch;
  //Variable which has the tableName as it's value - change accordingly
  string tableName = "devices";
```

```
 //Variable that tells the no of Columns for the table - change accordingly
 int noOfColumns = 14;


 //Each line in the input file is processed by the following loop
 while(getline(cin,line)){
   stringstream ss(line);
   while(getline(ss,n,',')){
     values.push_back(n);
   }

 //Remove the comment in the next line to know the no of Columns in the table
   //cout<<"Size of "<<tableName<<" table is:"<<values.size()<<endl;



   //Printing the query  -- START
   cout<<"insert into "<<tableName<<" values(";

   //noOfColumns in the below for loop can be replaced with values.size() if the no of
Columns in the table are unknown
   for(int i=0;i<values.size();i++){
   if(i==0){
       cout<<"'"<<values[i]<<"'";
```

```
      }
      else{
        cout<<",'"<<values[i]<<"'";
      }
    }
    cout<<");"<<endl;
    //Printing the query -- END

    //Removes all the values read so far
    values.clear();
  }
  return 0;
}
```

REFERENCES

[1] W. H. Organization. (2016). *Global Cooperation on Assisstive Technology*. Available: http://www.who.int/phi/implementation/assistive_technology/en/

[2] W. H. Organization. (2016). *Priority Assisstive Products List*. Available: http://apps.who.int/iris/bitstream/10665/207694/1/WHO_EMP_PHI_2016.01_eng.pdf?ua=1

[3] A. S. L. H. A. (2016). *Augmentative and Alternative Communication*. Available: https://www.asha.org/PRPSpecificTopic.aspx?folderid=8589942773&section=Key_Issues#Assessment

[4] J. M. Johnson, E. Inglebret, C. Jones, and J. Ray, "Perspectives of speech language pathologists regarding success versus abandonment of AAC," *Augmentative and Alternative Communication,* vol. 22, pp. 85-99, 2006.

[5] W. H. Organization. (2014). *International Classification of Functioning, Disability and Health*. Available: http://www.who.int/classifications/icf/en/

[6] X. Su and S. A. Zenios, "Patient choice in kidney allocation: A sequential stochastic assignment model," *Operations research,* vol. 53, pp. 443-455, 2005.

[7] X. Su and S. A. Zenios, "Recipient choice can address the efficiency-equity trade-off in kidney transplantation: A mechanism design model," *Management Science,* vol. 52, pp. 1647-1660, 2006.

[8] D. L. Segev, S. E. Gentry, D. S. Warren, B. Reeb, and R. A. Montgomery, "Kidney paired donation and optimizing the use of live donor organs," *Jama,* vol. 293, pp. 1883-1890, 2005.

[9] P. Biró and K. Cechlárová, "Inapproximability of the kidney exchange problem," *Information Processing Letters,* vol. 101, pp. 199-202, 2007.

[10] M. Akan, O. Alagoz, B. Ata, F. S. Erenay, and A. Said, "A broader view of designing the liver allocation system," *Operations research,* vol. 60, pp. 757-770, 2012.

[11] A. S. Koyuncugil and N. Ozgulbas, "Donor research and matching system based on data mining in organ transplantation," *Journal of medical systems,* vol. 34, pp. 251-259, 2010.

[12] D. Bertsimas, V. F. Farias, and N. Trichakis, "Fairness, efficiency, and flexibility in organ allocation for kidney transplantation," *Operations Research,* vol. 61, pp. 73-87, 2013.

[13] S. Ahmadvand and M. S. Pishvaee, "An efficient method for kidney allocation problem: a credibility-based fuzzy common weights data envelopment analysis approach," *Health Care Management Science,* pp. 1-17, 2017.

[14] Q. Cao and Q. Wang, "Optimizing vendor selection in a two-stage outsourcing process," *Computers & operations research,* vol. 34, pp. 3757-3768, 2007.

[15] R. M. Ebrahim, J. Razmi, and H. Haleh, "Scatter search algorithm for supplier selection and order lot sizing under multiple price discount environment," *Advances in Engineering Software,* vol. 40, pp. 766-776, 2009.

[16] A. S. Erdem and E. Göçen, "Development of a decision support system for supplier evaluation and order allocation," *Expert Systems with Applications,* vol. 39, pp. 4927-4937, 2012.

[17] S.-C. Ting and D. I. Cho, "An integrated approach for supplier selection and purchasing decisions," *Supply Chain Management: An International Journal,* vol. 13, pp. 116-127, 2008.

[18] H. Beauchamp, C. Novoa, and F. Ameri, "Supplier Selection and Order Allocation Based on Integer Programming," *International Journal of Operations Research and Information Systems (IJORIS),* vol. 6, pp. 60-79, 2015.

[19] J. A. Tompkins, J. A. White, Y. A. Bozer, and J. M. A. Tanchoco, *Facilities planning*: John Wiley & Sons, 2010.

[20] L. Chen and Z. Lu, "The storage location assignment problem for outbound containers in a maritime terminal," *International Journal of Production Economics,* vol. 135, pp. 73-80, 2012.

[21] K.-W. Pang and H.-L. Chan, "Data mining-based algorithm for storage location assignment in a randomised warehouse," *International Journal of Production Research,* vol. 55, pp. 4035-4052, 2017.

[22] M. Bazzazi, N. Safaei, and N. Javadian, "A genetic algorithm to solve the storage space allocation problem in a container terminal," *Computers & Industrial Engineering,* vol. 56, pp. 44-52, 2009.

[23] P. R. Harper, V. de Senna, I. T. Vieira, and A. K. Shahani, "A genetic algorithm for the project assignment problem," *Computers & Operations Research,* vol. 32, pp. 1255-1265, 2005.

[24] K.-K. AUNG, C. HILL, J. BENNET, Z. SONG, and N. E. ORIOL, "The emerging business models and value proposition of mobile health clinics," *American journal of accountable care,* vol. 3, p. 36, 2015.

[25] A. Higier, A. Arbide, A. Awaad, J. Eiroa, J. Miller, N. Munroe, *et al.*, "Design, development and deployment of a hybrid renewable energy powered mobile medical clinic with automated modular control system," *Renewable energy,* vol. 50, pp. 847-857, 2013.

[26] J. Ferreira and S. Hignett, "Reviewing ambulance design for clinical efficiency and paramedic safety," *Applied ergonomics,* vol. 36, pp. 97-105, 2005.

[27] S. Hignett, E. Crumpton, and R. Coleman, "Designing emergency ambulances for the 21st century," *Emergency Medicine Journal,* vol. 26, pp. 135-140, 2009.

[28] Y.-R. Chen, C. Chang-Halpenny, N. A. Kumarasamy, A. Venegas, and C. H. Braddock III, "Perspectives of mobile versus fixed mammography in Santa Clara County, California: a focus group study," *Cureus,* vol. 8, 2016.

[29] A. Kossiakoff, W. N. Sweet, S. J. Seymour, and S. M. Biemer, *Systems engineering principles and practice* vol. 83: John Wiley & Sons, 2011.

[30] C. N. Calvano and P. John, "Systems engineering in an age of complexity," *Systems Engineering,* vol. 7, pp. 25-34, 2004.

[31] J. Reilly, A. Hanson, J. Mindock, K. McGuire, and B. Reyna, "Using a Model-Based Systems Engineering Approach for exploration Medical System Development," 2017.

[32] M. Hazare and P. Venhovens, "An Integrated Systems Engineering Method for Conceptual Design of Vehicle Handling Dynamics," *Systems Engineering,* vol. 18, pp. 659-675, 2015.

[33] R. Kopach-Konrad, M. Lawley, M. Criswell, I. Hasan, S. Chakraborty, J. Pekny, *et al.*, "Applying systems engineering principles in improving health care delivery," *Journal of general internal medicine,* vol. 22, pp. 431-437, 2007.

[34] *PHP: Hypertext Preprocessor*. Available: http://www.php.net/

[35] W. H. Organization. *Global Cooperation on Assistive Technology*. Available: http://www.who.int/phi/implementation/assistive_technology/phi_gate/en/

[36] D. R. Beukelman, L. J. Ball, and S. Fager, "An AAC personnel framework: Adults with acquired complex communication needs," *Augmentative and Alternative Communication,* vol. 24, pp. 255-267, 2008.

[37] Z. Matthews, A. Channon, S. Neal, D. Osrin, N. Madise, and W. Stones, "Examining the "urban advantage" in maternal health care in developing countries," *PLoS medicine,* vol. 7, p. e1000327, 2010.

[38] J. Light and K. Drager, "AAC technologies for young children with complex communication needs: State of the science and future research directions," *Augmentative and alternative communication,* vol. 23, pp. 204-216, 2007.

[39] K. Pohl, *Requirements engineering: fundamentals, principles, and techniques*: Springer Publishing Company, Incorporated, 2010.

[40] B. S. Blanchard, W. J. Fabrycky, and W. J. Fabrycky, *Systems engineering and analysis* vol. 4: Prentice Hall Englewood Cliffs, NJ, 1990.

[41] A. DIeTz, W. Quach, S. K. Lund, and M. McKelvey, "AAC assessment and clinical-decision making: The impact of experience," *Augmentative and Alternative Communication,* vol. 28, pp. 148-159, 2012.

[42] D. M. Buede and W. D. Miller, *The engineering design of systems: models and methods*: John Wiley & Sons, 2016.

[43] S. W. Blackstone, M. B. Williams, and D. P. Wilkins, "Key principles underlying research and practice in AAC," *Augmentative and alternative communication,* vol. 23, pp. 191-203, 2007.

[44] L. Phillips Jr, "Exterior power supply connection for recreation vehicles," ed: Google Patents, 1972.

[45] A. Kintsch and R. DePaula, "A framework for the adoption of assistive technology," *SWAAAC 2002: Supporting learning through assistive technology,* pp. 1-10, 2002.

[46] A. Van Lamsweerde, "Goal-oriented requirements engineering: A guided tour," in *Requirements Engineering, 2001. Proceedings. Fifth IEEE International Symposium on*, 2001, pp. 249-262.

[47] *The Diesel Owners Resource*. Available: http://www.dieselhub.com/specs/ford-6.8-triton-v10.html

[48] *Tesla Semi and Roadster*. Available: https://www.tesla.com/semi

[49] *Portable Generator 2 -Speed 12 HP 120/240 -Volt Diesel Motor* Available: https://www.homedepot.com/p/Boss-Precision-Products-Inc-Portable-Generator-2-Speed-12-HP-120-240-Volt-Diesel-Motor-with-Single-Cylinder-Vertical-4-Stroke-Air-Cooled-DY8500LN-D/306061038

[50] *5000 Watt Power Inverter 12V DC to AC 110V 120V*. Available: https://www.sigineer.com/product/5000-watt-power-inverter-12v-dc-ac-110v-120v-140a-builtin-charger-lf-pure-sine-wave-industrial-grade/

[51] *ODYSSEY Extreme Series Battery Model PC2250*. Available: https://shop.odysseybattery.com/p/pc2250

[52] *Dell XPS Desktops*. Available: https://www.dell.com/en-ca/shop/desktops/sf/xps-desktops

[53] *Nighthawk AC1900 Smart WiFi Dual Band Gigabit Router*. Available: https://www.netgear.com/support/product/r7000.aspx

[54] *Sarix IMP Series Indoor Mini Domes*. Available: https://www.schneider-electric.com.eg/en/product-range-presentation/62170-sarix-imp-series-indoor-mini-domes/

[55] *Spot™ Vision Screener*. Available: https://www.welchallyn.com/en/products/categories/physical-exam/eye-exam/vision-screeners/spot-vision-screener.html

[56] *Mini Audiology Booths*. Available: http://www.iacacoustics.com/mini-audiology-booths.shtml

[57] *Preferred Care Recliner*. Available: https://www.phc-online.com/Clinical_Geri_Chair_p/preferred-care-recliner.htm

[58] Types of AAC device, Available: http://www.augcominc.com/whatsnew/ncs5.html

[59] S. Robitaille, *The Illustrated Guide to Assistive Technology and Devices: Tools and Gadgets for Living Independently: Easyread Super Large 18pt Edition*: ReadHowYouWant. com, 2010.

[60] C. Keating, R. Rogers, R. Unal, D. Dryer, A. Sousa-Poza, R. Safford, *et al.*, "System of systems engineering," *Engineering Management Journal,* vol. 15, pp. 36-45, 2003.

[61] *SEBoK Guide to the Sytems Engineering Body of Knowledge*. Available: https://www.sebokwiki.org/wiki/System_Validation